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Application of the InTIME Methodology for the Transition of Office Buildings to Low Carbon—A Case Study

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Abstract: The COP21 Paris Agreement requires urgent abatement of 80% of the current fossil-based energy consumption to keep global warming below dangerous levels. Heating loads in commercial buildings can be reduced by retrofitting the building envelope, upgrading the efficiency of heating equipment, implementing energy management strategies, substituting renewable energy sources, and influencing energy-saving behavior. However, achieving the downshift of gas or coal heat is a wicked problem. The Interdisciplinary Transition Innovation Management and Engineering (InTIME) methodology was applied to address the wicked problem of district heating of campus buildings of the University of Canterbury, in Christchurch, New Zealand. The carbon downshift scenario requires a reduction in coal purchase by 80% from the first year through the engineering of adaptive measures for facility operators and occupants. Accordingly, a successful downshift of fossil-fuel energy would depend on the effective adaptation of the office workers. Adaptation plans to facilitate demand participation and sustained worker productivity could be designed once the actual heating behaviour is known. The contribution of this work is a novel fossil fuel abatement concept: the Targeted Heating Energy—Assessment and Intervention Design (THE-AID), which focuses on the assessment of the heating behavioural patterns of office workers. Building services engineers can use the THE-AID concept to develop adaptation plans through intervention design and resource facilitation focused on building occupants. THE-AID projects could achieve significant emissions reduction in the near term at a low cost and increase resilience to heat supply disruptions.

Keywords: energy transition; commercial buildings; demand participation; adaptive demand; adaptive behavior; low carbon; office occupant behaviour

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1. Introduction

In 2020, buildings accounted for 36% of the global energy consumption, with 36% of energy consumption by end-use being assigned to space heating [1]. The building energy demand in 2020 had a decline compared to previous years. This drop was due to the pandemic and is thought to be temporary [2]. For the same year, the International Energy Agency (IEA) Global Energy Review reported that the global energy-related CO_2 emissions were 31.5 Gt and the average annual atmospheric CO_2 concentration was 412.5 parts per million [3]. Roughly one-third of the total CO_2 emissions from buildings was attributed to non-residential building operations [2]. Signatory countries of the COP21, also known as the 2015 Paris Climate Conference, have committed to a structural change in the way they manage their energy resources, referred to as energy transition. The commitment to hold the increase in the global average temperature to well below 2 °C and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels [4] entails a dramatic reduction in greenhouse gas emissions from the production and use of fossil fuels, manufacturing, agriculture, and land use change. Limiting the temperature increase to below 2 °C above pre-industrial levels, as reinforced in the Glasgow Climate Pact [5], means that 80% of the current global fossil-based energy consumption in buildings must be avoided or replaced by non-fossil alternatives within less than 20 years [6,7].

1.1. Energy Management Background

Building environment and energy management has undergone developments in response to contemporaneous socioeconomic pressures. More than a century ago the 1911 presentation of Rational Psychrometric Formulae by Willis H Carrier, the father of air conditioning, began the era of building services engineering focus on comfort through mechanical systems [8]. The methods for energy management developed around temperature, humidity and ventilation comfort tended to rely on high energy intensity [9].

The OPEC oil embargo in 1973 reduced oil supply to Western countries by less than 15% over several years but caused American electricity shortfalls due to diesel peak generation, and natural gas shortages [10]. Building services quickly adopted energy auditing and focused on reducing energy use through operation conservation [11]. Energy policies had a strong focus promoting technological improvements of energy efficiency, as well as applying short-lived regulations to promote energy conservation [12]. These engineering practices achieved energy use reductions in existing buildings in the range of 25–50% [13]. Engineered retrofits on the building envelope (e.g., insulation, glazing, weather stripping), equipment (i.e., lamp and appliance replacement), and system operation (e.g., Building Management System BMS) became important as concerns about healthy indoor conditions resulted from early energy conservations measures like reducing fresh air intake [14].

The 1990 global oil crisis caused by the Gulf War and the embargo on oil exports forced the shutdown of oil refineries [15], leading to a price shock and influencing changes in building operations. Existing free-market-oriented policies did not work during the energy crisis and oil price shocks [16]. Thus, price-stabilization agreements and adding domestic stocks and refining capacity were the main strategies. Demand Side Management (DSM) first emerged in the 1980s and grew further after the 2000 US Natural gas crisis and the California electricity crisis [17], followed by the 2008 Central Asia energy crisis and the Pakistan energy crisis [18,19], all of which were caused by disruptions to gas and oil supplies. The above-mentioned cases represent energy shortages caused by supply insecurity exacerbated by rapid demand growth. Other events such as financial crises, natural disasters, or power plant shutdowns have also driven abrupt changes in energy management in several countries. In such cases, DSM and legislation mandating conservation measures were vital for managing the market breakdown during the crisis and the immediate recovery.

Climate change targets are not short-term disruptions imposed by political events or natural disasters. The current responses to global emission reduction targets in the building energy research sector have mainly focused on green building design methods and materials selected in building design [20] for new construction, and the use of smart appliances. Energy management and efficiency retrofit cost savings have not driven carbon emissions reductions quickly enough to meet COP21 Paris Agreement targets set in 2015 and reinforced in the COP26 Glasgow agreement of 2022. The established usage patterns for buildings adjust incrementally through innovations and renovations. However, energy supply and price shocks, such as the Russian invasion of Ukraine, prompt interactions between policy and socio-technical processes that can increase pressures for energy system changes [21]. Thus, the question arises of how to intentionally engineer transitions of buildings and adaptation to downshift fossil fuel use as required to meet net-zero targets.

1.2. Energy Transition Engineering

Energy Transition Engineering is a new area of research that uses international emissions targets as constraints on energy-related carbon emissions and resource availability, and as triggers for innovations in effective, long-lived engineered adaptations. One of the hallmarks of the Transition Engineering (TE) methodology is to flip the perspective of the situation around, start with the constraints and adapt to the new situation. The problem is global warming, and the standard perspective emphasizes the need to reduce emissions by substituting the use of fossil fuels to low carbon energy. In New Zealand, the governmental Building for Climate Change Programme [22] presents an outlook for reducing emissions from the building and construction sector. It envisions cap levels for new buildings toward the international climate change goals, but it acknowledges that existing buildings are projected to make up approximately 65% of the building stock in 2050. Despite the advancement in building energy engineering and management, there is still a significant gap between the actual energy-related building carbon emissions pathway [23,24] and the IPCC's Representative Concentration Pathway (RCP) 2.6 scenario, which requires a 100% decline in carbon emissions by 2100, to meet the COP21 agreements. The types of solutions from a standard perspective include punitive measures like applying a carbon tax to emissions, or tailpipe technologies like carbon capture and storage. Correspondingly, fiscal incentives have been introduced in many countries to promote the adoption of energy-saving measures [25]. The flipped perspective of TE, on the other hand, emphasizes the reality of the fossil fuel supply constraints. The types of solutions that emerge from this approach include altered perceptions of value, adaptive infrastructural systems, and adaptive behaviours.

The scope of energy transition engineering assessment goes beyond the engineering analysis and encompasses social and environmental aspects, as well as effective ways to integrate infrastructure and technology realities with the expectations and needs of all stakeholders. Krumdieck and Hamm [26] contributed a strategic analysis tool to deal with this complexity that utilized energy modeling, feasibility analysis, and risk assessment, along with a novel communication concept, to contrast a range of societal development visions with viable opportunities. Specifically, a graphical interface elucidated three converging operational spaces. The first is the possibility space, represented through a matrix of energy supply and energy service options; service levels reflect the range of different home sizes, appliances, efficiency, and behaviour of a study area. Supply options depended on local resources, and sustainability intentions and values were determined through surveys. The feasibility space is created from the possibility space by modeling and evaluating the supply–demand combinations. Lastly, the opportunity space was identified by evaluating the remaining options in terms of costs, environmental impact, development time, and risk.

Previous research in the area of passenger transport is aligned with TE's consideration of constraints on fossil fuel availability and GHG emissions reduction and has allowed exploring solutions that can be evaluated in terms of risk and adaptive capacity [27–29]. The method presented in [27] incorporates risk analysis to investigate the implications of future transport fuel supply for long-range urban planning. The method also proposed a metric that categorized trips as essential, necessary, and optional to wellbeing. The risk was calculated by multiplying fuel shortfall probability with the impacts of travel demand changes, that is, a large supply–demand disparity would lead to trip elimination and reduced participation in activities [27]. In the context of urban and transport planning, the adoption of risk assessment can be an effective resource to communicate complex technical issues like the vulnerability to oil supply disruptions and the importance to plan for adaptation. Watcharasukarn et al. [28] proposed adaptive capacity as a metric for long-range resilience of activity systems to fuel supply decline. Adaptive capacity was defined as the volunteered change in travel demand patterns that afford maximum fuel reduction without reducing participation in activities [28]. A computer survey program was developed to investigate participants' decision-making and travel behaviour in response to fuel shocks, aiming to provide an understanding of the long-range adaptive capacity for a given urban form [28].

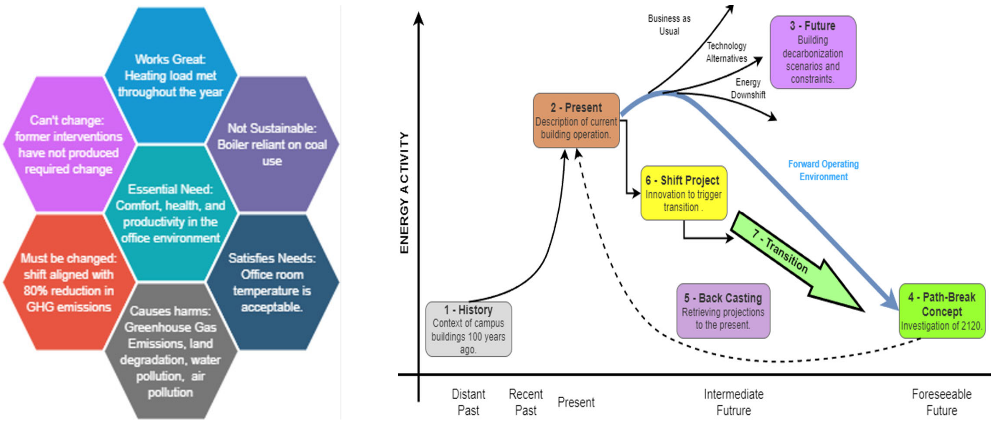
2. Methodology: Transition Engineering Analysis

In this paper, the InTIME methodology [6] is applied to address the wicked problem of District Heating (DH) of the campus buildings of the University of Canterbury, in

Christchurch, New Zealand. The result of the process is a novel targeted assessment method to identify cost-effective adaptation plans for a reduced coal supply. The project involves the application of energy auditing and building energy science, but also new knowledge about the behavioural heating patterns of the occupants that can help engineer successful interventions to maintain worker productivity and health.

The Interdisciplinary Transition Innovation Management and Engineering (InTIME) is a seven-step approach to wicked problems, aiming to support the redesign and redevelopment of existing systems [6]. The core of InTIME contemplates a constraint for fossil fuel reduction leading to the development of a "path-break concept". For example, work reported in [30] incorporates InTIME's constraint (Forward Operating Environment) and strategic concept development. The method integrated network analysis with discrete event simulation to determine how to achieve the shift of freight to low carbon modes through infrastructure and technology development projects [30]. The method embraced a whole systems approach; its embedded interconnection between optimization and simulation provided the versatility needed to connect network and terminal planning perspectives [30]. Another application of InTIME is documented in a study focused on the wicked problem of urban personal transport [29]. Through the implementation of the TE methodology, it was possible to identify a shift project that was based on the concept of a "Work Unit Retrofit". The method departed from gathering historic socio-economic data for the case study (Beijing) and explored different infrastructure and technology options including the development of cycleways, work units, and e-bikes. Every technology-infrastructure combination was assessed using the aforementioned opportunity space approach [26,29].

The InTIME methodology used in transition engineering is illustrated in Figure 1. It starts with a definition of the wicked problem (Figure 1a) for a specific location and energy end-use, then proceeds through the 7-step InTIME method (Figure 1b) to develop an original and effective shift project, which is step 6 of the process. In this study, details of the heating system and the heating loads were set out at one building of the Ilam Campus of the University of Canterbury (UC) in Christchurch, New Zealand as a case study.



(**a**) (**b**)

Figure 1. (**a**) The wicked problem definition and (**b**) the 7-Step Interdisciplinary Transition Innovation, Management and Engineering (InTIME) Methodology [31] used in this research for triggering insight into shift projects.

To understand the complex district heating system, available data were gathered and processed through the seven steps, described in [6]. Reports, datasheets, utility bills, and publicly accessible databases were used as resources for steps 1, 2, and 3. A scenario analysis in step 3 was used to examine the different development assumptions for energy technology options. Step 4 adopts the constraints on emissions and resources as an engineering requirement to delineate the forward operating environment. This step is based on the conceptualization of a long-term vision of the studied system after a successful energy transition. A concept emerged following group brainstorming that began with the identification of the assets and needs in the current system that are expected to exist in 100 years. Steps 5 and 6 were carried out through concept exploration in the fields of engineering and the social sciences. Step 7 is the adoption of the down-shift project in the direction of an energy transition pathway [6].

3. Wicked Problem Definition: Description of the Heating System and Energy Use Considerations

Heat for indoor space is an essential need. The lowest temperatures experienced in Christchurch are around −1.9 °C [32] overnight, in winter. The main UC campus, located in Ilam since 1975, is a 76-hectare site that features administrative buildings, libraries, lecture theatres, laboratories, and student accommodation and services buildings. The Boiler complex serves a pressurized hot water network with a Medium Temperature Hot Water (MTHW) 12 MW boiler and a 3.5 MW steam boiler. The boiler plant uses a blend of 50% lignite and 50% bituminous coal originally sourced by two local mines [33]. The heating load for the campus buildings is seasonal and the boilers are shifted according to weather conditions. The steam boiler is generally started up in the second term of the academic year in April. The MTHW boiler enters into operation when the heating load is raised. The district heating system operates until the end of the academic year in October. The Heating Degree Days (HDD) calculated for base temperature T_b = 18 °C [34] for campus buildings are shown in Figure 2. During the spring and fall (shoulder) seasons the temperature can fluctuate between 25 °C and 12 °C from one day to the next. There is no space heating required during the summer, but the nights are often cooler than the base temperature which produces HDD in the calculation. Domestic hot water also benefits from the MTHW system throughout the year, except during the December-January holidays.

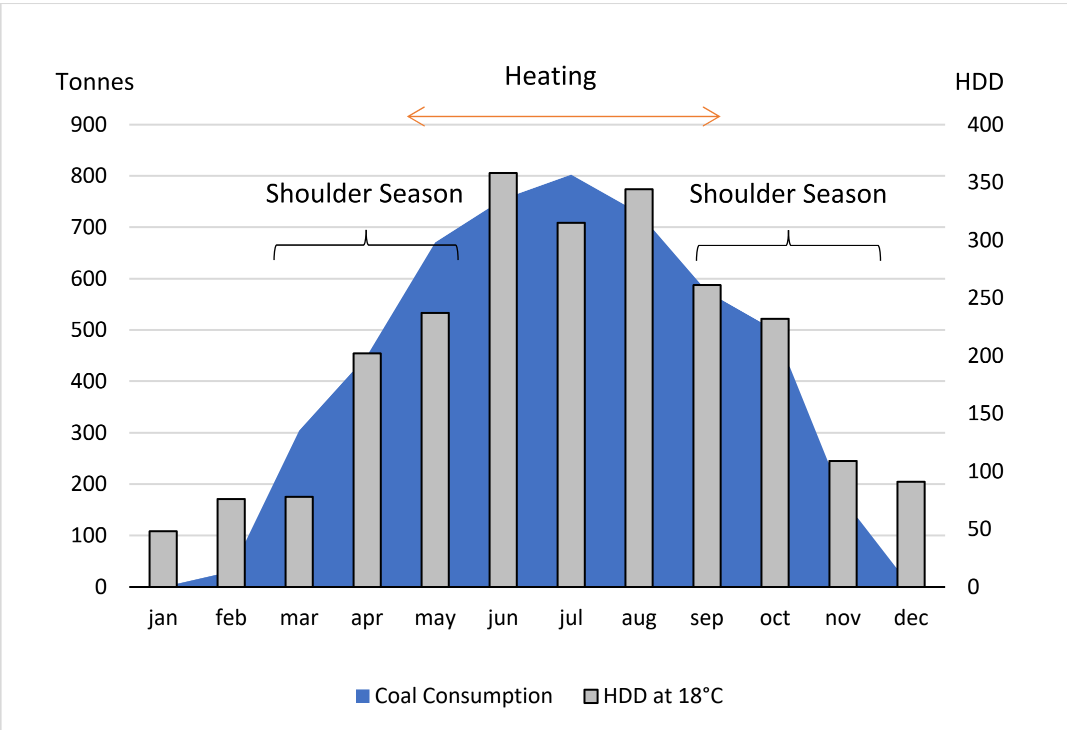


Figure 2. Heating degree days for Christchurch, New Zealand 2019 with the indication of the seasons, and the operation of the coal boiler district heating system.

Following the wicked problem definition (Figure 1a), the essential need satisfied by the boiler heating is for the comfort, health, and productivity in the office environment. The heating system objectively works well, as the heating load can be met reliably throughout the year. The use of coal is not sustainable, and to meet the COP21 Paris Agreement requirements, coal use is required to be reduced by 80% [6]. The system meets the needs for heating, although because it is not thermostatically controlled, many spaces can become overheated as the penetrating solar energy has a significant impact on the heat fluxes through the surfaces of a building zone [35]. Overheating in cold seasons often happens in buildings, leading to excessive energy consumption [36–38]. Mining and burning coal cause harm including land degradation, acid mine drainage water pollution, and urban air pollution [39]. The current district heating system needs to shift as UC is committed to reducing 80% of the 2018 carbon emissions by 2023, as stated in the Low Carbon Energy Scheme Roadmap strategy [40]. However, after numerous studies and investigations, the alternatives and costs of changing the system have not produced the required change.

4. Application of the InTIME Methodology to the Case Study

Step 1 Historical context of the building

100 years ago, UC was a thriving college with an engineering school. The campus was located in the city centre in old neo-Gothic buildings (Figure 3) heated with open coal grate fires in individual rooms. Professors and staff would have worn woolen suits with several layers of undergarments during work in the winter months. The air pollution in Christchurch during winter was greatly in violation of current clean air standards, and it was mainly due to smoke and sulfur dioxide from domestic fires [41]. In 1963 the construction of a new campus started in the suburb of Ilam. Most of the buildings were uninsulated and the heating loads were very high so a high-temperature steam boiler was installed, fired by coal sourced from local mines. Over the years many of the buildings were improved and a new medium temperature boiler replaced the old steam boiler. In the past two decades all but one of the local coal mines have shut down [42], and in the 2000s there was concern about the security of supply of the thermal coal. Nevertheless, the coal demand for the MTHW system remained constant from 2012 to 2017 [43] and is rising with new buildings being commissioned.

Figure 3. Canterbury College repurposed building, 2022.

Step 2 Present: Description of the building operation

The university heating system uses medium temperature hot water (MTHW) that comes from a centralized coal-fired boiler, then is fed to 28 building blocks through the university district heating system. At present, heat is delivered around the campus to radiators that have manual thermostatic radiator valves (TRVs) for office spaces, as shown in Figure 4. During the shoulder seasons in spring and fall in Christchurch, New Zealand, the temperature varies over a week between warm and cool. Since the radiators in offices are manually controlled, during the shoulder season it is typical for overheating to occur when occupants turn them up on a cold day, but then have excess heat on the following warm days. Cold weather in Christchurch during shoulder seasons is nearly always occasioned with clouds, so the solar gain is minimal.

Figure 4. Manually controlled radiator in a typical office.

In 2019, UC used nearly 6000 tonnes of coal [44] that were supplied in 400 truckloads. In 2018 the coal-based heating system generated 48.77% of the UC's total greenhouse gas (GHG) emissions by source. In 2020, this percentage of GHG emissions went up to 69% [45]. The current boiler and district heating system has at least 10 years of expected operation with only regular maintenance requirements and can continue to function for several decades. The source of heating coal has been affected as the production of coal in NZ's South Island decreased from 3057 tons in 2013 to 1785 tons in 2019; this is a reduction of 41.6% in 6 years [46], and the number of operating coal mines is reduced.

The total boiler capacity is 15.5 MW, and the annual heat demand is 24,000 MWh (with a plant efficiency of 80%, and network efficiency of 90%) [33]. From yearly utility data, 6 MW is enough to satisfy the heating demand 80% of the time and 4 MW is enough to satisfy 60% of the time. Based on the utilized building floor area, the heating energy intensity for the buildings on campus is 115 kWh/m^2—per year. This is the Business As Usual (BAU) benchmark for the analysis.

Step 3 Future scenarios of building decarbonization and constraints

Several scenarios have been explored for decarbonizing the campus heat. Some of the options considered to replace the coal boiler are analyzed in Table 1. There is no realistic prospect of supply of natural gas or LPG for heating the campus. The electricity supply is from the national grid which is 60% hydro, 17% geothermal, 5% wind, and 17% gas, coal, and others [47]. However, the electricity price is relatively high, so direct resistance heating to replace the boiler would represent towering bills. Heat pumps with circulating artesian water is a technology that has been implemented in some of the buildings on campus and it has the downside of water extraction viability if scaled up. A new wood chip boiler has been identified as a replacement for the existing coal boilers. The wood chip boiler will cost US $11 m plus US $2.5 m for coal-to-wood chip conversion [48]. Operation-related carbon emissions will be significantly reduced if this technology is adopted. However, the number of truckloads for fuel delivery during operation will be increased 1.84 times based on the calorific values [49] of the existing coal and the wood chip offered by the local provider. The embedded energy of a new boiler house and boiler is also considerable.

Table 1. Analysis of technology alternatives to replace coal boiler.

Technology Alternative	Initial Investment	Cost Burden in Time	Supply Chain Risks	Future Environmental Commitment	Estimated Implementation Time
Biomass (wood chip/pellet boiler)	New boiler + tech conversion + fuel storage and handling space	Fuel storage Lessened revenues from UC forestry lease Increasing carbon cost	Finite resources A limited number of suppliers.	Reforestation and implications of plantation forestry	2 years +
Electric heaters/ heat pumps	New equipment + transformer upgrade	Costly operation and maintenance	Blackout/Brownout	Peak management (fossil fuels required)	3 years +
Ground source heat pumps	New infrastructure	Maintenance of equipment and bores	Limited resource access	Artesian wells at risk of over-extraction	N/A to supply all buildings

Upgrades of the building envelope and energy efficiency of existing equipment are normal practices of building energy management and are also included in the decarbonization plan for the UC campus. Such improvements often come with the challenge of implementation time and budget. At the time of writing, the UC sustainability plan is to replace the coal boiler with a wood chip/pellet boiler within the next five years. The scenario analysis below includes BAU as a benchmark, the replacement of the coal burner with a 15.5 MW wood chip/pellet burner (WCPB), the replacement of the coal burner with multiple air-sourced heat pumps (ASHP), and a building envelope retrofit (BER). The comparative metrics for the different scenarios are primary energy input, fuel mass, operational carbon emissions, peak heat power, air pollution, capital expenditure (CAPEX), and fuel operational expenditures (OPEX), as shown in Table 2 [50–58].

Table 2. Future Scenarios of Energy Downshift.

Scenario	BAU − Coal	WCPB	ASHP	BER + Coal
Primary Energy Input (MWh/year)	30,000 (−0%)	30,000 (−0%)	8000 (−73%)	17,100 (−43%)
Fuel Mass (T/year)	6000	8500	n/a	3420
Operational Carbon Emissions [53] (TCO_2/year)	12,300 (−0%)	140 (−98%)	400 (−96%)	7000 (−43%)
Peak Heat Power (MW)	15.5 (−0%)	15.5 (−0%)	11.2 (−28%)	12.4 (−20%)
Air Pollution	Unchanged	Unchanged	None	Reduced
CAPEX (MNZ$)	0	15	11	51
Fuel OPEX (MNZ$/yr)	1.9	1.3–2.2	1.6	1.1

While the BAU scenario does not incur more CAPEX, the boiler would still have to be replaced in the incoming years. The price of coal has greatly increased and so has the price of carbon. Replacing the current coal boiler with a wood chip/pellet burner requires the same amount of primary energy to provide the current heat output, as the boiler efficiency is assumed to remain unchanged whether the boiler runs with coal or biomass. While direct emissions from the combustion of wood are low [53] compared to those from burning fossil fuels, the decrease in energy density requires more truck loads. Similar wood biomass boilers in New Zealand incurred a CAPEX of 1 MNZ$/MW installed [54], although the cost of the wood biomass can highly vary with quality and provider. Using ASHPs would significantly reduce the amount of primary energy required to provide the same heat output, compared to the existing system. This is due to higher efficiency (i.e., seasonal performance factor of 3.26 [50] and the absence of heat losses through the heat piping system). Hence, carbon emissions can be heavily reduced. OPEX is similar to that of previous scenarios. The downsides are power availability as the Christchurch power grid is constrained, and the embedded energy of multiple individual units that are required to heat the buildings. In an independent study conducted for the University of Canterbury as part of the Low Carbon Energy Scheme Roadmap strategy [40], a 100% insulation improvement (with low emissivity double glazed windows, insulated walls, floors, and roofs [59]) would lead to a 43% and 20% decrease in energy and power requirements, respectively. The retrofitted envelope would cost up to 244 NZ$/m^2 for a total surface of 210,600 m^2.

The proposed scenarios have serious drawbacks or even prohibitive parameters. While a fuel replacement would allow for greater than 90% emissions reductions, resource availability is not guaranteed. The New Zealand industrial and commercial heat uses 31 TWh from fossil fuels [60] with a potential competition for resources as other sub-sectors, may consider using wood to reach their own emissions targets. Even with ASHP, the current heat consumption makes this scenario unlikely without major grid and electricity generation upgrades. On the other hand, retrofit measures incur a high CAPEX and construction disruption that requires many years to achieve. This scenario analysis concludes that the implementation of technological solutions alone is not enough, and retrofitting could take decades.

Step 4 Path-Break: New Century Investigation of 2120

Step 4 requires to follow the "forward operating environment" forward one century to explore the successful systems engineering for carbon-free operation of the building. The first projection about the year 2120 is that the majority of the University of Canterbury campus buildings are still being used on the current campus, and they are all at a high standard of energy efficiency. UC is a major university in the country with a wide range of subjects and an engineering school. For this step, we will postulate that tertiary education will continue to serve society similarly over the next century as it has in the past century. The forward operating environment for coal production is framed by the government policy for reducing net emissions of greenhouse gases (other than biogenic methane) to zero by 2050 as embodied in the Zero Carbon Amendment Act [61]. In choosing the future where the scientific requirements for abatement of anthropogenic global warming, the forward operating environment is characterized by an 80% reduction in coal use by 2030, and no further coal mining after 2040. 100 years in the future most of the current buildings should still be in service with regular maintenance as 80% of the campus has been recently renovated or newly built following the earthquakes of 2011. The remaining low-standard buildings will have been retrofitted with low U-value windows and insulation. Wood pellet boilers and space heaters will serve whole floors of buildings and distribute hot water to radiators with thermostatic control. Academics and staff will have woolen robes that they can use if the temperature becomes uncomfortably cool for their sedentary office work during the winter. There will be no spaces overheated in cold seasons.

Step 5 Back Casting: Retrieving projections to the present

The back-casting analysis helped identify what the system has in 2120 that the current one does not. This missing element is the management of the occupant's flexibility to thermal adaptation and reduced energy demand. Thermal adaptation can be categorized as physiological, psychological, and behavioural [62]. The types of actions that define adaptive behaviour for thermal comfort are two: changing the conditions to accord with comfort and changing the comfort temperature to accord with prevailing conditions [63]. Several studies have focused on the psychological factors affecting thermal comfort. For example, [64] studied the psychological adaptation to changes in environmental stimuli that are perceived as discomforting; they found that adaptation includes any psychological reactions to sensory information, such as habituation, relaxation of thermal expectations, and gradual change of preferences. [65] analyzed the range of behavioural responses driven by thermal stimuli in non-air-conditioned office buildings over one year. They found that occupants used personal adjustments as a first choice over operating mechanical devices such as fans or HVAC units. They also noted that people could tolerate warmer or cooler thermal environments compared to thermal neutrality to some extent. The adaptive responses of occupants were found to be thermally, socially, and habitually conditioned. Evidence shown by [66] indicated that behavioural adjustment and expectation had a greater influence on thermal adaptation compared to the observed physiological process of acclimatization in their study. In office settings, worker performance has been proven to be affected by environmental stressors such as thermal stress. For example, researchers have found a correlation between ambient air temperature and cognitive performance [67]. As studied by [68], reduced work performance after exposure to office environmental stressors is related to the mediating role of negative emotions.

Integrative approaches have recently emerged to investigate energy-related occupant behaviour from a multidisciplinary perspective. For example, the International Energy Agency (IEA) Energy and Buildings and Community (EBC) Programme Annex 66 developed a methodological framework to simulate occupant behaviour in buildings. The modeling framework accounts for multiple physiological, psychological, and socio-cultural parameters to address energy-related behaviours that affect comfort provisions and operational costs [69]. D'Oca et al. [70] presented an interdisciplinary framework for occupant behaviour research that focused on the interaction between humans and buildings by analyzing energy-related behaviours and their socio-cognitive drivers. The authors proposed a survey to measure the motivational drivers for adaptive behaviours, group behaviour, ease and knowledge of control, and satisfaction and productivity of office workers. They use a combination of 39 variables to analyze the influence of socio-cognitive constructs, user profiles, demographics, building type, location, and external weather conditions on heating and cooling adaptive behaviours. The heat usage component of this evaluation as various other research outcomes [71–74] are based on surveys for reported heating behaviour. Surveys of occupant behaviour are often a preferred tool to assess heating usage, given the complexity of direct measurements. Moreover, traditional occupant heating behaviour assessment is based on thermal comfort and business-as-usual energy consumption; this research presents an assessment method that aims at the energy reduction COP21-compliant target, with occupant adaptation and sustained worker productivity.

Step 6 Resulting shift project concept

The previous steps highlighted that the key to transition is the capability to achieve fossil fuel reduction of 80% over a year, from 6000 to 1200 tonnes. The shift project concept that has been identified through the insight of constraint emerges from the requirement to curtail the order for coal by 80% in 2023 and to engineer the adaptive response: the engineering management solution to the constrained coal supply hypothesis. The innovative shift project is a program called Targeted Heating Energy—Assessment and Intervention Design (THE-AID). The program offers an evaluation methodology to target improvements towards user adaptation to reduced-energy heating services. The components of the program are the energy audit of the building, the evaluation of the occupants' heating behaviour, and the intervention design, as described in detail in Section 3.

Two options are generated for the shift project, these are shown in Table 3. The first scenario (adaptive capacity + coal) suggests a hypothetical behavioural adaptation leading to an immediate 80% reduction in coal use for no CAPEX. Building users adapt and change the way they use facilities; people use their adaptive capacity to still achieve their necessary activities while using significantly less energy. The second scenario (sustainable transition) proposes a mix of technological solutions with adaptive capacity where a 4 MW WCPB provides 60% of the current heat needs (for the calculation of peak heat power). The current capacity to provide 100% of heat needs is 15.5 MW as a reference of the percentages shown in Table 3. This is based on operator data of current use [44]. Fuel mass is derived from energy density whereas operational carbon emissions are derived from carbon intensity. The calculation for CAPEX and OPEX are based on Step 3. Selective investments could lead to the targeted installation of ASHPs and insulation. The installation of a small WCPB would allow reducing emissions even further with minimal supply risks, time and investment.

Table 3. Advanced Future Scenarios of Energy Downshift.

Scenario	Adaptive Capacity + Coal	Sustainable Transition
Primary Energy Input (MWh/year)	6000 (−80%)	6000 (−80%)
Fuel Mass (T/year)	1200	1700
Operational Carbon Emissions (TCO_2/year)	2500 (−80%)	30 (−99%)
Peak Heat Power (MW)	4 (−75%)	4 (−75%)
Air Pollution	Significantly reduced	Significantly reduced
CAPEX (MNZ$)	0	>4
Fuel OPEX (MNZ$/yr)	0.4	0.3–0.5

The Forward Operating Environment is the requirement to meet the COP21 agreement pledges, this means the decline of coal production to zero within the next 30 years. At UC, facilities energy managers will make the best use of the coal heating during the coldest winter work periods. From the annual 6000 tonnes of coal that are currently used [44], only 1200 tonnes will be available for use and will be designated specifically for heating in winter, as shown in Figure 5.

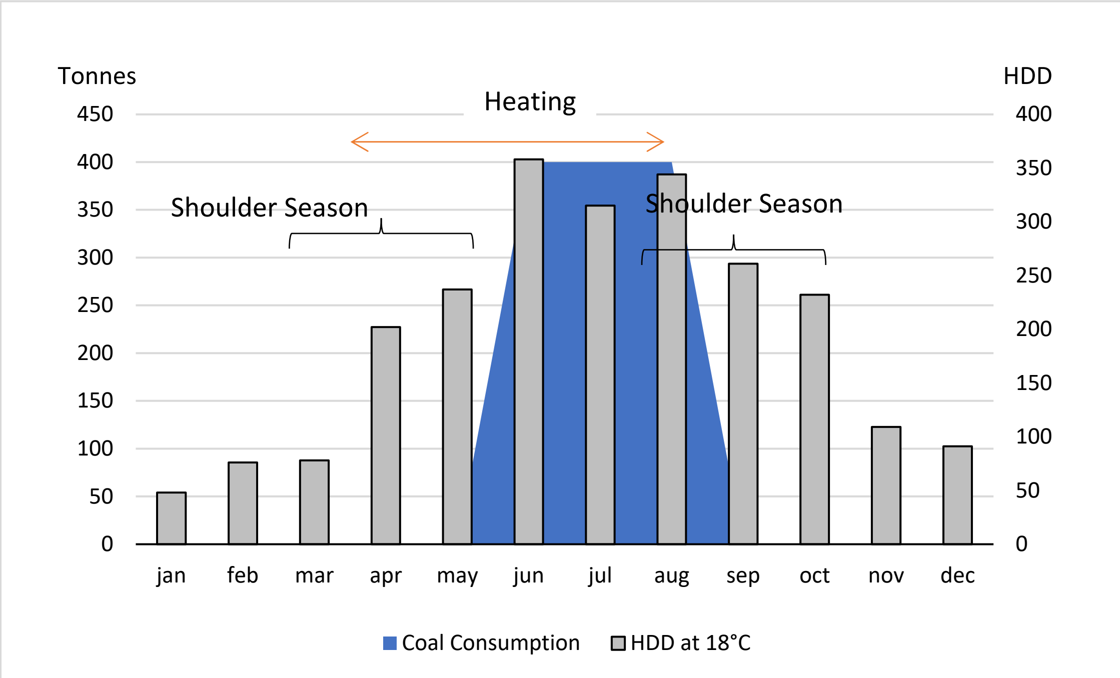


Figure 5. Heating degree days for Christchurch, New Zealand 2019 with the indication of the seasons, and the proposed operation of the coal boiler district heating system.

Step 7 Analysis outcome: Energy Transition

Successful adaptation to a COP21 compliant scenario can be achieved through the implementation of shift projects, such as the one proposed in this paper. Integral assessment programs focused on occupants are vital for the energy transition and decarbonization era. If the shift project of using building thermal capacitance and behaviour adaptation is demonstrated to be successful, then the standard design and HVAC system operation approach could be modified to greatly reduce overheating and overcooling in regions with spring and fall HDD fluctuations.

5. Emerging Concept: THE-AID Program

The first phase of the program is a general level 1 energy audit of the building using standard techniques. A combination of observations and available building information is used to identify the offices with poor thermal performance. This evaluation helps understand the physical component of the building. The second phase is the assessment of the users' behavior, through surveys, heat output measurements of individual offices, and indoor air quality measurements, where possible. The third phase is the design of interventions that include a technical/technological/operational component and a behavioural component at the end-user level.

5.1. Energy Audit

A walk-through building energy audit or ASHRAE Level 1 Energy Audit covers a brief visit to the studied building to identify areas where simple actions can achieve energy reductions [75]. The building envelope materials and their conditions are of special interest, thus they are observed in detail. Data on heating energy consumption should be collected, if available. Weather data or heating degree days can be retrieved from national databases as a reference for the local heating requirements.

5.2. Evaluation of Heating Behaviour

The proposed method includes occupant surveys and observational studies during shoulder and winter seasons to investigate the individual heating behaviour. A self-administered ten-question survey with a five-level scale (Appendix A) gathers information about personal thermal history in the building, habitual adaptive behaviour, and perceived control over the heating system. The factors assessed in the survey are taken from theories of Social Research: perceived control over heating behaviour (PBC) from the Theory of Planned Behaviour [76], and habitual adaptive behaviour and facilitating conditions (FC) from the Theory of Interpersonal Behavior [77]. Each participant is assigned an overall score representing a measure of each variable. The radiator heat output and indoor conditions are monitored with the aid of data loggers. Measured room dry-bulb temperature, relative humidity, and air speed provide useful information about usual thermal working conditions and help understand user behaviour (e.g., high heat output plus windows fully open might result in acceptable indoor temperature, but at high energy cost). Observations of office features, the position of the desk, window openness, and clothing can also be registered during the evaluation.

A combination of qualitative and quantitative data analysis is applied to capture the social dimension of heating energy use and the behavioural patterns of interest. To determine the adaptive signals of each participant, subjective survey data are coupled with objective data of radiator heat through statistical analysis or other analysis methods (e.g., cross-tabulation). The individual room conditions and weather data are used as an objective reference.

5.3. Intervention Design

The results of the energy audit are aimed to identify areas for immediate physical intervention. The evaluation of the socio-cognitive factors that are included in the survey, along with the individual heating usage, inform the intervention designer about the behavioural component of the THE-AID Program. As an example of possible outcomes from this evaluation, low scores on perceived control over heating behaviour and low scores on the available conditions that facilitate the use of the radiators indicate an opportunity for intervention through targeted information campaigns. Low scores on habitual adaptive behaviour, on the other hand, can signal an opening for educational programs or training. These factors are qualitatively assessed in conjunction with the measured heat output from the individual radiators and other available data (e.g., indoor conditions and weather monitoring) to understand the drivers of heating user behaviour and to categorize users according to their actual energy-related behaviour. Changes in office settings can be considered for users that report frequent dissatisfaction with the indoor environment despite frequent use of the radiator controls. Table 4 shows examples of possible interventions based on the assessment of user attributes.

Table 4. Examples of interventions of the THE-AID Program.

Type of Behavioural Intervention	**Sub-Class**	**User Attribute**
Information	Targeted information campaigns	Low PBC/FC
	Educational programs/training	Low habitual adaptive behaviour
Type of Physical Intervention	**Sub-Class**	**Office Characteristics/User Attribute**
Office modifications	Reallocation to a different thermal zone in the building	Low thermal performance (office) Physiological deficiencies
	Furniture rearrangement	Low thermal performance (office) Low habitual adaptive behaviour
	Access to heating controls	Low PBC/FC
	New heating equipment	Physiological deficiencies

6. Discussion

The university wishes to reduce carbon emissions, but the majority of emissions come from heating the buildings with coal. There is no local gas supply for switching to lower carbon heating, and the prospects for substituting electricity or wood are not economically viable or technically practical. What can the university do to meet the nationally agreed COP21 target of 80% emissions reduction? The direct option is to burn 80% less coal. This direct approach has not previously been reported in the literature. How would the facilities managers address the challenge of simply having 80% less coal for the university central heating system? The obvious answer given from the analysis of the heating degree days and the way the current heating system is operated is to curtail central heating during the shoulder fall and spring seasons when the weather is unsettled, and warm and cold days are interspersed. This would allow the use of the thermal mass of the building and avoid the problems of overheating during warm days.

The question then is: how to help occupants of these offices to manage their thermal comfort and productivity during shoulder seasons in the existing office spaces? The THE-AID program has been designed to assess the variables that affect individual radiator usage hence, energy consumption from survey data, measured heat output, and building data, and to design interventions as adaptation plans. In the energy field, structural social norms appear to play a significant role that translates into acquired habits, this could be incorporated as part of this program in future research. The intervention design stage of the program represents an opportunity to manage demand participation through understanding the social and personal contexts as well as the particular office characteristics and perceived thermal environment. The application of the InTIME approach indicates that a significant amount of fossil fuel emissions could be reduced by designing transition programs to strategically take advantage of known current patterns of energy usage.

7. Conclusions

The carbon downshift scenario requires a reduction in coal purchase by 80% from the first year through the engineering of adaptive measures for facility operators and occupants. The question of how to engineer transitions of buildings and adaptation to downshift fossil fuel use needed to be addressed. The analysis of available improvement alternatives showed the barriers to their implementation (i.e., time and budget).

Based on the results of the InTIME exploration, described in Section 4, the THE-AID Program was proposed in response to the engineering requirement of immediate curtailing of the current carbon emissions. This assessment program, which includes an energy audit, the evaluation of heating behaviour, and the intervention design, was conceived to target support areas in office buildings on campus, as a case study, but its implementation may benefit the whole academic community. At its core, THE-AID captures behavioral aspects of heating energy demand from survey data and measured heat output, in addition to building information from audit data, to identify prioritized areas of intervention according to individual predispositions to energy use. This integrative method allows to engineer cost-effective adaptation plans to reduce coal dependency while maintaining the productivity and health of building occupants. The program has the potential to be expanded and it requires the active participation of building owners, managers, and occupants.

The energy transition to low carbon still needs research efforts to understand the multifarious nature of complex systems, such as space heating in office buildings, in time. By identifying a shift project concept, this work has contributed to a new approach to addressing wicked problems of unsustainability, in the hope to lead to future ways to increase resilience in energy systems. The shift project acknowledges that a higher level of adaptation is feasible during the shoulder seasons and can be supported through the implementation of occupant adaptation strategies and targeted technology, and infrastructure modifications.

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Appendix A

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Transition Engineering of Zero Carbon Building Retrofits

Survey Questionnaire

Please circle the answer that best describes the frequency and level of agreement on the statements below. Because this study is only focused on the times when hot water is supplied to the radiator, please restrict your responses to apply only to the following hours: Monday-Friday 5am-5pm.

	Never	Hardly ever	Sometimes	Most of the times	Always
1. To keep warm in my office, I wear warm clothes or use a lap blanket.	1	2	3	4	5
2. To keep warm in my office, I change the settings of the panel radiator* for comfort.	1	2	3	4	5
3. Before leaving my office, I turn off the panel radiator.	1	2	3	4	5
4. I keep the panel radiator at a fixed setting. (Specify setting here if applicable: _____).	1	2	3	4	5
5. To keep warm in my office, I use an extra portable heater.	1	2	3	4	5
6. I open the windows in my office to let fresh air in, even on cold days.	1	2	3	4	5
7. In cold weather, my office space is too cold regardless of how I operate the panel radiator.	1	2	3	4	5
8. In cold weather, my office space is too hot regardless of how I operate the panel radiator.	1	2	3	4	5

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
9. I know how the heating in my office is supplied.	1	2	3	4	5
10. My choice of actions can affect the energy usage to heat my office.	1	2	3	4	5

Additional comments on the use of the radiator (optional):

____

____

____

____

*Panel radiator

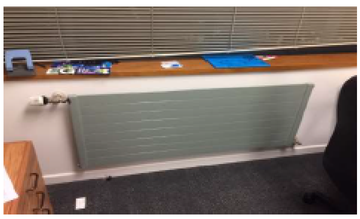

Figure A1. DTHE-AID Survey.

References

1. UNEP. *2021 Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Programme: Nairobi, Kenya, 2021.
2. IEA. *Tracking Buildings 2021*; IEA: Amsterdam, The Netherlands, 2021.
3. IEA. *Global Energy Review*; IEA: Amsterdam, The Netherlands, 2021.
4. UNFCCC. *Paris Agreement*; UNFCCC: Bonn, Germany, 2015.
5. UNFCCC. *The Glasgow Climate Pact*; UNFCCC: Bonn, Germany, 2021.
6. Krumdieck, S. *Engineering Transition: Building a Sustainable Future*; CRC Press LLC: Milton, ON, Canada, 2019.
7. Rogelj, J.; Shindell, D.; Jiang, K.; Fifita, S.; Forster, P.; Ginzburg, V.; Handa, C.; Kheshgi, H.; Kobayashi, S.; Kriegler, E.; et al. *Mitigation Pathways Compatible with 1.5 °C in the Context of Sustainable Development*; IPCC: Paris, France, 2018.
8. Simha, R.V. Willis H carrier: Father of air conditioning. *Resonance* **2012**, *17*, 117–138. [CrossRef]
9. Economidou, M.; Todeschi, V.; Bertoldi, P.; D'Agostino, D.; Zangheri, P.; Castellazzi, L. Review of 50 years of EU energy efficiency policies for buildings. *Energy Build.* **2020**, *225*, 110322. [CrossRef]
10. Lifset, R.D. A New Understanding of the American Energy Crisis of the 1970s. *Hist. Soc. Res.* **2014**, *39*, 22–42. [CrossRef]
11. Soeder, D.J. The Energy Crisis and Unconventional Resources. In *Fracking and the Environment*; Springer International Publishing: Cham, Switzerland, 2020; pp. 63–78.
12. McKay, M.H. New Zealand and the Oil Crisis: An Examination of Foreign Policy Reactions. Master's Thesis, University of Canterbury, Christchurch, New Zealand, 1975.
13. IPCC. *Fifth Assessment Report*; IPCC: Paris, France, 2014.
14. Spiru, P.; Simona, P.L. A review on interactions between energy performance of the buildings, outdoor air pollution and the indoor air quality. *Energy Procedia* **2017**, *128*, 179–186. [CrossRef]
15. Verleger, P.K., Jr. Understanding the 1990 Oil Crisis. *Energy J.* **1990**, *11*, 15–33. [CrossRef]
16. Joskow, P.L. *U.S. Energy Policy during the 1990s*; National Bureau of Economic Research: Cambridge, MA, USA, 2001. Available online: https://www.nber.org/papers/w8454 (accessed on 9 August 2022).
17. Uz, D. Energy efficiency investments in small and medium sized manufacturing firms: The case of California energy crisis. *Energy Econ.* **2018**, *70*, 421–428. [CrossRef]
18. Sajid, Z.; Javaid, A. A stochastic approach to energy policy and management: A case study of the Pakistan energy crisis. *Energies* **2018**, *11*, 2424. [CrossRef]
19. Lodhi, R.N.; Malik, R.K. Impact of Electricity Shortage on Daily Routines: A Case Study of Pakistan. *Energy Environ.* **2013**, *24*, 701–709. [CrossRef]
20. MacGregor, C.; Dowdell, D.C.; Jaques, R.A.; Bint, L.; Berg, B.L. *The Built Environment and Climate Change: A Review of Research, Challenges and the Future*; BRANZ: Jugendford, New Zealand, 2018.
21. Monstadt, J.; Wolff, A. Energy transition or incremental change? Green policy agendas and the adaptability of the urban energy regime in Los Angeles. *Energy Policy* **2015**, *78*, 213–224. [CrossRef]
22. Ministry of Business, Innovation and Employment. *Transforming Operational Efficiency*; MBIE: Wellington, New Zealand, 2020.
23. IEA. *Global CO2 Emissions in 2019*; IEA: Amsterdam, The Netherlands, 2020.
24. Ministry of Business, Innovation and Employment (MBIE). *Electricity Demand and Generation Scenarios: Scenario and Results Summary*; Ministry of Business, Innovation and Employment (MBIE): Wellington, New Zealand, 2019.
25. Risch, A. Are environmental fiscal incentives effective in inducing energy-saving renovations? An econometric evaluation of the French energy tax credit. *Energy Econ.* **2020**, *90*, 104831. [CrossRef]
26. Krumdieck, S.; Hamm, A. Strategic analysis methodology for energy systems with remote island case study. *Energy Policy* **2009**, *37*, 3301–3313. [CrossRef]
27. Krumdieck, S.; Page, S.; Dantas, A. Urban form and long-term fuel supply decline: A method to investigate the peak oil risks to essential activities. *Transp. Res. Part A Policy Pract.* **2010**, *44*, 306–322. [CrossRef]
28. Watcharasukarn, M.; Page, S.; Krumdieck, S. Virtual reality simulation game approach to investigate transport adaptive capacity for peak oil planning. *Transp. Res. Part A Policy Pract.* **2012**, *46*, 348–367. [CrossRef]
29. Bai, M.; Krumdieck, S. Transition engineering of transport in megacities with case study on commuting in Beijing. *Cities* **2020**, *96*, 102452. [CrossRef]
30. Gallardo, P.; Murray, R.; Krumdieck, S.J.E. A Sequential Optimization-Simulation Approach for Planning the Transition to the Low Carbon Freight System with Case Study in the North Island of New Zealand. *Energies* **2021**, *14*, 3339. [CrossRef]
31. Global Association for Transition Engineering. Interdisciplinary Transition Innovation, Management and Engineering (InTIME). 2019. Available online: https://www.transitionengineering.org (accessed on 9 August 2022).
32. American Society of Heating, Refrigerating, and Air-Conditioning Engineers. *ASHRAE Handbook—Foundamentals (SI)*; ASHRAE: Atlanta, GA, USA, 2017.
33. Facilities Management, University of Canterbury. *Ilam Campus MTHW Boilerplant*; University of Canterbury: Christchchurch, New Zealand, 2016.
34. Clifford, G.E. *Heating, Ventilating and Air Conditioning*; Reston Pub: Seattle, WA, USA, 1984.
35. Zenginis, D.G.; Zenginis, D.G.; Kontoleon, K.J.; Kontoleon, K.J. Influence of orientation, glazing proportion and zone aspect ratio on the thermal performance of buildings during the winter period. *Environ. Sci. Pollut. Res. Int.* **2018**, *25*, 26736–26746. [CrossRef]

36. Arriazu-Ramos, A.; Monge-Barrio, A.; Bellod, J.S.M.; Martínez, P.G.; Gutiérrez, A.S.-O. Difficulties in the energy renovation processes of district heating buildings. Two case studies in a temperate climate. *Sustain. Cities Soc.* **2021**, *75*, 103246. [CrossRef]
37. Zhao, S.; Yang, L.; Gao, S.; Li, M.; Yan, H.; Zhai, Y. Field investigation on the thermal environment and thermal comfort in shopping malls in the cold zone of China. *Build. Environ.* **2022**, *214*, 108892. [CrossRef]
38. Huang, L.; Zhai, Z. Critical review and quantitative evaluation of indoor thermal comfort indices and models incorporating solar radiation effects. *Energy Build.* **2020**, *224*, 110204. [CrossRef]
39. Young, J. *Fuelling Dissension: Coal and Coal Mining in 21st Century New Zealand*; Triple Helix Resources Ltd.: Owaka, New Zealand, 2019.
40. Sustainability Office. Sustainable Operations—Our Energy Journey. Available online: https://www.canterbury.ac.nz/life/sustainability/sustainable-operations/energy-and-carbon/ (accessed on 18 July 2022).
41. Graham, B.N.H. Air Pollution Monitoring in New Zealand 1960–1992. 1994. Available online: https://www.moh.govt.nz/notebook/nbbooks.nsf/0/BC5A0A6EBA09992A4C256655000C6518/$file/air-pollution-monitoring-in-New-Zealand-1960-1992.pdf (accessed on 9 August 2022).
42. Petroleum&Minerals New Zealand. Operating Coal Mine Production Figures. 2019. Available online: https://www.nzpam.govt.nz/nz-industry/nz-minerals/minerals-statistics/coal/operating-mines/ (accessed on 9 August 2022).
43. University of Canterbury, Facilities Management, Sustainability Office. 2018 UC Sustainability Report. Available online: https://www.canterbury.ac.nz/media/documents/reports/UC-Sustainability-Report-2018.pdf (accessed on 9 August 2022).
44. University of Canterbury, Facilities Management, Sustainability Office. 2019 UC Sustainability Report. Available online: https://www.canterbury.ac.nz/life/sustainability/sustainability-office-and-programme-board/sustainability-office-reports/UC-Sustainability-Report-2019-V5.pdf (accessed on 9 August 2022).
45. University of Canterbury, Facilities Management, Sustainability Office. 2020 UC Sustainability Report. Available online: https://www.canterbury.ac.nz/life/sustainability/sustainability-office-and-programme-board/sustainability-office-reports/UC-Sustainability-Report-2020.pdf (accessed on 9 August 2022).
46. New Zealand's Minerals and Petroleum Industry. In *Operating Coal Mine Production Figures*; New Zealand's Minerals and Petroleum Industry: Wellington, New Zealand, 2021.
47. New Zealand Ministry of Business, Innovation and Employment. Energy in New Zealand. 2018. Available online: https://www.mbie.govt.nz/assets/d7c93162b8/energy-in-nz-18.pdf (accessed on 9 August 2022).
48. Canterbury, U.O. UC News. Available online: https://www.canterbury.ac.nz/news/2020/biomass-boiler-funding-of-6m-takes-uc-closer-to-sustainability-targets-.html (accessed on 26 November 2020).
49. Eng, G.; Bywater, I.; Hendtlass, C.A. *New Zealand Energy Information Handbook*, 3rd ed.; New Zealand Centre for Advanced Engineering: Christchurch, New Zealand, 2008.
50. Naumann, G.; Schropp, E.; Gaderer, M. Life Cycle Assessment of an Air-Source Heat Pump and a Condensing Gas Boiler Using an Attributional and a Consequential Approach. *Procedia CIRP* **2022**, *105*, 351–356. [CrossRef]
51. Association, B. *Wood Fuel in New Zealand is Produced from Carbon Neutral Biomass from Plantation Forests*; World Bioenergy Association: Stockholm, Sweden, 2019.
52. Research, F. Typical Calorific Values of Fuels. Available online: https://www.forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-biomass/facts-figures/typical-calorific-values-of-fuels/ (accessed on 9 August 2022).
53. Walmsley, M.R.W.; Walmsley, T.G.; Matthews, L.; Atkins, M.J.; Neale, J.R.; Kamp, P. Pinch Analysis Techniques for Carbon Emissions Reduction in the New Zealand Industrial Process Heat Sector. *Chem. Eng. Trans.* **2015**, *45*, 1087–1092. [CrossRef]
54. EECA. Fonterra Coal Boiler Conversion. 2020. Available online: https://www.eeca.govt.nz/insights/case-studies-and-articles/fuel-switching-captures-economic-and-climate-benefits-for-fonterra/ (accessed on 9 August 2022).
55. Wood Energy SouthCase Study: Splash Palace, Invercargill. 2020. Available online: https://www.bioenergy.org.nz/resource/case-study-675kw-binder-chip-boiler-splash-palace-invercargill (accessed on 9 August 2022).
56. Department of Energy. Best Practice Guideline for Life Cycle Analysis of Heat Supply Projects. 2018. Available online: https://www.energy.gov/sites/default/files/2022-06/FECM%20DACS%20LCA%20Best%20Practices.pdf (accessed on 9 August 2022).
57. Ashfaq, A.; Ianakiev, A. Cost-minimised design of a highly renewable heating network for fossil-free future. *Energy* **2018**, *152*, 613–626. [CrossRef]
58. MBIE. Energy Prices. Available online: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/energy-prices/ (accessed on 9 August 2022).
59. BECA. *Analysis to Inform A Review of Large Non-Residential and Apartment Building Thermal Performance Settings and Climate Zones*; BECA: Auckland, New Zealand, 2021.
60. NZ MBIE. *Process Heat in New Zealand*; MBIE: Wellington, New Zealand, 2018.
61. New Zealand Parliamentary Counsel Office.Climate Change Response (Zero Carbon) Amendment Act 2019. 2019. Available online: https://environment.govt.nz/acts-and-regulations/acts/climate-change-response-amendment-act-2019/ (accessed on 9 August 2022).
62. Liu, J.; Yao, R.; McCloy, R. A method to weight three categories of adaptive thermal comfort. *Energy Build.* **2012**, *47*, 312–320. [CrossRef]
63. Nicol, J.F.; Humphreys, M.A. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy Build.* **2002**, *34*, 563–572. [CrossRef]

64. Coley, D.; Herrera, M.; Fosas, D.; Liu, C.; Vellei, M. Probabilistic adaptive thermal comfort for resilient design. *Build. Environ.* **2017**, *123*, 109–118. [CrossRef]
65. Liu, J.; Yao, R.; McCloy, R. An investigation of thermal comfort adaptation behaviour in office buildings in the UK. *Indoor Built Environ.* **2014**, *23*, 675–691. [CrossRef]
66. Brager, G.S.; de Dear, R.J. Thermal adaptation in the built environment: A literature review. *Energy Build.* **1998**, *27*, 83–96. [CrossRef]
67. Yeganeh, A.J.; Reichard, G.; McCoy, A.P.; Bulbul, T.; Jazizadeh, F. Correlation of ambient air temperature and cognitive performance: A systematic review and meta-analysis. *Build. Environ.* **2018**, *143*, 701–716. [CrossRef]
68. Soriano, A.; Kozusznik, M.W.; Peiro, J.M. From Office Environmental Stressors to Work Performance: The Role of Work Patterns. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1633. [CrossRef]
69. Yan, D.; Hong, T.; Dong, B.; Mahdavi, A.; D'Oca, S.; Gaetani, I.; Feng, X. IEA EBC Annex 66: Definition and simulation of occupant behavior in buildings. *Energy Build.* **2017**, *156*, 258–270. [CrossRef]
70. D'Oca, S.; Chen, C.-F.; Hong, T.; Belafi, Z. Synthesizing building physics with social psychology: An interdisciplinary framework for context and occupant behavior in office buildings. *Energy Res. Soc. Sci.* **2017**, *34*, 240–251. [CrossRef]
71. Paone, A.; Bacher, J.-P. The impact of building occupant behavior on energy efficiency and methods to influence it: A review of the state of the art. *Energies* **2018**, *11*, 953. [CrossRef]
72. Gunay, H.B.; O'Brien, W.; Beausoleil-Morrison, I. A critical review of observation studies, modeling, and simulation of adaptive occupant behaviors in offices. *Build. Environ.* **2013**, *70*, 31–47. [CrossRef]
73. Harputlugil, T.; de Wilde, P. The interaction between humans and buildings for energy efficiency: A critical review. *Energy Res. Soc. Sci.* **2021**, *71*, 101828. [CrossRef]
74. Lopes, M.A.R.; Antunes, C.H.; Martins, N. Energy behaviours as promoters of energy efficiency: A 21st century review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 4095–4104. [CrossRef]
75. Goswami, D.Y.; Kreith, F. *Energy Management and Conservation Handbook*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2017.
76. Ajzen, I. The theory of planned behavior. *Organ. Behav. Hum. Decis. Process.* **1991**, *50*, 179–211. [CrossRef]
77. Triandis, H. *Interpersonal Behavior*; Brooks/Cole Pub. Co.: Monterey, CA, USA, 1977; Volume 1.