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SIMULATING THE IMPACT ON BUILDINGS OF CHANGING CLIMATE - CREATION AND APPLICATION OF ERSATZ FUTURE WEATHER DATA FILES

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ABSTRACT

Predicted climate change is often reported as the mean seasonal change between climate variables averaged over a given period, while thermal and other energy engineering simulations often require hourly representation of climate variables (elements). This paper describes a method of combining seasonal increments with hourly data representing the present climate. The resulting hourly data are representative of future climate estimates. These future climate estimates have then been used to simulate the effects of future climate change on the energy consumption and plant sizing of buildings. Similar simulations were also carried out to assess the future impacts on the performance of solar water heaters and building integrated photovoltaics.

INTRODUCTION

Within a team led by Lynda Amitrano of BRANZ Pty. Ltd, the authors were engaged with the CSIRO to develop a set of ersatz climate data sets to allow the analysis of the potential impact of climate change on buildings and their design over a 25 and a 65 year time frame. The task was to evaluate both threats and opportunities, so the team needed to create projected future data sets to allow the estimation of the impact on space conditioning plant size and annual energy consumption as well as the future likely effectiveness of building integrated photovoltaics (BIPV) and solar water heating. Parts of this work were previously presented in [Lee and Ferrari, 2006a], while full results of the study were published in [BRANZ, 2007].

FIRMING UP THE BASELINE

“Present” weather data

The CSIRO [2005a] as cited by BRANZ [2005 and 2007] reported predicted climate changes as the mean seasonal change between climate variables averaged over the period 1964 to 2004 (ie, the 40 year *basis* period centred at 1984) against the 40 year periods centred on 2030 and 2070. Subsequent work by CSIRO [2005b, 2006 and 2007] has developed more advanced scenarios, perhaps better suited to the application described here, but these post-date the work reported on in this paper.

Thermal and other energy engineering simulations often require hourly representation of climate variables (elements), and for this purpose the CSIRO increments were applied by Energy Partners to representative hourly data for each location in current use for system design and evaluation.

While the CSIRO work included forecasting the frequency and intensity of extreme weather events, these were generally not of pertinence to our purpose in predicting plant size and mean annual energy consumptions in a variety of building types in the foreseeable future.

Baseline hourly data

Unfortunately, no hourly data were available to specifically represent the basis period described above, and for this purpose the ACDB “Test Reference Year” (TRY)[i] [ACADS-BSG, 2004] was used. The TRY is a list of historic readings, derived as the statistically “best” representative year of those for which data are available. The TRYs were selected on the basis of not having unusually hot summers or unusually cold winters relative to the decade or two (depending on data availability) prior to 1987. Only dry bulb temperature was used in the selection process for these TRYs, however more recent work has expanded the process (see [Lee and Snow, 2006b] and [Lee and Stokes, 2006c]).

The TRY data were not modified to create a

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[i] To avoid confusion with the TMY acronym used internationally, the title “Typical Meteorological Year” (TMY) has since changed to “Reference Meteorological Year” (RMY) by agreement with ACADS-BSG, the Australian Building Codes Board (ABCB) and the Australian Greenhouse Office (AGO).

representation for warming or other climate change between the original reference year (and the cohort from which it was selected) and the CSIRO basis of the 4 decades centred on 1984. Therefore, it may be expected that some minor but conservative underestimation of future temperatures (in the order of 0.1 to 0.2°C) is implicit in the process we adopted.[ii]

PROJECTED CLIMATE CHANGE

Data produced by the CSIRO were supplied in one of two forms – either a direct additive change (eg, °C for ambient temperature) or a proportional change (eg, percentage change in rainfall) – which we will term *arithmetic* and *geometric* increments, respectively. Furthermore, the predicted increments were specified for regions (approximating 500 x 500 km squares) across a range of feasible seasonal values, with no indication of probability distribution or relationships between variables. For example, spring temperatures in Sydney for the 40 years centred on 2070 were projected to average between 1.0 and 6.0°C higher than the "present".

The interdependence of climate variables prohibits direct application of the CSIRO predictions separately to each parameter, a fact that was especially apparent given the non-linear relationship between dry bulb temperature, absolute humidity (AH in g/kg) as required by the ACDB format, and relative humidity (RH in %) as forecast by CSIRO. Where the temperature rises, a reduction in RH implies a change in AH of anything from a significant decrease to a small increase. Data representing a number of scenarios were created by selecting increments within the ranges specified by the CSIRO. However, no level of certainty of the feasibility of these scenarios is assumed nor estimated.

METHODOLOGY

Changes to the key elements

Temperature (dry bulb)

The temperature data produced by the CSIRO are largely presented in the form of figures indicating "warming ranges" (arithmetic temperature increments) for each of the four seasons along with a spatial variation across Australia. An example of this presentation is provided in Figure 1. We applied this information as an "offset" to the TRY temperatures, by making the assumption that the given "warming range" is accurate in the middle month of the season (eg January for summer), and applying a piecewise constant interpolation to these data points to calculate offsets for other months. For example, where the warming is predicted to be +2.0°C in Summer and +1.0°C in Autumn, we apply the offset set shown in Table 1.

With the background noise of daily fluctuations, this interpolation reduces "jumps" (discontinuities) to an acceptable level.[iii]

Table 1: Example conversion of seasonal to monthly temperature increments

January	+2.0°C
February	+1.67°C
March	+1.33°C
April	+1.0°C

Humidity (relative and absolute)

CSIRO estimated the geometric increment range for Relative Humidity in the two forecast eras and this had to be converted to absolute humidity (humidity ratio, g/kg dry air) for use in most simulation programs. The following steps were applied to develop the ersatz files from the TRYs for each location:

1. Calculate the mean dry bulb temperature for each season.
2. Calculate the mean humidity for each season.
3. From 1 and 2 calculate the mean relative humidity for each season.
4. Apply the CSIRO increment to the mean RH and mean dry bulb temperature.
5. From 4 calculate the forecast mean humidity for each season.

[ii] Ideally, the impact of climate change on the re-selection of a "true" TRY for the 4 decades to 2004 as the baseline should be undertaken as a sensitivity analysis in the future. Alternatively, a separate project with the AGO to create Reference Meteorological Years (RMYs) has subsequently been undertaken by Energy Partners (Energy Partners, 2006) in association with the University of South Australia and Adelaide Applied Algebra. The re-creation of ersatz weather data of this project could be built on those RMYs to achieve a much more robust forecast result. An RMY is a constructed "year" built by concatenating the most indicative of each of the 12 months from the years for which data is available.

[iii] The resulting data (ACDB-TRY + CSIRO forecast increment) could then be compared against other predictions described by CSIRO, such as the frequency of extreme hot events, to test the robustness of this off-set method in matching the overall climates predicted by the global models used by CSIRO. The climate is not necessarily forecast to be more peaky for all elements, only the peaks (defined by fixed high temperature thresholds) are more frequent; but if our testing shows poor concurrence with the macro model it would be grounds for further work to check the concurrence of the TRYs with the frequency of occurrence values to refine our forecasting and/or climate data modification techniques.

6. From 2 and 5 calculate the forecast mean humidity increment for each season.
7. Apply this CSIRO/EP increment to the humidity values using the monthly step interpolation described above for dry bulb temperatures.

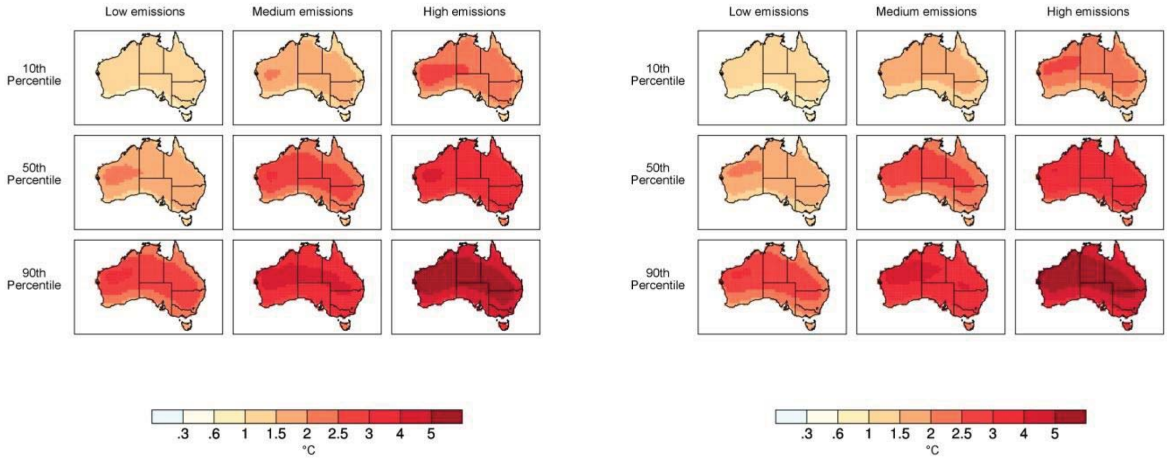

Figure 1: Example of predicted (a) summer and (b) autumn dry-bulb temperature change scenarios to 2070, from [CSIRO, 2007]

Solar Radiation (direct and diffuse)

CSIRO estimated the geometric increment range for global irradiation (direct plus diffuse) in the two forecast eras and this had to be converted to its components (direct, diffuse and direct normal to the solar beam) for use in most simulation programs. The following steps were applied to develop the ersatz files from the TRYs for each location for every hourly value.

All irradiance values were retained wherever cloud level is zero octas (clear sky).

For each season, we intend the total (sum) of global irradiation to be the original level multiplied by the CSIRO increment. Therefore, each non-clear hourly global irradiance is multiplied by the factor X calculated such that the following condition holds:

$$\sum_{season} \left(X_{season} . dS . I_{glob} + I_{glob} \right) = \sum_{season} dS . I_{glob}$$

i.e.

$$X_{season} . \sum_{cloud \neq 0} \left(dS . I_{glob} \right) = \sum_{season} \left(ds . I_{glob} \right) - \sum_{cloud = 0} \left(I_{glob} \right)$$

so

$$X_{season} = \frac{\sum_{season} \left(dS . I_{glob} \right) - \sum_{cloud=0} \left(I_{g;lob} \right)}{\sum_{cloud \neq 0} \left(dS . I_{glob} \right)}$$

where dS is the geometric increment factor for that season.

It is understood that forecast irradiation changes are typically due to increased atmospheric humidity and resultant cloud formation [CSIRO, 2005], and we therefore expect to observe future change in the ratio of direct to diffuse irradiation with an overall (global) decrease occurring through an increase in diffuse radiation and a greater decrease in direct (beam) radiation. The CSIRO did not report on the direct:diffuse ratio of this change, so an optimisation[iv] was performed for the purpose of estimation of this ratio. Specifically, for each season the parameters x_1 and x_2 were optimised to minimise the function:

$$\sum_{cloud \neq 0} \left(I_{global} - x_1 I_{diffuse} - x_2 I_{direct} \right)^2$$

where x_1 and x_2 were constrained such that:

$1 \le x_1 \le 2$; and

$x_2 \le 1$.

That is, direct irradiation was not permitted to increase over TRY levels, while diffuse irradiance was permitted to increase, but restricted to less than double TRY levels.

Finally, given the CSIRO increments (dS) along with x_1 and x_2 we calculate the forecast irradiance data:

[iv] The advice of Dr John Boland, Senior Lecturer, School of Mathematics and Statistics, University of South Australia on this technique is gratefully acknowledged.

- For all hours in which cloud cover is zero octas, keep TRY levels.
- For all other hours,

$I_{global}' = dS \times I_{global}$;
$I_{diffuse}' = x_1 \, I_{diffuse}$
$I_{direct}' = x_2 \, I_{direct}$

Wind (calms, breezes and strong)

CSIRO estimated the geometric increment range for mean wind speeds, and these have been applied to each hourly value in the following way:

- Keep all wind directions unchanged.
- Increase all non-zero wind speeds by the same factor that CSIRO forecasts for mean wind speeds.

Cloud Cover (cover, type and height)

CSIRO had not estimated the increment range for cloud cover. It would be possible to infer an increment from the solar irradiation values calculated as described above but this has not been done. At the time of the work reported on here, the technique for this estimation had not been developed[v] and the values in the TRY files are all integer values ranging from 0 to 8 octas so that a probablistic technique would need to be used to occasionally increment the values by 1 (except the 8 octas values which represent fully overcast skies) to produce the mean increment estimated for the full year. Additionally, the use of the value by the simulation software packages is to estimate the far infrared radiation exchange between the building and its surroundings (especially the night sky) and this is generally a second-order effect in determining its energy performance.

Formatting to suit simulation packages

The sample of residential buildings was simulated using the then current beta version of the AccuRate software package (CSIRO, 2005) which accepts the ACDB format for its climate data. Hence no reformatting was required.

Similarly, the BiPVsim software used a reduced subset version of the ACDB citing only temperature, diffuse irradiation, direct irradiation, wind speed and cloud cover data for this application.

The simulation of the solar water heaters was undertaken using the AS4234 software provided by Standards Australia (based on TRNSYS v13.1) and the data within the ACDB was manually manipulated into its specific format.

The simulation of the commercial buildings was undertaken with the DOE2 software which has an entirely different format but the package comes with its own suite of file converters and the appropriate one of these was used to convert each new data set into the DOE2 format.

Application of data in simulation packages

Residential

For the housing, simulation was undertaken using the then current version of the 2nd Generation NatHERS software AccuRate for a set of seven base house types (including one apartment). To simulate a variety of solar orientations, the orientation of each house was modified so that the façade with the largest glazed area was oriented north, south, east and west, resulting in four versions of each house.

These houses were then simulated using the three time/era variants of the climate data (today, 2030, 2070) in order to see the effect of climate change on the energy performance of each house variant in locations of interest covering all BCA climate zones except Alpine.

- Zone 1 (Hot Humid): Darwin, Cairns
- Zone 2 (Warm Humid): Brisbane, Gold Coast
- Zone 3 (Hot Dry, Warm Winter): Alice Springs
- Zone 4 (Hot Dry, Cool Winter): Mildura
- Zone 5 (Temperate): Adelaide, Perth, Sydney, Coffs Harbour
- Zone 6 (Mild Temperate): Melbourne
- Zone 7 (Cool Temperate):Canberra, Hobart

Offices

Using the same technique as for the housing above, two archetypal office buildings were simulated using the DOE-2e software package and the office details identical to those used for the parametric studies for the ABCB (2005). One is a 10-storey office tower thought to be indicative of CBD construction throughout the country and the other is a 3-storey walk-up office thought to be indicative of suburban office developments and the CBDs of provincial centres. While 10-storeys may seem low by current standards, it is tall enough to ensure that the energy efficiency of the roof/ceiling construction is insignificant in determining the overall performance. Hence, it was preferred to use

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[v] The University of South Australia (Ridley and Boland, 2005) developed such a technique for the subsequent project it had with Energy Partners for the AGO to update the ACDB as the switch by the Bureau of Meteorology to Automatic Weather Stations (AWS) has led to a decline in the ground station measurement of this element of the weather.

the ABCB's archetype for reasons of comparability of published results.

Each was simulated in a N-S and in an E-W orientation to avoid biasing the results in favour of design for high energy efficiency.

Although outwardly identical buildings, each has been simulated with the DTS (deemed-to-satisfy) construction pertinent to the climate of the location concerned. Thus, the versions in the cold climates of Canberra and Hobart are better insulated, and the versions in the hot climates like Darwin are better protected from solar heat gain. This can give counter-intuitive results such as that the DTS office tower uses more heat energy in Melbourne than it does in Canberra.

In all cases, the HVAC plant sizing routine within DOE-2e was used to determine the relevant parameters of the archetypal HVAC systems. The results disaggregate the Cooling by separately calculating the Heat Rejection (cooling tower fans and pumps) and Fans (forced ventilation and delivery of conditioned air). Depending on climate, part of the Fans energy is also a component of Heating.

The equipment loads used were those assumed in the Australian Building Greenhouse Rating Scheme (http://www.abgr.com.au/new/default.asp), 15% of lights and 50% of equipment remain on out of hours. For comparison purposes, the simulated energy performance results were graphed against the respective energy performance targets published by the PCA (2001).

RESULTS

Limitations of the climate data sets

As well as the limitations cited above, the ersatz climate data sets created for this project have one overall limitation in that the changes to the four key weather elements of temperature, humidity, solar and wind are not independent of each other but their future values have been predicted as though they are. For the purpose of analysing the impacts of worst case scenarios, we put together the most challenging values for each in the one "future climate" for each location. This, however, is likely to overestimate the impact of climate change.

To explore that qualification to the realism of the ersatz data files, we have undertaken several sensitivity analyses on the impacts of several weather elements in differing combinations, but this is methodologically inferior to the creation of data sets with scenarios in which the interplay of dependencies (such as higher solar irradiance tending to correlate with higher temperatures) is fully incorporated in the climate models used to generate them. Then the building sets used in the resultant report [BRANZ, 2006] can be simulated again using a series of internally consistent incremental changes to the climate elements for the future dates of interest.

Solar Water Heating

Solar water heating loads were simulated for the future climate data sets using 2 different scenarios. Both scenarios used the 2070 (High) data files, however, scenario 1 used current cold water temperatures while scenario 2 used increased cold water temperatures.

Table ***2*** displays the results of the future simulations. It can be seen that under both future scenarios the performance of solar water heaters improves significantly. Further, scenario 2, using increased cold water temperatures shows a further performance improvement in comparison to scenario 1.

Table 2: Auxiliary energy consumption for solar water heaters under 2070 climatic conditions

Climate Zone	Current kWh/year	Scenario 1 kWh/year	Scenario 2 kWh/year
Zone 1	189	64	20
Zone 2	106	53	20
Zone 3	787	463	282
Zone 4	1638	1195	948

Building Integrated Photovoltaics (BiPV)

Similar to the results obtained from the solar water heating simulations, building integrated photovoltaics are predicted to experience improved performance under future climatic conditions. Amorphous silicon photovoltaic systems were predicted to experience a greater increase in performance compared to mono crystalline silicon systems due to the material's ability to contend with higher ambient temperatures. Table 3 shows the predicted increase in annual electricity generation for BiPV in 2070.

Table 3 Annual performance increase under 2070 climatic conditions

	Performance Increase	
	M-Si	A-Si
Darwin	4.4%	6.6%
Sydney	3.2%	5.5%
Melbourne	6.9%	8.8%

Residential Buildings

It has been estimated that total residential thermal conditioning requirements will increase by 76% by 2070. This is primarily due to a 3-fold increase in cooling requirements. Warmer climates have been predicted to experience a greater increase in thermal conditioning requirements due to increases in cooling energy demand. Decreased heating demand is expected to result in an overall decrease in thermal conditioning energy requirements in cooler climates such as Melbourne, Canberra and Hobart. Figure 2 shows the changes in heating and cooling requirements as predicted using the ersatz future weather data.

Non-Residential Buildings

The effects of climate change on the total energy consumption of office buildings will be relatively minor compared to residential buildings. This is due to the smaller share of end-use consumption attributed to heating and cooling. Simulations were carried out considering 10 storey office blocks in the same 13 locations. The increase in energy consumption was greater in the warmer climates such as Sydney and Darwin as compared to the cooler climates such as Canberra. As with residential buildings the increased energy consumption is the result of increased cooling energy requirements. Figure 3 displays the simulated results for the 10 storey office block in Canberra, Sydney and Darwin.

Energy modelling and analysis was carried out on a Melbourne based hospital to assess the impacts of climate change on energy consumption for this energy intensive building type. Several future scenarios were simulated with each showing significantly reduced energy consumption compared to current levels. On average the simulations predicted a 21% reduction in total energy consumption. This is due to significantly reduced operation of gas boilers for heating purposes.

Despite the reduction in total energy consumption however, greenhuse gas emissions are predicted to increase by an average of 37%. This is due to electricity providing an increased share of energy use due to increased operation of chillers.

It was not possible within the confines of this project to directly check the IWEC against its TRY or ACDB equivalent but the results suggest that a substantial unexplained difference exists.

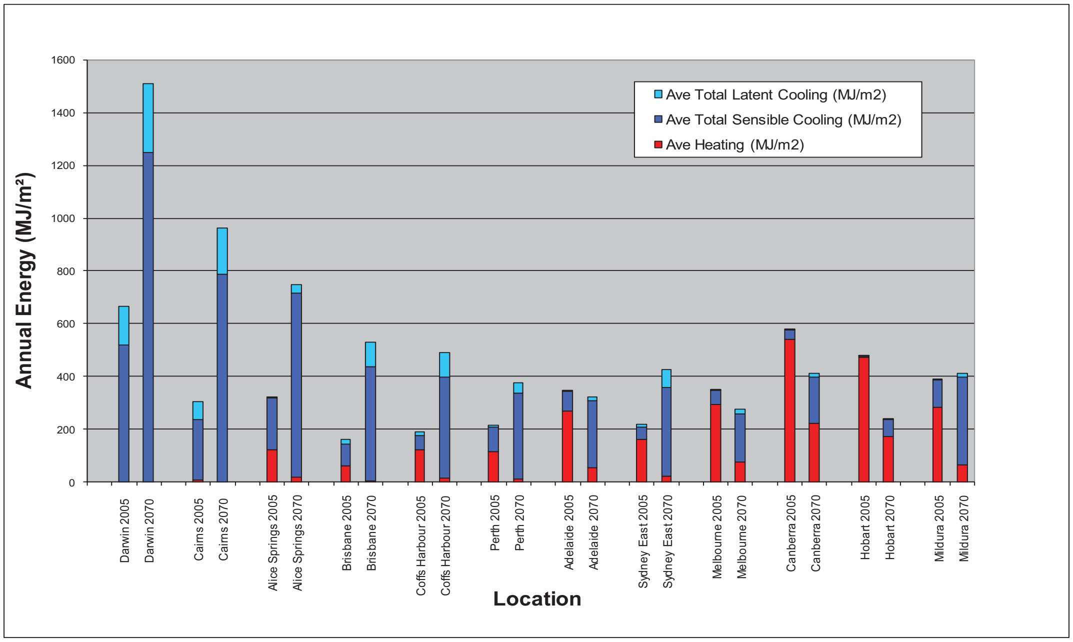

Figure 2: Differences in thermal conditioning energy, 2005 vs 2070 after BRANZ 2007

Plant Size

Simulations of residential heating and cooling loads were carried out using the future weather files. The results predicted an average reduction in the required peak heating capacity of dwellings of 3.66 kW. This reduction was offset by a predicted increase in the required peak cooling capacity of 4.38 kW.

Simulation results for the 10-storey office buildings indicated an average increase in cooling plant capacity of 17% along with a reduction in heating plant capacity of 5%. The results for the Melbourne based hospital were somewhat different with an average predicted increase in the peak cooling capacity required of just 3% compared to an average 32% reduction in the peak heating capacity required.

CONCLUSIONS

The project predicted a general increase in the energy consumption of air conditioned buildings and a decrease in the heating:cooling ratio for the cooler climates as a result of predicted climate change. The project also analysed the impact of the projected climate change on the sizing of air conditioning plant. Here there was a reduction in the required size of heating plant (and its obviation in some warmer climates) and an increase in the size of cooling and dehumidifying plant.

On a more positive note, the auxiliary energy required of flat plate solar water heaters is reduced and the output of BiPV systems is predicted to increase.

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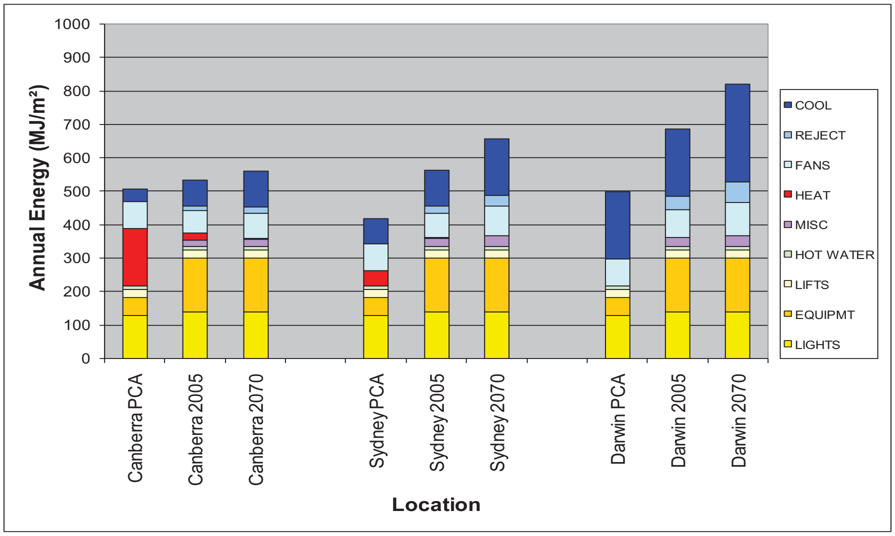

Figure 3: Simulated end-use energy consumption of 10 storey office block after BRANZ 2007

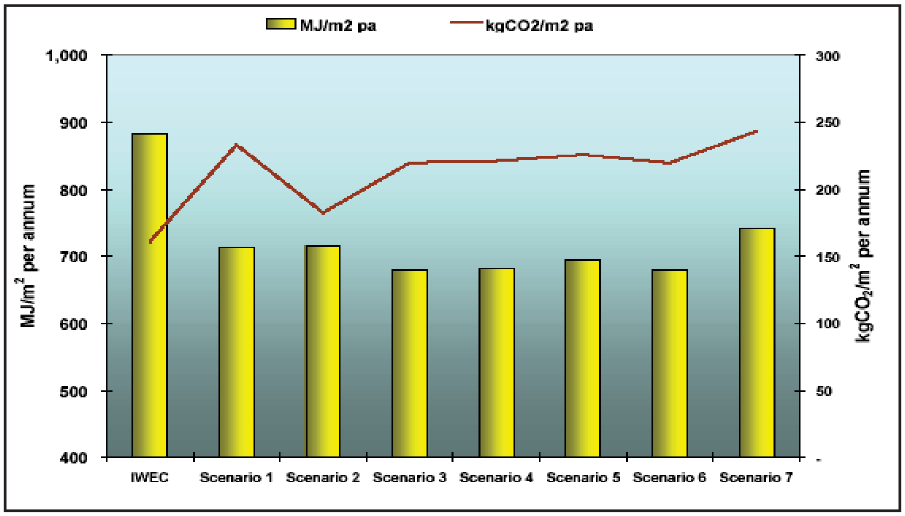

Figure 4: Hospital energy consumption and greenhouse gas emissions based on predicted weather files for Melbourne (after BRANZ 2007)

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NOMENCLATURE

$\boldsymbol{X}$ – geometric increment factor [-]

$\boldsymbol{I_{global}}$ – global irradiance on a horizontal plane [kW/m^2]

$\boldsymbol{I_{direct}}$ – direct irradiance on a horizontal plane [kW/m^2]

$\boldsymbol{I_{diffuse}}$ – diffuse irradiance on a horizontal plane [kW/m^2]

$\boldsymbol{dS}$ – geometric increment factor [-]

$\boldsymbol{x_1, x_2}$ – optimisation parameters [-]