buildings

MDPI

Article

Impact of a Warming Climate on Hospital Energy Use and Decarbonization: An Australian Building Simulation Study

Yunlong Ma [1,2], Sherif Zedan [1,2], Aaron Liu [1] and Wendy Miller [1,*]

[1] School of Architecture and Built Environment, Queensland University of Technology, Brisbane 4000, Australia
[2] Anderson Energy Efficiency, Mount Gravatt East 4122, Australia
* Correspondence: w2.miller@qut.edu.au

Abstract: The high energy use of hospitals and healthcare facilities globally contributes to greenhouse gas emissions. At the same time, a large percentage of this energy use is attributed to space heating, cooling and ventilation, and is hence correlated to the climate. While the energy performance of Australian hospitals at the design stage is evaluated using historical weather data, the impact of the warming climate on Australian hospitals into the future remains unknown. The research question addressed is: What is the impact of future climates on the energy use of Australian hospitals built with the current design conditions? Two archetype hospital models were developed (a small single-story healthcare facility and a large multi-story hospital). DesignBuilder was used to simulate the performance of these models in 10 locations, ranging from the tropics to cool temperate regions in Australia. Current (1990–2015) and future climate files (2030, 2050, 2070 and 2090) were used. The results show that with the warming climate, the heating demand decreased, while the cooling demand increased for both hospital models for all sites. Cooling dominated climates, such as Darwin and Brisbane, were significantly impacted by the changing climates due to a substantial increase in cooling energy use. Heating based climates, such as Hobart and Canberra, resulted in an overall small reduction in total building energy use. In addition, the single-story facility was more impacted by the change in climate (in terms of energy use intensity) than the multi-story facility. The study highlights the importance of future climate files in building simulation and decarbonization planning.

Keywords: building simulation; climate change; energy use; future climate; hospitals; net zero carbon; resilience

check for updates

Citation: Ma, Y.; Zedan, S.; Liu, A.; Miller, W. Impact of a Warming Climate on Hospital Energy Use and Decarbonization: An Australian Building Simulation Study. *Buildings* **2022**, *12*, 1275. https://doi.org/10.3390/buildings12081275

Academic Editor: Alan Short

Received: 22 July 2022
Accepted: 16 August 2022
Published: 19 August 2022

1. Introduction

1.1. Need for Emission Reductions in the Built Environment

The National Oceanic and Atmospheric Administration (NOAA) reported in June 2022 that the earth's average surface temperature in 2021 (averaged over land and ocean) was 1.04 °C warmer than the pre-industrial period (1880–1990) and that the rate of warming per decade since 1981 was double that of the rate of warming per decade since 1880 [1]. Furthermore, the 9 years from 2013 to 2021 ranked among the 10 warmest on record [1].

Australia has warmed by more than 1 °C since 1910 [2] and is expected to warm by 1.5 °C in the next two decades [3]. It was also reported that Australia will face up to 6 °C mean annual temperature increase by 2100 (compared to the pre-industrial era) if no strong actions are taken to reduce carbon emissions [3]. Science indicates that emission reductions in the order of 7.5% every year are required for the decade 2020–2030 to meet the 1.5 °C Paris Agreement target [4]. The International Renewable Energy Agency (IRENA) argues that 38% of the carbon reductions needed for the world's energy transition can come from energy conservation and energy efficiency [5].

Globally, the built environment is said to be responsible for at least a third of the world's energy consumption and more than a third of energy-related carbon emissions [6,7], leading the World Green Building Council to call for a radical transformation in the way buildings are designed, built and deconstructed, and a total decarbonization of the sector by 2050 [8].

1.2. Health Facility Emissions

The healthcare sector is responsible for approximately 4.4% of global net emissions (direct and indirect), and energy use (electricity, gas, steam and air conditioning) accounts for more than half of the sector's emissions [9]. The evaluation of healthcare emissions per capita shows Australia as the top emitter, followed by Canada, Switzerland and the United States [9].

Multiple academic and gray literature globally reports on benchmarking of hospital energy use—for example, in the UK [10,11], USA [12], China [13], India [14], Greece [15] and Australia [16]. Heating, ventilation and air conditioning (HVAC) are reported as a major end-use energy service in many jurisdictions, accounting for 35–70%. Global comparisons and benchmarking of HVAC energy use intensity (EUI) are not advisable because of the differences in energy supply (e.g., differences in energy sources used for heating and cooling) and differences in approach to the application of HVAC to hospital settings due to (i) climate and cultural expectations regarding indoor climate; (ii) the age of buildings, infrastructure and equipment, and hence, their relative energy efficiency; (iii) building size, structure and configuration (e.g., thermal mass, external wall/roof area); and (iv) national and regional healthcare budgets (and the extent to which HVAC is seen as a necessity).

In Australia, buildings consume more that 40% of the national electricity energy use [17], and healthcare facilities are among the most energy-intensive commercial building types [18]. Australian hospitals, for example, accounted for 14% of the total national building energy consumption a decade ago [16], and in the financial year 2018–2019, Australian public hospitals used 4122 gigawatt hours (GWh) of stationary energy, comprising 61% electricity and 35% natural gas [19]. In the financial year 2014–2015, healthcare buildings were estimated to account for 7% of Australia's total carbon emissions [20] compared to the estimated 8.5% contribution of the healthcare sector to the USA's total emissions [21] and the 4% contribution of the National Health Service (NHS) to the UK's total emissions [22]. The UK's NHS has a target for net zero emissions (from sources under direct control) by 2040, with the ambition of an interim 80% reduction by 2028–2032 [22]. It is also addressing emissions from the broader healthcare supply chain, with the aim of net zero by 2045 and the ambition of 80% reduction by 2036–2039 [22].

Ambitions and targets such as these are gaining momentum across the healthcare sector through organizations such as Global Green and Health Hospitals and Health Care Without Harm and from the government and private sectors, supported by academic and clinical studies that examine the future of healthcare, ethical perspectives and co-benefits [23–25]. In Australia, the decarbonization of the healthcare sector is being driven by multiple sectors: from the clinicians (for example, the Climate and Health Alliance and Doctors for the Environment Australia), the asset and facilities managers (for example, the Australasian Health Infrastructure Alliance) and the government.

1.3. Healthcare Resilience to Climate Change

In addition to contributing to the problem, the resilience of Australia's healthcare facilities, in particular their energy systems, will be impacted by climate change (Table 1) and climate-related hazards (Table 2), as identified by the government and industry. These concerns, of healthcare facilities contributing to and being impacted by climate change, are mirrored globally and have been raised for some time [26–29]. The resilience of buildings to provide cooling in a warming climate is a particular focus of the International Energy Agency (IEA) Annex 80, whose outputs to date provide critical reviews of the nature of the problem (a warming climate), the importance of resilience and the challenges presented to buildings, cooling technologies and power systems [30].

Table 1. Healthcare energy systems impacted by climate change (Derived from Ref. [31] Tonmoy, Fahim, Jean Palutikof, Sarah Boulter, Peter Schneider, and Sue Cooke. "Climate Change Adaptation Planning Guidance Guidelines." 2019. and Ref. [32] AIRAH. "Resilience Checklist." ed Liza Taylor: The Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH), 2021).

Major System	Sub-System
STRUCTURAL SYSTEM	Materials and structural systems used in the building
EXISTING SERVICE SYSTEMS	Electrical system
	Fuel storage facility
	HVAC system
PLANNING SYSTEMS	Demand planning
	Policy and procedure development
	Capability and service planning
	Energy planning
	Procurement planning

Table 2. Climate-related hazards and energy-associated impacts for healthcare facilities (Derived from Ref. [33] Palutikof, Jean, Sarah Boulter, Peter Schneider, and Fahim Tonmoy. "Climate Change Adaptation Planning Guidance Almanac." 2019. and Ref. [32] AIRAH. "Resilience Checklist.").

Hazard Category	Specific Hazard Example	Impact on Energy Systems
Heat related	Increase in mean temperature and extreme heat (frequency, duration, magnitude and intensity of heat waves), impacting both day-time and night-time temperatures	Building/s overheating—health impact/potential heat stress for occupants Increased cooling load/requirement Increased energy demand (and cost) Heat island effect for heating, ventilation, air conditioning and refrigeration (HVAC&R) equipment (reduced performance and energy efficiency) Increased pressure on site energy capacity Increased risk of HVAC&R failure Reduced network capacity and increase in load-shedding/blackouts
Relative Humidity related	Increase in RH	Decrease in effectiveness of some cooling systems (e.g., evaporative coolers, ceiling fans) Decrease in thermal performance of buildings Higher dew point, and hence, mold and mildew on building materials and HVAC&R ducts
Rainfall related	Disruption to utilities, e.g., loss of mains power Inundation of facilities (e.g., plant room and essential services) Flooding leading to damage/preventing transport access	Reliance on backup systems (with impacts on building services, not on critical or essential services circuits) Damage to HVAC&R equipment Loss of power Limited access for service providers Inability to secure further diesel supplies for generators

Public healthcare facilities in Australia are built and operated by state governments. In an effort to address these risks, each Australian state and territory government has a target year for achieving net-zero carbon emissions (NZCE), and most jurisdictions have interim emissions reduction targets (Table 3) [3]. It should be noted that the "targets" may be legislated or aspirational.

Table 3. NZCE and interim emissions reductions targets in Australian states and territories.

State/Territory	Interim Emissions Reduction Target	NZCE Target	Renewable Energy (Electricity) Target
Australian Capital Territory (ACT)	50–60% on 1990 levels by 2025 65–75% on 1990 levels by 2030 90–95% on 1990 levels by 2040	2045	100% by 2030
New South Wales (NSW)	50% on 2005 levels by 2030	2050	Nil
Northern Territory (NT)		2050	50% (elec.) by 2030
Queensland (QLD)	30% on 2005 levels by 2030	2050	50% by 2030
South Australia (SA)	50+% on 2005 levels by 2030	2050	100% by 2030 (Actual 62% in 2021)
Tasmania (TAS)	NZCE in 6 of last 7 years	2030	100% achieved 2018
Victoria (VIC)	28–33% on 2005 levels by 2025 45–50% on 2005 levels by 2030	2050	50% by 2030
Western Australia (WA)	>50% on 2005 levels by mid-2030	2050	Nil

The hospital sector still lags behind these goals, even though the renewable energy contribution to public hospital energy use in Australia has been rising (Table 4).

Table 4. Australian baseline renewable energy and public hospital energy use and renewable energy [19].

Energy	2016/17	2017/18	2018/19
National baseline renewables	15.7%	17.0%	24.0%
Total hospital energy consumed	4,132,162 MWh	4,213,694 MWh	4,121,911 MWh
Hospital renewable energy produced	13,651 MWh	18,350 MWh	94,415 MWh
Hospital energy % renewable	0.33%	0.44%	2.29%

Building simulation and weather data are used in the design and planning stages of buildings. Ideally, for good stress testing of the adequacy of a building over its proposed lifespan, the weather files used for such simulations should include typical and extreme conditions, sufficient temporal and geographic resolution for the site and possible future climates [34]. In Australia, however, the simulation of hospital facilities, if it takes place at all, utilizes typical meteorological year (TMY) data based on historical records (1990–2015), ignoring hospital resilience and energy performance in the future climates in which these facilities will be expected to operate.

1.4. Rationale and Novelty of the Study

Within this global and national context, the purpose of this study is to understand the impact future climates may have on hospital heating, ventilation and air conditioning (HVAC) energy use in Australia. The research question addressed is: What is the impact of future climates on the energy use of Australian hospitals built with the current design conditions? The objective of the study is to assist healthcare facility asset managers in designing, operating and managing their building and energy infrastructure assets in a warmer and carbon-constrained future.

Australia has over 1300 public and private hospitals, and 148 of these are major hospitals with over 100 beds [35]. There is a need to better understand how the changing climate will influence the energy use of these facilities. This is important at both the early design stage for new facilities but also for the planning of major retrofits for existing facilities, including electrification and decarbonization of space heating and cooling services. This research is the first case study to evaluate hospital energy performance in future climates in a variety of Australian climates, ranging from tropical to cool temperate. It is also the first study to develop archetype hospital models, representative of Australian healthcare facilities, for use for this purpose. The novelty of this study is that it establishes a framework to predict the future hospital energy performance under the current design parameters, enabling the refinement of existing healthcare facility design guidelines to prepare for the changing climate. It also supplies the tools (the archetype hospital models) to enable the sector to further examine future options. This study implies the importance of utilizing future climate files in building simulation at the early building design stage and in the planning for decarbonization of healthcare energy services.

2. Materials and Methods

The methodology utilized in this study is shown in Figure 1. Each step is explained in detail in Sections 2.1–2.4.

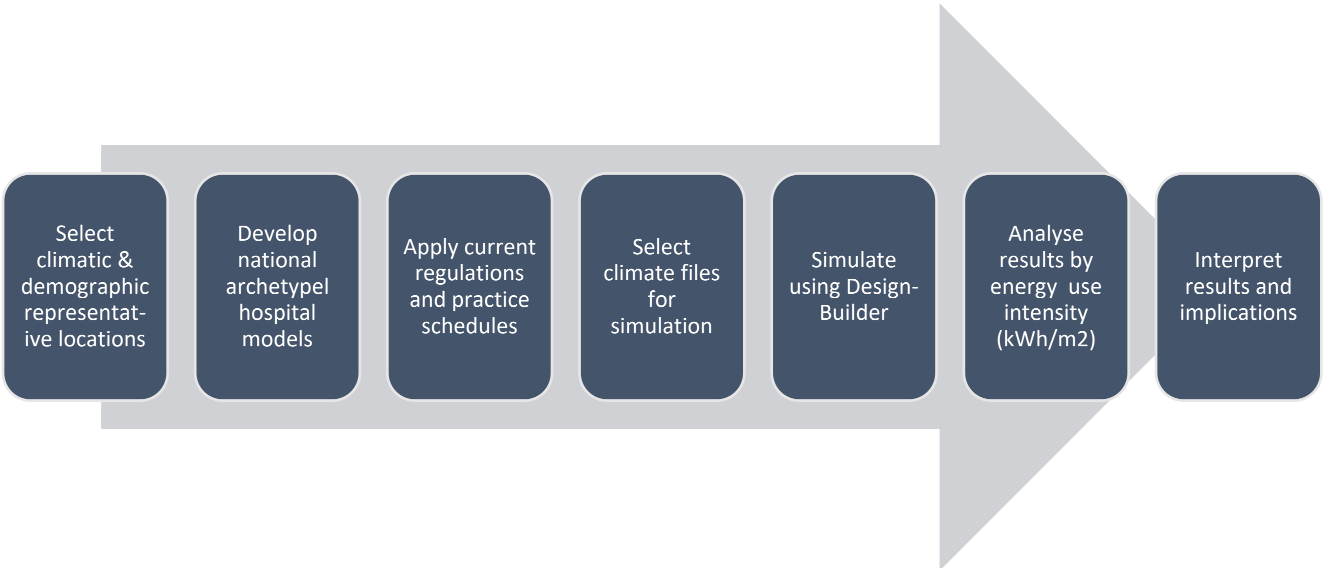

Figure 1. Study methodology.

2.1. Geographic Locations and Climate Classifications

The study locations were discussed with the Australasian Health Infrastructure Alliance (AHIA), which comprises the senior asset managers from the public health authority of each Australian state and territory and from New Zealand. The AHIA manages the Australasian Health Facility Guidelines. The selected locations include Australia's eight capital cities and two regional population centers. They also represent seven of Australia's eight broad climate zones for building regulations (Figure 2). Table 5 presents these ten locations in ascending order of latitude (from north to south) and presents the climate classification according to Australia's National Construction Code (NCC) [36] in comparison with the Köppen–Geiger Climate Classification [37,38]. The Köppen–Geiger climate classification zone map for Australia is shown in Figure 3 [39].

As seen in Figure 2, seven of the cities are located on the coast, and three are located inland (including Australia's capital city Canberra). This is indicative of Australia's population distribution, with an estimated 85% of Australians living within 50 km of the ocean. Inland towns are significantly smaller than their capital city coastal counterparts (e.g., Mt Isa population 22,000; Mildura population 50,000), but their healthcare facilities cater for a more broadly distributed regional population.

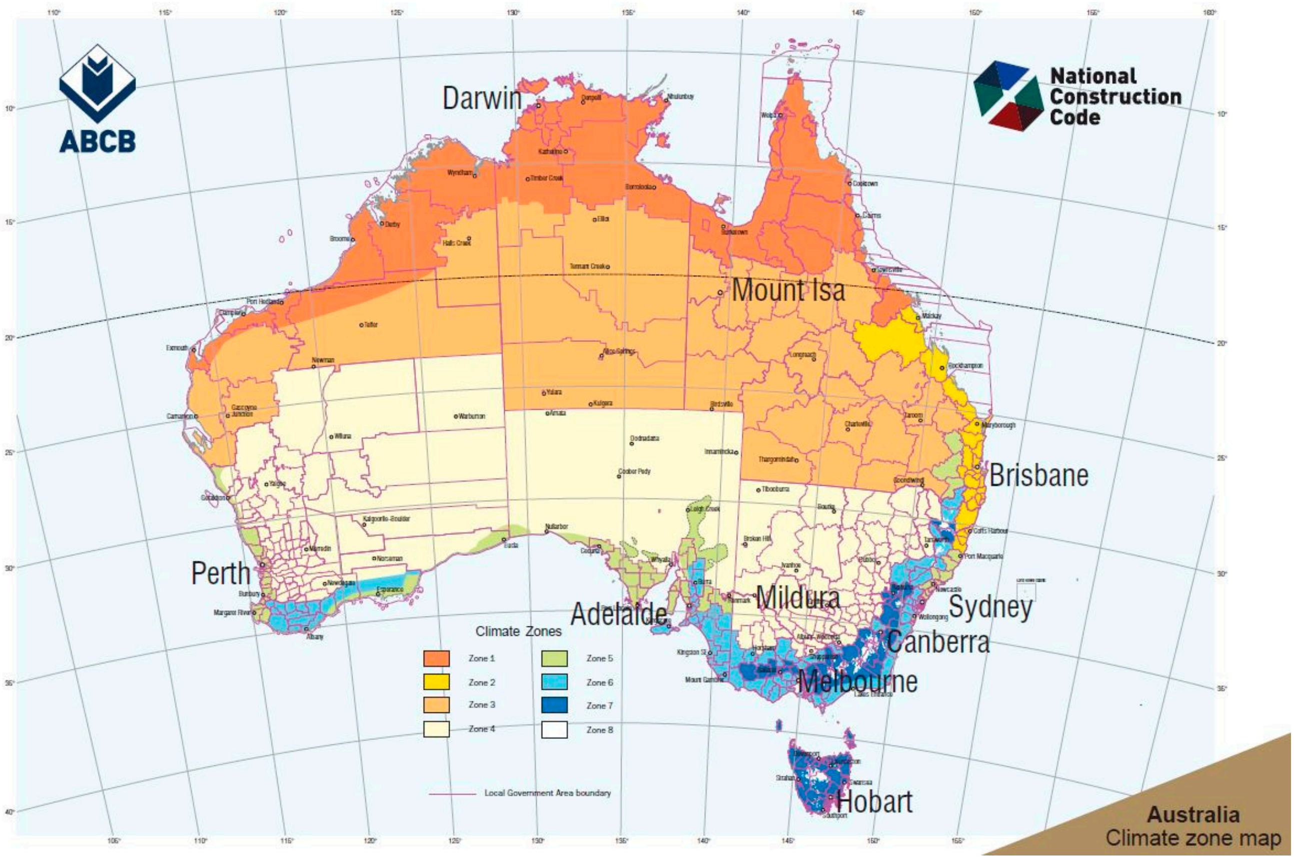

Figure 2. Australia's eight broad climate zones for building regulations (Source: NCC).

Table 5. Locations and climates.

Location	Latitude	Longitude	Altitude	Australian Climate Classification (for Buildings)	Köppen–Geiger Climate Classification
Darwin	12.4637° S	130.8444° E	31 m	High humid summer, warm winter	Aw (Tropical Savanna)
Mt Isa	20.7264° S	138.4930° E	356 m	Hot dry summer, warm winter	Bsh (Mid-Latitude Steppe and Desert)
Brisbane	27.4705° S	153.0260° E	22 m	Warm humid summer, mild winter	Cfa (Humid, Sub-tropical)
Perth	31.9523° S	115.8613° E	13 m	Warm temperate	Csa (Mediterranean)
Sydney	33.8688° S	151.2093° E	58 m	Warm temperate	Cfa (Humid, Sub-tropical)
Adelaide	34.9285° S	138.6007° E	50 m	Warm temperate	Csa (Mediterranean)
Canberra	35.2802° S	149.1310° E	578 m	Cool temperate	Cfb (Marine West Coast)
Mildura	35.2902° S	142.1367° E	33 m	Hot dry summer, cool winter	BSk (Mid-Latitude Steppe/Semi-Arid Cool)
Melbourne	37.8136° S	144.9631° E	31 m	Mild temperate	Cfb (Marine West Coast)
Hobart	42.8826° S	147.3257° E	17 m	Cool temperate	Cfb (Marine West Coast)

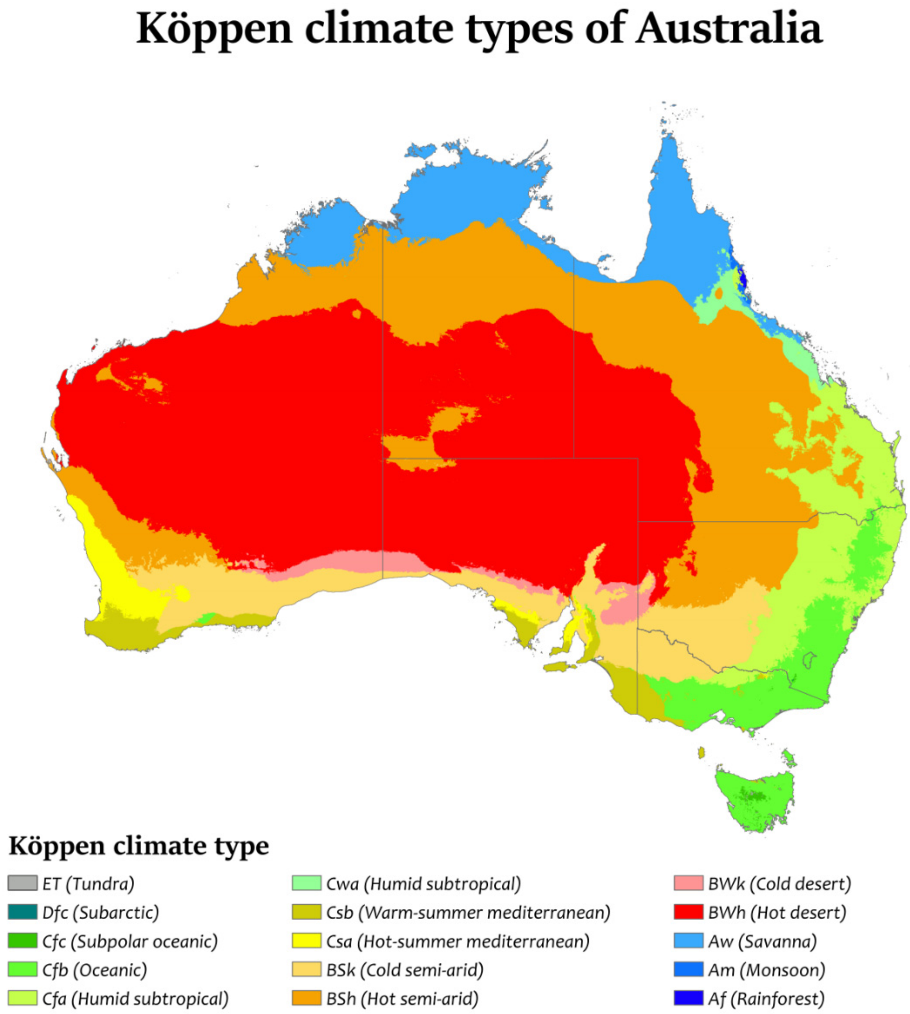

Figure 3. Köppen–Geiger climate classification zone map for Australia [39] (Adam Peterson, Australian Koppen.svg. Created 13 August 2016. CC BY-SA 4.0. No changes made).

2.2. Archetype Building Models

Prototype building models are referenced in the ASHRAE Standard 90.1 improvements program [40] and are used not only for individual building simulations but also for urban-scale building performance simulation [41]. Similar to the US Department of Energy (https://www.energycodes.gov/prototype-building-models, accessed on 2 March 2022), the Australian Building Codes Board uses archetype building models (building prototypes) to simulate and assess the impact of the proposed changes to energy efficiency regulations in buildings. Such models exist for a range of dwelling types and commercial buildings, such as offices. No archetype hospital models existed in Australia prior to this study. (Note that a small and large hospital model have been developed by the Pacific Northwest National Laboratory in the USA for their purposes). The AHIA was consulted regarding typical hospital facilities within their jurisdiction, and the plans for two recently constructed hospital buildings were provided to the authors as the basis for developing two archetype models for small healthcare facilities (<8300 m^2) and large healthcare facilities (>9300 m^2), respectively, as defined by ASHRAE [42,43]. The AHIA provided feedback on the initial model development and approval for the finalized models.

The two models described below were both developed as “Class 9a” buildings (healthcare buildings) with specific schedules for occupancy, internal loads and HVAC operations, as specified in Australia’s National Construction Code (NCC). The building envelope, internal load profiles and HVAC setpoints for the two models were designed to meet the

NCC 2019 Deemed-to-Satisfy provisions [36] for climate zone 2 (subtropical; warm humid summer, mild winter).

The small hospital model (Figure 4) is a single-story hospital building with a total floor area of 8203 m^2, representing a regional or peri-urban hospital or healthcare facility. The HVAC systems were assumed to be a centralized air-cooled chilled water system and a centralized boiler hot water heating system that provide space cooling and heating, respectively. Different types of air handling units (AHUs), such as single-zone constant-air-volume (CAV), multi-zone CAV and fan coil units (FCUs), were used to deliver supply air to different zones. The modeling specifications are summarized in Table 6.

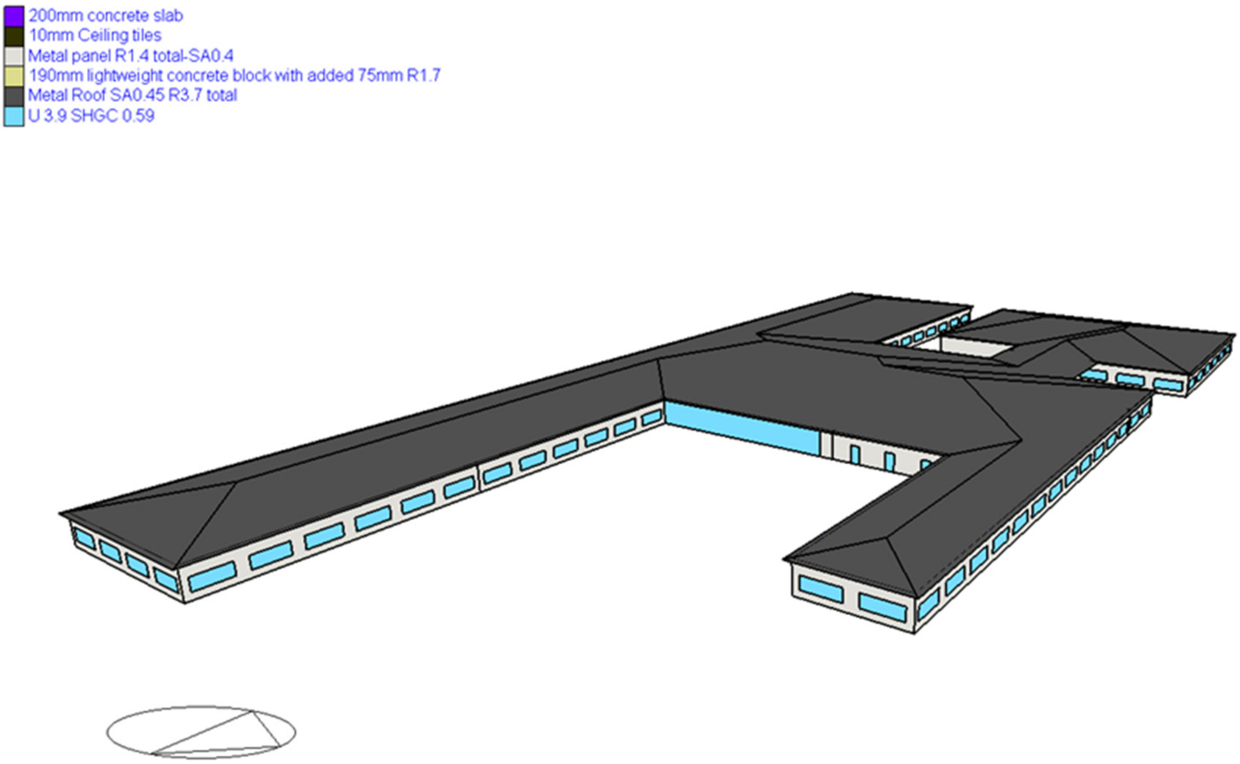

Figure 4. Small hospital building model.

Table 6. Summary of the small hospital model specification.

Building Geometry	
Floor	Single floor
Total floor area	8203 m^2
Number of people	1235
Building thermal properties	**Total R-values or U-values**
External wall	R1.4 m^2·K/W
Roof and Ceiling	R3.7 m^2·K/W
Floor	R0.4 m^2·K/W
Window-to-Wall Ratio	31%
Window U-value	U5.0 W/m^2·K
Window SHGC	0.44
Internal loads	
Weighted average lighting power density	4.19 W/m^2
Weighted average plug load power density	9.54 W/m^2
HVAC AHU types	**Zones**
FCUs	Back of House
CAV single zone	Offices, Toilets

Table 6. *Cont.*

Building Geometry	
CAV single zone 100% Outside Air	Operating Theater
CAV multi zone	Ambulatory Care, Birthing, Emergency and Imaging, Entry and Café, Gym, IPU (inpatient unit), Pathology, Pharmacy
CAV multi zone 100% Outside Air	CSSD (critical service and storage department) and Sterile Store
Thermostat setpoints	
Heating	21 °C ± 0.5 °C
Cooling	23 °C ± 0.5 °C for Back of House, 22 °C ± 0.5 °C for others
Relative humidity	50% ± 5%
HVAC control	
System type	Centralized Air-cooled Chilled Water Cooling and Centralized Boiler Hot Water Heating
Chiller COP efficiency	2.6
Electric boiler heating efficiency	95%
Chilled water setpoint temperatures	6 °C/12 °C
Hot water setpoint temperatures	55 °C/45 °C
Supply air temperature	Maximum 35 °C, Minimum 12 °C
HVAC sizing	Auto-sized to design days
Heat recovery	No
Infiltration (ACH)	0.7 when HVAC is off, 0.35 when HVAC is on

The large hospital model (Figure 5) is a six-story hospital complex with a total floor area of 142,789 m^2, representing a typical large hospital in Australian high-population urban areas. The HVAC systems were assumed to be a centralized water-cooled chilled water system to provide space cooling and a centralized boiler hot water heating system to provide space heating. Different types of AHUs, such as single-zone variable air volume (VAV), multi-zone VAV and FCUs, were used to deliver supply air to different zones. The specifications for this model are summarized in Table 7.

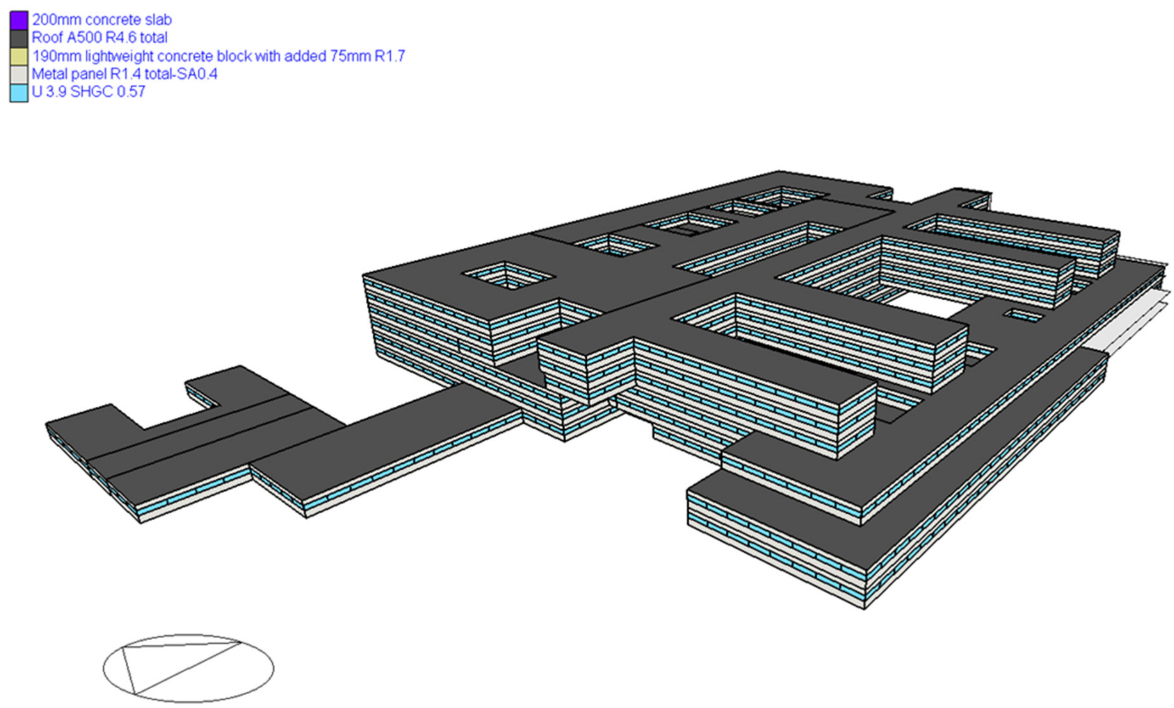

Figure 5. Large hospital building model.

Table 7. Large hospital model specification summary.

Building Geometry	
Floor	6 Stories
Total floor area	142,789 m^2
Number of people	13,907
Building thermal properties	**Total U-values**
External wall	R1.4 $m^2 \cdot K/W$
Roof and Ceiling	R4.6 $m^2 \cdot K/W$
Floor	R0.4 $m^2 \cdot K/W$
Window-to-Wall Ratio	30%
Window U-value	U5.0 $W/m^2 \cdot K$
Window SHGC	0.43
Internal loads	
Weighted average lighting power density	4 W/m^2
Weighted average plug load power density	12 W/m^2
HVAC AHU types	**Zones**
VAV single zone with FCUs	Corridor, Dining Lounge, Morgue, Plant and Services, Retail, Toilets, Transformer and Generator, Trolley Hold, Circulation, Stores, HVAC Plant
VAV multi zone	Offices, Staff and Clinics, Imaging and Labs, Birthing
VAV multi zone 100% Outside Air	Ward and Bed areas
Thermostat setpoints	
Heating	21 °C ± 0.5 °C
Cooling	24 °C ± 0.5 °C
Relative humidity	50% ± 5%
HVAC control	
System type	Centralized Water-cooled Chilled Water Cooling and Centralized Boiler Hot Water Heating
Chiller COP efficiency	6.28
Electric boiler heating efficiency	100%
Chilled water setpoint temperatures	6 °C/12 °C
Hot water setpoint temperatures	80 °C/70 °C
Supply air temperature	Maximum 35 °C, Minimum 12 °C
HVAC sizing	Auto-sized to design days
Heat recovery	Yes
Infiltration (ACH)	0.7 when HVAC is off, 0.35 when HVAC is on

A resistive electric boiler was applied to all locations and all scenarios for both the small hospital model and the large hospital model in recognition of the move toward full electrification and away from the use of gas for heating [44]. The boilers selected for the models are not meant to be a comprehensive analysis of all boiler options but as a demonstration of the process of evaluating HVAC energy use in future climates.

The schedules for occupancy, lighting, plug load equipment and HVAC operations for both models are shown in Figures 6–8. [36].

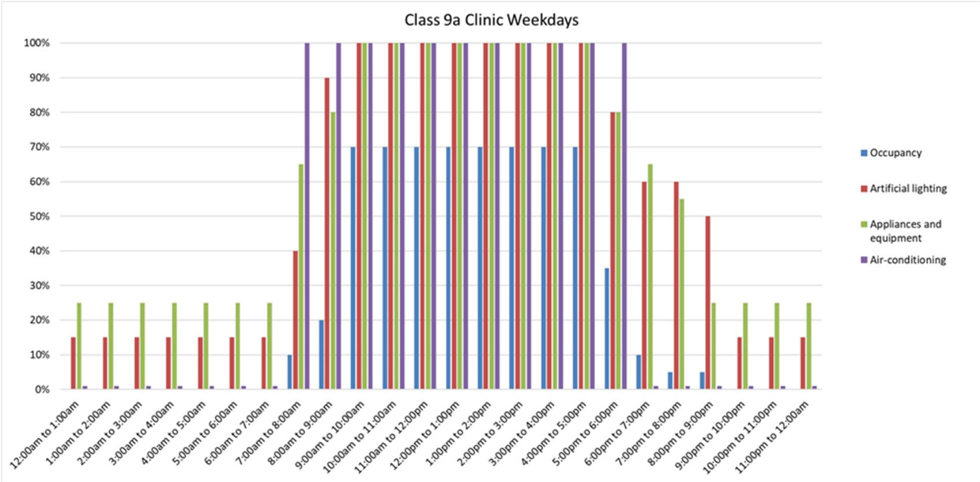

Figure 6. Operation schedules for "Class 9a Clinic"—weekdays.

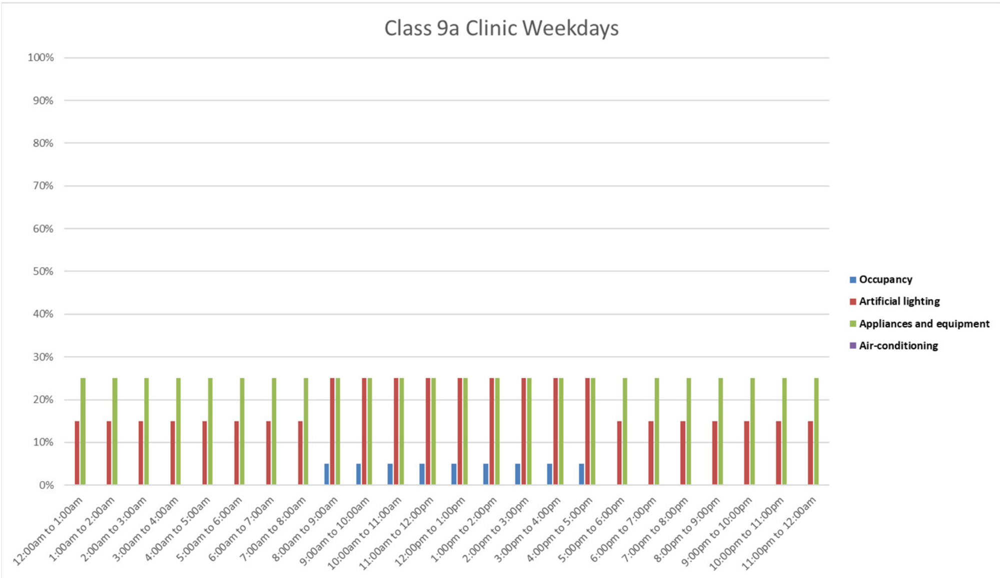

Figure 7. Operation schedules for "Class 9a Clinic"—weekends.

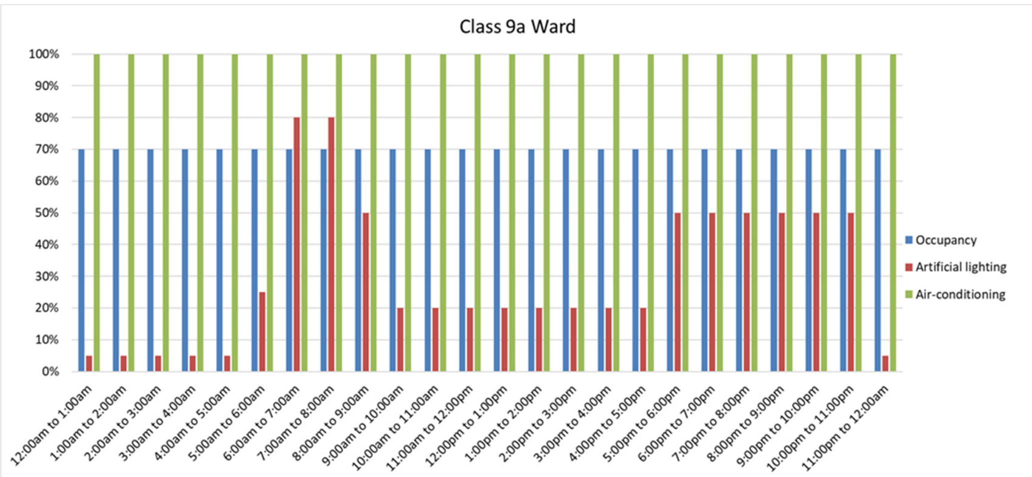

Figure 8. Operation schedules for "Class 9a Ward".

2.3. Climate Weather Files

Historical weather files are commonly used for predicting building energy performance when designing buildings in building energy modeling [45]. However, this practice does not give an indication of how the proposed building will perform into the future, over the life of the building, particularly in terms of the effect on morbidity, mortality and building services failure [34]. Different techniques have been used to create future climate files for use in building energy modeling [46–48], each approach typically including climate scenarios out to 2090 and a range of greenhouse gas (GHG) reduction scenarios (Representative Concentration Pathways (RCP), as developed by the Intergovernmental Panel on Climate Change (IPCC)). In this study, five climate scenarios are considered: current typical meteorological year (TMY) files used in practice and future climate scenarios 2030, 2050, 2070 and 2090 for RCP8.5 (business as usual). The future weather files (Table 8) were provided by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) specifically for the purposes of building simulation [49,50]. The RCP8.5 scenarios (i.e., assuming business as usual) were chosen because they represent the "worst-case" scenario in terms of actions to reduce carbon emissions [2]. Note that these future weather files do not include extreme heat events.

Table 8. Description of CSIRO weather files used in this study.

Scenarios	Description	Note
Current	CSIRO TMY2 files	Historical weather based on 1990–2015 data
2030	representing the typical year for 2020–2040	CSIRO RCP8.5: Business-as-usual pathway, Representative Concentration Pathway 8.5
2050	representing the typical year for 2040–2060	
2070	representing the typical year for 2060–2080	
2090	representing the typical year for 2080–2100	

2.4. Simulation Software and Analysis

In order to investigate the effects of future climates on Australian hospital building energy performance, dynamic building energy simulations were performed using DesignBuilder [51], a building simulation software commonly used by the industry. The building models were simulated for a full year (8760 h). The reporting metric is kWh/m^2/annum, a widely understood and utilized energy use intensity (EUI) metric.

The impacts of future climates on Australian hospital energy performance were compared with the current TMY file scenario in terms of three main aspects of energy use:

- space heating only (boiler) energy use;
- HVAC system energy use, including chillers, boilers, air handling units (AHUs), fans, pumps and fan coil units (FCUs);
- site total energy use, including HVAC system energy use, boilers, lighting and all plug-in loads.

3. Results and Discussion

3.1. Small Hospital

3.1.1. Heating Energy Use

Table 9 displays the normalized annual boiler heating electricity energy use for the small hospital model for all ten Australian locations for the current and future climates, while Figure 9 benchmarks future boiler heating energy use against the current TMY. As expected, all sites will have reduced space heating needs into the future (62–71% of current needs). Note the different rates of decrease in space heating energy use.

Table 9. Small hospital's yearly boiler heating energy needs in kWh/m^2.

Locations	Current	2030	2050	2070	2090
DARWIN	29.9	28.1	24.6	22.7	20
MOUNT ISA	43.4	38.5	34	30.4	28.2
BRISBANE	63.6	53.9	50.7	44	39.7
PERTH	83.1	74.2	71	65	59.2
SYDNEY	77.1	67.7	60.4	56.1	49.9
ADELAIDE	93.4	84.8	81.2	72.7	65.3
CANBERRA	133	121	112.9	101.2	90.7
MILDURA	100.5	90.4	87	76	67.9
MELBOURNE	101.5	90.5	87.3	79.5	69
HOBART	136.9	124.6	116.5	103.6	90.3

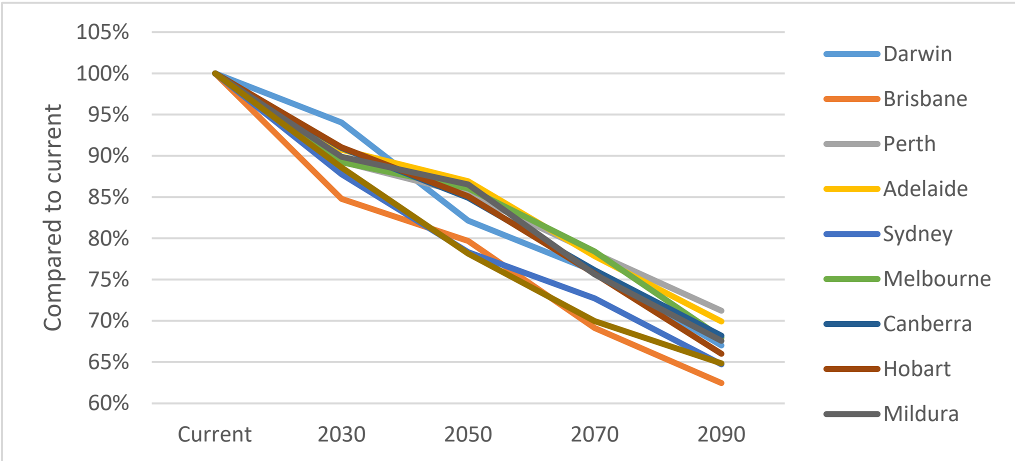

Figure 9. Benchmarking of small hospital's yearly boiler heating needs.

The main reason for the reduced space heating needs for all sites into future is the warming climate. The IPCC RCP8.5 for future climate assumes the business-as-usual emission scenario that indicates the "worst case", i.e., no significant reduction in emissions. For each of the modeled climate zones, the increase in the average outside air temperature reduces the heating degree hours/days, resulting in heating needs being reduced for all locations. This rate of decrease in heating degree hours is not consistent across all climates, as one would expect to see with climate zones spanning latitudes from 12 to 42° S and encompassing six different climate classifications.

3.1.2. HVAC Energy Use

Table 10 and Figure 10 demonstrate the increase (or decrease) in HVAC system energy use over time (i.e., total heating and cooling and HVAC system components). They show that all locations, except for Canberra and Hobart (the coldest locations), will experience an increase in HVAC energy use by 2090, ranging from 103% for Mildura to 136% for Darwin. The increase is greatest for the two tropical/subtropical humid locations (Darwin and Brisbane), and the rate of increase is fastest in the eastern and northern (from latitude 33° S) locations. Canberra and Hobart show an overall decrease in HVAC energy use because the rise in space cooling needs is offset by the decrease in space heating needs.

Table 10. Small hospital's yearly HVAC energy use in kWh/m^2.

Locations	Current	2030	2050	2070	2090
DARWIN	311.51	332.50	376.25	399.41	423.22
MOUNT ISA	199.42	209.81	230.19	237.23	252.21
BRISBANE	189.64	199.82	211.00	232.99	253.77
PERTH	168.94	169.21	173.26	176.79	186.49
SYDNEY	166.70	171.32	184.98	189.26	203.63
ADELAIDE	164.45	162.17	163.38	165.22	169.14
CANBERRA	197.53	190.30	186.32	184.71	183.61
MILDURA	179.59	176.08	178.62	180.13	184.85
MELBOURNE	163.90	160.18	161.44	167.14	170.94
HOBART	185.19	176.36	170.96	166.22	162.22

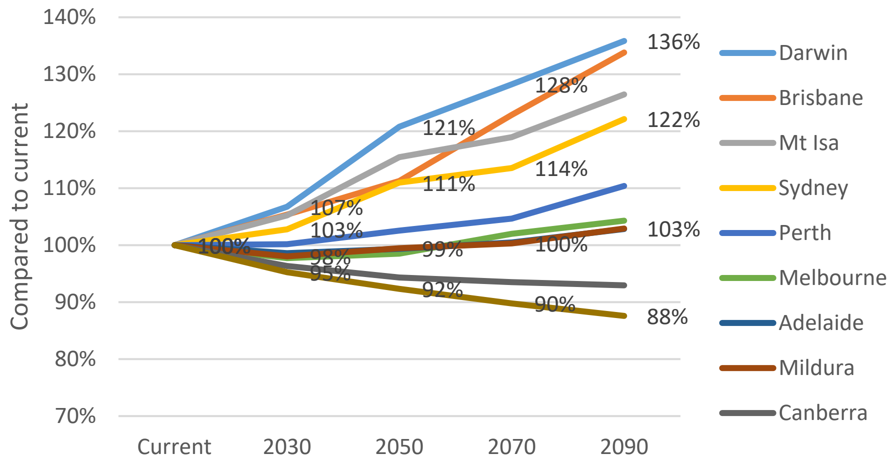

Figure 10. Small hospital's yearly HVAC energy use benchmarking.

It is noted that cooling based climates (Darwin and Brisbane) demonstrate a totally different pattern to heating based climates (Canberra and Hobart) in terms of the annual total HVAC energy use into the future. Darwin and Brisbane suffer from an increase in the total yearly HVAC energy use by more than 30% by 2090, while Hobart and Canberra would have a total yearly HVAC energy use decrease by around 10% in 2090. This is because for cooling based climates, the warming climate in the future would have more impacts on cooling demand increase than heating demand reduction, and vice versa for heating dominated climates. For heating dominated climates, however, the reduced heating demand into the future outweighs the increased cooling use, leading to a reduction in the total yearly HVAC energy use.

3.1.3. Site Total Energy Use

Figure 11 shows the normalized (kWh/m^2) site annual total building energy use for the 10 studied climates for the small hospital over time. It shows tropical Darwin's already high energy use intensity will increase even more. The next northernmost locations (Mt Isa and Brisbane) have similar increases in energy use intensity (119% and 124%, respectively). These results reinforce the point that the energy intensity impact of future climates on single-story health facilities will be much greater for hotter climates than for colder climates.

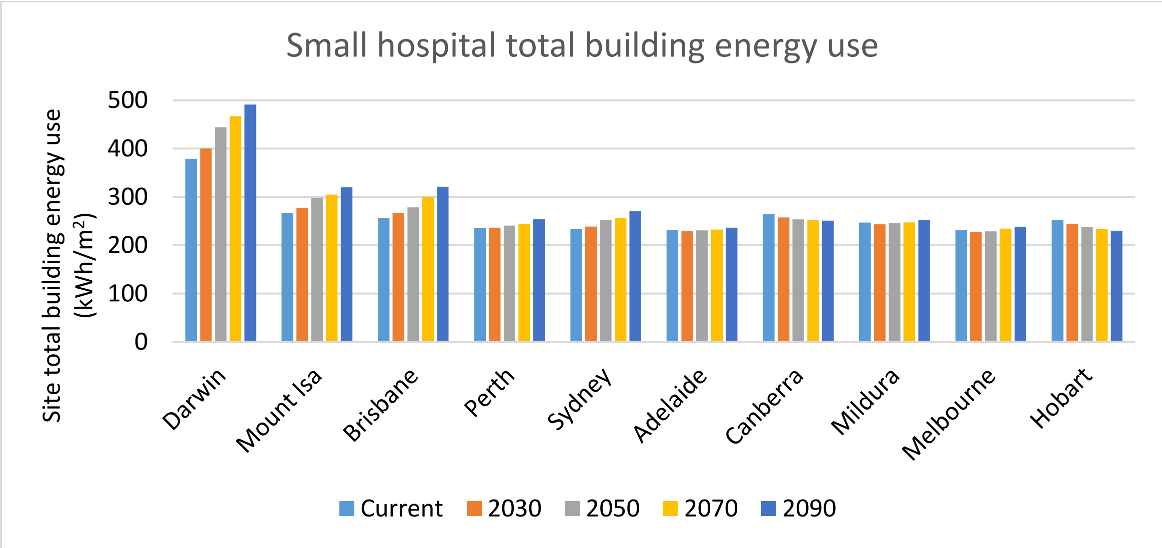

Figure 11. Small hospital's yearly site total energy use in kWh/m^2.

3.2. Large Hospital

Large hospitals have quite a different architecture, building configuration, equipment and occupancy compared to small hospitals. In particular, the surface to volume ratio is substantially different, making the building's energy demand potentially less susceptible to the external conditions [52,53]. This section presents the analysis and results for the large hospital model into future climate scenarios.

3.2.1. Heating Energy Use

Table 11 and Figure 12 show the large hospital's normalized boiler heating demand profiles over time. For the large hospital, there is no consistent heating energy reduction into future scenarios, for all locations. Although heating energy use is reduced into the future, the heating energy reduction is more significant in Hobart, for example, compared to Darwin and Mt Isa. This is because the northern locations of Darwin and Mt Isa have a relatively low heating energy base level. It is worth noting, however, that even modest reductions in heating energy use intensity (e.g., 1.1 kWh/m^2 for Darwin) can result in substantial yearly energy reductions, given the size of the large hospital (e.g., >157 MWh/year for Darwin).

Table 11. Large hospital's yearly boiler heating energy needs in kWh/m^2.

Locations	Current	2030	2050	2070	2090
DARWIN	13.5	13.45	13.3	13	12.4
MOUNT ISA	12.7	11.6	11	10.2	10
BRISBANE	18.7	17.0	16.7	15.8	15.3
PERTH	21.9	19.4	19	17.8	17.1
SYDNEY	22.5	19.8	18.5	17.6	16.5
ADELAIDE	23	20.2	19.5	17.9	16.8
CANBERRA	41.7	37	34.2	30.2	26.5
MILDURA	28	24.4	23.3	19.9	17.9
MELBOURNE	27.6	24.2	23.1	21.7	19.3
HOBART	42.4	37.6	34.9	30.5	26

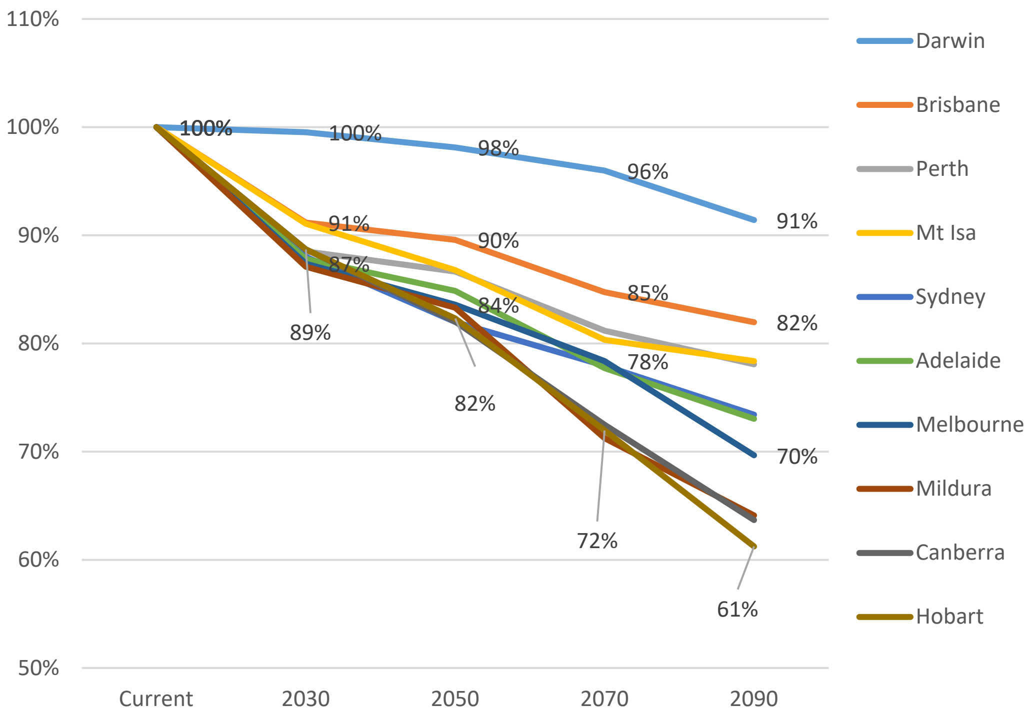

Figure 12. Large hospital's boiler heating needs yearly benchmarking.

Figure 12 shows that by 2090, the large hospital heating demand in Darwin does not diminish greatly compared to the current baseline, while southern locations experience a much greater percentage reduction in heating demand. Hobart's heating demand, for example, will be approximately 61% of its current use by 2090. This represents an annual heating load reduction of almost 2342 MWh of electricity per year.

3.2.2. HVAC Energy Use

The normalized HVAC energy use values in kWh/m^2 are presented in Table 12, and the benchmarked HVAC energy use of the large hospital model is visualized in Figure 13. Similar to the small hospital model, the two northernmost humid climates (Darwin and Brisbane) will have the greatest increase in HVAC energy use (114% and 112%, respectively), with the drier northern location of Mt Isa having a 108% increase. Both Sydney and Perth (similar latitudes but on opposite sides of the continent) will have similar increases of approximately 107%. Interestingly, even the warm temperature and mild temperature locations of Adelaide and Melbourne will have HVAC energy increases of 108% and 105%, respectively. HVAC energy use in inland Mildura will only increase approximately 1%, while Canberra and Hobart will both see a slight decrease.

Table 12. Large hospital's yearly HVAC energy use in kWh/m^2.

Locations	Current	2030	2050	2070	2090
DARWIN	131.18	133.97	140.58	144.58	149.96
MOUNT ISA	108.51	109.98	113.38	114.31	116.82
BRISBANE	111.82	115.33	117.44	121.77	125.25
PERTH	101.70	102.60	104.15	105.47	108.43
SYDNEY	108.60	109.75	112.67	114.08	116.81
ADELAIDE	95.37	95.95	97.15	99.83	103.14
CANBERRA	106.93	105.77	105.87	105.93	106.33

Table 12. *Cont.*

Locations	Current	2030	2050	2070	2090
MILDURA	102.05	101.56	101.56	101.98	103.49
MELBOURNE	99.97	100.41	100.64	103.49	105.95
HOBART	106.14	104.83	104.64	104.82	104.69

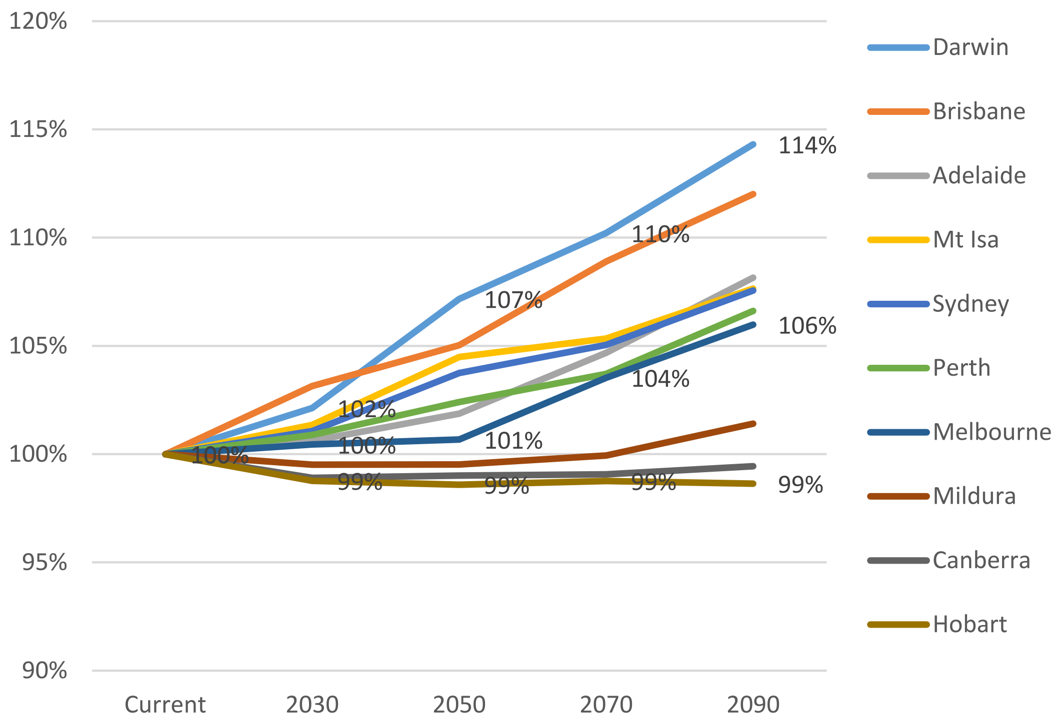

Figure 13. Large hospital's yearly HVAC energy use benchmarking.

3.2.3. Site Total Energy Use

Figure 14 shows the site annual total building energy use for all the 10 climates for the large hospital over time. The results demonstrate a totally different pattern compared to the small hospital model. The large hospital energy performance seems to be more resilient to future climates than the small hospital when looking at the energy use intensity. Using the three northernmost locations as an example, the site building energy use in the small hospital increases in Darwin, Mt Isa and Brisbane by 129%, 119% and 124%, respectively, whereas for the large hospital, these increases are 108%, 104% and 107%, respectively. This would seem to indicate that, based on energy use intensity, small hospitals (single story) are much more prone to energy use increases in the future than large hospitals. However, taking into account the relative differences in floor areas, the smaller increases in energy use intensity in the large hospital have much larger consequences in terms of total energy consumption.

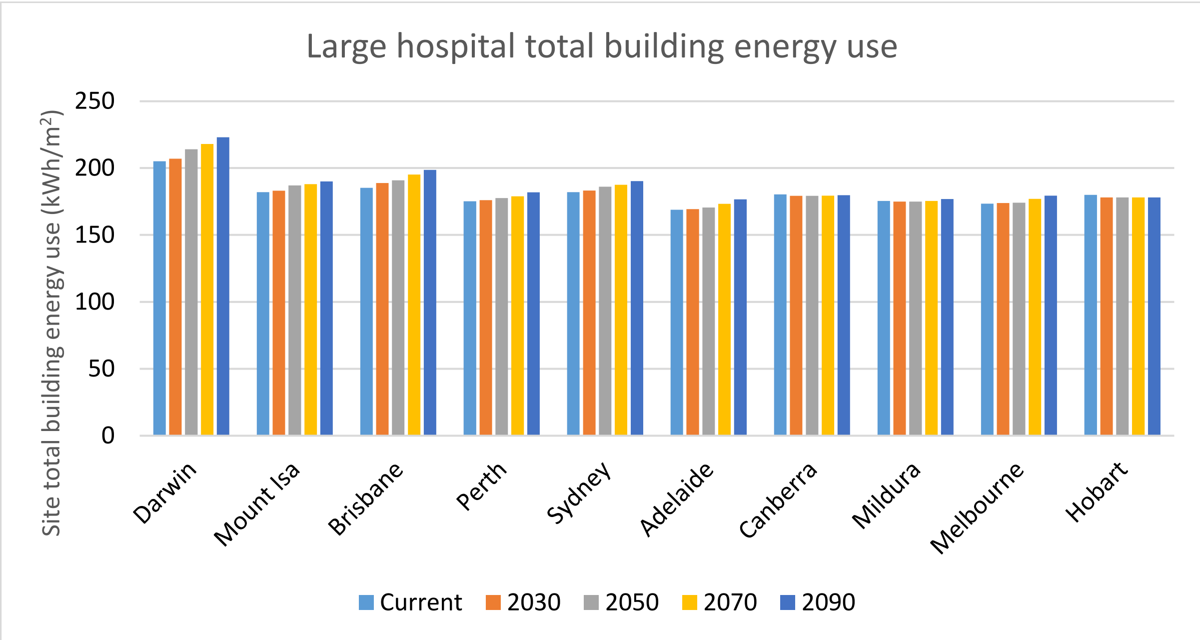

Figure 14. Large hospital's total building energy use intensities.

4. Conclusions

Climate change plays an increasingly significant role in Australian hospital energy performance. Understanding how the future climates affect the hospital operations into the future is imperative at the design stage of new or refurbished hospitals in Australia. This study developed two archetype hospital models for Australia and used building simulation to investigate the impacts of future climates on hospital energy performance in ten locations around Australia.

This study demonstrates the reduction in heating energy demand and increase in cooling energy demand for all locations. The two coldest locations (Canberra and Hobart) would have a net decrease in annual HVAC energy use, while the other eight locations would all see a rise in total HVAC energy use over time. The northern locations will have increased levels of HVAC energy use and total site energy use for both the small and large hospital models, indicating that northern Australia may be more negatively impacted in terms of using more energy and having a faster rate of change in HVAC energy use. The single-story hospital appears to be more impacted by the changing climate, in all locations, compared to the multi-story larger hospital. This is likely because of the greater volume to surface area ratio of multi-story buildings.

This analysis is only the first step in understanding the importance of future climate files for the planning and design of healthcare facilities. Future work needs to include:

- Analysis of the impact of future climate, and decarbonization, on hospital peak demand, and hence, the electrical infrastructure required;
- Development of climate files suitable for HVAC selection and sizing, as well as for renewable energy system sizing (for example, rooftop solar photovoltaics);
- Development of climate files for extreme conditions, such as heat waves; and
- The development of guidelines and a decision-making framework for healthcare asset managers to enable "whole of life" and "whole of system" approaches to the design, procurement, decarbonization and operation of healthcare facilities into the future.

Author Contributions: Conceptualization, W.M.; methodology, Y.M., S.Z., A.L. and W.M.; model development and simulations, Y.M. and S.Z.; data curation, A.L.; data analysis, Y.M. and A.L.; resources, W.M.; writing—original draft preparation, Y.M., S.Z. and A.L.; writing—review and editing, Y.M., A.L. and W.M.; visualization, Y.M. and A.L.; project administration, W.M.; funding acquisition, A.L. and W.M. All authors have read and agreed to the published version of the manuscript.

Funding: This study was undertaken as part of the Innovation Hub for Affordable Heating and Cooling (iHub) led by the Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH). The project received funding from the Australian Government's Australian Renewable Energy Agency (ARENA), as part of ARENA's Advancing Renewables Program, and from the Australasian Health Infrastructure Alliance (AHIA), a collaboration of public health authorities from each Australian state and territory and New Zealand. Project LLHC5: Net-zero Energy and Resilient Hospitals.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data, including the hospital models, are not publicly available. Contact the corresponding author for enquiries regarding possible access to data and the models.

Conflicts of Interest: The authors declare no conflict of interest. AHIA provided input into the study conceptualization. ARENA, iHub and AHIA provided comments on the design of the study at the time of the funding application. AHIA provided information to assist in the development of the hospital models and in providing feedback on the initial findings. AHIA, ARENA and iHub had no role in the collection, analyses or interpretation of the data; the writing of the manuscript; or in the decision to publish the results.

Abbreviations

ABCB	Australian Building Codes Board
ACH	Air change per hour
AHIA	Australasian Health Infrastructure Alliance
AHU	Air handling unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CAV	Constant air volume
CSSD	Critical service and storage department
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
EUI	Energy use intensity
FCU	Fan coil unit
GHG	Greenhouse gas
HVAC	Heating, ventilation and air conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPU	Inpatient unit
IRENA	The International Renewable Energy Agency
NCC	National Construction Code (Australia)
NHS	National Health Service (UK)
NOAA	National Oceanic and Atmospheric Administration
NZCE	Net-zero carbon emissions
RCP	Representative Concentration Pathways
TMY	Typical Meteorological Year
VAV	Variable air volume

References

1. Lindsay, R.; Dahlman, L. Climate Change: Global Temperature. National Oceanic and Atmospheric Administration (NOAA). Available online: https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature (accessed on 28 June 2022).
2. Foo, G. *Climate Change—Impact on Building Design and Energy*; COAG Energy Council: Canberra, Australia, 2020.
3. Bragge, P.; Alyse, L.; Pattuwage, L.; Capon, T.; Armstrong, F.; Burgess, M.; Watts, C.; Cooke, S.; Bowen, K.; Liew, D. *Climate Change and Australia's Health Systems: A Review of Literature, Policy and Practice*; Monash Sustainable Development Evidence Review Service: Melborune, VIC, Australia, 2021.

4. IPCC. Global warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change. 2018. Available online: https://www.ipcc.ch/sr15/ (accessed on 20 February 2019).
5. IRENA. World Energy Transitions Outlook—1.5 °C Pathway. Available online: www.irena.org/publications (accessed on 12 June 2022).
6. Riffat, S.; Mardiana, A. Building Energy Consumption and Carbon Dioxide Emissions: Threat to Climate Change. *J. Earth Sci. Clim. Chang. S3* **2015**. [CrossRef]
7. Ali, A.; Khozema; Ahmad, M.I.; Yusup, Y. Issues, Impacts, and Mitigations of Carbon Dioxide Emissions in the Building Sector. *Sustainability* **2020**, *12*, 18.
8. Stagrum, A.E.; Andenæs, E.; Kvande, T.; Lohne, J. Climate Change Adaptation Measures for Buildings—A Scoping Review. *Sustainability* **2020**, *12*, 1721. [CrossRef]
9. Karliner, J.; Slotterback, S.; Boyd, R.; Ashby, B.; Steele, K.; Wang, J. Health care's climate footprint: The health sector contribution and opportunities for action. *Eur. J. Public Heal.* **2020**, *30*. [CrossRef]
10. Morgenstern, P.; Li, M.; Raslan, R.; Ruyssevelt, P.; Wright, A. Benchmarking Acute Hospitals: Composite Electricity Targets Based on Departmental Consumption Intensities? *Energy Build.* **2016**, *118*, 277–290. [CrossRef]
11. Aspinall, P. Benchmarking and Best Practice—Energy Management for Healthcare in the UK, Hospital Engineering & Facilities Management. 2004.
12. EPA. Data Trends—Energy Use in Hospitals. Environmental Protection Agency—the U.S. Available online: www.energystar.gov (accessed on 8 August 2022).
13. Ji, R.; Qu, S. Investigation and Evaluation of Energy Consumption Performance for Hospital Buildings in China. *Sustainability* **2019**, *11*, 1724. [CrossRef]
14. Satish, K. *Energy Efficiency in Hospitals, Best Practice Guide*; Bureau of Energy Efficiency: New Delhi, India, 2009.
15. Kolokotsa, D.; Tsoutsos, T.; Papantoniou, S. Energy conservation techniques for hospital buildings. *Adv. Build. Energy Res.* **2012**, *6*, 159–172. [CrossRef]
16. pitt&sherry. *Baseline Energy Consumption and Greenhouse Gas Emissions in Commercial Buildings in Australia Part-1 Report*; Council of Australian Governments (COAG): Canberra, Australia, 2012.
17. Ma, Y.; Saha, S.C.; Miller, W.; Guan, L. Comparison of Different Solar-Assisted Air Conditioning Systems for Australian Office Buildings. *Energies* **2017**, *10*, 1463. [CrossRef]
18. Liu, A.; Miller, W.; Chiou, J.; Zedan, S.; Yigitcanlar, T.; Ding, Y. Aged Care Energy Use and Peak Demand Change in the COVID-19 Year: Empirical Evidence from Australia. *Buildings* **2021**, *11*, 570. [CrossRef]
19. Burch, H.; Anstey, M.H.; McGain, F. Renewable energy use in Australian public hospitals. *Med. J. Aust.* **2021**, *215*, 160. [CrossRef]
20. Malik, A.; Lenzen, M.; McAlister, S.; McGain, F. The carbon footprint of Australian health care. *Lancet Planet. Health* **2018**, *2*, e27–e35. [CrossRef]
21. Dzau, V.J.; Living, R.; Barret, G.; Witty, A. Decarbonizing the U.S. Health Sector—A Call to Action. *N. Engl. J. Med.* **2021**, *385*, 2117–2119. [CrossRef]
22. NHS. *Delivering a 'Net Zero' National Health Service*; NHS England and NHS Improvement: London, UK, 2020.
23. Tomson, C. Reducing the Carbon Footprint of Hospital-Based Care. *Future Healthc. J.* **2015**, *2*, 57–62. [CrossRef]
24. Quitmann, C.; Sauerborn, R.; Danquah, I.; Herrmann, A. Climate Change Mitigation Is a Hot Topic, but Not When It Comes to Hospitals': A Qualitative Study on Hospital Stake-Holders' Perception and Sense of Responsibility for Greenhouse Gas Emissions. *J. Med. Ethics* **2022**. [CrossRef] [PubMed]
25. MacNaughton, P.; Cao, X.; Buonocore, J.; Cedeno-Laurent, J.; Spengler, J.; Bernstein, A.; Allen, J.G. Energy savings, emission reductions, and health co-benefits of the green building movement. *J. Expo. Sci. Environ. Epidemiol.* **2018**, *28*, 307–318. [CrossRef]
26. Brown, L.H.; Buettner, P.G.; Canyon, D.V. The Energy Burden and Environmental Impact of Health Services. *Am. J. Public Health* **2012**, *102*, e76–e82. [CrossRef] [PubMed]
27. Gupta, R.; Gregg, M. Care Provision Fit for a Warming Climate. *Archit. Sci. Rev.* **2017**, *60*, 275–285. [CrossRef]
28. Hiete, M.; Merz, M.; Schultmann, F. Scenario-based impact analysis of a power outage on healthcare facilities in Germany. *Int. J. Disaster Resil. Built Environ.* **2011**, *2*, 222–244. [CrossRef]
29. Khahro, S.; Kumar, D.; Siddiqui, F.; Ali, T.; Raza, M.; Khoso, A. Optimizing Energy Use, Cost and Carbon Emission through Building Information Modelling and a Sustainability Approach: A Case-Study of a Hospital Building. *Sustainability* **2021**, *13*, 3675. [CrossRef]
30. Zhang, C.; Kazanci, O.B.; Levinson, R.; Heiselberg, P.; Olesen, B.W.; Chiesa, G.; Sodagar, B.; Ai, Z.; Selkowitz, S.; Zinzi, M.; et al. Resilient cooling strategies—A critical review and qualitative assessment. *Energy Build.* **2021**, *251*, 111312. [CrossRef]
31. Tonmoy, F.; Palutikof, J.; Boulter, S.; Schneider, P.; Cooke, S. *Climate Change Adaptation Planning Guidance Guidelines*; Queensland Health: Brisbane, Australia, 2019.
32. AIRAH. *Resilience Checklist*; Liza Taylor, L., Ed.; The Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH): Melbourne, Australia, 2021.
33. Palutikof, J.; Boulter, S.; Schneider, P.; Tonmoy, F. *Climate Change Adaptation Planning Guidance Almanac*; Queensland Health: Brisbane, Australia, 2019.

34. Herrera, M.; Natarajan, S.; Coley, D.A.; Kershaw, T.; Ramallo-González, A.P.; Eames, M.; Fosas, D.; Wood, M. A review of current and future weather data for building simulation. *Build. Serv. Eng. Res. Technol.* **2017**, *38*, 602–627. [CrossRef]
35. Liu, A.; Ma, Y.; Miller, W.; Xia, B.; Zedan, S.; Bonney, B. Energy Analysis and Forecast of a Major Modern Hospital. *Buildings* **2022**, *12*, 1116. [CrossRef]
36. Australian Building Codes Board. *Ncc 2019 Building Code of Australia—Volume One*; Australian Building Codes Board: Canberra, ACT, Australia, 2019.
37. Chen, D.; Chen, H.W. Using the Köppen classification to quantify climate variation and change: An example for 1901–2010. *Environ. Dev.* **2013**, *6*, 69–79. [CrossRef]
38. Peel, M.C.; Finlayson, B.L.; McMahon, T.A. Updated World Map of the Köppen-Geiger Climate Classification. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1633–1644. [CrossRef]
39. Beck, H.E.; Zimmermann, N.E.; McVicar, T.R.; Vergopolan, N.; Berg, A.; Wood, E.F. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci. Data* **2018**, *5*, 180214. [CrossRef]
40. Goel, S.; Athalye, R.; Wang, W.; Zhang, J.; Rosenberg, M.; Xie, Y.; Hart, R.; Mendon, V. *Enhancements to Ashrae Standard 90.1-Prototype Building Models*; Pacific Northwest National Laboratory: Richland, DC, USA, 2014.
41. Carnieletto, L.; Ferrando, M.; Teso, L.; Sun, K.; Zhang, W.; Causone, F.; Romagnoni, P.; Zarrella, A.; Hong, T. Italian prototype building models for urban scale building performance simulation. *Build. Environ.* **2021**, *192*, 107590. [CrossRef]
42. ASHRAE. *Advanced Energy Design Guide for Small Hospitals and Healthcare Facilities, Achieving 30% Energy Savings toward a Net Zero Energy Building*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Peachtree Coreners, GA, USA, 2009.
43. Advanced Energy Design Guide for Large Hospitals. In *Achieving 50% Energy Savings toward a Net Zero Energy Building*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Peachtree Coreners, GA, USA, 2012.
44. D'Agostino, D.; Parker, D.; Epifani, I.; Crawley, D.; Lawrie, L. How will future climate impact the design and performance of nearly zero energy buildings (NZEBs)? *Energy* **2021**, *240*, 122479. [CrossRef]
45. Pyrgou, A.; Castaldo, V.L.; Pisello, A.L.; Cotana, F.; Santamouris, M. Differentiating responses of weather files and local climate change to explain variations in building thermal-energy performance simulations. *Sol. Energy* **2017**, *153*, 224–237. [CrossRef]
46. Nielsen, C.N.; Kolarik, J. Utilization of Climate Files Predicting Future Weather in Dynamic Building Performance Simulation—A review. *J. Phys. Conf. Ser.* **2021**, *2069*. [CrossRef]
47. Troup, L.; Eckelman, M.J.; Fannon, D. Simulating future energy consumption in office buildings using an ensemble of morphed climate data. *Appl. Energy* **2019**, *255*, 113821. [CrossRef]
48. P.Tootkaboni, M.; Ballarini, I.; Zinzi, M.; Corrado, V. A Comparative Analysis of Different Future Weather Data for Building Energy Performance Simulation. *Climate* **2021**, *9*, 37. [CrossRef]
49. Zhengen, R.; Tang, Z.; James, M. *Typical Meteorological Year Weather Files for Building Energy Modelling—User Guide*; CSIRO: Canberra, Australia, 2021.
50. CSIRO. *Predictive Weather Files for Building Energy Modelling User Guide*; CSIRO: Canberra, Australia, 2021.
51. DesignBuilder. Designbuilder Simulation Documentation for Designbuilder V7: UK 2022. Available online: https://designbuilder.co.uk/ (accessed on 21 July 2022).
52. Araji, M.T. Surface-to-volume ratio: How building geometry impacts solar energy production and heat gain through envelopes. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*, 012034. [CrossRef]
53. Lim, H.S.; Kim, G. Analysis of Energy Performance on Envelope Ratio Exposed to the Outdoor. *Adv. Civ. Eng.* **2018**, *2018*, 7483619. [CrossRef]