Assessment of Climate Change Impact on Residential Building Heating and Cooling Energy Demand in Australia

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ABSTRACT

Projecting the local climate for buildings based on nine General Circulation Models (GCMs) under three carbon emission scenarios, this study investigated the potential impact of climate change on the heating and cooling (H/C) energy requirements of modern houses in five regional climates varying from cold to hot humid in Australia. The study is based on the detailed sensitivity and scenario assessment with a unified reference to the global warming temperature, to which the local climate of buildings is correlated. It was found that a significant climate change impact on H/C energy demands is envisaged within the lifespan of existing houses, especially in the regions with either hot/warm, cold, or H/C balanced temperate climates. The energy demand of 5 star houses is projected to vary significantly in the range of -30% to 100% by 2050 and -50% to 350% by 2100 for A1B, A1FI and 550ppm stabilisation emission scenarios, depending on the regional climates. It was also found that the climate change impacts depend on the energy efficiency of houses. Although more efficient or higher energy star rating houses may experience less absolute changes in energy requirement due to changing climate, they appear to have greater percentage changes in H/C energy demand, especially in regions with a H/C balanced temperate climate such as in Sydney where the increase is projected to be up to 120% and 530% for high star rating houses when the global temperature increases 2°C and 5°C respectively, potentially posing significant pressures on the capacity of local energy supply.

Keywords: Residential building energy, climate change, impact assessment, energy ratings

1. INTRODUCTION

The residential building sector contributed around 13% of the total Australia national greenhouse gas (GHG) emissions in 2005-06 [1]. It is anticipated that the projected population growth, the trend of smaller family sizes, and the desire for more comfortable indoor environment and larger houses etc, will put more upward pressure on the energy demands and increase the GHG emissions from the residential building sector.

While the residential building sector may contribute significantly to the GHG emissions and climate change, the energy demand of currently designed buildings may also be impacted by climate change due to the changing local climate. Buildings, once built, may last several decades. Data from the Australian housing survey in 1999 by the Australian Bureau of Statistics (ABS) shows that there were about 45% of the houses between 20 and 50 years of age, and 18% older than 50 years. Over such a long period, the local climate of buildings, such as the averaged ambient temperature, may undergo considerable changes exacerbated by changing climate. Since the energy demand of residential houses is closely correlated to the local climate [2, 3], the conventional building energy demand calculation, which assumes the local climate following the historical patterns during the building's life span, may no longer be valid.

It has been found [4] that regional electricity demand is closely correlated to Heating Degree Days (HDD) as well as Cooling Degree Days (CDD), based on the analysis of weekly demand data published by the National Electricity Management Marketing Company (NEMCO) in Australia, and climate change may considerably change the demand, especially peak demand. Meanwhile, initial studies carried out in UK [5] and New Zealand [6] found that a mean temperature rise might lead to energy saving and emission reduction. Simulation for Switzerland also indicated that the warming climate scenario would reduce the heating demand, and demonstrated a reduction of HDD in relatively cool climates [7]. However, a warming climate will increase cooling demand, which may offset or exceed the benefit from the heating energy saving [8], and compromise thermal comfort [9]. It may also affect the performance of building insulation, adding more loads on cooling [10]. The impact of climate change will pose challenges in the design and renovation of residential houses.

Much progress in low-energy house development [11, 12] and renewal energy technology, especially distributed renewable energy, could potentially be utilised to counter the impacts of climate change [13-19]. However, it is important to understand in detail the impacts of changing climate on the energy demand of buildings, so targeted adaptation technologies for residential buildings can be developed.

BRANZ [20] conducted comprehensive investigations for different building types on the consequences of climate change in Australia. Energy consumption was considered to be one of the major issues under changing climate. However, as far as we know, there have been no detailed sensitivity assessments for residential houses, in terms of the relationship of energy demand in response to changing climate at different magnitudes, especially considering the uncertainties of climate projection models as well as the influence of factors such as regional climate and energy efficiency of buildings. The projected energy demand at any given emission scenario in a specified year, or scenario assessment, can be located on the sensitivity curve, as shown in Figure 1, making the sensitivity assessment a more useful method to characterise climate change impacts.

Also, it is questionable that the average climate projections, particularly of multiple climate variability, from multiple climate models or General Circulation Models (GCMs) were suitable for use in assessing the impact of energy demand. In fact, any sensitivity and scenario assessment should be based on individual climate models or GCM to maintain the consistency among the projected climate variables of interest. Model uncertainties are subsequently described by the deviation of sensitivity and scenario assessment using different GCMs.

(Insert Figure 1. Sensitivity, scenario and their relationship)

The investigation carried out in this paper is to address those issues and elucidate the impact of climate change on the heating and cooling (H/C) energy demand of residential buildings in Australia on the basis of detailed sensitivity and scenario assessment. Following the introduction of climate change and outcomes of GCMs that will be used in the investigation, the sensitivity and scenario assessment of house H/C demand in response to climate change is to be carried out with a unified reference to the global warming temperature as well as a consideration of model uncertainties. It aims to illustrate the extent to which changing climate may impact on the H/C energy requirement for residential houses in Australian cities, which represent diverse regional climate conditions varying from cold, temperate to hot humid. In addition, the influence of energy efficiency on the climate change impact will also be considered.

2. CLIMATE CHANGE

2.1 Carbon Emission Scenarios and Global Warming Projections

Climate change is considered as the changes in the state of the climate that persists for an extended period, typically in decades or centuries either due to natural driving forces and/or as a result of human activities. Currently, the major concern is the change caused by anthropogenic activities, especially related to greenhouse gas emissions. The fourth assessment report – Climate Change 2007, by the Intergovernmental Panel on Climate Change (IPCC) [21], indicated a significant increase of CO_2 concentration in the atmosphere from 280 ppm in 1750 to 380 ppm in 2005 with an accelerated increasing rate. In comparison with pre-industrial temperature, the best estimation of the temperature increase caused by increasing greenhouse gas concentration is 2.1°C for 450 ppm CO_2-eq, 2.9°C for 550 ppm, 3.6°C for 650ppm, 4.3°C for 750ppm and 5.5°C for 1000 ppm CO_2-eq.

To address the climate change due to increasing carbon dioxide in the atmosphere from anthropogenic activities, IPCC defined a set of 40 emission scenarios in its Special Report on Emission Scenarios (SRES) [22, 23], each making different assumptions for future greenhouse gas emissions, land-use and other driving forces. Among them, for example, they are:

- A1FI considers a carbon emission scenario, which assumes very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies, substantial reduction in regional differences in per capita income, intensive fossil energy consumption;

- A1B has similar assumptions as A1FI except balanced fossil and non-fossil energy consumption;
- A1T assumes emphasis on non-fossil energy consumption.

A1FI may be considered as the extreme high GHG emission scenario, A1B is the medium, and A1T is the low emission scenario. In addition, the scenarios of CO_2 stabilisation at 450 and 550ppm etc were also introduced to incorporate the effect of policy intervention [24]. Considering the uncertainties in future global carbon emissions, the scenario assessment in the current study is about to investigate the impacts of climate change on the energy demand of buildings with three carbon emission scenarios, i.e. A1B, A1FI and 550ppm stabilisation scenarios, representing medium emission, high emission and the emission under policy influences, respectively.

With A1B, A1FI and 550ppm stabilisation emission scenarios, the corresponding global CO_2 concentration and global warming projections can be obtained by the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC), developed by Wigley's Group in USA [24], as shown in Figure 2. The figure also includes the lower and upper bounds of the global CO_2 concentration and global warming projections.

(Insert Figure 2 Projections of atmospheric CO_2 concentration and global warming to 2100)

2.2 Climate Models and Regional Climate Change Projections

To project spatially dependent climates in the future under different emission scenarios, various climate models or Atmosphere-Ocean General Circulation Models (AOGCMs) have been developed based on physical principles at the continental scale. Selecting an AOGCM to be used in an impact assessment is not a trivial task, given the variety of models. The IPCC suggested that due to the varying sets of strengths and weaknesses of various AOGCMs, no single model can be considered the best. Therefore, it is necessary to use multiple models to take into account the uncertainties of models in any impact assessment. In the current study, climate projections from nine climate models, as shown in Table 1, were used. More details of the climate models can be found in the IPCC report [21].

(Insert Table 1. Atmospheric-Ocean General Circulation Models Applied in this study)

From the global CO_2 concentration and global warming projections obtained by MAGICC for a given emission scenario, climate changes in Australia with different GCMs can be simulated using *OZClim*. *OZClim* is a climate change projection software developed by CSIRO, which is based on the WCRP CMIP3 multi-model dataset developed by the Program for Climate Model Diagnosis and Intercomparison (PCMDI), and the Working Group on Coupled Modelling (WGCM) of World Climate Research Programme (WCRP). As examples, Figure 3 shows the projected median changes in the ambient temperature, relative humidity and solar radiation by 2050 using CSIRO Mk3.5 GCM at given A1FI emission scenario across Australia.

(Insert Figure 3 Projections of climate variability by 2050 by CSIRO-Mk3.5 GCM, given A1FI emission scenario)

For A1B, A1FI and 550ppm stabilisation scenarios, Figures 4, 5 and 6 show the projections of changes in temperature, relative humidity and solar radiation in five cities, i.e., Hobart, Melbourne, Sydney, Alice Springs and Darwin, representing different regional climate conditions in Australia, ranging from cool temperate, temperate with cold winter, temperate, hot dry with cold winter to hot humid climate, as shown in Table 2. The projections in Figures 4, 5 and 6 are based on the nine GCMs as listed in Table 1, with each of them plotted in light colour curves. The average value of all the nine models is plotted by the dark curves in the figures. The changes in temperature, relative humidity and solar radiation since 1990 are described in degree Celsius, percentage and W/m^2, respectively. As seen in Figures 4-6, the average trend of temperature and solar radiation increases in the five cities, following the global warming projection, while the average trend of relative humidity decreases. It was also found that the increases in the air temperature in a hot/warm regional climate are higher than those in a cold climate. All the projections based on the nine climate models and three emission scenarios will be used in the scenario assessment of the energy demand of a modern residential house later on.

(Insert Table 2 Climate conditions in five Australian cities)

(Insert Figure 4 Projections of temperature change in degree Celsius in Australian cities for A1B, A1FI and 550ppm stabilisation scenarios)

(Insert Figure 5 Projections of relative humidity change in percentage in Australian cities for A1B, A1FI and 550ppm stabilisation scenarios)

(Insert Figure 6 Projections of solar radiation change in W/m^2 in Australian cities for A1B, A1FI and 550ppm stabilisation scenarios)

3. IMPACT OF CLIMATE CHANGE ON COOLING AND HEATING ENERGY DEMAND OF RESIDENTIAL BUILDINGS

3.1 Energy Demand Assessment by AccuRate

Energy demand of residential buildings is modelled by AccuRate, a residential house energy rating software used in Australia [25]. Taking into account the local climate and building fabric, AccuRate calculates hourly H/C energy demands of a house to satisfy occupant thermal comfort over a period of one year. The heating and cooling thermostat settings used in AccuRate for house energy rating are based on the Protocol for House Energy Rating Software published by Australian Building Codes Board [26]:

For living spaces (kitchens and other spaces typically used during the waking hours), a heating thermostat setting of 20°C is used. For sleeping spaces (including bedrooms, bathrooms and dressing rooms, or other spaces closely associated with bedrooms), a heating thermostat setting of 18°C from 7:00 to 9:00 and 16:00 to 24:00, and 5 °C from 24:00 to 7:00. The cooling thermostat setting varies according to the climate region, which are 23.0 ºC, 24.0ºC, 25.5ºC, 26.5ºC and 26.5ºC for Hobart, Melbourne, Sydney, Alice Springs and Darwin respectively.

It is debatable whether these thermostat settings will be appropriate for the five cities in the future with the warming climate. Considering adaptive thermal comfort [27], it is possible that the cooling thermostat settings will be higher for Hobart and Melbourne when occupants adapt warming local climate. However, in this study, the same heating and cooling thermostat settings as listed in the Protocol for House Energy Rating Software [26] were used.

Based on the annual total H/C energy demand, AccuRate assigns a star rating between 0 and 10 stars to the residential building for the specified climate zone. The more stars, the less likely the occupants need cooling or heating to stay comfortable. The Nationwide House Energy Rating Scheme (NatHERS) in Australia specifies that:

- Zero stars means the building shell does practically nothing to reduce the discomfort of hot or cold weather.
- A 5 star rating indicates good, but not outstanding, thermal performance.
- Occupants of a 10 star home are unlikely to need any artificial cooling or heating.

Currently, most Australian states and territories require a minimum of 4 to 5 stars for new house designs with this requirement scheduled to rise to 6 stars in two years. It is a common approach to use Typical Meteorological Year (TMY) weather files for the simulation of building energy demand [28]. AccuRate contains 69 TMY files with each linked to a climate zone, covering all Australian states and territories. In order to achieve reasonable consistency in house energy rating, each climate zone has its specific star bands to map the total cooling and heating demand to star rating as detailed in the Protocol for House Energy Rating Software by the Australian Building Codes Board [26].

3.2 Descriptions of the Residential House

To illustrate the impacts of global warming on the energy demand of residential houses, a modern single-storey brick veneer house was modelled in this study, which is currently one of eight house examples used for energy rating software accreditation purposes in Australia. It has a gross floor area of 314.7 m^2 and a net air-conditioned floor area of 207.4 m^2. As shown in Figure 7, the house has four bedrooms, a kitchen/family area, a living room, a laundry, a separate bathroom and toilet, a rumpus room and a double garage.

In the study, the floor plan was maintained whilst various combinations of wall insulation, ceiling insulation, window types, floor insulation, infiltration controls etc were used to achieve ratings of 2 stars, 5 stars and 7 stars in the five cities.

Table 3 shows the annual H/C demands of these houses in the five cities with the existing TMY weather files. The annual cooling and heating demands and the annual total H/C energy demand are expressed as MJ per air conditioned floor area, i.e., MJ/m^2.

The house energy demands are found to correlate well with the local climate, i.e. cooling dominated in Alice Springs and Darwin, heating dominated in Melbourne and Hobart, and heating/cooling balanced in Sydney.

(Insert Table 3 Cooling and heating demands of the 2 star, 5 star and 7 star houses in the five cities)

(Insert Figure 7 A floor plan of a conventional four bedroom house in Australia)

3.3 Cooling and Heating Energy Demand Patterns under the Changing Climate

The existing TMY weather files in AccuRate are assumed to be the reference climate at 1990 considering that most of the data in the weather files were composed from the weather data from 1970 to around 1990. Projected changes in local ambient temperature, relative humidity and solar radiation from 1990 to 2100, in relation to the global warming temperature and 9 GCMs, have been incorporated to construct new weather files, by a so-called 'morphing' approach [28], for the five Australian cities. The approach will also later be applied for the sensitivity and scenario assessment.

The H/C energy demands of the houses using the TMY weather files (refer to Table 3) are described as the reference H/C energy demands. Figure 8 shows the projected, daily H/C energy demands in MJ in 2050 and 2100, in comparison with the reference demands, for the 5 star houses in Alice Springs (hot dry summer/cold winter climate, cooling dominated) and Melbourne (temperate/cold winter climate, heating dominated), when the A1FI scenario and CSIRO Mk3.5 GCM model are applied. It is noted that the daily H/C energy demands shown in Figure 8 should be considered as a projection at the best estimation, in relation to the projected global warming, and it should not be viewed as an exact prediction of real H/C demands on a specified day in the future. In general, there is a considerable increase in cooling energy demand in Alice Springs due to its hot summer, relatively with a large increase in air temperature, and a small change in heating demand, resulting in an overall increase in energy demand for heating and cooling. In contrast, there is an obvious reduction in heating demand in Melbourne due to the improved climate condition from its currently relatively cold winter as a result of an average temperature increase. Considering a moderate increase in the cooling energy demand in summer, there is a possibility that the overall energy demand for heating and cooling in Melbourne may be reduced.

(Insert Figure 8 Daily H/C energy demand for a modern four bedroom house of five-star energy rating in Alice Springs and Melbourne, in 2050 and 2100, in comparison with the reference demand)

3.4. Sensitivity Assessment of Energy Demand to Climate Change

The sensitivity here is described by the variation of heating, cooling and the total H/C energy demand of a residential house in response to the increase of global warming temperature, which is correlated to the local climate, such as ambient temperature, relative humidity and solar radiation change and so on.

The existing TMY weather files in AccuRate are used as a reference climate. As before, the files are then modified by the ‘morphing’ approach, based on the projection of nine GCMs, to construct projected local climates that follow the global warming temperature increasing from 0 to 6°C with a 0.5°C interval. The brick veneer houses applied in the assessment are those described in section 3.2. For the sensitivity study, the H/C energy demands of 2 star, 5 star and 7 star houses in five cities are investigated using AccuRate, with the projected local climates. This resulted in a total of 1485 simulations.

For a 5 star house in the five cities, the sensitivity of H/C energy demands to the global warming temperature is illustrated in Figure 9. The average H/C energy demand from the nine GCMs is shown in a dark curve in each diagram of the figure. The H/C energy demands based on individual GCMs are drawn in the light coloured curves, demonstrating the scattering of the estimations due to the uncertainties of GCMs.

(Insert Figure 9 Sensitivity of the changes in heating and cooling energy demand to the global warming temperature for a 5 star house in five cities)

It can be found that the reduction in heating demand as well as the increase in cooling demand at all locations shows a change proportional to the global warming temperature. In a cooling dominated hot or warm regional climate, such as in Darwin and Alice Springs, or a cooling and heating balanced temperate climate such as in Sydney, the increase in cooling energy demand is much more dramatic than the decrease in heating energy demand, when responding to global warming. In other words, the changes in total H/C energy demand in these climates are dominated by the increase in cooling demand. In contrast, the reduction of heating energy demand prevails in a relatively cold temperate regional climate, such as in Hobart, in response to the global temperature increase. Meanwhile, locations at a heating dominated temperate regional climate, such as in Melbourne, show relatively balanced changes in H/C energy demand in relation to the global warming temperature.

The sensitivity of the total energy demand of a five-star house in five cities to global warming is shown in Figure 10. In terms of the percentage changes in energy demand, Sydney appears most sensitive to global warming due to the rapid increase in cooling demand and the negligible reduction in heating demand (refer to Figure 9) on a relatively small reference energy demand in 1990 (refer to Table 3), followed by Alice Springs and then Darwin. It implies that global warming may potentially pose more pressures to the capacity of local energy supply in Sydney. Moreover, there appears to be an acceleration in the cooling demand. From Figure 10, the trend becomes significant after reaching a global warming temperature of 2°C in Sydney.

(Insert Figure 10 Sensitivity of the total H/C energy demand (in percentage terms) to global warming for a 5 star energy rating house in five cities)

Compared with the current H/C energy demand status, the regions in cold climates may benefit from global warming in terms of the reduction in the energy demand. Melbourne, where the climate is temperate with cold winter, may achieve the most benefit when the global warming temperature reaches 2.5°C. However, it may eventually lose all the benefit when the global warming temperature reaches 5.5°C. Hobart, where the climate is relatively cold, may always benefit, represented by the energy reduction within the range of 6°C global warming investigated in this study.

The sensitivity of total H/C energy demand to global warming differs for residential housing, currently with different energy performance or energy ratings. Figure 11 demonstrates the difference of the sensitivity considering 2, 5 and 7 star houses in the five cities. The energy demand of houses with a lower energy rating appears to be more sensitive to global warming in terms of the absolute value of changes in energy demand. However, on a percentage basis, the change in the energy demand of houses with a higher energy rating generally appears more sensitive to global warming. In H/C balanced temperate climates, such as Sydney, the sensitivity to global warming (in percentage) is more than doubled when energy ratings change from 2 to 5 stars. The H/C energy demand was found to increase 120% for 7 star houses when the global temperature increases 2°C and 530% with a 5°C increase, much higher (in percentage terms) than those for 2 star houses (though a little less than those for 5 star houses when the global temperature increase less than 1°C). The high sensitivity to global warming may need to be considered in the planning of high performance buildings in terms of their future energy demand.

(Insert Figure 11 Sensitivity of total H/C energy demand to global warming for a house with different energy ratings in five cities)

It is also interesting to find that, houses, with a 7 star energy rating in a cold climate, such as in Hobart, benefit more initially from global warming, represented by greater percentage reductions in energy demand. However, the saving benefits level off as the global warming temperature increases. The pattern becomes even clearer for the sensitivity curve of percentage change in Melbourne. The energy demand reverses the trend from energy reduction to greater energy demand when the global warming temperature reaches 4.3°C. For comparison, the energy demand reversal happens at 5.4°C for 5 star houses, and it does not happen at all within the range of 6°C global warming for 2 star houses.

3.5. Scenario Assessment of Energy Demand Response to Climate Change

The purpose of scenario assessment is to understand the change of energy demand over time in response to global warming represented by specific emission scenarios, such as A1B, A1FI and 550ppm stabilisation. The existing TMY weather files of AccuRate in the five Australian cities were again used as the reference climate. They were modified with the projected changes in local ambient temperature, relative humidity and solar radiation under the three emission scenarios, on the basis of 9 GCMs from 1990 to 2100 in a five year interval. Under the modified weather files, H/C energy demands of 2 star, 5 star and 7 star houses were simulated using AccuRate. Considering all the combinations of house star ratings, locations, years, emission scenarios and GCMs, there are a total of 9315 simulations for the scenario assessment.

Figure 12 describes the projection of the total annual H/C energy demand variations of a 5 star house in the five cities given the three emission scenarios and nine climate models. The variation displays three trends within the projected time period up to 2100:

- Locations at a cooling dominated warm or H/C balanced temperate regional climate: the total H/C energy demand consistently increases over time, and the increase is more significant for a hot humid climate (Darwin), followed by the hot and dry summer climate (Alice Springs), and then H/C balanced temperate climate (Sydney). In Darwin, there is an increase of 227MJ/m^2 by 2050 and 540MJ/m^2 by 2100 for the A1FI scenario. In Alice Springs, there is an increase of 80MJ/m^2 by 2050 and 305MJ/m^2 by 2100. In Sydney, there is a smaller increase of 49MJ/m^2 by 2050 and 170MJ/m^2 by 2100;

- Locations at a heating dominated temperate but cold winter climate: the total H/C energy demand declines initially, and then increases. In Melbourne, for the A1FI scenario, there is a reduction of 29MJ/m^2 by 2050, and the demand continues to drop until 2065 when the reduction reaches the maximum at 33MJ/m^2. The demand trend then reverses, and energy reduction goes back to 20MJ/m^2 by 2100;
- Locations at a heating dominated cool temperate climate: the total H/C energy demand declines over time. In Hobart, there is a consistent decrease of energy demand, dropping 51MJ/m^2 by 2050 and 95MJ/m^2 by 2100 for the A1FI scenario.

(Insert Figure 12 Projections of H/C energy demand variation in Australian cities for A1B, A1FI and 550ppm stabilisation scenarios (light colour curves: projections based on the nine GCMs; dark curves: average values of the nine GCMs))

The average percentage of changes in energy demand from the nine climate models in comparison with the reference energy demands for the five cities are described in Table 4. Although the assessment is carried out for a specific house type, it demonstrates that both increase in cooling energy and decrease in heating energy over the lifespan of residential buildings can be significant due to global warming. The energy demand of five star houses is projected to vary in the range of -30% to 100% by 2050 and -50% to

350% by 2100 for the three emission scenarios, depending on the regional climates. For the A1FI scenario, the total H/C energy demand in Sydney may increase 101% by 2050 and 350% by 2100, while the total energy demand in Hobart may decrease 26% by 2050 and 48% by 2100. With the moderate emission scenario A1B, the total annual H/C energy demand in Sydney is projected to increase 81% by 2050 and 193% by 2100, while the total H/C energy demand in Hobart may decrease 23% by 2050 and 37% by 2100.

(Insert Table 4 The average percentage changes (%) in annual H/C energy demand for 5 star houses by 2050 and 2100 due to global warming)

It should be noted that the changes in energy requirement for any emission scenario can be described by the sensitivity curves (refer to Figures 9 and 10) that represent the relationship between the changes in energy demand and the global warming temperature, as shown in Figure 13, for 5 star houses. In Figure 13, three different symbols were used to indicate the percentage change in the energy demand at 550ppm stabilisation, A1B and A1FI scenarios, with the energy demand in 2100 for the three scenarios highlighted.

(Insert Figure 13 The trajectories of energy demands for A1B, A1FI and 550ppm stabilisation emission scenarios on sensitivity curves)

It should also be noted that the change in energy demand due to the changing climate can also affect the energy rating of residential houses if the current energy rating standard is maintained. As shown in Table 5, the energy rating of houses, which currently have 5 star rating, will decline significantly in a hot climate, such as in Alice

Springs and Darwin, if the same energy rating standard is used. The energy rating in the two cities is projected to drop between 1.2 and 2.9 stars by 2050 and between 1.8 and 5 stars by 2100. With the moderate emission scenario A1B, the drop in star rating is around 0.4 stars per 10 years in Darwin. Even for a temperate climate in Sydney, the energy rating is projected to drop considerably by between 1.5 and 2.1 stars by 2050 and between 2.2 and 3.9 stars in 2100. In contrast, 5 star houses in a cool climate such as in Hobart and Melbourne could increase their energy rating by between 1.1 stars by 2050 and 2.2 stars by 2100.

(Insert Table 5 Influence of climate change on the energy star rating of residential houses that currently have an energy rating of 5 stars)

The changes in the energy star rating, either increase or decrease, are not the consequence of the variations in building fabric and energy efficiency, instead they are the result of the changing climate. The changes in energy star rating could occur during the lifespan of the existing house stock in Australia. Considering that the changes in star rating are different in different climate zones, building regulators may need to take into account the impact of climate change when reviewing the energy rating scheme.

Similar to the findings in the sensitivity assessment, current energy performance in terms of energy rating may also affect the extent of climate change impact. Figure 14 shows the projected changes in the total annual H/C energy demand for 2 star, 5 star and 7 star houses in the five cities, estimated from the average demand projections based on the nine GCMs considering the A1FI scenario. The plots on the left hand side show the absolute changes in total annual H/C energy demand, while the plots on the right hand show the percentage changes in comparison to the reference energy demands. As found in the sensitivity assessment, the changing climate generally has more impact on the houses with a lower energy rating over their lifespan, in terms of the absolute amount of change in the total annual H/C energy demand. However, the houses with a higher energy rating are more sensitive to the changing climate in percentage terms.

(Insert Figure 14 Changes in the total annual H/C energy demand for a house with different energy ratings in five cities, under the emission scenario of A1FI)

In Alice Springs, the total annual energy demand may increase 33%, 66% and 85% by 2050, and 109%, 212%, and 279% by 2100, for a house with a 2, 5 and 7 star energy rating, respectively.

In Hobart, the house with a 2 star energy rating reduces the energy demand mostly, in terms of the absolute change. However, the percentage change in energy demand of 2, 5 and 7 star houses is -22%, -26% and -27% respectively by 2050, and -43%, -48% and -49% respectively by 2100. In other words, the house with a higher energy rating in a cold climate condition may benefit more in terms of the percentage reduction in energy demand.

In Melbourne, where the climate condition will transit from temperate to warm conditions due to climate change, the percentage reduction in energy demand of 7 star houses is higher than 2 star and 5 star houses before 2055, albeit marginally. However, similar to the sensitivity study (refer to Figure 11), the benefit of energy demand reduction due to climate warming starts to diminish quickly after 2055. The saving benefit drops from a 20% reduction by 2055 – the largest reduction among the three star ratings, to a 2% reduction by 2100 – the least reduction among the three star ratings. For other emission scenarios including A1B and 550ppm stabilisation, the trends of energy demand variation due to global warming, in relation to energy rating, are similar. These are not presented here.

4. CONCLUSIONS

The contribution of building energy consumption to carbon emissions has attracted significant attention. Many technology, policy and regulation initiatives and have been developed in order to reduce energy use as a climate change mitigation measure. However, climate change may also alter the local climate of buildings, which can in turn affect the energy demand of buildings, especially for heating and cooling (H/C). The current study demonstrated that H/C energy demands of residential houses may be significantly impacted upon by changing climate.

OZClim is applied to project climate change in Australia for the assessment of climate change impact on H/C energy demand of residential buildings. Outcomes from nine GCMs are used to simulate the local climates of buildings, including temperature, relative humidity and solar radiation, all of which are correlated to the global warming temperature. Incorporating with current Typical Meteorological Year (TMY) weather files by a so-called 'morphing' approach, new weather files with hourly data are developed in relation to the changing climate, especially for the sensitivity and scenario assessment with the aid of *AccuRate,* a residential house energy rating tool. A modern Australian detached brick veneer four bedroom house was considered to demonstrate the impact of changing climate on the H/C energy demand of houses located in five cities, i.e., Alice Springs, Darwin, Hobart, Melbourne and Sydney in Australia, representing a diverse regional climate environment including hot dry, hot humid, cold, temperate with cold winter, and temperate climates.

The sensitivity assessment illustrates the relationship between H/C energy demand and global warming. It was found that the reduction in heating demand as well as the increase in cooling demand at all locations shows changes proportional to the global warming temperature. In a cooling dominated hot or warm climate, such as in Darwin and Alice Springs, or a cooling and heating balanced temperate climate such as in Sydney, the increase in the cooling energy demand is much more dramatic than the decrease in the heating energy demand when responding to global warming. In contrast, the reduction of heating energy demand prevails in a relatively cold temperate climate, such as in Hobart. It is interesting to note that in a heating dominated temperate climate, such as in Melbourne, the increase in cooling demand is at a magnitude similar to the reduction of heating demand for the majority of scenarios. The total H/C energy demand may therefore decrease initially and then rise later in the longer term with the increased global warming. In terms of the percentage change in H/C energy demand, houses in a H/C balanced temperate climate are more sensitive to the changing climate represented by an increasing trend to meet more cooling demand. In Sydney, the trend becomes very significant after the global temperature increase reaches 2°C. Meanwhile, the energy performance or energy rating of current buildings may also considerably affect the sensitivity of H/C energy demand to the changing climate. In particular, in a H/C balanced temperate climate, the sensitivity to global warming (in percentage terms) is more than doubled when energy ratings change from 2 to 5 stars. The H/C energy demand is found to increase 120% for 7 star houses when the global temperature increases 2°C and 530% for an increase of 5°C.

In addition, scenario assessment shows the H/C energy demand over the lifespan of buildings in relation to the A1B, A1FI and 550ppm stabilisation emission scenarios, which are considered to represent moderate, aggressive, and policy-intervened circumstances. In fact, results from the scenario assessment can be displayed as a trajectory along the specific sensitivity curves obtained in the sensitivity assessment. It is found that a significant climate change impact on the H/C energy demand is envisaged within the lifespan of existing houses, especially in the regions either with hot/warm, cold, or heating and cooling balanced temperate. As expected in the simulations by AccuRate, the heating energy will decrease, and cooling energy will increase over the service life of buildings, as a result of global warming.

Whether the total energy demand would be reduced or increased due to global warming over the lifespan of existing houses will depend on the relative extent of energy reduction in winter and increase in summer. The energy demand of 5 star houses is projected to vary significantly in the range of -30% to 100% by 2050 and -50% to 350% by 2100 for the A1B, A1FI and 550ppm stabilisation emission scenarios, depending on the regional climates. For a hot, warm regional climate as well as a H/C balanced temperate climate, such as in Alice Springs, Darwin and Sydney, the variation in cooling energy demand is larger than the heating energy. The total H/C energy demand of a house with a 5-star energy rating may rise by up to 61% by 2050 and 112% by 2100 for the 550ppm stabilisation scenario, 81% by 2050 and 193% by 2100 for the A1B scenario, and by 101% by 2050 and 350% by 2100 for the A1FI scenario. For a cold climate, such as in Hobart, the variation in cooling energy demand is smaller than heating energy demand. As a result, the total H/C energy demand may be reduced by up to 19% by 2050 and 27% by 2100 for the 550ppm stabilisation scenario, 23% by 2050 and 37% by 2100 for the A1B scenario, and 26% by 2050 and 48% by 2100 for the A1FI scenario.

It should be mentioned that the energy rating may also be significantly affected by the changing climate. For 5 star houses in a hot or warm climate, the rating may drop considerably in accordance with the current energy rating classification. In Darwin, it declines to 2.4 stars by 2050 and 0.9 stars by 2100 for the A1B scenario, and to 2.1 stars by 2050 and 0 stars by 2100 for the A1FI scenario. In contrast, the rating may rise in a cold climate. In Hobart, it goes up to 5.9 stars by 2050 and 6.7 stars by 2100 for the A1B scenario, and 6.1 stars by 2050 and 7.2 stars by 2100 for the A1FI scenario. However, the change is not due to the deterioration or improvement of building energy efficiency. Instead, it is purely caused by the change of local climates due to global warming. It is arguable as to whether the energy rating classification should consider the impact of changing climate in the future.

The current study demonstrated that a significant climate change impact may occur within the service life of most new dwellings based on the simulations. Understanding of energy demand of residential buildings under the impact of climate change is important for the selection of mitigation and adaptation strategies in the design of new houses as well as the renovation of existing ones, especially linked to housing typologies. While there is a general sense that the building attributes, such as building envelop, orientation, and building materials are more closely related to H/C energy demand intensity (MJ/m^2), it is necessary to assess the sensitivity of energy demand to those attributes that may also include the floor size. It is also useful for further assessment of energy demand at the residential building stock level for planning purposes. All will be discussed in our further studies.

It should be noted that the current study was carried out using the thermostat settings for the five cities, which are currently listed in the Protocol for House Energy Rating Software [26]. Considering adaptive thermal comfort [27], the cooling thermostat settings may become higher when occupants start to adapt to the future warmer climate. Together with occupant behaviour, they may change the H/C energy demand. Further study is required to address the possible occupant adaptive behaviours under climate change.

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The authors would like to thank Kevin Hennessy and Jim Ricketts of CSIRO Marine and Atmospheric Research, and Roger Jones of Centre for Strategic Economic Studies at Victoria University for their generous assistance and advice on climate projections using OZClim and MAGICC. The authors would also like to express their appreciation for the assistance of Michael Syme of CSIRO Sustainable Ecosystems in finalising the paper.

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Table 1. Atmospheric-Ocean General Circulation Models Applied in this study

Models	**Developers**
CCCMA	Canadian Centre for Climate Modelling and Analysis, Canada
CNRM	National de Researches Meteorologiques, France
CSIRO-Mk3.5	Commonwealth Scientific and Industrial Research Organisation, Australia
GISS-AOM	National Aeronautics and Space Administration, Goddard Institute for Space Studies, USA
GISS-EH	Goddard Institute for Space Studies, National Aeronautics and Space Administration, USA
IAP-FGOALS	National Key laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, China
IPSL-CM4	Institut Pierre Simon Laplace, France
MICRO-M	Centre for Climate System Research, National Institute for Environmental Studies, and Frontier Research Centre for Global Change, Japan
MRI-GCM232	Meteorological Research Institute, Japan

Table 2. Regional climate conditions in five Australian cities

Locations	**Climate Conditions**	**Heating and Cooling Requirement**
Alice Springs	Hot dry, cold winter	Cooling dominated
Darwin	Hot humid	Cooling dominated
Hobart	Cool Temperate	Heating dominated
Melbourne	Temperate/cold winter	Heating dominated
Sydney	Temperate	Balanced heating/cooling

Table 3 Cooling and heating demands of 2 star, 5 star and 7 star houses in the five cities.

Annual Cooling/Heating Energy Demand		Alice Springs	Darwin	Hobart	Melbourne	Sydney
2 Stars	Heating (MJ/m^2)	103	-	480	326	66
	Cooling (MJ/m^2)	270	628	7	48	78
	Total (MJ/m^2)	**373**	**628**	**487**	**374**	**144**
5 Stars	Heating (MJ/m^2)	27	-	194	124	10
	Cooling (MJ/m^2)	117	400	3	20	39
	Total (MJ/m^2)	**143**	**400**	**197**	**144**	**49**
7 Stars	Heating (MJ/m^2)	14	-	107	66	11
	Cooling (MJ/m^2)	68	277	3	13	18
	Total (MJ/m^2)	**82**	**277**	**110**	**79**	**29**

Table 4. The average percentage changes (%) in annual heating and cooling energy demand for 5 star houses by 2050 and 2100 due to global warming

			Alice Springs	Darwin	Hobart	Melbourne	Sydney
550ppm	2050	Heating	-50	-	-20	-30	-66
		Cooling	62	39	79	69	93
		Total	**41**	**39**	**-19**	**-16**	**61**
	2100	Heating	-68	-	-30	-44	-83
		Cooling	106	61	153	123	161
		Total	**67**	**61**	**-27**	**-21**	**112**
A1B	2050	Heating	-59	-	-25	-36	-74
		Cooling	80	48	104	90	120
		Total	**54**	**48**	**-23**	**-19**	**81**
	2100	Heating	-83	-	-42	-60	-94
		Cooling	169	90	275	208	193
		Total	**122**	**90**	**-37**	**-22**	**193**
A1FI	2050	Heating	-65	-	-28	-42	-81
		Cooling	84	57	133	111	146
		Total	**56**	**57**	**-26**	**-20**	**101**
	2100	Heating	-94	-	-58	-78	-99
		Cooling	283	135	572	380	462
		Total	**213**	**135**	**-48**	**-14**	**350**

Table 5. Influences of climate change on the energy star rating of residential houses that currently have an energy rating of 5 stars

	A1B		**A1FI**		**550 ppm**	
	2050	**2100**	**2050**	**2100**	**2050**	**2100**
Alice Springs	3.5	2.4	3.4	1.5	3.8	3.2
Darwin	2.4	0.9	2.1	0	2.8	1.9
Hobart	5.9	6.7	6.1	7.2	5.8	6.2
Melbourne	5.7	5.9	5.8	5.9	5.9	5.6
Sydney	3.5	2.8	3.2	2.1	2.9	1.1

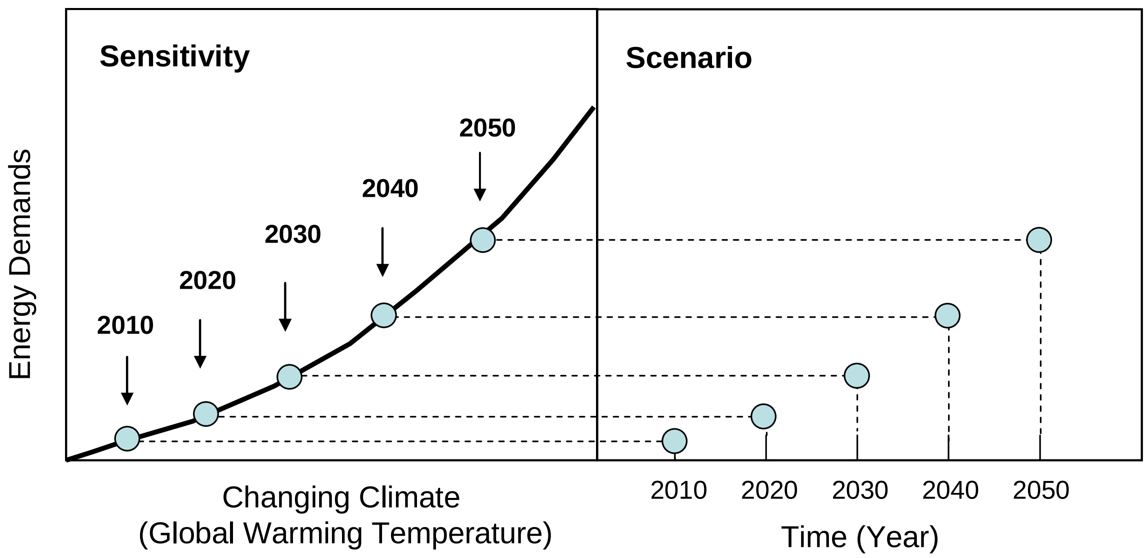
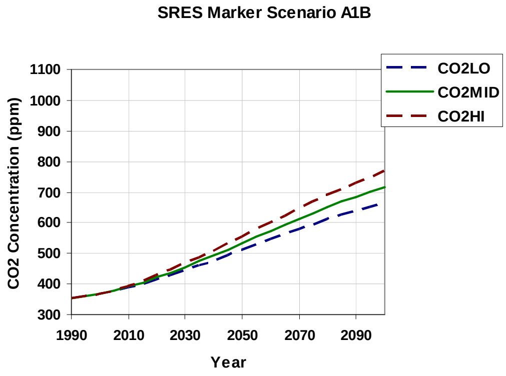
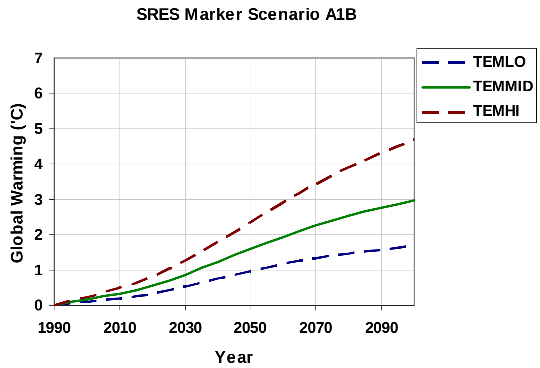


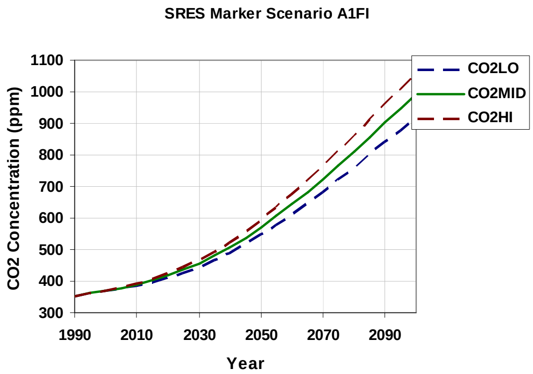
Figure1. Sensitivity, scenario and their relationship



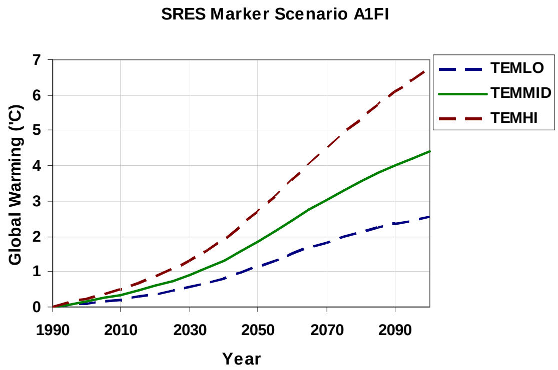
(a) CO_2 concentration (A1B)



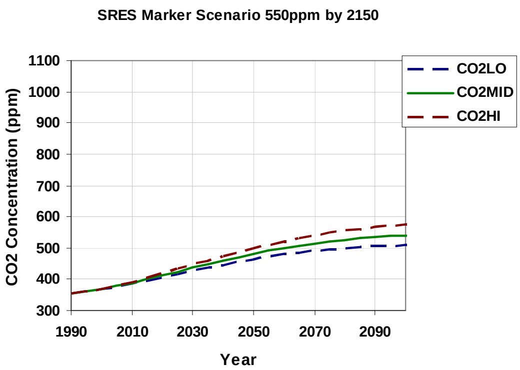
(b) Temperature (A1B)



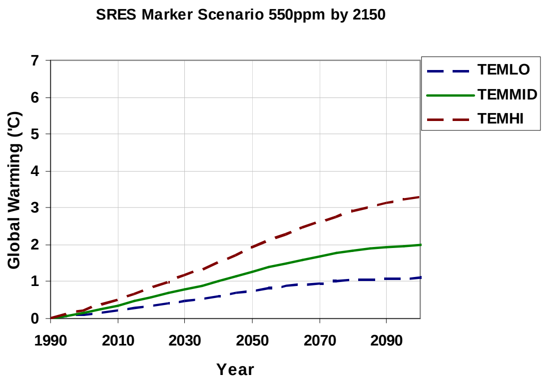
(c) CO_2 concentration (A1FI)



(d) Temperature (A1FI)

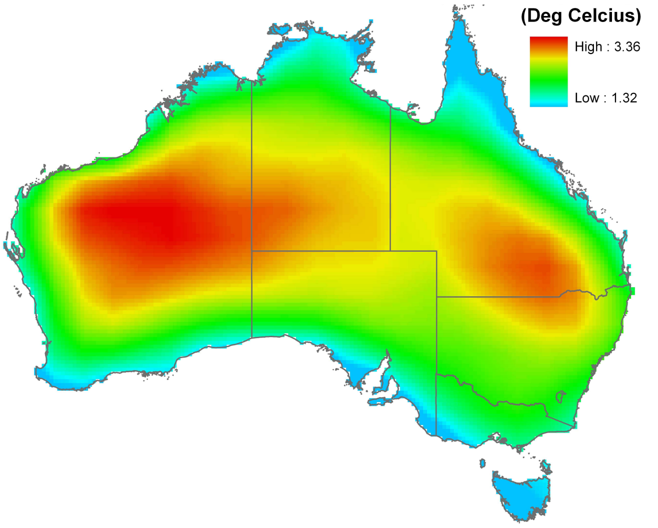


(e) CO_2 concentration (550ppm stabilisation)

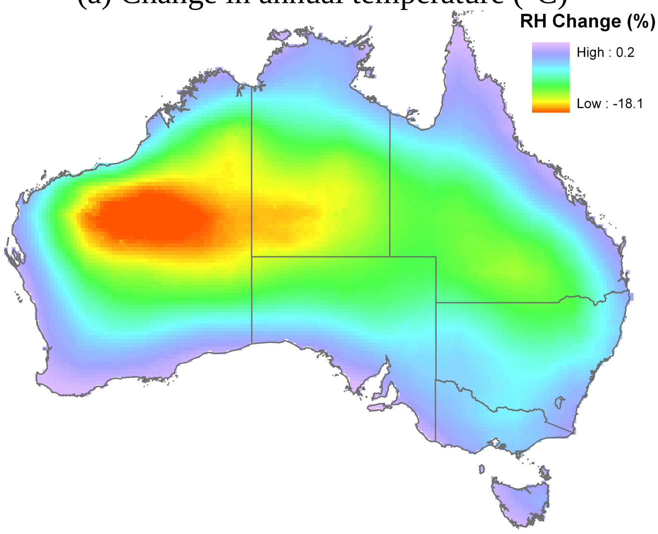


(f) Temperature (550ppm stabilisation)

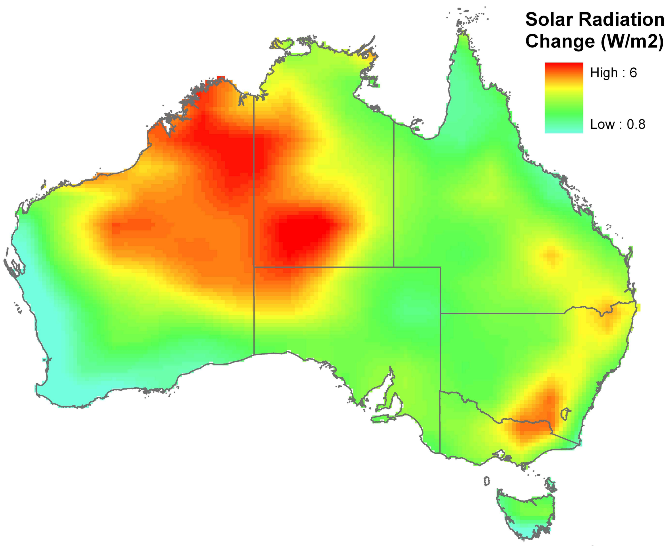
Figure 2. Projections of atmospheric CO_2 concentration and global warming to 2100



(a) Change in annual temperature (°C)



(b) Change in annual relative humidity (%)



(c) Change in annual solar radiation (W/m^2)

Figure 3. Projections of climate variability by 2050 by CSIRO-Mk3.5 GCM, given A1FI emission scenario.

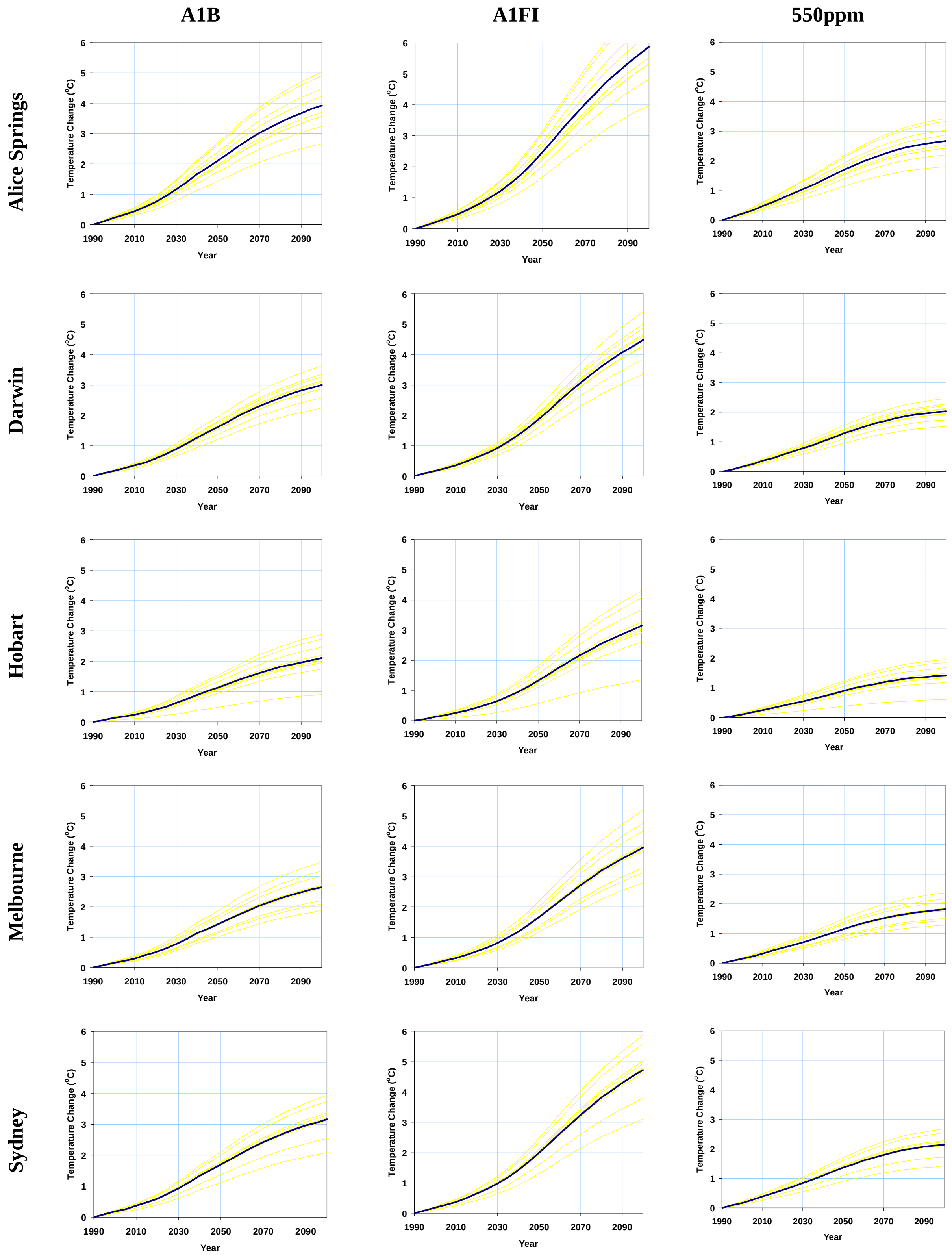


Figure 4. Projections of temperature change in degree Celsius in Australian cities for A1B, A1FI and 550ppm stabilisation scenarios.

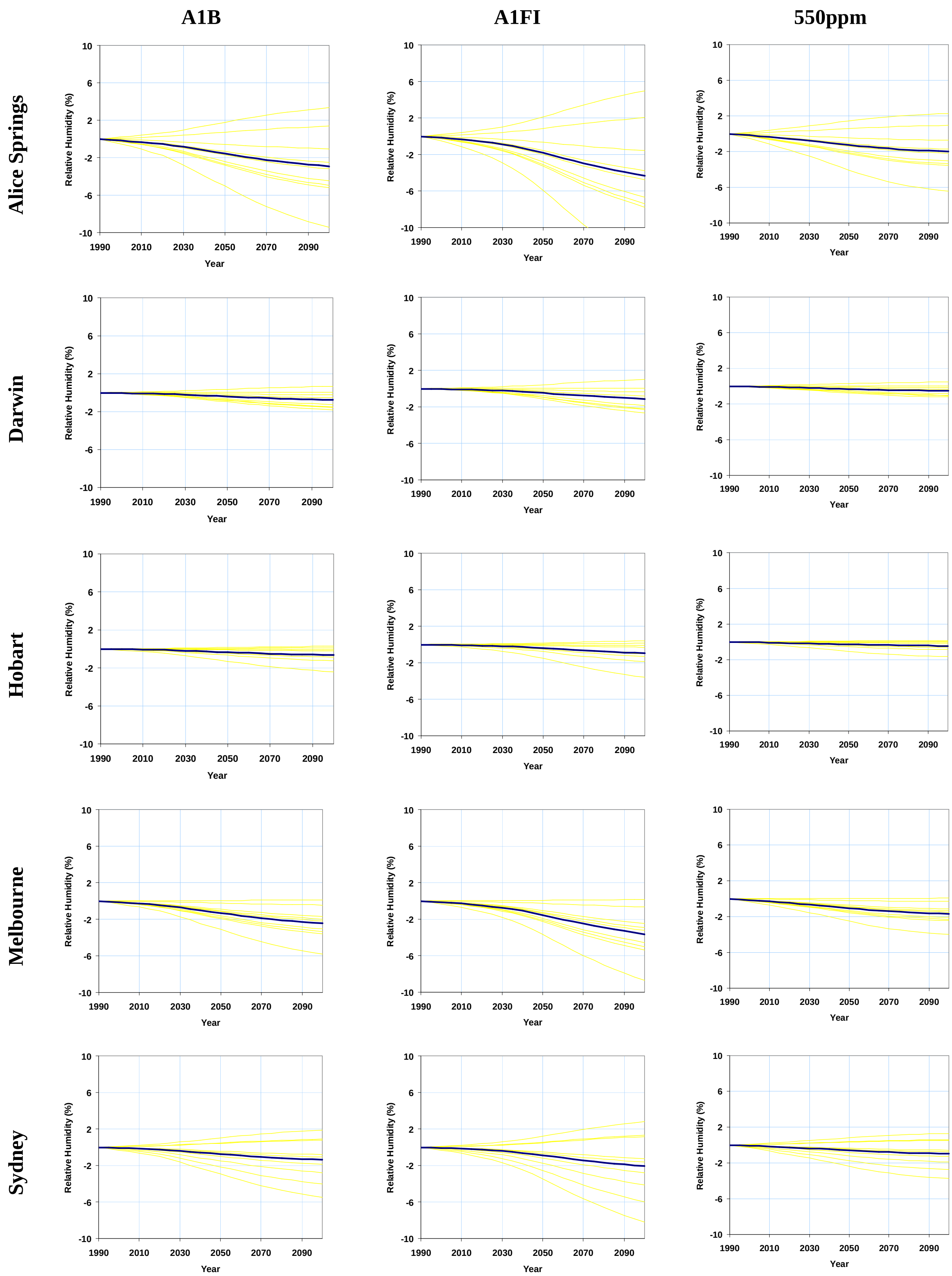


Figure 5. Projections of relative humidity change in percentage in Australian cities for A1B, A1FI and 550ppm stabilisation scenarios.

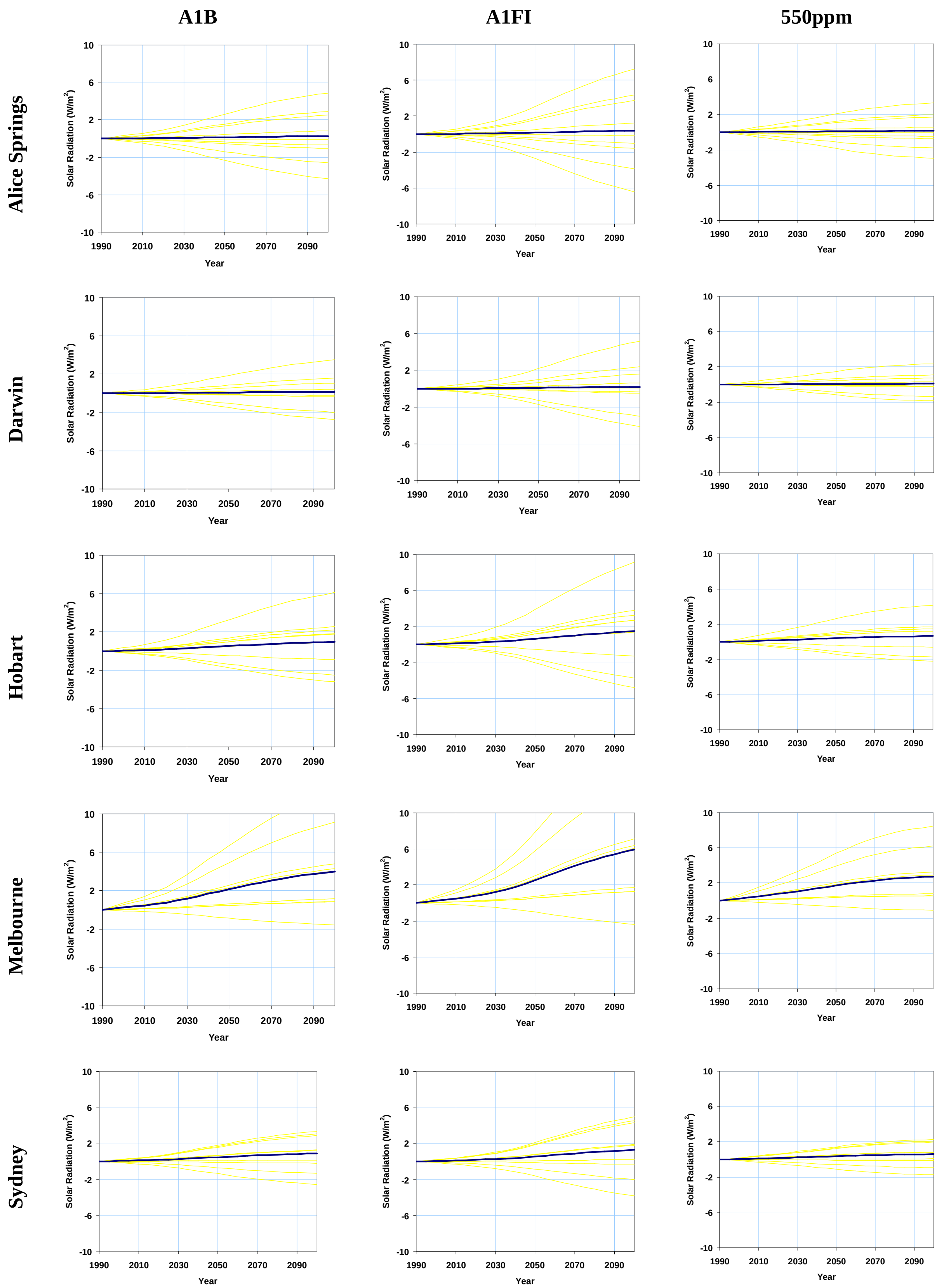


Figure 6. Projections of solar radiation change in W/m^2 in Australian cities for A1B, A1FI and 550ppm stabilisation scenarios.

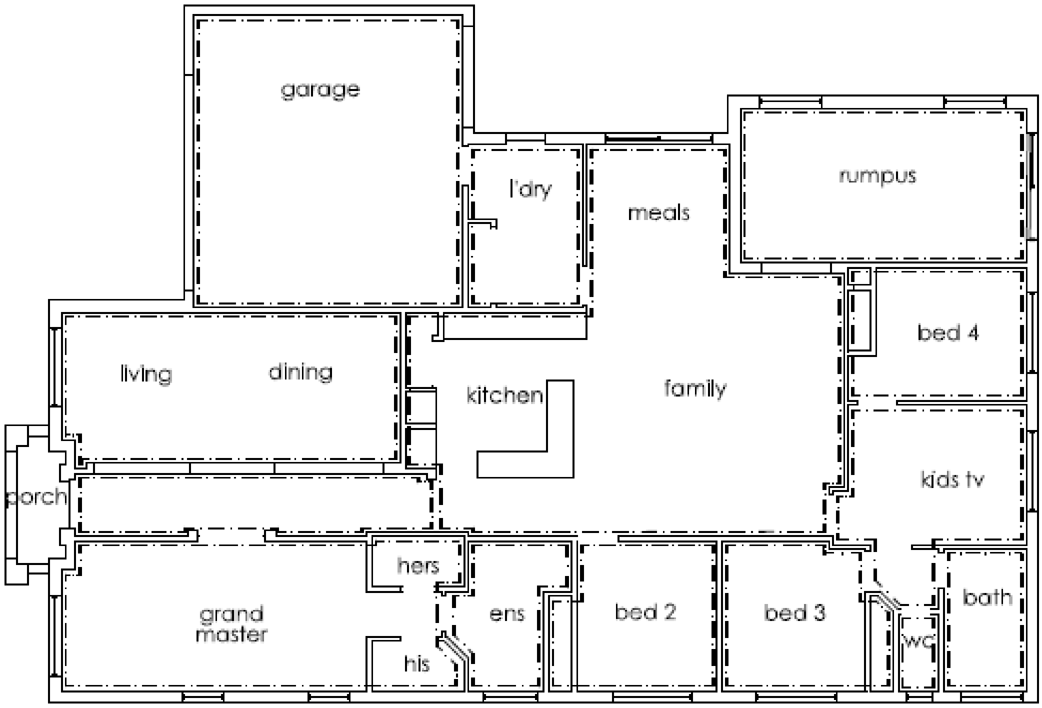


Figure 7. A floor plan of a conventional four bedroom house in Australia

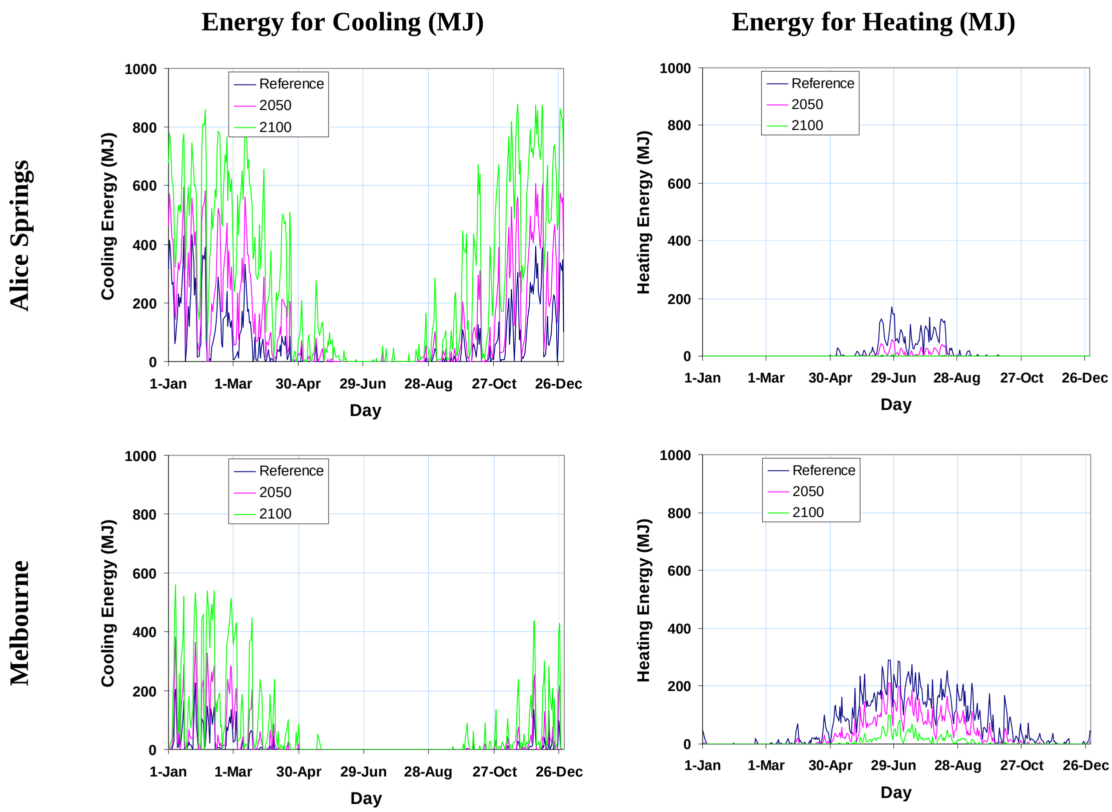
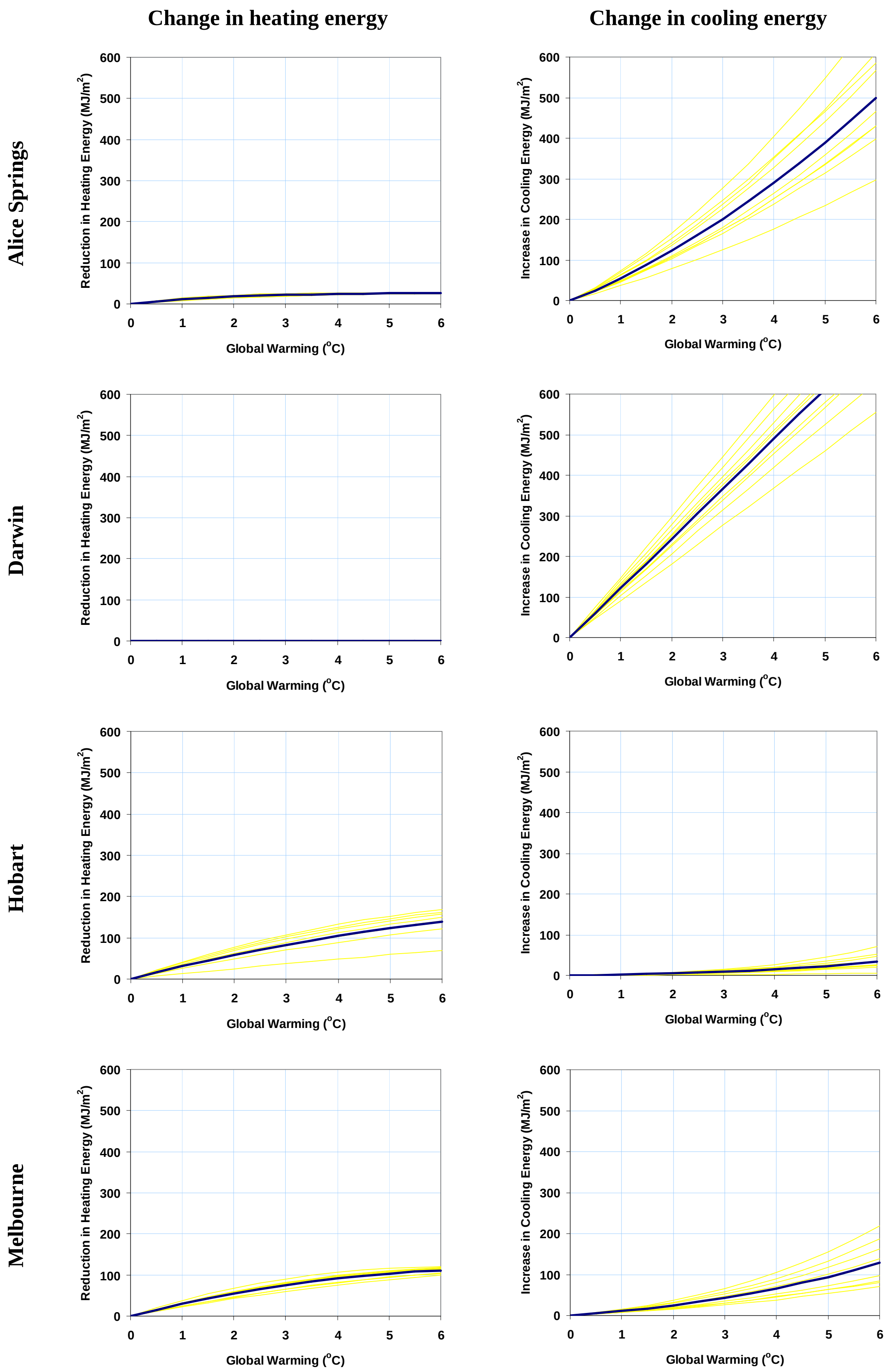


Figure 8. Daily H/C energy demand for a mordern four bedroom house of five-star energy rating in Alice Springs and Melbourne, in 2050 and 2100, in comparison with the reference demand.


Change in heating energy
Change in cooling energy
Alice Springs
Darwin
Hobart
Melbourne
Reduction in Heating Energy (MJ/m^2)
Increase in Cooling Energy (MJ/m^2)
Global Warming (^{o}C)

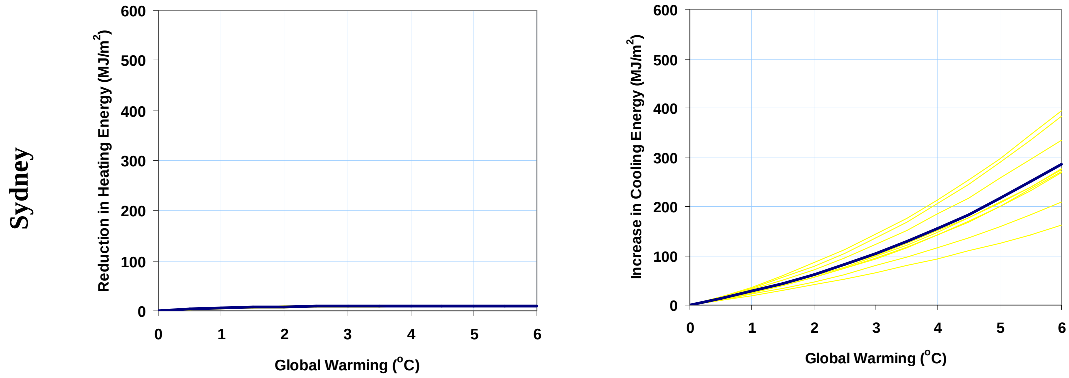


Figure 9. Sensitivity of the changes in H/C energy demand to the global warming temperature for five star houses in five cities.

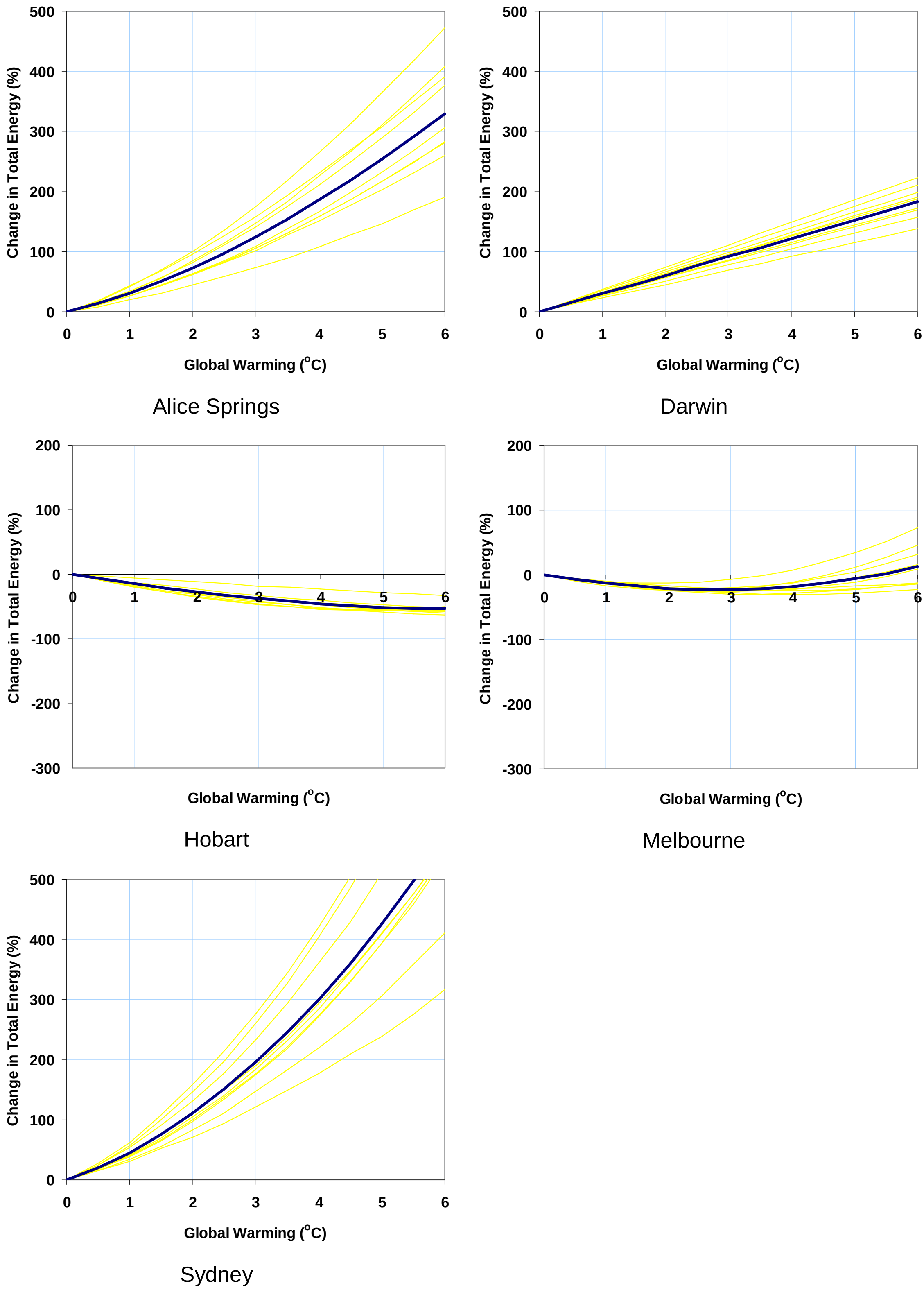
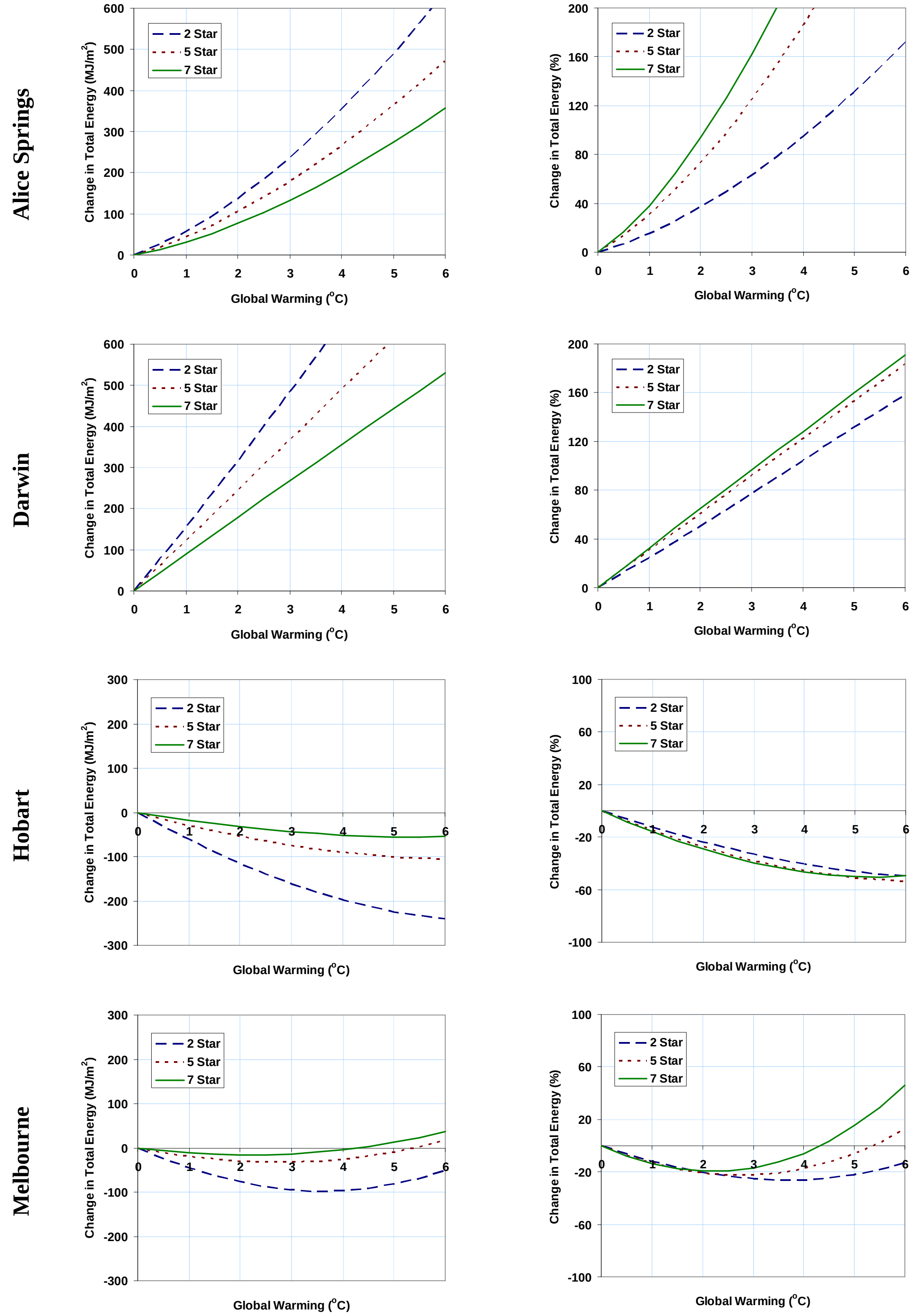
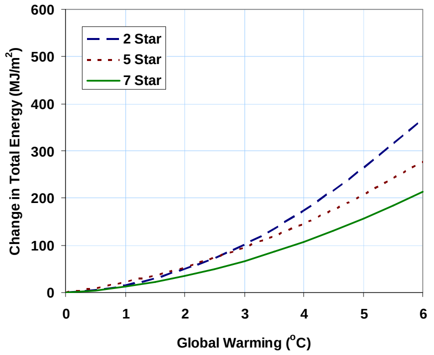


Figure 10. Sensitivity of the total H/C energy demand (in percentage terms) to global warming for a 5 star energy rating house in five cities.

Change in total energy | Percentage change in total energy



Sydney



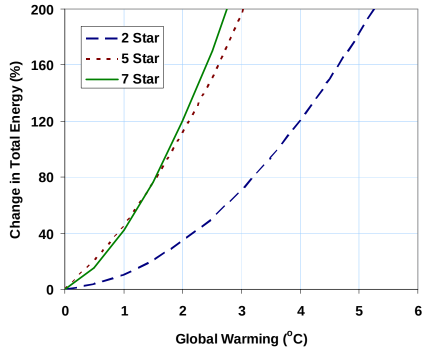


Figure 11. Sensitivity of total H/C energy demand to global warming for a house with different energy ratings in five cities.

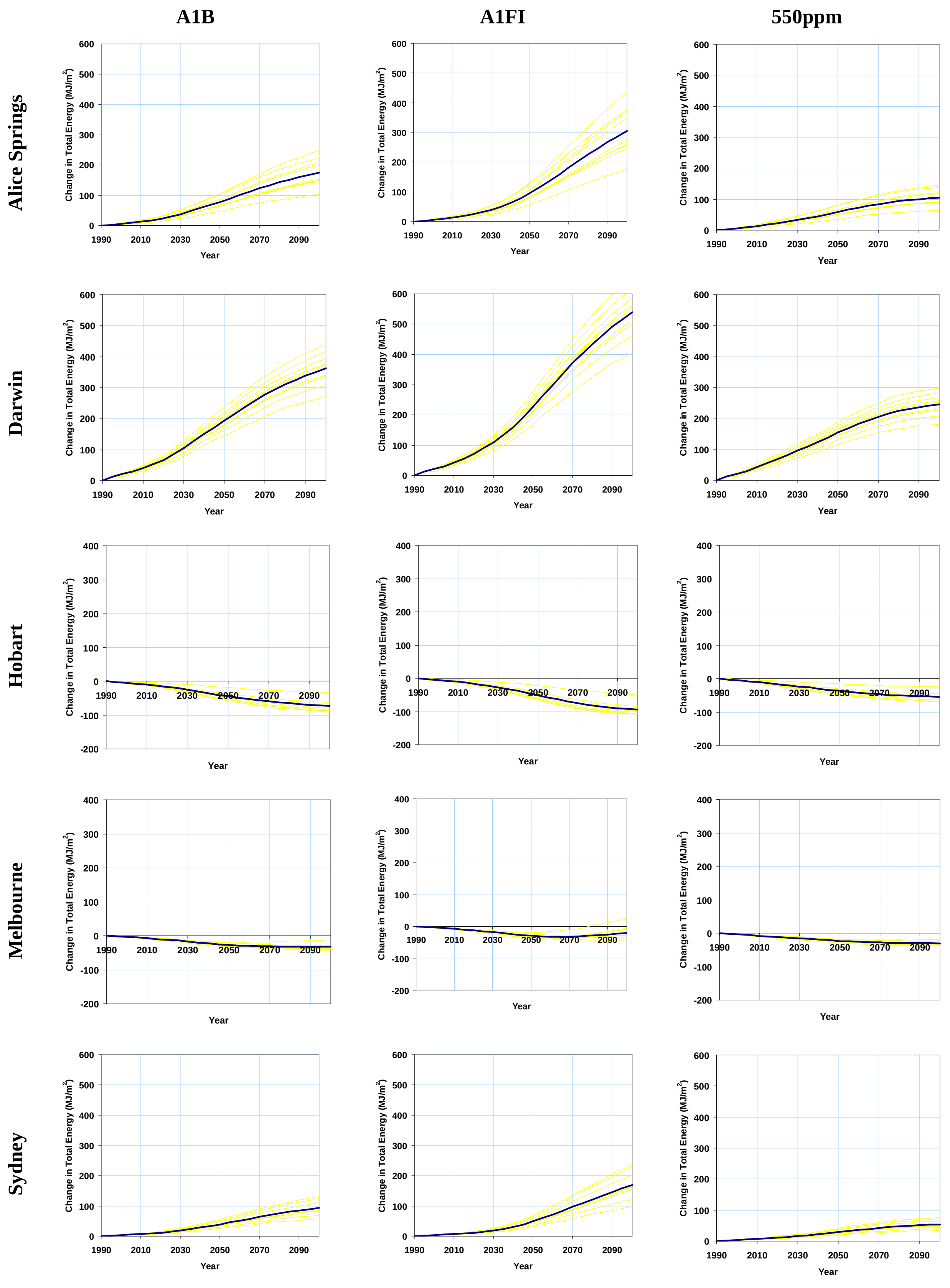
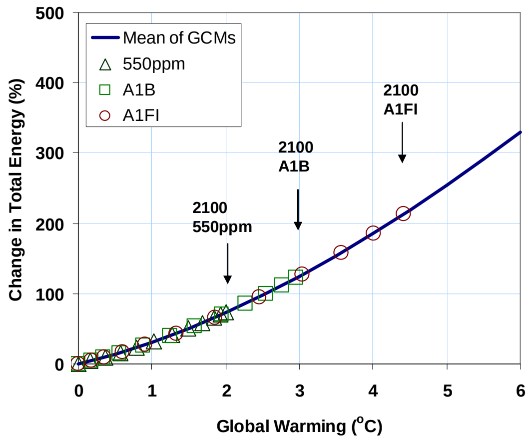
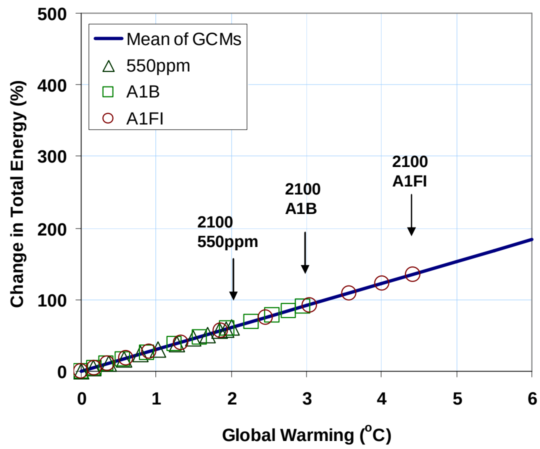


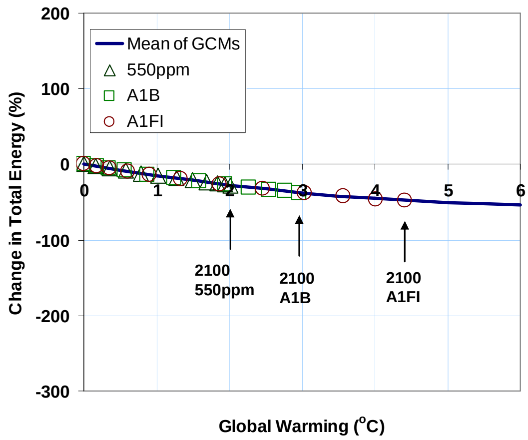
Figure 12. Projections of H/C energy demand variation in Australian cities for A1B, A1FI and 550ppm stabilisation scenarios (light colour curves: projections based on the nine GCMs; dark curves: average values of the nine GCMs)



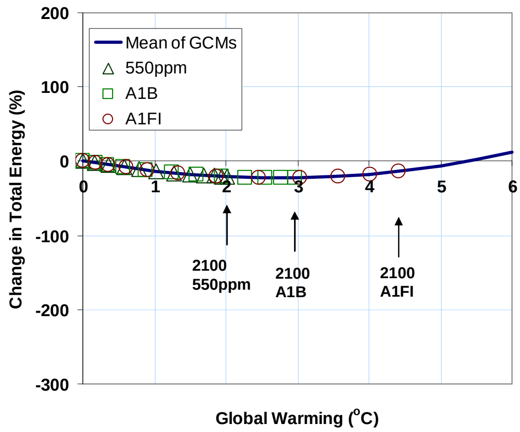
Alice Springs



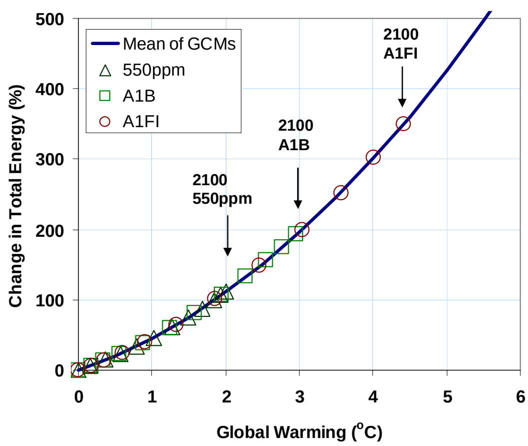
Darwin



Hobart



Melbourne



Sydney

Figure 13. The trajectories of energy demands for A1B, A1FI and 550ppm stabilisation emission scenarios on sensitivity curves.

Change in total energy

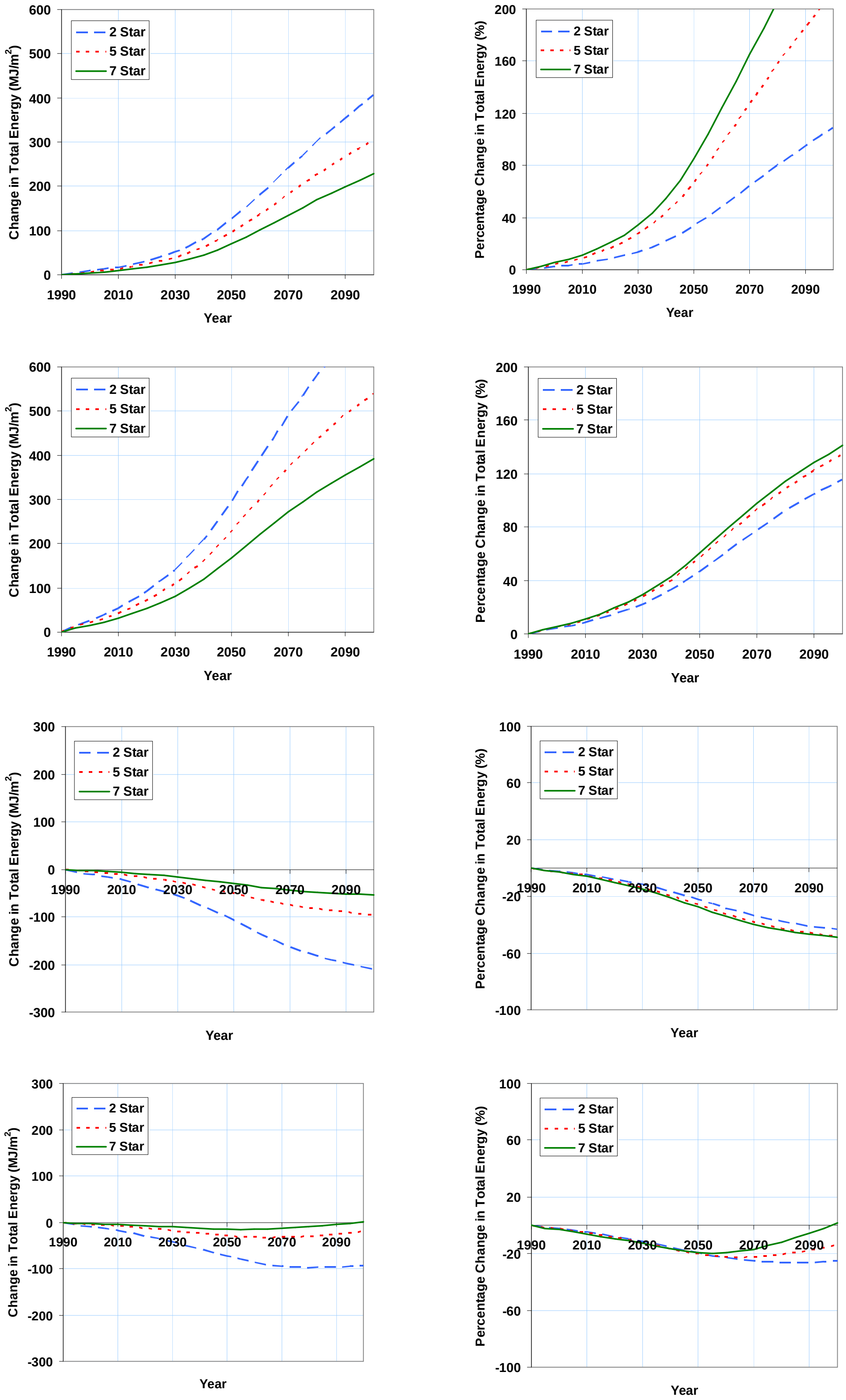
Percentage change in total energy

Alice Springs

Darwin

Hobart

Melbourne



Sydney

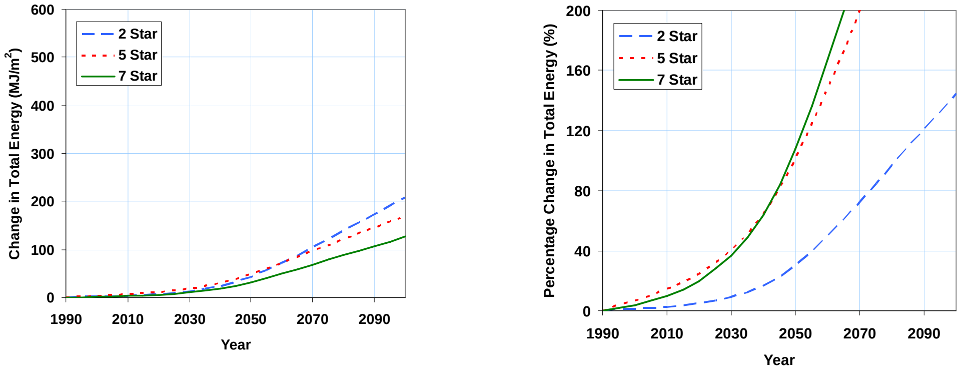


Figure 14. Changes in the total annual H/C energy demand for a house with different energy ratings in five cities, under the emission scenario of A1FI.