OPTIMUM INTEGRATION OF ALBEDO, SUB-ROOF R-VALUE, AND PHASE CHANGE MATERIAL FOR COOL ROOFS

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ABSTRACT

A cool roof aims to reduce total seasonal cooling loads and peak summer loads. It is often rated just in terms of its solar reflectance R_{sol} (or albedo), with some impact of infrared emittance considered. However the sensitivity of cooling loads to R_{sol} varies as the R-value of sub-roof insulation changes. Knowing joint impacts led to better integrated energy savings design with R-value chosen on the basis of R_{sol} and local climate. This study extends previous work (Gentle et al., 2011) (Smith et al., 2012) (Aguilar et al., 2012) by considering the impact of phase change materials (PCM) within a roofing module on energy savings. The aim is to show how building simulation helps pinpoint the optimum combination.

INTRODUCTION

Ideally in summer PCM's in a roof will store sufficient thermal energy when changing from solid to liquid at the transition or melting/freezing temperature T_c to keep room temperatures comfortable most of the day and be easily discharged at night. This ability will depend on R_{sol} while discharge rates overnight will depend on ambient temperatures, evening sky conditions, roof emittance, and wind speeds. Part of the heat can be discharged into the interior and night ventilation can help this aspect. In this study only the passive use of PCM was considered, though to maximise their impact active thermal control can be used (Rodriguez-Ubinas et al., 2012). Conventional roofs have low R_{sol} of around 0.3, while cool roofs have high R_{sol} and high infrared emittance (Boixo et al., 2012). Emittance is fixed in this study at 0.90 as most (but not all) roofs have high emittance.

The roofing module of interest includes a layer of insulation, and a layer of PCM material which is light, and easy to install. Unlike insulation, which must be installed so that all relevant area is covered, PCM area coverage can be incomplete if desired. The cross section of the roof module is shown in Figure 1.

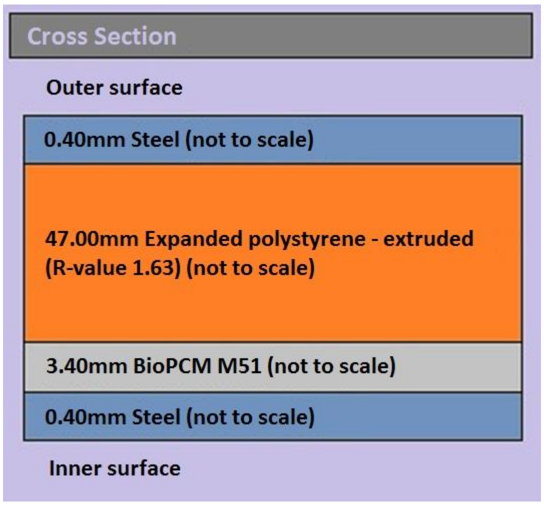

Figure 1 Cross section of the roof structure using PCM and insulation.

ENERGY SIMULATION (TYPICAL SINGLE FAMILY HOUSE)

The data and simulations in this study span sufficient combinations of the four parameters $R_{sol} = 1 - A_{sol}$ (solar absorptance), PCM mass-thickness, T_c, and roof insulation R-value to establish the relative merits of using PCM layers as a function of each of the other roofing parameters, and their various combinations, rules or guidelines for better design integration, and better energy savings result. Simulation studies used "Energy Plus" (energy building analysis and thermal load simulation program) (Energy Plus, 2011) for heating and cooling loads in a typical single family house occupying 186 m^2. From two hundred and seventy two simulations matrices of energy use for each of heating, cooling and total annual load were constructed. Each parameter combination spans all groupings of: A_{sol} set at 0.2, 0.4, 0.6, 0.8; insulation R-value at 0.05, 0.81, 1.63, 2.5 (m^2K/W); with no PCM and various PCM settings. PCM parameters span different PCM mass and T_c values. Product data used are for BioPCM M27, M51, M91 and M182 of thicknesses at 1.8, 3.4, 6 and 12.1mm respectively. T_c values used are 21 °C, 23 °C, 25 °C and 27 °C (Muruganantham, 2010). Infiltration via air changes per hour (ACH) is fixed at 1.0. Roof insulation R-value of 3.2 is typically used in Sydney which still rarely have high Rsol roofs but existing stock mostly have less ceiling or roof insulation. Statistical and parameter cross-coupling analysis has been used to locate optimum designs for energy savings (Cappelletti et al., 2011) (Bambrook et al., 2011).

Simulation results are for a typical moderately sealed, single family house located in a temperate climate: Sydney (Australia), in a cold climate: London (United Kingdom) and in a warm-humid climate: Singapore. The weather data used is the Representative Mean Year (RMY) file for Sydney (Sydney RMY, 2012) and the International Weather for Energy Calculations (IWEC) file for London and Singapore (London Gatwick IWEC, 2012) (Singapore IWEC, 2012).

Modelling a construction with PCM in Energy Plus required the following specific algorithms to be used:

- Surface convection inside: adaptive convection algorithm.
- Surface convection outside: adaptive convection algorithm.
- Heat balance: conduction finite difference.
- Number of time-steps per hour: 20

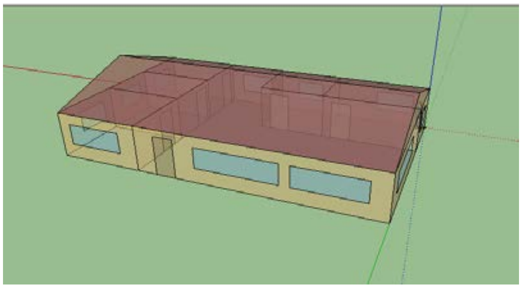

Figure 2 Typical single family house: 186 m^2 with 3 bedrooms, bathroom, open kitchen and living room, without roof space.

Table 1
Parameters

PARAMETERS	VALUE
Roof Solar absorptance	0.2, 0.4, 0.6, 0.8
Roof emissivity	0.9
Roof insulation (R-value)	0.05, 0.81, 1.63, 2.5 (m^2 K/W)
Walls insulation (R-value)	0.91 (m^2 K/W)
BioPCM	No PCM and M27 (1.8mm), M51 (3.4mm), M91 (6mm), M182 (12.1mm)
PCM Transition temperature	21 °C, 23 °C, 25 °C, 27 °C
Infiltration (ACH)	1
Internal Loads	4 people + 14.5 kWh/day: 325 W (lights scheduled) + 800 W (electric equipment scheduled) + 195 W (electric equipment permanent)
Ventilation	4 ACH (scheduled & controlled)
Window Shades	Shade if solar radiation is higher than 200 W/m2 & cooling system was previously ON and also always during the nights
Windows	U-Value=5.8 W/m^2 K, SHGC=0.79
Glazing area:	North: 11.85 m^2 (28.38% W:W) East: 5.90 m^2 (22.65% W:W) South: 6.28 m^2 (15.04% W:W) West: 5.98 m^2 (22.94% W:W)
Cooling Setpoints	25 °C (All year around)
Heating Setpoints	20 °C (All year around)
Internal Mass (m^2 Furniture)	35 m^2
Roof angle	16.15°

RESULTS (TYPICAL SINGLE FAMILY HOUSE)

Sydney

Sydney has a temperate climate, where heating and cooling loads are both significant and can overlap in time to satisfy the required heating and cooling set-points. The following two plots contain a sub-set of results (80 of the 272 simulations) to highlight relative and combined impacts of A_{sol}, roof insulation R-value, without PCM and with different PCM quantities. Only T_c= 25 °C is plotted for clarity as the T_c changes in table 1 had least impact relative to other parameter changes.

Sydney heating loads

Heating loads (MJ/m^2/year) are in Figure 3. The x-axis is divided initially into four sections with A_{sol} 0.2, 0.4, 0.6, 0.8. Each of these is then divided into another four sections for R-values 0.05, 0.81, 1.63, 2.5. The sequence of points for in effect no insulation (R= 0.05) is labelled according to increasing PCM thickness. The same sequence persists for each R-value sub-set. The key result is that large changes in A_{sol} still have little impact, as found without PCM (Smith et al., 2012), so cool roofs will only weakly enhance these winter loads. This enables good integration of low cooling and low heating loads. Reducing A_{sol} is also the lowest cost option.

Other points (i) PCM's have a major impact only if insulation is absent (ii) With ACH just 1.0 higher R-value is worthwhile but ACH dominates if it gets higher (see earlier study (Smith et al., 2012)) (iii) Thicker PCM's reduce heating load but by less than thickening insulation. Issues with space would be the only motivation to thicken PCM for low heating load.

Sydney cooling loads

Cooling loads are shown in Figure 4 using the same plot point divisions used in Figure 3. Key setting impacts are different in this case though again PCM's have greatest impact with no insulation, but with more sensitivity to PCM thickness. Some added insulation is thus needed with the preferred R-value depending on the value of Asol. Then (i) If A_{sol} is low PCM's add little value (ii) Changes in R-value above R-value = 0.81 have little value unless A_{sol} is high. (iii) Loads diminish less with each additional increase in PCM thickness.

The optimum combination, for this home, considering both cooling energy and cost savings is estimated from these results to be with BioPCM M51 (3.4mm) and T_c= 25 ^oC.

Figure 5 shows the sensitivity of cooling loads to changes in PCM thickness and A_{sol} with roof insulation fixed at R-value= 1.63 and PCM T_c= 25 ^oC. It shows that some PCM is of value at all A_{sol} but higher thicknesses are not essential.

Sydney annual loads

In this study T_c= 25 ^oC gave the lowest annual energy consumption. A detailed annual summary and the best overall PCM thickness is in table 2 and 3 for the case where PCM M51 is used and R-value = 1.63 with A_{sol} the leading variable as in the above plots. This is near optimal. In summary roof PCM has use in reducing cooling loads but has minimal value for reducing heating loads.

Relative to no PCM the impacts of PCM for heating range from load gains of 2.51% to reductions of 31.23% and for cooling from load reductions of 3.30% to 47.25%. Simulation has enabled a clear identification of the best combination of parameters. For roofs PCM can be considered in temperate climates, but low roof A_{sol} is the most important factor and has lowest cost.

Table 2
Energy use with No PCM and with PCM M51, T_c = 25^oC for a typical single family house in Sydney

	NO PCM		**PCM M51 T_c 25 ^oC**	
A_{sol}	Heating MJ/m^2/yr	Cooling MJ/m^2/yr	Heating MJ/m^2/yr	Cooling MJ/m^2/yr
0.2	98.2	51.7	96.6	40.3
0.4	96	60.2	94.2	44.1
0.6	94.2	68.8	91.9	48.2
0.8	92.6	77.6	89.8	52.6

Table 3
Savings using PCM M51, $T_{c\,=}$ 25 ^oC for a typical single family house in Sydney

	SAVINGS			
A_{sol}	Heating MJ/m^2/yr		Cooling MJ/m^2/yr	
0.2	1.6	1.6%	11.4	22%
0.4	1.9	1.9%	16.1	26.7%
0.6	2.2	2.4%	20.6	30%
0.8	2.7	2.9%	25	32.2%

Sydney peak cooling loads

Figure 6 shows the peak cooling loads with changes in PCM thickness and roof insulation fixed at R-value= 1.63, A_{sol} = 0.6 and PCM T_c = 25 ^oC. Relative to no PCM peak cooling loads are reduced by 5%, 10%, 15% and 20% using PCM M27 (1.8mm), M51 (3.4mm), M91 (6mm) and M182 (12.1mm) respectively. With no PCM and with roof insulation fixed at R-value = 1.63, reducing A_{sol} from 0.8 to 0.6, 0.4 and 0.2 peak cooling loads are reduced by 8%, 14% and 21% respectively.

Singapore

In Singapore cooling loads are required all year round with cooling set-points at 25^oC, while no heating is needed. From the same set of simulations as Sydney roof PCM is only very useful here if A_{sol} is high with no roof insulation (R-value= 0.05). With R-value = 0.81 PCM was found to have little influence on cooling loads. Despite being cooling dominated, roof PCM becomes useful only when the diurnal temperature variation crosses the phase change temperature for charge and discharge on many days. In Singapore this does not happen enough.

London

London has a cold climate where heating loads are large and cooling loads are small, but the latter will increase with climate change and the urban heat island effect. The passive use of PCM from our simulations only impacts at present with effectively no insulation (R-value = 0.05), but no house in London should have its roof or ceiling uninsulated. For R-value = 0.81 or higher PCM has little influence on heating loads.

Thus roof PCM is thus mainly of use in temperate climates or climates with hot days followed by cool nights, not a common combination in London or Singapore. Use of PCM's in interior walls, which is outside this study may however be worthwhile in London, and even in Singapore if night air conditioning is used to discharge such PCM's.

SIMULATION RESULTS FOR A SYDNEY OFFICE BUILDING

Simulations studies were also carried out for a two storey office building occupying 800 m^2 per floor located in Sydney (Australia) facing north, with and without PCM in the roof construction. Total conditioned area is 1520 m^2. Building parameters are in table 4 with occupancy and operation profiles for lights, electric equipment, people and air-conditioning as per the Building Code of Australia (BCA, 2011).

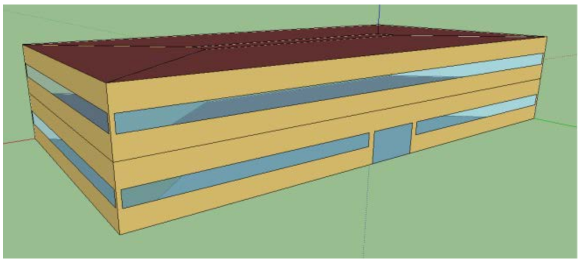

Figure 7 Two storey office building occupying 800 m^2 per floor.

Table 4
Parameters

PARAMETERS	**VALUE**
Roof Solar absorptance	0.7
Roof emissivity	0.9
Roof insulation (R-value)	3.2 (m^2 K/W)
Walls insulation (R-value)	2.8 (m^2 K/W)
Walls solar absorptance	0.6
BioPCM	M51 (3.4mm)
PCM Transition temperature	25 °C
Infiltration (ACH)	1
Lights	9 (W/m^2)
Electric Equipment	15 (W/m^2)
People	10m^2/person
Windows	U-Value=2.4 W/m^2 K, SGHC=0.42
Cooling Setpoints	25 °C from 7am to 6pm during weekdays
Heating Setpoints	20 °C from 7am to 6pm during weekdays

Relative to no PCM, roof PCM gave 9.3% savings with the installation in the roof of BioPCM M51 (3.4mm) with T_c= 25 °C. Savings are 14.7MJ/m^2/year, or 6194 kWh per year.

Running many multi-parameter combinations in simulations as before and considering only daytime occupancy and internal loads in office buildings, cooling loads are predominant and heating loads are very low. The savings resulting from roof PCM are listed in table 5 for various R-values in the roof.

Table 5
Energy use and savings with PCM M51, T_c = 25 °C for a two storey office building in Sydney

Roof Insulation	No PCM	PCMM51 T_c 25 °C	Savings using PCM	
R-value	Total MJ/m^2/yr	Total MJ/m^2/yr	MJ/m^2/yr	Savings %
0.19	211	158	52.9	25.1%
0.5	183	149	34.3	18.7%
1	170	146	24.5	14.4%
1.5	165	144	20.3	12.3%
1.88	162	144	18.3	11.3%
2.66	159	144	15.8	9.9%
3.2	158	143	14.7	9.3%
3.7	157	143	13.9	8.9%

DISCUSSION

Use of roof based PCM has the greatest potential where buildings are required to move from a heating mode to cooling mode in the course of the same day, and is particularly relevant in some regions in Australia where high diurnal temperatures swings are more common. The use of PCM needs to be considered in relation to all other parameter settings. The ability of PCMs to discharge efficiently and store cool at night using compressor cooling is an additional attraction. They are a high-energy density store so need an efficient custom designed heat transfer mechanism. A passive night purge often does not have the capacity to do this for moderate mass.

Initial evaluation of the potential of PCM has been provided and it is not in the scope of this paper to provide cost analysis because from the cost savings point of view it will be required to find the optimum area to cover with PCM. Increasing evening-night ventilation when outside temperatures falls will help to release heat from the PCM or the use of air conditioning crossing the phase change temperature. Solar photo-voltaics to run the air conditioning and release heat from PCM will be an advantage. Cost savings will be higher when cooling loads are large for example office buildings and restaurants at lunch time, when solar radiation, internal loads and temperatures are high.

CONCLUSION

Roof solar reflectance remains the parameter with the biggest impact on energy savings in temperate zones. The addition of PCM further reduces cooling energy demand. The sensitivity to PCM is however reduced as R_{sol} rises and is not worthwhile in a roof with very high R_{sol}. However PCM may be worthwhile in locations where R_{sol} decreases a lot due to dust, dirt or aging. In several cases using PCM or increasing roof R-value led to similar energy savings. PCM is thin and light and can be useful for retrofitting where there is not space for thicker insulation. In a warm humid climate (Singapore), and colder climate (London), the installation of roof PCM is not attractive in homes but may have value in some offices. Further studies are needed to evaluate PCM's in other climates. PCM's add complexity to the analysis of an already complex multi-parameter system. In such systems simulation has proven to be invaluable for systematic location of energy optima within this multi-parameter space.

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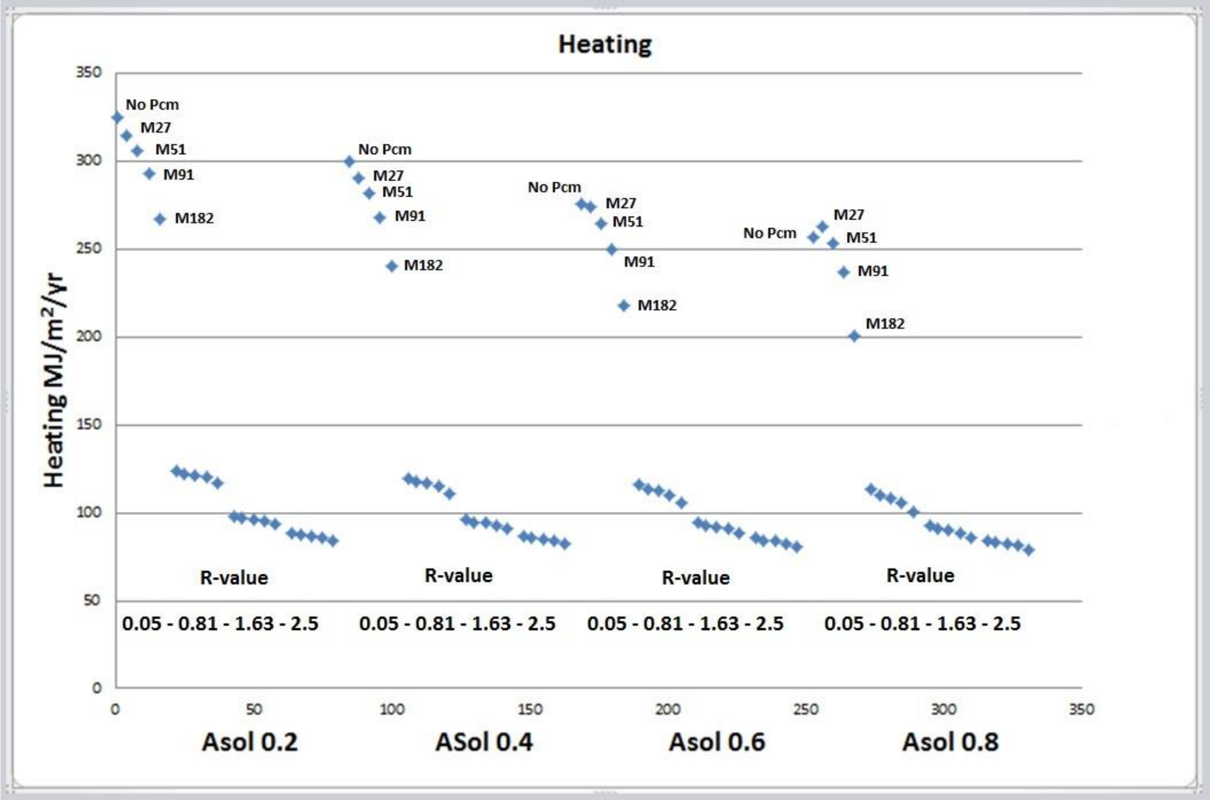

Figure 3 Sensitivity of heating loads for a typical single family house in Sydney to combinations of changes in solar absorptance, R-value and PCM mass.

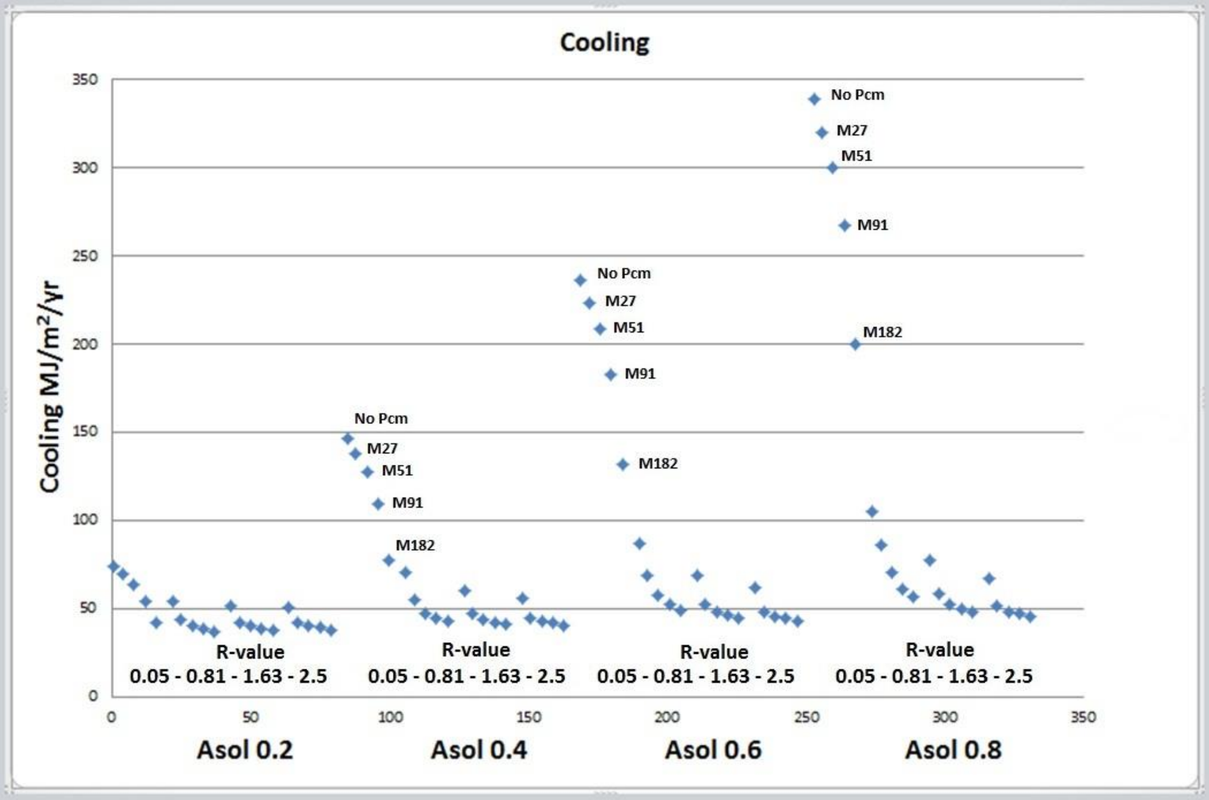

Figure 4 Sensitivity of cooling loads for a typical single family house in Sydney to combinations of changes in solar absorptance, R-value and PCM mass.

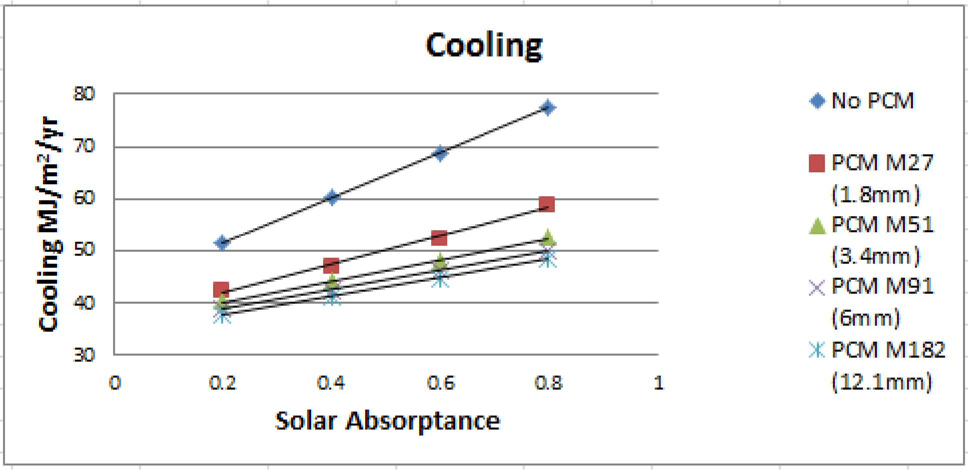

Figure 5 Cooling loads with T_c = 25 °C and roof R-value 1.63 for a typical single family house in Sydney.

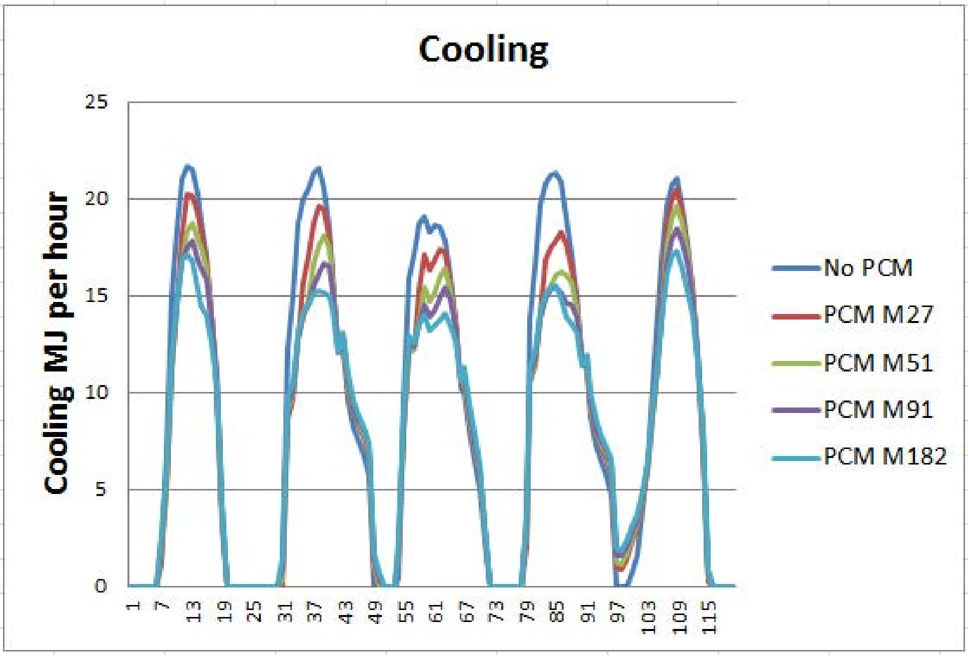

Figure 6 Peak cooling loads with A_{sol} = 0.6, roof R-value = 1.63 and T_c = 25 °C from 1st to 5th of January for a typical single family house in Sydney.