Environmental evaluation of energy efficiency refurbishment in New Zealand’s commercial office buildings

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Agneta Ghose

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Executive summary

In New Zealand, 80 % of existing commercial office buildings are more than 20 years old and consume approximately 40 % more energy than newer counterparts. Moreover, nearly 38 % of the energy-related emissions in New Zealand's cities are due to the heating and cooling requirements of commercial office buildings. Therefore, energy efficiency measures in office buildings are recommended to reduce operational energy related costs, provide better working conditions, and enhance business value. An energy efficiency refurbishment which involves adoption of multiple energy saving measures such as thermal insulation, improved glazing, air conditioning and lighting systems, can reduce the energy consumption of existing buildings by nearly 60 %. However, such a refurbishment also involves substantial construction work associated with the demolition and replacement of several building components, and this is associated with additional environmental impacts. It is therefore important to evaluate if the environmental benefits associated with reductions in energy demand can outweigh the environmental impacts of refurbishment.

This research investigated the comprehensive environmental impacts of energy efficiency refurbishments in New Zealand's office buildings using Life Cycle Assessment (LCA). The research used existing data collected for Building Energy End-use Study (BEES) by the Building Research Association of New Zealand (BRANZ). In particular, this research used the information on building design and annual energy consumption of existing and refurbished building prototypes. These building prototypes provided - construction details adopted in buildings of different sizes; and the operational energy performance based on typical climatic conditions found in New Zealand. The environmental performance of the buildings was calculated for Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photo-chemical Oxidation Potential (PCOP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion of resources (AD_r), Abiotic Depletion of fossil fuels (AD_{ff}), Human toxicity carcinogenic (HT-carc), Human toxicity non-carcinogenic (HT-non carc), Eco-toxicity freshwater ($ET_{freshwater}$), Particulate Matter Formation (PMF), and Ionizing Radiation (IR).

A series of studies were performed to: (i) assess the environmental impacts and identify the environmental hot-spots of energy efficiency refurbishment, (ii) assess the influence of building's service life, energy, resource and waste management on the environmental performance of energy efficiency refurbishment, (iii) assess the influence of building size, design and location on the environmental performance of energy efficiency refurbishment, and (iv) to evaluate the contribution of energy efficiency refurbishment to New Zealand's 2050 climate change mitigation target compared to the environmental performance of existing office building stock.

The results showed that at energy efficiency refurbishments can reduce emissions for environmental impact categories affected by energy demand particularly for global warming, acidification and photochemical oxidation. However, the refurbishment is also associated with increase in environmental impacts affected by resource demand such ozone depletion potential, abiotic depletion of resources, human toxicity (carcinogenic) and ionizing radiation. Service life of over 25 years is required to compensate the embodied environmental impacts of refurbishment for most of the impact categories, particularly if the electricity is sourced from renewable energy sources.

Refurbished components such as- on-site photovoltaic (PV), aluminium framed windows, façade components and heat pumps were identified as the major environmental hot-spots for most impact categories. The embodied environmental impacts to most categories could be reduced by 20 - 40 % if the waste recovery and recycling at construction site is improved. However, the overall environmental impacts of refurbished office buildings are highly sensitive to the choice of energy supply.

Energy supply from grid electricity generated from renewable resources should be prioritised over the use of on- site PV. Benefits from on-site PV is limited if the grid electricity supply is mainly from renewable sources; moreover, the production of photovoltaic panels is energy and resource intensive. It can increase nearly 50 - 100 % of the embodied environmental associated with building refurbishment. If on- site photovoltaic is installed, it should be prioritised in buildings with large roof area located in regions with long sunshine hours. The results also show that in large buildings- efficient heating, ventilation and lighting equipment; and smaller wall to window ratios should be prioritised to reduce environmental impacts. In small buildings, the choice of façade materials with low embodied impacts should be prioritised to reduce environmental impacts.

With respect to New Zealand's 2050 target for the existing office building sector 60 - 90 % greenhouse gas emissions reductions is possible only if the office building stock refurbishment is combined with a renewable energy supply. Nearly 60 – 70 % of the greenhouse gas emissions can be reduced if the refurbishment of the existing office building stock is limited to existing large office building stock (>3500 m^2) or to buildings in Auckland and Wellington.

The main conclusions based on the results of this research are to prioritise better resource and waste management, to prioritise strategies for maintenance of refurbished buildings to promote longer service life, to support national level policies on increased use of renewable sources for grid electricity generation, and to prioritise refurbishment for a share of the building stock based on size and location which contributes to maximum energy reduction and minimal environmental impacts. The outcomes of this research can support national policy makers and independent building stakeholders (e.g. architects, owners, and engineers) who are keen on promoting energy efficiency refurbishments in New Zealand's office buildings.

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“It is not the mountain we conquer, but ourselves.”- Sir Edmund Hillary

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I dedicate this work to Michele and my family.

List of Abbreviations

AD_{ff}	Abiotic Depletion (fossil fuels)
AD_r	Abiotic Depletion (resources)
AP	Acidification Potential
AISI	American Iron and Steel Institute
BAU	Business As Usual
BRANZ	Building Research Association of New Zealand
CCANZ	Cement and Concrete Association of New Zealand
CIS Russia	Commonwealth of Independent States (Russia)
EP	Eutrophication Potential
$ET_{freshwater}$	Eco-toxicity (freshwater)
FAO	Food and Agriculture Association
GWP	Global Warming Potential
GHG	Greenhouse gas emissions
HT carc	Human Toxicity (carcinogenic)
HT non carc	Human Toxicity (non- carcinogenic)
IAI	International Aluminium Institute
IEA	International Energy Agency
IR	Ionizing Radiation
LCA	Life Cycle Assessment
LED	Light Emitting Diode
MBIE	Ministry of Business, Innovation and Employment
NZ	New Zealand
ODP	Ozone Depletion Potential
OECD	Organization for Economic Cooperation and Development
PCOP	Photochemical Oxidation Potential
PET	Polyethylene Terephthalate
PMF	Particulate Matter Formation
RoW	Rest of the World
REBRI	Resource Efficiency in the Building and Related Industries
UNCOMTRADE	United Nations international COMmercial TRADE statistics
UN FCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environmental Program
USGS	United States Geological Survey

Table of Contents

Executive summary iii

Acknowledgements iv

List of Abbreviations vii

List of Figures xiii

List of Tables xiv

1.1Energy efficiency refurbishments - a strategy to improve environmental performance of commercial buildings 2

1.2 Relevance of energy efficiency refurbishment for commercial buildings in New Zealand 3

1.3 Assessment methods to evaluate energy efficiency refurbishments 6

1.4 Relevance of LCA to evaluate the environmental effects of energy efficiency refurbishment in New Zealand's commercial buildings 8

1.5 Research aim and objectives 9

1.5.1 Research aim and questions 9

1.5.2 Materials and Methods 10

1.5.3 Structure of the thesis 12

1.6 List of publications 13

2.1 Introduction 19

2.2 LCA standards for the building sector 21

2.2.1 Goal and Scope 21

2.2.2 Inventory analysis in building LCA 22

2.2.3 Impact assessment and Interpretation of building LCA 24

2.3 Definition of building refurbishment in LCA 25

2.4 Methodology 27

2.5 Discussion on methodological approaches 31

2.5.1 Scope 31

2.5.2 Inventory Analysis 32

2.5.3 Impact Assessment 33

2.5.4 Number and Location 34

2.6 LCA of whole office buildings 35

2.6.1 Energy conservation in operation 38

2.6.2 Environmental improvement in material production 39

2.6.3 Material recycling 40

2.7 LCA of refurbishment for energy efficiency in office buildings 41

2.7.1 Environmental impacts of multiple refurbishment measures 41

2.7.2 Environmental impacts of single building component refurbishment........42
2.8 Conclusion........45
3.1 Introduction........52
3.2 Methodology........55
3.2.1 Case study description........55
3.2.2 Functional unit and system boundaries........56
3.2.3 Data acquisition for inventory analysis........58
3.2.3.1 Building façade elements........59
3.2.3.2 Technical components........60
3.2.3.3 Construction activities related to refurbishment........61
3.2.3.4 Inventory for construction materials and energy........61
3.2.3.5 Building operation........63
3.2.3.6 Inventory for electricity mix and potential scenarios........63
3.3 Results........66
3.3.1 Environmental impacts of refurbishment........66
3.3.2 Cumulative environmental impact........67
3.3.3 Environmental Payback........70
3.4 Discussion........71
3.4.1 Environmental hotspots in building refurbishment........71
3.4.2 Relevance of deep energy refurbishment in offsetting environmental impacts from New Zealand's electricity grid mix........73
3.4.3 Comparison of results with existing studies........74
3.4.4 Limitations and Future Work........76
3.5 Conclusion........77
4.1 Introduction........86
4.1.1 Use of Consequential LCA modelling in the building sector........87
4.2 Methodology........89
4.2.1 Base case and scenarios........90
4.2.2 Inventory analysis........94
4.2.2.1 Identification of marginal suppliers........94
4.2.2.2 Substitution and avoided burdens........97
4.2.3 Impact Assessment........99
4.2.4 Sensitivity analysis........99
4.3 Results........100
4.3.1 Contribution analysis........100
4.3.2 Scenario analysis........100

4.3.3 Sensitivity analysis 104
4.4 Discussion 107
4.4.1 Contribution Analysis 107
4.4.2 Scenario Analysis 108
4.4.3 Sensitivity Analysis 109
4.4.4 Limitations 110
4.5 Conclusion 111
5.1. Introduction 125
5.2. Methodology 127
5.2.1 LCA modelling 129
5.2.2 Statistical Analysis 133
5.2.2.1 Model selection 134
5.3 Results 136
5.3.1 Kruskal-Wallis and post hoc Dunn test results 136
5.3.1.1 Buildings in BAU compared to other scenarios 136
5.3.1.2 Comparison of buildings in RE, PV and BCP scenarios 136
5.3.2 GAM results 138
5.4 Discussion 140
5.4.1 Refurbished buildings in the BAU scenario 140
5.4.2 Refurbished buildings in the PV scenario 142
5.4.3 Refurbished buildings in RE scenario 143
5.4.4 Refurbished buildings in the BCP scenario 144
5.4.5 Limitations and future work 144
5.5 Conclusion 145
Abstract 153
6.1 Introduction 154
6.2 Methodology 158
6.2.1 New Zealand specific office building prototypes 158
6.2.1.1 Building characteristics and Energy simulation 158
6.2.1.2 Life cycle assessment of building prototypes 159
6.2.1.3 New Zealand's Electricity grid scenarios 160
6.2.1.4 Environmental impact of building prototypes up to 2050 161
6.2.2 New Zealand's office building stock 162
6.2.2.1 Stock Aggregation Analysis 163
6.2.2.2 Accounting for New Zealand's 2050 GHG emission target 164
6.3 Results 167

6.3.1 Environmental performance of New Zealand's office building stock......167
6.3.2 Environmental performance based on building location and building size groups......168
6.3.3 Target 2050 - New Zealand's office building stock......171
6.3.4 Targeting refurbishment towards specific building stock......173
6.4 Discussion......176
6.4.1 Role of electricity supply......176
6.4.2 Impacts embodied in refurbishment......177
6.4.3 Refurbishment and 2050 GHG mitigation target......178
6.4.3.1 Targeting GHG mitigation with specific location......179
6.4.3.2 Targeting GHG mitigation towards buildings of specific sizes......179
6.4.4 Limitations and future work......180
6.5 Conclusion......182
7.1 Introduction......188
7.2 Influence of study design......188
7.2.1. Inventory modelling......190
7.2.2 Life Cycle Stages......191
7.2.3 Analytical approaches adopted to strengthen LCA results......192
7.3 Key findings......195
7. 3. 1. Environmental Hotspots......195
7. 3 .2. Influence of electricity supply......196
7. 3 .3. Influence of waste and resource management......197
7. 3 .4 Influence of building characteristics......199
7. 3 .4. 1 Building Lifetime......199
7. 3 .4. 2 Building size......200
7. 3 .4. 3 Buildings in different location......200
7.3.5 Maximizing net environmental benefits......201
7.4 Applicability of results to policy makers......205
7.4.1 National policy: prioritise renewable grid electricity generation......205
7.4.2 National policy: prioritise deep energy refurbishment of existing building stock as an immediate climate change mitigation strategy......205
7.4.3 National policy: prioritise services that support segregation and recycling of construction wastes......206
7.4.4 National policy: prioritise refurbishment strategies based on building size and location......206
7.4.5 Building Level: prioritise construction waste and resource management 206

7.4.6 Building Level: prioritise longer operational period of refurbished buildings with maintenance 207

7.4.7 Building Level: prioritise refurbishment strategies based on building design, size and location 207

7.5 Limitations and future work 207

7.5.1 Limitations - case studies 207

7.5.2 Limitations - methodology 209

7.6 Conclusions 212

Supporting Information - 1 233

Supporting Information - 2 237

Supporting Information - 3 246

Supporting Information - 4 261

Appendix 267

List of Figures

Chapter 1

Figure 1.1 Energy Performance Indicators (EnPI) of different commercial premises based on their use……………………………………………………………….....5

Chapter 2

Figure 2.1 Life cycle stages of a building represented as adapted from building LCA standard EN 15978 (2011))………………………………………….…………22

Figure 2.2 Building performance with predicted modifications in its functional timeframe……………………………………………………………………….26

Chapter 3

Figure 3.1 Activities and flows associated with materials and energy modelled in this study for building refurbishment and subsequent operational use……………..…58

Figure 3.2 The impact assessment results for refurbished building and the relative contributions of the different refurbished components, construction activities and waste treatment…………………………………………………………………67

Figure 3.2.(a and b) Cumulative impact assessment results for the refurbished and existing building operating for 25 or 50 years using different electricity grid mix scenarios……………………………………………………………………...68

Chapter 4

Figure 4.1 System boundary, base case and the three scenarios on share of materials recycled or re-used assessed……………………………………………………94

Figure 4.2 (a and b) Impact assessment results for the building refurbishment in Business As Usual scenario, waste minimization scenario, alternative material procurement scenario, and combination of waste minimization and alternative material procurement scenario………………………………………………...103

Figure 4.3 (a and b) Net impact results (per functional unit) in each scenario for sensitivity analysis of a) recycling efficiency, b) specific marginal suppliers and c) potential change in electricity grid mix of specific marginal suppliers …………106

Chapter 5

Figure 5.1 Representative office building prototypes and seven regions across New Zealand. Schematic representation of data and methodology used in chapter 5……………………………………………………………………………..132

Figure 5.2 (a and b) The comparative results per functional unit for the four scenarios on energy and resource management ……………………………………………138

Chapter 6

Figure 6.1 Representative office building prototypes and seven regions across New Zealand. Schematic representation of data used in chapter 6…………….….…...160

Figure 6.2 (a and b) The stock aggregated impact assessment results from 2017 - 2050 for buildings in four different refurbished or non-refurbished conditions (nRb, Rb, Rb BCP, Rb PV) and two scenarios on NZ grid electricity generation….…..171

Figure 6.3 Cumulative GWP between 2017 to 2050 for buildings in in four different refurbished or non-refurbished conditions (nRb, Rb, Rb BCP, Rb PV) and two scenarios on NZ grid electricity generation…………………………..................174

Chapter 7

Figure 7.1 Heat map built to represent the influence of building condition and strategies for building refurbishment on the overall environmental performance of New Zealand's existing office building stock...…………………….…………205

List of Tables

Chapter 1

Table 1.1 Energy Performance Indicators (EnPIs) for electricity use by commercial buildings in New Zealand……………………………………………….……..4

Chapter 2

Table 2.1 Whole building Life cycle assessment studies on office buildings….….29

Table 2.2 Life cycle assessment studies on refurbishment in office buildings……30

Chapter 3

Table 3.1 Building Characteristics - existing and refurbished building…………..56

Table 3.2 Scenarios used to represent the New Zealand Grid electricity mix…….64

Table 3.3 Inventory data for refurbishment activities and annual building operation for case study building……………………………………………………….65

Table 3.4 Payback period of the deep energy refurbishment for the case study using different electricity grid mix scenarios……………………………………………71

Chapter 4

Table 4.1 Specifications of the existing and refurbished building and related refurbishment measures ………………………………………………………..91

Table. 4.2 Marginal suppliers of construction materials and products……..……..97

Table 4.3 Marginal electricity supply of identified material and product suppliers……………………………………………………………..……………98

Table 4.4 Modelling assumptions for secondary materials produced from the recovery of demolition waste or used to substitute primary materials during refurbishment and associated avoided burdens……………………………………99

Chapter 5

Table 5.1 Summary of building characteristics which were considered as predictor variables in the GAM modelling to test their influence on the environmental impact……………………………………………………………………………133

Chapter 6

Table 6.1 Environmental impact categories and related impact assessment methods…………………………………………………………………………..161

Table 6.2 Marginal sources of electricity production in New Zealand and the environmental impacts associated with 1 kWh of low voltage electricity produced…………………………………………………………………………162

Table 6.3 Total floor area of office buildings in New Zealand based on size and location…………………………………………………………………………...164

Table 6.4 GWP in 2050 of whole office building stock with respect to New Zealand's 2050 target……………………………………………………………….……….175

Table 6.5 GWP in 2050 of whole office building stock with respect to 2050 target-if buildings in specific regions are refurbished…………………………………..175

Table 6.6 GWP in 2050 of whole office building stock with respect to 2050 target-if buildings in two or more major cities and adjoining regions are refurbished…175

Table 6.7 GWP in 2050 of whole office building stock with respect to 2050 target-if buildings of specific sizes are refurbished……………………………………..176

Chapter 7

Table7. 1 Summary and comparison of the study design………………………..195

Chapter 1- Introduction

The rise in demand for building services and higher comfort levels together with the increased time spent inside buildings have led to increased global consumption of energy and resources in the building sector (Pérez-Lombard et al., 2008). In particular, buildings alone contribute to 40 % of global energy consumption and it is projected that commercial building energy use will grow worldwide (Urge-Vorstaz et al., 2015). Promotion of energy efficiency, adopting new technologies for energy sufficiency, and raising awareness about rational use of energy resources are recommended to support progress towards a more sustainable future (Lucon & urge-Vorstaz, 2014).

Refurbishment offers opportunities for reducing the energy demand of existing buildings. Hestnes and Kofoed (2002) evaluated several refurbishment strategies such as improving the building envelope, lighting, heating, cooling and ventilation system, and showed that it is possible to significantly reduce building energy use. According to the International Energy Agency, energy efficiency refurbishment has the potential to achieve two-thirds of the required reduction in energy-related CO_2 eq. emissions in order to meet global climate change mitigation goals (Davis, 2012). However, existing buildings would require large scale energy efficiency refurbishment (i.e. several refurbishment measures) to achieve a substantial reduction in operational energy demand whilst providing optimum comfort (IEA EBC, 2014, 2015). This raises the issue that there may be trade-offs with respect to the environmental costs of large refurbishments and the subsequent benefits related to reduced operational energy demand.

This chapter introduces the role of energy efficiency refurbishment in the context of improving the environmental performance of commercial buildings (section 1.1) and more specifically the relevance of energy efficiency refurbishments for commercial buildings in New Zealand (section 1.2). Furthermore, the assessment methods to evaluate energy efficiency refurbishments are discussed (section 1.3); specifically addressing the relevance of LCA to evaluate energy efficiency refurbishment in New Zealand (section 1.4). This is followed by the research aim and objectives (section 1.5); and details of the publications arising from the research (section 1.6).

1.1Energy efficiency refurbishments - a strategy to improve environmental performance of commercial buildings

Refurbishment of commercial buildings is usually undertaken in response to a change of tenant, new government regulations or market demand. BREEAM, an international building rating tool (BREEAM UK, 2014), has categorized refurbishment into four types based on modification of different building elements:

1. **Refurbishment of fabric and structure:** involves modification of the external envelope, cladding, façade, doors, windows, roof, floor and foundation. A building's fabric has a significant role in determining the thermal performance of a building.

2. **Refurbishment of core services:** involves modification of centralized heating, cooling, ventilation and air-conditioning (HVAC) services. The function of the HVAC system is to provide constant temperature and maintain the air quality.

3. **Refurbishment of local services:** modification of lighting, other local electrical services, plumbing. Artificial lighting is installed to negate the dependency on natural light.

4. **Refurbishment of fit-outs and furnishings**: includes modification of interior finishes, carpeting, partitioning, addition of furniture and equipment.

Energy efficiency refurbishments that target substantial reduction in a building's energy demand include refurbishment of the building's fabric and structure, core and local services (IEA EBC, 2015); refurbishment of building fit-outs is associated with improvement of the building's aesthetics. Owners and tenants of commercial buildings undertake refurbishment in order to optimize functionality coherent with economic benefits; functionality may be concerned with comfort and aesthetic considerations as well as addressing energy and environmental aspects (Ardente et al., 2011).

There is an increasing focus on refurbishment of urban commercial built structures, particularly in developed countries that have an established stock of existing buildings. According to the U.S. Energy Information Administration (EIA), the combined energy use of the office and retail building stock constitutes the highest proportion of building energy consumption and energy-associated CO_2 emissions (Pérez-Lombard et al., 2008). In the US and the UK, the energy use of office buildings are 18 % and 17 % respectively of the total energy use in commercial buildings, contributing 3.2 % and 2 % respectively to national energy consumption (Pérez-Lombard et al., 2008). Investment in maintenance, repair and refurbishment in the UK and the US is 50 % and 40 % respectively of the total investment in the construction sector in both countries (Bowyer et al., 2013). The member states of the EU are projecting high investments in building refurbishment aiming to achieve nearly 80-90 % energy efficiency targets by 2050 (EU Energy Efficiency Directive, 2012).

Existing studies have shown that refurbishment for energy efficiency in buildings contributes to environmental benefits. For example, Ascione et al. (2011) performed an operational energy audit of an historic building in Italy that had undergone refurbishment for energy efficiency. The study analyzed five energy efficiency measures: increased wall insulation; modification of the indoor temperature by increasing the summer set point and decreasing the winter set point by 2 degree Celsius; air draught reduction; replacement of the heating system; and improved glazing systems. These measures reduced the building's primary energy requirement and associated carbon dioxide emissions by 22 % in comparison with its pre-refurbishment operational energy requirement. Another study calculated the embodied energy and carbon of different materials used in construction and the operational energy of different types of existing buildings in USA (Meeks, 2017). They found that usually the re-use of an existing building structure saves energy and carbon emissions of a building equivalent to 80 years of operational energy use.

1.2 Relevance of energy efficiency refurbishment for commercial buildings in New Zealand

New Zealand's commercial building stock consists of approximately 50,000 buildings of which nearly 33,000 buildings are used as offices or have retail use (Isaacs & Hills, 2013).This is low compared to the large residential stock of approximately 1.8 million units (Department of Building and Housing, 2010; MBIE, 2016b). Yet the commercial building sector uses 9 % of the total national energy use and 21 % of national electricity use (NABERS NZ & NZGBC, 2012). This operational energy consumption contributes to 1,011 kilotons of CO_2 eq. gases (Ministry for the Environment (NZ), 2011). Nearly 38 % of the energy-related emissions in New Zealand's cities are due to the heating and cooling needs of commercial buildings (NZEECS, 2007). Furthermore, over NZ$ 1 billion is spent on electricity annually (Saville-Smith & Fraser, 2012).

In New Zealand, the Building End Energy use Study (BEES) was undertaken in order to better understand energy use in commercial buildings, based on measurement. One output of the study was the development of Energy Performance Indicators (EnPI) (annual average energy use per square metre of floor area) for commercial buildings. Table 1.1 show that annual energy use per m^2 is higher in office and retail buildings compared to other commercial buildings (Amitrano & Isaacs, 2014a); the "other" category includes buildings providing educational, healthcare or public (post offices/police stations) services (DBH, 2011).

Table 1.1 Energy Performance Indicators (EnPIs) for electricity use by commercial buildings in New Zealand. Source: (Amitrano et al., 2014a)

Building use	**EnPI (kWh/m^2 yr) estimate**	**± 95% confidence interval**
Commercial office	186	61
Commercial retail	176	45
Other	158	36
Average	173	28

Although it is generally accepted that commercial buildings are responsible for a significant proportion of total energy consumption in most developed countries, the variations between different commercial buildings in energy consumption make it difficult to propose effective efficiency measures. The variations in energy consumption are related to the variability in the building use (Saville-Smith et al., 2012). There is a higher variability in energy consumption in retail buildings than in office buildings (Bishop, 2013). This is due to the influence of different types of retail activities; for example, restaurants or supermarkets may have high refrigeration requirements and thus higher energy use compared with retail buildings with no refrigeration requirements where 65 % of the energy use is for lighting (Amitrano et al., 2014a). As an example, the BEES study in NZ shows that EnPI in a butcher shop is approximately750 kWh/m^2/yr and in typical retail store is approximately 45 kWh m^2/yr.

The main function in an office building is to provide an environment to support occupants to work efficiently and productively. Offices provide spaces for primarily desk-based work, meetings and presentations. Operating energy in office buildings can be attributed mainly to the need to maintain constant comfortable working conditions which include energy use for lighting, heating, air conditioning, IT and other services for more than 40 hours a week (Amitrano et al., 2014a). In New Zealand's office buildings the energy use can be attributed approximately one third for lighting, one-third for space conditioning (heating and cooling), and one-third for plug loads of electronic appliances (see Figure 1.1) (Amitrano et al., 2014a). However, building size and location play an important role in influencing the energy use in offices. For example, office premises in multi- story office buildings in central business districts have a tendency to use more energy per square metre than premises from smaller buildings in suburbs (Saville-Smith et al., 2012). Moreover, 85 % of the vacant stock in major commercial office spaces is of secondary quality; while the current investments in commercial property isdriven by the demand for high performance buildings which have low operating costs and energy consumption (Colliers International research, 2014). It is speculated that investment in refurbishment could have positive economic returns within two years of major refurbishment (Colliers International Research, 2014).

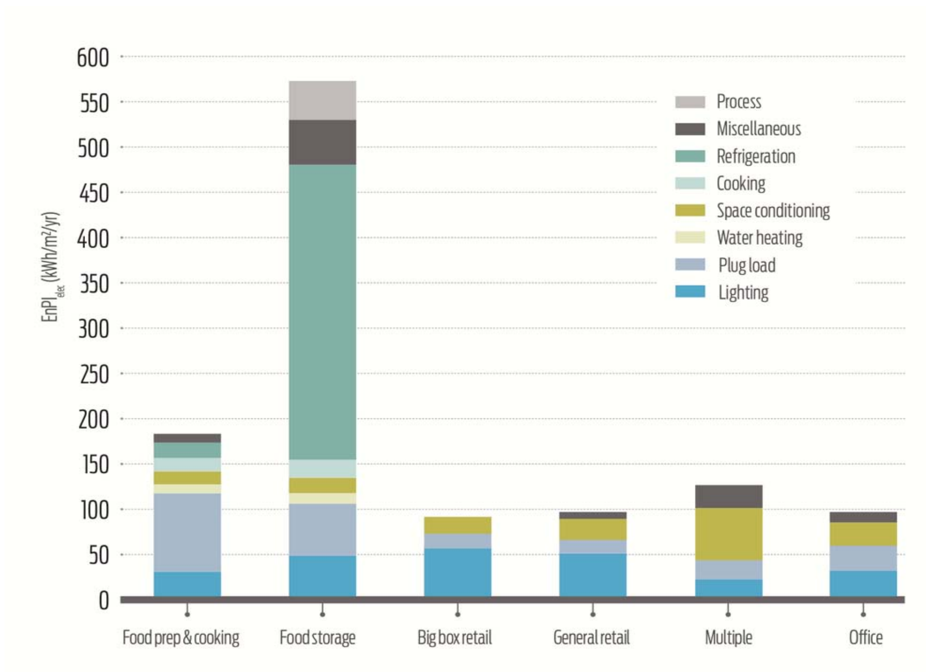

Figure 1.1 Energy Performance Indicators (EnPI) of different commercial premises based on their use. Source: (Amitrano et al., 2014a)

In accordance with the Paris Agreement, New Zealand aims to reduce 50 % of its greenhouse gas emissions compared to 1990 levels by 2050 (Ministry for the Environment, 2015; United Nations, 2015). Refurbishment of existing commercial buildings is considered as a potential strategy to reduce the impacts from the operational energy use (Bedford et al., 2016). Green Star New Zealand and NABERS NZ[1] are building rating tools promoted by the New Zealand Green Building Council (NZGBC) and the Ministry for the Environment (MfE) to integrate goals of environmental and energy improvement in New Zealand's commercial buildings. Both rating tools address the performance of both new and existing buildings. Existing buildings are expected to meet the performance benchmark of new buildings. Thus these rating tools are driving the upgrade of the existing building stock towards energy efficiency (Green Star Tool, 2016). The Energy Efficiency and Conservation Authority (EECA) provides funding and consulting services to businesses in New Zealand to improve energy efficiency and adopt technology using renewable sources of energy (EECA, 2014).

1.3 Assessment methods to evaluate energy efficiency refurbishments

Several assessment methods are used to support decision-making about energy efficient refurbishment. They include energy auditing, building energy performance assessment, quantification of energy benefits, economic analysis, risk assessment, and measurement and verification of energy savings (Ma et al., 2012). Most of these analysis methods are concerned with evaluating the energy saving benefits and investment costs associated with energy efficiency measures without addressing other environmental issues such as, climate change mitigation, ozone depletion, acidification, photo-chemical oxidation, etc. associated with using additional resources during refurbishment (Ma et al., 2012). Due to the focus on the operational energy savings these methods neglect the effect of embodied energy which is the energy sequestered in building materials during production, on-site construction, demolition and disposal and the environmental issues associated with it (Dixit et al., 2010). Based on a review of building case studies in Europe and Asia, it was identified that commercial buildings in particular had a higher embodied energy in constructions with more efficient design (Ramesh et al., 2010; Sartori & Hestnes, 2007; Ürge-Vorsatz et al., 2012). It may therefore be questioned whether it is actually possible to make general statements about how to improve the energy and environmental profile of buildings through focusing on net energy consumption alone.

[1] National Australian Built Environment Rating System for New Zealand (NABERS NZ)

Life Cycle Assessment (LCA) is an analytical tool where the material and energy flows of a system are quantified and inventoried along the life cycle of the system under analysis. Subsequently, the environmental impacts (e.g. global warming, ozone depletion, eutrophication, and acidification) associated with the material and energy flows are calculated. The building sector uses large quantities of different materials for construction, operation and demolition, and the range of environmental impacts that can be attributed to buildings is enormous. Similar to energy profiles, evaluating emissions associated with the life cycle of existing and future buildings prove to be useful to inform decision-making (Junnila et al., 2006).

In general, the LCA results of conventional buildings show that emissions related to operational energy overshadow the impacts from the rest of the life cycle (Berggren et al., 2013; Dahlstrøm et al., 2012; Ghose, 2012). However, existing studies on the LCA of low energy buildings show that the reduction in the environmental impacts associated with operational energy consumption could be outweighed by the additional embodied energy associated with the adoption of multiple energy efficiency measures(Cabeza et al., 2014). In an evaluation of a low energy building Blengini and Di Carlo (2010a) identified the substantial contribution of materials-related impacts. The study emphasized the important role of the waste recovery and recycling potential to reduce the overall environmental impact of the building. Building components installed as energy efficiency measures such as LED lamps or multiple glazed windows, have resource and energy-related environmental impacts during production, as reported in LCA studies by Tähkämö et al. (2013) and Salazar and Sowlati (2008a), respectively. Furthermore, if in future the deployment of renewable electricity supply increases, the impacts associated with a building's operational energy will further reduce. For example, on-site energy production units such as photo-voltaic panels on buildings supply electricity that can substitute fossil fuel-intensive electricity supplied from the national grid (Gerbinet et al., 2014) – but these benefits would be reduced if electricity generation from renewables was increased (International Resource Panel, 2017). Moreover, the environmental impacts of buildings or building components are dependent on several factors, including different building sizes, structure, construction material, building function, and geographic location (Babaizadeh et al., 2015; Cabeza et al., 2014).

1.4 Relevance of LCA to evaluate the environmental effects of energy efficiency refurbishment in New Zealand's commercial buildings

In New Zealand, extensive work has been carried out to evaluate the energy performance of commercial buildings (office and retail) (Amitrano et al., 2014b; BEES, 2013) as well as on potential refurbishment measures to improve the energy performance of existing commercial buildings (office and retail) (Cory et al., 2012). However, these studies have not focused on the life cycle environmental impacts associated with commercial buildings.

Use of LCA in New Zealand's building sector has been limited to analysing the energy and carbon emissions associated with building structure (Alcorn, 2003, 2010; Buchanan & Honey, 1994; Mithraratne & Vale, 2004). Moreover, most of the existing work has been restricted to individual case studies of residential buildings (Alcorn, 2010; Mithraratne et al., 2004). The work on single case studies in existing research has some advantages and disadvantages. An advantage of analyzing the impacts of single buildings is the increased level of detail in the analysis and reduced uncertainty in calculations. However, a disadvantage of performing analyses on single case study buildings is that there is limited potential to inform policy making. As discussed in section 1.3, the overall environmental performance of buildings is dependent on several factors such as building design, size and location. Therefore it is difficult to draw general conclusions from the analysis of a single building. Another limiting factor in the application of LCA in New Zealand's building sector has been the lack in availability of country-specific data in existing international databases such as ecoinvent (2013). Although international databases are useful for providing generic model results (Nebel, 2009), adapting the inventory with country-specific data in LCA could improve the quality of the analysis as well as reduce the uncertainty in results (Mutel & Hellweg, 2009).

The Building Energy End-Use study provides extensive information on the diverse existing commercial building stock in New Zealand (Amitrano et al., 2014b). Using this information, Cory (2016) showed the adoption of multiple refurbishment measures for energy efficiency can substantially reduce the energy demand of existing commercial buildings in New Zealand. In addition to reduction of energy demand, energy efficiency refurbishment of existing commercial buildings could be prioritised as a policy for climate change mitigation with respect to New Zealand's 2050 target from the business sector (Bedford et al., 2016; NZ Ministry of Economic

Development, 2011). However, in New Zealand a large share of electricity generation is currently from renewable energy sources (MBIE, 2015), and so the CO_2 eq. emissions associated with electricity use are very low compared to the global average (IEA, 2010; MBIE, 2016a). Therefore based on the discussion in section 1.3, it is worth investigating the net benefits of reduction in operational energy related CO_2 eq. emissions compared with the emissions embodied in refurbishment activities.

LCA can provide information about the environmental impacts associated with alternative refurbishment measures. This information can be used to inform current and future strategies on resource and energy supply for building refurbishment activities. Given the extensive information developed by Cory (2016) and BEES (2013), LCA on commercial buildings could be expanded to multiple case studies taking account of the diversity in building size, location and other building characteristics. Performing a detailed analysis with New Zealand specific information adds to the development of inventories which can be used for other LCA studies in New Zealand.

1.5 Research aim and objectives

This section summarises the overarching research aim and research questions (section 1. 5.1), materials and methods (section 1.5.2), and structure of the thesis (section 1.5.3).

1.5.1 Research aim and questions

This research aims to provide a comprehensive environmental understanding about building refurbishment activities that contribute to substantial operational energy savings in New Zealand commercial buildings. In addition, this research aims to provide guidance on development of policies on resource and energy management; and climate change mitigation targets associated with existing buildings.

More specifically this research will address the following questions with respect to energy efficiency refurbishments.

1) What are the potential environmental tradeoffs associated with energy efficiency refurbishments that contribute to substantial operational energy savings in New Zealand's commercial buildings?
2) How do resource procurement and waste management strategies influence the environmental impacts?

3) How do potential changes in the future electricity mix influence the environmental impacts of refurbished buildings?
4) How do the building size, location and other building characteristics (such as building specific construction details) influence the environmental impacts of refurbished buildings?
5) What is the contribution of refurbished buildings with respect to New Zealand's 2050 climate change mitigation target?

1.5.2 Materials and Methods

To address the above mentioned research questions and objectives, this research involved conducting a life cycle assessment of commercial buildings in New Zealand.

More specifically this research involved conducting life cycle environmental evaluation of commercial office buildings. The BEES study identified that the diversity in a building's function influences the way energy is used. This adds to the complexity in identifying more general solutions for improvement. But, as explained in section 1.2, there is limited variability in commercial office building energy use as compared to other commercial retail buildings. This is helpful for drawing general conclusions from the research on buildings with similar construction and use. Moreover, the average EnPI (kWh/ m^2/ yr**)** in existing commercial office buildings is higher than other existing commercial buildings (see table 1.1). Therefore, prioritizing energy efficiency measures in office buildings is a suitable strategy for improving the overall energy performance of the commercial building stock.

The case studies analyzed in this research were based on the information on New Zealand's existing commercial buildings collected by BEES (2013) and the recommended refurbishment measures identified by Cory (2016). The BEES (2013) research collected the construction details and energy load of real office buildings in New Zealand. Using this information, Cory (2016) developed building prototypes on EnergyPlus. Cory simulated the annual energy consumption of the buildings based on the major climatic conditions found in New Zealand. In addition, Cory also estimated the energy consumption of the buildings if the buildings were refurbished with a set of energy efficiency measures. These measures were primarily focussed on reducing the thermal transmission of the existing building façade and adopting energy-efficient air-conditioning and lighting units.

The major criticism of developing prototypical models for energy simulation is associated with the assumptions used for building energy loads and their operation. In general, prototypical building models are developed based on "informed engineering judgements about typical values for building energy loads and their operation" (Cory et al., 2015). Energy consumption simulated from prototypes of high performance building designs is therefore criticised because it is asserted that such designs in reality perform as modelled in a very narrow band of scenarios based on the assumed parameters (Bordass et al., 2004). Cory et al. (2015) argued that the use of measured data on energy loads of real existing buildings reduces the uncertainties associated with "assumed" values. Measured data on energy usage patterns or equipment loads and New Zealand specific construction details from BEES allowed Cory (2016) to establish and test realistic energy efficiency strategies for existing office buildings.

Another advantage of using the data from the prototypical models developed by Cory (2016) was that it allowed the possibility of examining the environmental performance of multiple building designs based on their energy performance across New Zealand. Using the data provided by Cory (2016), the environmental performance of refurbishment could be calculated for over 100 office buildings in New Zealand. At the time of this research, empirical data on energy efficiency refurbishments and subsequent energy consumption of office buildings of a similar scale was unavailable. Therefore, given the reduced uncertainty and the limited information available, the data from the building energy models developed by Cory (2016) were deemed suitable for use in the current research.

To estimate the environmental performance of refurbishment using LCA requires extensive data on the value chain of products and services required for refurbishment. The ecoinvent database (version 3.2) was used as the main source for data on materials, products and processes assessed in this research. The ecoinvent database currently provides well documented, consistent and transparent life cycle inventories for thousands of products (ecoinvent, 2013). Each inventory includes data on final product(s) output and associated resource inputs and emissions. The use of ecoinvent data is relatively common in most LCA studies especially for products and processes in Europe (ecoinvent, 2013). Recent advances in the availability of data for several other major manufacturing and markets around the world has made this database internationally reliable for use as background data in LCA studies (ecoinvent, 2013). However, as this version of the ecoinvent database did not have New Zealand specific information, ecoinvent inventories of construction materials and products manufactured in New Zealand were modified with information from the Ministry of Environment, BRANZ and local industries. In addition, inventories were developed for construction materials used and discarded during refurbishment using the data provided in the EnergyPlus software. This included details on the building geometry, associated modifications with respect to the adoption of energy efficiency measures and the energy consumption of existing and refurbished office buildings. Details on the inventories used are given in Chapters 3 and 4. The main adaptations made to the ecoinvent data used in this research are provided in the Supporting Information (SI) (SI 1 - 3).

1.5.3 Structure of the thesis

The thesis comprises seven chapters. **Chapter 1** introduces the overall rationale, research aim, research questions and research objectives. **Chapter 2** presents a review of published the applications of LCA on office buildings and associated energy efficiency refurbishments. This chapter evaluates the LCA methodological issues and recommendations in the building sector. Chapters 3-6 were developed sequentially to address each of the five Research Questions (RQ) (see section 1.5.1) and objectives individually or in combination.

Chapter 3 presents the environmental profile of energy efficiency refurbishment based on a typical office building construction located in Auckland. This chapter addressed RQ 1 and 3. More specifically in this chapter the refurbishment measures that have the highest contribution to the environmental impact were identified. The environmental performance of refurbished and non-refurbished buildings was compared. And the influence of building's operating timespan on the total environmental impact of the building was calculated.

Chapter 4 presents the environmental profile of the same building with specific focus on resource and waste management (RQ 1 and 2). Material procurement and waste management strategies which can contribute to significant reduction in environmental impact were identified. The influence of energy supplied to manufacture refurbished components and waste recycling efficiencies was calculated.

Chapters 3 and 4 were also developed to provide additional detail on key construction materials and activities associated with refurbishment in New Zealand. The inventory and findings from Chapters 3 and 4 were expanded in Chapters 5 and 6 to evaluate the environmental impacts based on the diversity of the existing office buildings in New Zealand.

In **Chapter 5** the analysis was performed on multiple refurbished office buildings differing in size, location and other building characteristics (RQ 1 and 4). In this chapter, the influence of resource and energy supply management was assessed. Strategies that should be prioritised based on building size, location and other building characteristics were determined.

In **Chapter 6**, the analysis was further expanded to analyse the environmental profile of refurbishing the entire existing office building stock in New Zealand. This chapter addressed all research questions with respect to the whole office building stock with specific focus on RQ 5. The feasibility of reaching the 2050 climate target based on current and future scenarios of grid electricity supply was calculated.

Chapter 7 summarizes the key findings of this research with recommendations to support policies on reducing the environmental impact of commercial office buildings. This chapter concludes with recommendations for future research.

1.6 List of publications

Chapter 3 to 6 have been modified and submitted/accepted for publication in different peer-reviewed scientific journals. Parts of the research have also been presented at national and international conferences

The journal publications arising from this research are listed below:

- **Ghose, A.,** McLaren, J. S., Dowdell, D., and Phipps, R. 2017. Environmental assessment of deep energy refurbishment for energy efficiency- case study of an office building in New Zealand, Building and Environment, doi: 10.1016/j.buildenv.2017.03.012 (Chapter 3)
- **Ghose, A.,** Pizzol, M., and McLaren, J. S. 2017. Consequential LCA modelling of office building refurbishment in New Zealand: an evaluation of resource and waste management scenarios. Journal of Cleaner Production, doi: 10.1016/j.jclepro.2017.07.099 (Chapter 4)
- **Ghose, A.,** Pizzol, M., McLaren, J. S., Vignes, M., and Dowdell, D. Refurbishment of office buildings in New Zealand: identifying priorities for reducing environmental impacts. *Submitted to International Journal of Life Cycle Assessment* (Chapter 5)
- **Ghose, A.,** McLaren, J. S., and Dowdell, D. Comprehensive environmental impact assessment of New Zealand's office building stock. *Accepted with revision in Journal of Industrial Ecology* (Chapter 6)

The statement of contribution for each manuscript has been presented in the Appendix.

Parts of this research were presented in the conferences listed below:

- **Ghose, A.,** Pizzol, M., and McLaren, J. S. 2017. Implications of resource management for building refurbishments in New Zealand. Oral presentation at: LCM and Industrial Ecology Symposium, Auckland 2017
- **Ghose, A.,** McLaren, J. S., Dowdell, D., and Phipps, R. 2015. Opportunities to apply Life Cycle Management in current refurbishment trends of commercial buildings in New Zealand. Poster presented at: LCM 2015, Bordeaux, September, 2015
- **Ghose, A.,** McLaren, J. S., and Dowdell, D. 2014. Identification of refurbishment trends in New Zealand.Poster presented at: Building a better New Zealand conference- Auckland, September 2014

The contribution of the first author for each of the above listed publications and presentations involved conceptualization of research design, data collection, data analysis, interpretation of the results and writing majority of the manuscript.

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Chapter 2- Use of Life Cycle Assessment (LCA) in the building sector and review of LCA studies on office buildings

2.1 Introduction

The building sector is responsible for large quantities of material and energy resource consumption worldwide (UNEP, 2007b, 2014). Buildings contribute to significant environmental impacts throughout the life cycle as resources are consumed during construction, operation and demolition. Over the last two decades the building sector has recognized the need for addressing sustainability and has promoted measures for energy and resource efficiency and environmental protection (IPCC, 2007; UNEP, 2009).

International standards for sustainability in building construction have been developed that focus on use of life cycle assessment (LCA) for evaluation of environmental impacts. These can be divided into standards that focus on application of LCA at the building level (ISO 21931, (2010); EN 15978, (2011)) and at the construction product level (ISO 21930 (2007); EN 15804, (2013)). LCA is used to support environmental certifications for construction products or processes in Environmental Product Declarations (EPDs). Additionally, there is an increasing recognition of EPDs and building LCA in green building rating tools such as BREEAM (UK and International) (BREEAM, 2008), LEED (USA and international) (Al-Ghamdi & Bilec, 2015) and Green Star (Australia and New Zealand) (Green Star Tool, 2016). It is also used to develop other sustainability tools and databases specific to the building industry, such as, Athena database developed in Canada and U.S (Bowick et al., 2014); Ökobaudat developed in Germany (Ökobaudat, 2017); and INIES developed in France (INIES, 2017) .

The International standard for sustainability assessment in buildings strongly recommends the use of Life Cycle Assessment (LCA) (ISO 21931, 2010). International standards have also been developed to provide basic guidelines for LCA (EN 15804, 2013; EN 15978, 2011; ISO 21931, 2010). There is an increasing recognition of LCA in green building rating tools such as BREEAM (UK and International) (BREEAM, 2008), LEED (USA and international) (Al-Ghamdi et al.,

2015) and Green Star (Australia and New Zealand) (Green Star Tool, 2016). It is also used to develop other sustainability tools and databases specific to the building industry (Bowick et al., 2014; Dowdell et al., 2016).

The application of LCA to support decision-making in the building sector is widely practiced (Cabeza et al., 2014; Chastas et al., 2016). However, LCA studies are generally incomparable and cannot be used as benchmarks because they are influenced by the building location, building type/size, building specific materials and construction techniques, behavioural patterns of occupants, and choice of impacts assessed (Cabeza et al., 2014). This necessitates the understanding of different methods and assumptions in existing studies for proper interpretation and use of these results in future for decision making.

Office buildings are among the largest energy consumers per m^2 floor area in the existing building stock (Pérez-Lombard et al., 2008). A rising number of life cycle studies can be found on office buildings, most of which focus on the impacts from energy consumption associated with these buildings (Cabeza et al., 2014). However, whilst earlier comprehensive LCA studies on office buildings simply considered refurbishment as a stage in the building lifecycle involving periodic replacement of building components, more recently this stage has evolved into a process that addresses potential improvements in the performance of the building (Vilches et al., 2017). A refurbishment could include improvement of the aesthetic or economic value of the building, but most often the focus is on adopting strategies to increase the energy efficiency of the building (Chastas et al., 2016; Vilches et al., 2017).

In existing reviews on the use of LCA in the building sector, few studies are directed towards commercial buildings as compared to residential buildings (Bribián et al., 2009; Cabeza et al., 2014) and even fewer studies evaluate the refurbishment of office buildings (Cabeza et al., 2014; Vilches et al., 2017). Given the limited information on this topic, this chapter aims to review the use of LCA for evaluation of commercial office buildings with a particular focus on adoption of energy efficiency measures during refurbishment. The review is structured with an introduction to LCA based on international standards (section 2.2) and the definition of refurbishment based on these standards (section 2.3). This is followed by the methodology adopted for a selection of reviewed studies (section 2.4), a discussion on the influence of methodological approaches in the selected studies (section 2.5); key findings from LCA of whole office buildings (section 2.6); LCA of refurbishment in office building (section 2.7); and a general conclusion (section 2.8).

2.2 LCA standards for the building sector

LCA methodology is standardized in international standards ISO 14040/44 and there is additional extensive documentation in the International Reference Life Cycle Data system handbook (ILCD) (JRC- IEA, 2010b). More specific details on the application of LCA to buildings is given in ISO 21931 (2010) for buildings and their related external works; and in the European standard (EN 15978, 2011) . The application of LCA to building products and services is considered in the international standard ISO 21930, (2007) and the European standard EN 15804 (2013). These standards provide requirements, recommendations and guidelines for LCA of building products and buildings. According to the international standard for LCA, ISO 14044 (2006), requires consideration of four main phases:

1. Goal and scope of the study
2. Inventory analysis
3. Impact assessment
4. Interpretation of results

Sections 2.2.1 to 2.2.3 briefly address how the requirements of ISO 14040/44 are applied in the context of building LCA studies for each of these four phases.

2.2.1 Goal and Scope

The primary goal of building LCA is to provide quantified information about environmental impacts to building designers, architects, construction companies and their customers in order to support decision making for better performing buildings. In support of this aim, this phase requires the description of a functional unit and system boundaries. The **functional unit** is defined for building or building product by ISO 21930 as related to the building or part of a building and its performance.

With respect to the **system boundaries**, the building LCA standards provide a series of modules that represent the various stages of the building life cycle (see Figure 2.1). An LCA study can include data for all modules or specific modules based on the defined scope of the study. An LCA study could be limited to manufacture of building products and only include modules A1-A3 and, possibly, data from module C3 and C4. This type of LCA information is usually found in Environmental Product Declarations (EPD) of building products (EN 15804, 2013). An LCA study may even be restricted to analysis of a single module; for example, it could involve the analysis of the maintenance (Module B2) or refurbishment (Module B5) of a building.

According to the building standards all LCA studies are required to report the data for modules A1-A3, while the data for other modules are optional (Anderson, 2017). The standards recommend the use of scenarios to determine the potential impacts from modules beyond A3. For LCA studies, focussing on single modules such as maintenance (Module B2) or Refurbishment (Module B5), the required data for modules A1-A3 includes the production of specific materials required for maintenance or refurbishment.

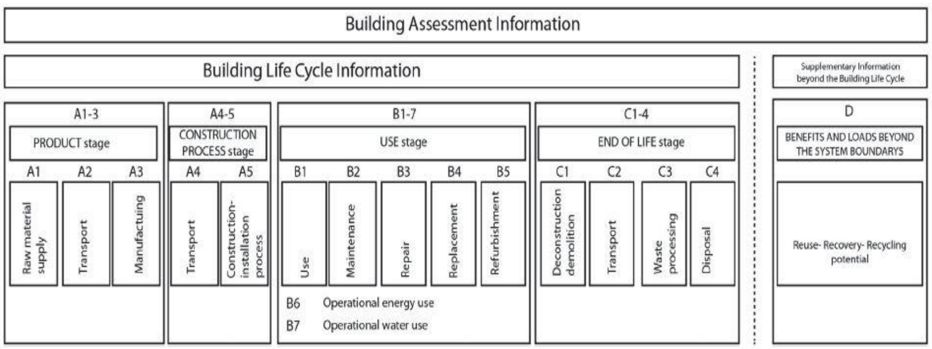

Figure 2.1 Life cycle stages of a building represented as modules (adapted from EN 15978 (2011))

The scope of LCA studies can be distinguished based on the quality of data used. A building LCA can be classified as screening, simplified or a complete study (EeBGuide Project, 2012) based on the quality of data used. A building LCA can be viewed as an iterative process, where the assessment at the early design level is closer to a screening LCA with use of more generic data, whilst the assessment at the planning stage uses more detailed data and/or assumptions to reflect the geographical and technological representativeness of the study (a simplified LCA). Finally, a complete LCA can be performed on a complete construction and functional building which uses temporally, geographically and technologically representative data.

2.2.2 Inventory analysis in building LCA

Inventory analysis mainly concerns data collection of material, energy and emission flows in and out of the defined system boundary. Development and validation of a building Life Cycle Inventory (LCI) can also be undertaken as a stand-alone study. These type of studies provide useful information for the building industry to further develop other LCA studies, databases and sustainability tools specific for the building industry (Bowick et al., 2014; Petek Gursel et al., 2014).The primary source of data for construction material inputs in building LCA is from construction drawings of the early design and planning stage, or bills of quantities developed by quantity surveyors of an on-going or completed construction. The data for energy during the operation of the building is available from energy simulation models (prior to construction) and post occupancy energy data (following occupancy). These quantified primary flows of materials and energy are connected to larger datasets; these may be process based LCI datasets (e.g. ecoinvent (2013c)) or national Economic Input Output tables which include secondary emission and energy data (Carnegie Mellon University Green Design Institute, 2008; Hendrickson et al., 1998).

There are two inventory modelling approaches in LCA described as Attributional and Consequential (Ekvall et al., 2016b). The two approaches differ in the choice of data used and the method to handle co-production to develop the inventory (Thomassen et al., 2008). The nature of the **attributional approach** is to model the system based on the current situation. This approach uses data from existing suppliers. If these data are unavailable, average data from all suppliers are used. In a multi-functional process i.e. when multiple products are produced, the resource flows and emissions associated with the process are allocated among all co-products based on the ratio of mass, economic value or other defined physical characteristic.

The **consequential approach** models the system based on a change in demand for the product under analysis. This approach identifies the influence of the change in demand on all suppliers. For example, for an increase in demand for a product or process certain resource suppliers could be constrained by legal, physical or market factors (Consequential-LCA, 2015; Weidema, 2003). In the consequential modelling approach, only the most competitive suppliers that are not constrained are considered to develop the inventory. Moreover, in this approach co-products are handled using substitution, also referred to as the avoided-burden method (Schrijvers et al., 2016). In this method, the studied system is expanded to include alternative production of the co-products. The potential environmental impacts from the alternative production routes is subtracted based on equivalent functionality (Thomassen et al., 2008). For building LCA, this method is applied to model Module D (Figure 2.1). The resources recovered from the building life cycle that can be recycled or re-used are modelled by subtracting potential impacts from primary production.

Although there is a debate on the more appropriate approach (Plevin et al., 2014; Suh & Yang, 2014), there is growing consensus that both modelling approaches can be used to address different research questions with respect to the analyzed system (Chobtang, 2016; Yang, 2016). As identified by Chobtang (2016), the attributional approach can be used to identify environmental hotspots to be prioritised for improvement. On the other hand consequential LCA can be used to produce environmental information resulting from implementation of improvement options, strategies or policies. This provides comparative information between the modified systems to the status quo.

2.2.3 Impact assessment and Interpretation of building LCA

Impact assessment concerns the classification and characterization of environmental emissions to their corresponding environmental impacts. The ISO 14044 standard does not recommend any specific impact method but requires a deliberate assessment of relevant impact categories for the study. Most impact assessment methods include a comprehensive set of impact categories (around 10-20) to include all potential impacts from a product or process. Some of the impact assessment methods commonly used are CML 2001, Impact 2002+ and ReCiPe. Some impact methods (e.g. Eco-indicator 99 and ReCiPe) also have an option of aggregating the impacts to fewer categories based on total damage to human health, ecosystem and resources (defined as 'endpoint' indicators) or a single score for easier interpretation for decision makers.

There are no impact assessment methods specifically used in the building sector globally. However, the EN 15978 (2011) standard requires calculation of the following potential impacts:

- Global warming potential (GWP) (kg CO_2 eq.)
- Ozone layer depletion (ODP) (kg CFC 11 eq.)
- Photochemical oxidant formation (PCOP) (kg C_2H_2 eq.)
- Acidification potential (AP) (kg SO_2 eq.)
- Eutrophication potential (EP) (kg O_2)
- Abiotic depletion- resources (AD_r) (kg Sb eq.)
- Abiotic depletion- fossil fuel (AD_{ff}) (MJ).

These impact categories are defined in common impact assessment methods such as CML 2001 or ReCiPe. Some other impact categories such as Cumulative Energy Demand (CED), water consumption, or impacts on human health, land use, eco-toxicity (land and water) are also reported but not mandatory. Impact categories relevant for buildings such as effects from indoor air and noise use can be reported but impact assessment methods for these categories are either unavailable or under development.

The **interpretation** phase involves identifying significant issues from the impact assessment and formulating recommendations for decision makers to reduce significant environmental impacts (ISO 14044, 2006). ISO 14044 recommends a contribution analysis to identify environmental hot spots and a number of checks such as uncertainty and sensitivity analysis to ensure the interpretation of results are adequately supported by the data and procedures used in the study (Goedkoop et al., 2016). In building LCA, it is recommended to use scenario or sensitivity analysis for all modules beyond A3 (Anderson, 2017; EN 15978, 2011). This highlights which life cycle stage(s) of the building can be improved to enhance the environmental performance.

2.3 Definition of building refurbishment in LCA

Building refurbishment is defined under module B5 in EN 15987. However, this module is often confused with modules B2 (maintenance), B3 (repair) and B4 (replacement). Each module from B2-B5 influence the service life of the building by maintaining or extending the 'reference service life' (see Figure 2.2). Service life of buildings is defined in the international standard for building and constructed assets as '*period of time after installation during which a building or an assembled system meets or exceeds the technical requirements and functional requirements ' (ISO 15686, 2000)*. The reference service life is defined as the expected service life of a building or its components situated in a well-defined set of conditions (Cole & Sattary, 2013). The European Commission and Innovation Research provides guidance on European standards EN 15978 and EN 15804, within the framework of the Energy-Efficient Building European Initiative (EeB) (EeBGuide Project, 2012). These guidelines are helpful to distinguish the different modules for building function.

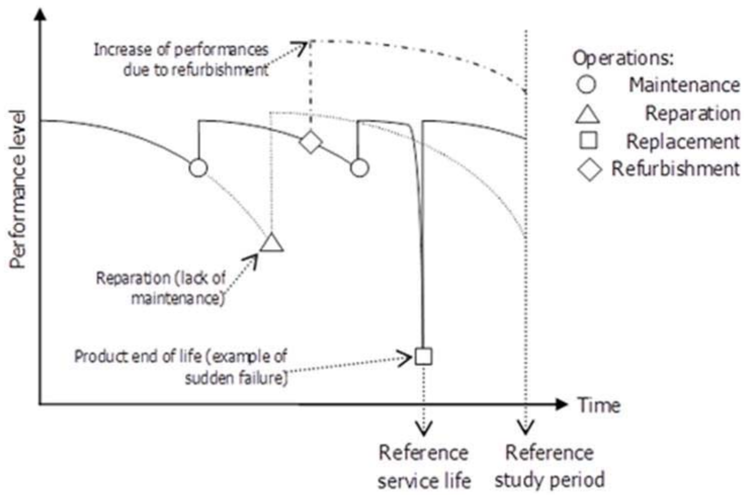

Figure 2.2 Building Performance with predicted modifications in a time frame. Source :EeBGuide Project (2012)

'Maintenance (Module B2)' is defined as '*the combination of all technical and associated administrative actions during the service life to retain a building or its parts in a state in which it can perform its required functions*' (EN 15987, section 7.4.4.3). Maintenance is to be considered as a periodic set of operations conducted under normal conditions of the reference service life. Maintenance scenarios should remain periodic and consistent. For example: scheduled replacement of light bulbs, periodic painting, etc.

'Repair (Module B3)' is defined as '*the return of a building or its parts to an acceptable condition by renewal, replacement or mending of worn, or damaged or degraded parts*'(EN 15987, section 7.4.4.4). Repair is an operation considered in case of unforeseen events, such as accidents outside the scope of normal events in the reference service life (flood, earthquake, fire, etc.). Lack of periodic maintenance could also lead to a requirement for repair.

'Replacement (Module B4)' is defined as '*the replacement of the whole construction element, including the production and installation of a new (and identical) construction element*' (EN 15987, section 7.4.4.5). Replacement occurs at the end of life of a product when it does not meet the initial performance. Replacement is related to the reference service life. Replacement due to sudden failure outside the reference service life is considered as repair.

'Refurbishment (Module 5)' is the '*modifications and improvements to an existing building or its parts to bring it up to an acceptable condition*' (EN 15987, section 7.4.4.6). It is considered in scenarios where there is a need for modification in the building performance or purpose of activity. For example: It can occur in response to new or modified regulations. Unlike maintenance and replacement, refurbishment is not planned within the reference service life.

According to the EN 15978 (2011) (p.24), the system boundaries to calculate the environmental impacts of building refurbishment are:

1) Production of components required for the building refurbishment;
2) Transportation of components (including the production of materials lost during transport);
3) Construction as part of the refurbishment process (including the production of materials lost during the refurbishment);
4) Waste management of the refurbishment process; and
5) End-of-life of the substituted building components.

In addition it is common to find other modules, particularly module B6 (operational energy use), included in the scope of LCA studies aimed at analysing the environmental impact of building refurbishment. This is because refurbishment is undertaken to improve the operation of the building. Given the uncertainty in determining the operation and use of buildings, it is strongly recommended to include multiple scenarios to include the influence of a building's service life, periodic maintenance and alternative sources of energy supply (Collinge et al., 2013; Scheuer et al., 2003).

2.4 Methodology

A wide number of peer reviewed articles can be found on LCA of buildings. With respect to the primary objectives of this chapter, a literature search was undertaken using the search terms: 'Life cycle assessment' or 'LCA' with 'commercial' or 'office', 'buildings', 'refurbishment', 'retrofitting' and 'energy efficiency' published from 1994 - 2016. Two key criteria were used to select the studies for the review. The first criterion was studies that focused on a comprehensive LCA of whole office buildings i.e. cradle to grave analysis of office buildings, and the second criterion was studies that evaluate the impact of refurbishment strategies for offsetting energy consumption in existing office buildings. Based on these criteria, 21 LCA studies were identified on whole office buildings, and 10 LCA studies on refurbishment. The selected studies are listed chronologically in Table 2.1 (LCA studies on whole office buildings) and Table 2.2 (LCA studies on refurbishment of existing office buildings) together with information on the case studies with respect to number of buildings, functional unit, system boundaries, data sources, chosen methodologies for inventory modelling, reported environmental impact categories.

Table 2. 1 Whole building Life cycle assessment studies on office buildings

Author (year)	Location	Number of buildings	Functional Unit	System Boundaries (according to EN 15978 modules)					Data source	Reported Environmental impact categories								
				A1-A3	A4-A5	B1-B7	C1-C4	D		GWP	ODP	PCOP	AP	EP	AD_e	AD_{ff}	CED	Other
Buchanan & Honey (1994)	Christchurch, NZ	1	m^2 GFA	✓	✓	-	-	-	literature	•	-	-	-	-	-	-	•	-
Cole & Kernan (1996)	Canada	1	m^2 GFA	✓	✓	B2,B6	✓	-	local industry + literature	-	-	-	-	-	-	-	•	-
Suzuki & Oka (1998)	Japan	10	1000 yen	✓	A5	B4,B6	-		EIO	•	-	-	-	-	-	-	•	-
Treloar (2001)	Sydney, Australia	5	m^2 GFA	✓	-	-	-	-	local industry + EIO	-	-	-	-	-	-	-	•	-
Yohanis & Norton (2002)	UK	1	m^2 GFA	✓	-	B4,B6	-	-	literature	-	-	-	-	-	-	-	•	-
Junnila & Horvath (2003)	Finland	1	m^2 GFA /yr.	✓	✓	B2,B6, B7	✓	-	local industry	•	-	•	•	•	-	-	-	•
Scheuer et al. (2003)	USA	1	m^2 GFA	✓	✓	B2,B4,B6,B7	✓	-	local industry + Athena	•	•	-	•	•	-	-	•	•
Junnila et al. (2006)	Finland & USA	2	m^2 GFA /yr.	✓	✓	B2,B6	✓	-	local industry + EIO	•	-	-	•	-	-	-	•	•
Chau et al. (2007)	Hong Kong	18	m^2 GFA	✓	✓	B2,B4	-	-	local industry +commercial databases (IVAM,US LCI, ecoinvent)	-	-	-	-	-	-	-	-	•
Kofoworola & Gheewala (2008)	Bangkok, Thailand	1	whole building	✓	✓	B2,B6	✓	-	local industry + EIO	•	-	•	•	-	-	-	-	-
Xing et al. (2008)	China	2	m^2 GFA	✓	-	B6	C3,C4	-	local industry	•	-	-	•	-	•	•	•	•
Dimoudi & Tompa (2008)	Greece	2	m^2 GFA	✓	-	B6	-	-	literature	•	-	-	•	-	-	-	•	-
Kneifel (2011)	USA	684	whole building	✓	-	B2,B4,B6	C1,C3,C4	-	local industry cost data + EIO+ US EPA	•	-	-	-	-	-	-	-	•
Wu et al. (2012)	China	1	m^2 GFA	✓	✓	B6	✓	-	local industry + literature	•	-	-	-	-	-	-	•	-
Robertson et al. (2012)	Canada	1	whole building	✓	A4	B4	-	-	US LCI+ literature	•	•	•	•	•	-	•	-	•
Kua & Wong (2012)	Singapore	1	whole building	✓	✓	B2,B4,B6	✓	-	local industry + EIO	•	-	-	•	-	-	-	•	•
Taborianski & Prado (2012)	Sao Paulo, Brazil	1	494 m^2 façade area with a 60 year service life	✓	✓	B2,B6	✓	-	National statistics + ecoinvent	•	-	-	-	-	-	-	•	-
Asdrubali et al. (2013)	Italy	1	m^2/year, m^3 of heated volume	✓	✓	B6	✓	-	ecoinvent	•	•	•	•	•	•	•	-	•
Collinge et al. (2013)	Pittsburg, USA	1	m^2 GFA	✓	-	B1,B5,B6,B7	✓	-	ecoinvent+ US LCI	•	•	•	•	-	-	•	-	•
Wang et al. (2016)	China & Australia	2	whole building	✓	✓	B6	C1,C3,C4	-	local industry+ literature	•	-	-	•	-	-	-	•	•
Berg, Dowdell & Curtis (2016)	Auckland, Wellington and Christchurch, NZ	30	m^2 GFA. year, m^2 NLA. year (60 year building life)	✓	✓	B2, B4, B6, B7	✓	✓	Building consent documents,, EnergyPlus, EPDs, ecoinvent 3.1	•	•	•	•	•	•	•	-	-

Here, GFA- Gross Floor Area; NLA- Net Lettable Area; EIO- economic input output tables; ecoinvent – Commercial international LCI database; US LCI- US based Lifecycle Inventory; EPA- Environmental Protection Authority; IVAM - Dutch LCA database; Athena- Canadian LCA database on building materials and products

Table 2.2 Life cycle assessment studies on refurbishment in office buildings. The system boundary in each of the listed study is based on module B5 (see section 2.3).

Author (year)	Location	Number of buildings	Functional unit	Refurbished components	Recycling benefits (Module D)	Data source	Reported Environmental impact categories								
							GWP	ODP	PCOP	AP	EP	AD_e	AD_{ff}	CED	Other
Rønning et al. (2008)	Norway	1	whole building	All building components except building structure	-	National statistics + EPD (Norway)	•	-	-	-	-	-	-	-	-
Techato et al. (2009)	Thailand	1	technical function of the equipment	HVAC & lighting systems	-	National statistics + local industry + GaBi	-	-	-	-	-	-	-	-	•
Ardente et al. (2011)	Brno, Gol, Plymouth, Provehalen, Stuttgart, Vilinus (Western Europe)	6	whole building/ year	Insulation, Low-e windows, HVAC, lighting, PV/ solar collector	-	National statistics + ecoinvent	•	•	•	•	•	-	-	•	-
Wallhagen et al. (2011)	Sweden	1	m^2 GFA	Insulation, Low-e windows, reduced window size, heat pumps, lighting, PV, automatized circuits	-	National statistics + local industry +ecoinvent	•	-	-	-	-	-	-	-	-
Huang et al. (2012)	Hong Kong	1	total construction (m^2) of solar shades	Solar shading	-	local industry + literature	•	-	-	-	-	-	-	•	-
Wadel et al. (2013)	Iberian peninsula	1	1m² of facade, with a useful life of 50 years	Different options of energy efficient building facade designs	-	literature+ international databases (ecoinvent, IVAM)	•	-	-	-	-	-	-	•	-
Principi & Fioretti (2014)	Italy	1	1 lm for 50,000 hrs; 1 lux for 50,000 hrs	Different office room lighting systems	-	local industry + ecoinvent	•	•	•	•	•	-	-	•	•
Pomponi et al. (2015)	London, England	1	3.6 m x 1.6 m x 0.4 m facade dimensions	Different options of double skin facades	✓	ecoinvent	•	-	-	-	-	-	-	•	-
Perino et al. (2015)	Czech Republic	1	3.3 m x 1.5 m curtain wall area	Building envelope of existing office buildings	-	EPD (Germany) + ecoinvent	•	•	•	•	•	-	•	-	-
Biswas et al. (2016)	Houston & Chicago, USA	2	kg/m² for required thermal resistance	Different insulation types	-	ecoinvent, US LCI	•	-	-	-	-	-	-	•	-

Here, GFA- Gross Floor Area; ecoinvent- Commercial international LCI database; EPD- Environmental Product Declaration; GaBi- Commercial international LCI database from ThinkStep; IDEMAT2001-LCA database from Delft University of Technology; BULWAL 250-LCA database European product packaging

2.5 Discussion on methodological approaches

There were some key differences in the methodological choices among the reported studies. This section will discuss the influence of methodological choices with respect to the scope of the selected studies (section 2.5.1), the inventory modelling (section 2.5.2) the impacts assessed (section 2.5.3) and choices with respect to number and location of case studies.

2.5.1 Scope

The scope of the selected studies (section 2.4) can be broadly divided into environmental assessment of whole office buildings and refurbishment of office buildings. The **functional unit** reported in the studies which evaluated the impact of the whole building or the influence of several refurbishment measures on one building was generally the total area of the building (whole building) or m^2 Gross Floor Area (GFA). Berg et al. (2016) also calculated impacts based on Net Lettable Area (NLA) along with GFA. Some of the studies also included an additional time component in the functional unit based on the service life of the building (Junnila et al., 2006; Taborianski & Prado, 2012). The service life considered in the reported studies differed from 10-100 years. In studies which focused on the influence of specific components the functional unit was defined based on the technological functionality of the product. For example, Principi and Fioretti (2009) evaluated the refurbishment of technical equipment for office lighting; the functional unit was defined as 1 lumen[2] for 50,000 hrs and 1 lux[3] for 50,000 hrs.

The **system boundaries** defined for the majority of studies on whole office building considered the cradle to grave approach which included the extraction of raw material, manufacture of products, construction, use and end of life treatment with some exceptions. All studies were consistent in reporting the impacts from raw material and manufacture of construction products. The impact from transport of materials to site and construction at site were not reported by six studies (Collinge et al., 2013; Dimoudi & Tompa, 2008; Kneifel, 2011; Treloar et al., 2001; Xing et al., 2008; Yohanis & Norton, 2002) while Suzuki and Oka (1998) only considered impacts from construction at site and Robertson et al. reported impacts only for transport of materials to site. With respect to the use stage, all except two studies considered the impacts from operational energy use. The scope of the study for Buchanan et al. (1994) and Treloar et al. (2001) was restricted to accounting for the

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[2] SI unit for luminous flux
[3] SI unit for measuring luminous flux per unit area

initial embodied impacts associated with construction. The recurring embodied impact in a building's lifetime was considered as periodic maintenance or replacement of components after the completion of its service life. Refurbishment was modelled only by Collinge et al. (2013). Impacts from operational water consumption was also calculated by Junnila (2003), Junnila et al. (2006) and Collinge et al. (2013). The end-of-life stage was modelled in all studies which considered a cradle to grave approach, although the impacts from building demolition, and transport to sorting plant was not considered in some studies. Interestingly, the benefits of material recovery after end-of-life treatment were not reported in any of the studies on whole office buildings. For LCA studies on refurbishment the system boundaries were as recommended in module B5 of the building standard EN 15 987 i.e. impacts of demolition of existing components removed from the building; and new materials/ products added to the building was considered. Benefits from recovery of materials was considered by Pomponi et al (2015) and Berg et al. (2016).

One of the main reasons for omission of certain building life stages is due to the lack in data quality or of data availability. The sources of data for the reported studies were mainly from material quantities estimated from building drawings or bills of materials (Kofoworola & Gheewala, 2008; Scheuer et al., 2003). Data on operational use was based on annual electricity bills or energy simulation software such as E-Quest or TRNSYS (Huang et al., 2012; Kneifel, 2011). Additional assumptions were made to calculate transportation distances and typical waste treatment methods in a region (Junnila, 2003; Wadel et al., 2013). Based on data quality, the reported studies could either be classified as screening or simplified LCA. Scheuer et al. (2003) and Wu et al. (2012) commented that complete LCA for a building was difficult due to data limitations and uncertainty in predicting future changes in the building's life cycle. Buildings consume a wide range of resources and also incur changes in performance and function throughout the lifetime. Moreover, there is a large range of construction techniques and material choices which makes it difficult to model the entire life cycle accurately.

2.5.2 Inventory Analysis

Although none of the studies explicitly mentioned the modelling approach for inventory analysis, it could be easily interpreted that all reported studies used the attributional approach. This is because most of the studies quantified the data based on status quo i.e. the current situation. Moreover, the avoided environmental burdens from waste recycling were not reported because the input material was considered to have recycled content. In general, attributional inventory analysis considers input of recycled material without environmental burdens or environmental burdens of production are allocated based on mass or economic value. One of the limitations on the use of consequential modelling approach in building LCA is due to the fact that identifying marginal technologies and suppliers for all building construction materials can be challenging (Vieira & Horvath, 2008). In addition, at the time of these studies none of the available databases used for background information on industrial processes and emissions had a version using a consequential modelling approach (ecoinvent, 2013c). And use of an attributional background datasets in a consequential inventory would make the analysis inconsistent.

With respect to data sources used to model inventories, it is interesting to note that the initial LCA studies on office buildings were dependent on local industry data and literature. To ensure the completeness and quality of the analysis, later studies used Economic Input Output (EIO) tables published for the respective countries as the background database to estimate the energy requirements (Suzuki & Oka, 1998; Treloar et al., 2001). EIO tables are standardized, publicly available data source representing the interdependencies between different industries in an economy (Carnegie Mellon University Green Design Institute, 2008). These tables report monetary transactions based on the products or services consumed by an industry to provide a product or service. Using the cost of materials and labour estimated for building construction, it is possible to estimate the total amount of product or service consumed and the relative impacts associated with it (Suzuki et al., 1998). It is also possible to improve the quality or accuracy of data in EIO if local industry data is available for certain products. Such an analysis is called hybrid LCA (Lenzen & Treloar, 2002; Treloar et al., 2001). The hybrid LCA method has been adopted by several studies when the availability of product/process/country specific data was limited (Junnila et al., 2006; Kneifel, 2011; Kofoworola et al., 2008; Kua & Wong, 2012). Although this method is widely recognized as a more complete approach the aggregation of heterogeneous industrial processes may introduce certain errors (Yang et al., 2017). With the development of more transparent and consistent process-based inventory database in recent years (ecoinvent, 2013c), the use of process based LCA has increased in building sector LCA.

2.5.3 Impact Assessment

The impact assessment methods adopted in most of the studies mainly focus on carbon dioxide (kg CO_2) or greenhouse gas emissions (kg CO_2 eq.) and the Cumulative Energy Demand (CED). In comparison, fewer studies provide an assessment of other potential environmental impacts such as ozone depletion, acidification, eutrophication, photochemical oxidation and abiotic depletion of resources and fossil fuels. Twelve out of twenty reported studies have performed a more comprehensive environmental assessment on whole office buildings. Some of the other impact categories reported were particulate matter formation, eco-toxicity of land and water; and carcinogenic and non-carcinogenic effects on human health. Kneifel (2011) and Huang et al. (2012) also reported the economic costs associated with construction and energy demand. Only three out of ten reported studies on energy efficiency refurbishment reported impacts on additional environmental impact categories. Techato et al. (2009) quantified the hazardous waste produced during energy efficiency refurbishment.

2.5.4 Number and Location

The energy demand and environmental performance of a building is largely influenced by specific building properties such as building use, design, energy regulations, sources of energy supply, predicted service life and location (Cabeza et al., 2014). Therefore it is difficult to generalize the LCA results for a single building. However, the primary use of LCA in buildings is to predict the environmental performance of a specific building design or construction process. Studies that present comparisons based on more than one case study provide the opportunity to understand the implications of a building design or performance based on multiple parameters. For example, Berg et al. (2016) calculated the environmental performance of 10 office buildings operating for 60 years in each of the three major cities (Auckland, Wellington and Christchurch) in New Zealand. The study concluded that as the environmental impact of buildings was dominated by operational energy use. Buildings in Wellington and Christchurch had greater energy demand for heating and cooling; and therefore had higher impacts compared to the buildings in Auckland by 16% and 19%, respectively. Kneifel (2011) had simulated the environmental performance of 3 office building prototypes in 228 locations in the US. The study showed that the energy and environmental performance of low energy building design was more preferable in the southern states along the coastline as compared to the northern states around the Great lakes. This was because the low energy design includes optimum solar shading and daylighting, which are most beneficial for energy reduction in warmer climate zones. However, the majority of the LCA studies on office buildings and energy efficiency refurbishment analysed one to two case studies.

The reported LCA studies were conducted on office buildings located in several regions such as, North America (Cole & Kernan, 1996; Collinge et al., 2013; Junnila et al., 2006; Kneifel, 2011; Robertson et al., 2012; Scheuer et al., 2003); China (Chau et al., 2007; Wang et al., 2016; Wu et al., 2012; Xing et al., 2008); Europe (Asdrubali et al., 2013; Dimoudi et al., 2008; Junnila, 2003; Junnila et al., 2006; Yohanis et al., 2002); Australia and New Zealand (Berg et al., 2016; Buchanan et al., 1994; Treloar et al., 2001; Wang et al., 2016); South East Asia (Kofoworola et al., 2008; Kua et al., 2012); and Brazil (Taborianski et al., 2012).

In comparison the LCA studies on energy efficiency refurbishment were mainly conducted in Europe (Ardente et al., 2011; Perino et al., 2015; Pomponi et al., 2015; Principi & Fioretti, 2014; Rønning et al., 2008; Wadel et al., 2013; Wallhagen et al., 2011); followed by single studies in Thailand (Techato et al., 2009), Hong Kong (Huang et al., 2012) and USA (Biswas et al., 2016).

2.6 LCA of whole office buildings

A primary focus of initial studies on office buildings was to evaluate the influence of different materials used for building construction (Buchanan et al., 1994; Cole et al., 1996; Suzuki et al., 1998; Treloar et al., 2001; Yohanis et al., 2002). Buchanan et al. (1994) investigated the energy requirements and CO_2 emissions for three alternative designs for an office building construction in New Zealand using concrete, steel or timber. The study reported that use of timber products for building structure can reduce 56% of the energy required and 69% associated CO_2 emissions from a similar concrete structure; or 66% of energy required and 56% associated CO_2 emissions from a similar steel structure. This study limited its focus on initial building construction and did not consider energy-related emissions from the building's use stage. Similar studies were conducted by Cole et al. (1996), Suzuki et al. (1998) and Yohanis et al. (2002) for office buildings in Canada, Japan and U.K., respectively. These studies quantified the initial embodied energy and operational energy requirements. Each study unanimously concluded that, although the operating energy represents the largest component of energy use based on current energy standards, the recurring embodied energy can easily outweigh the impacts from building operating energy. This recurring embodied energy is associated with building maintenance, repair and refurbishment for anticipated future energy efficiency standards for buildings. Suzuki et al. (1998) showed that the structural components had the highest contribution to initial embodied energy and CO_2 emissions. However, for buildings operating for 40 years, the façades and systems installed for air-conditioning, water supply and sewage had the maximum contribution to the recurring embodied impacts associated with maintenance and replacement. Similar to Buchanan et al. (1994), Cole et al. (1996) also concluded that the initial embodied energy requirement of timber structures was low compared to concrete or steel. However, the difference in energy requirements of timber structure was only 22% and 5% compared to steel and concrete structures, respectively. Yohanis et al. (2002) calculated the embodied energy could be as much as 67% of its life cycle energy use over a 25-year period. However the study also pointed out the difficulty in predicting the embodied energy and associated emissions due to the wide variation and the lack of reliability in the available data found in literature at the time of these studies. This issue was resolved in latter studies by using country specific EIO tables, local industry data and use of commercially available databases.

Evaluating the influence of size, Treloar et al. (2001) showed that construction of high-rise buildings (>30 floors) in Sydney, Australia, resulted in approximately 60% more embodied energy compared to low-rise buildings per m^2 GFA. This higher embodied energy was mainly associated with use of structural components such as load bearing walls, slabs, columns, external façades and staircases. Moreover, the influence of sub-structural components such as roof, windows or finishes was minimal. Similar findings were reported by Dimoudi et al. (2008) based on office building construction in Greece. All the above mentioned studies primarily focussed on the energy requirements and CO_2 emissions.

The first comprehensive environmental analysis of an office building in Finland was performed by Junnila (2003). This study calculated the life cycle potential environmental impacts of the office building in terms of climate change, acidification, eutrophication, dispersion of particulate matter and heavy metals. This study identified that over a 50 year period the building's contribution to all impact categories are associated with building use — in particular, electricity used in lighting, HVAC systems, and heat conduction through the structures; water use and wastewater generation; office waste management. In addition, energy used to manufacture building materials—in particular manufacturing and maintenance of steel products; concrete and paint also contributed to the impact categories. A follow up study was performed to compare the life cycle impacts of a similar office building construction in the United States (Junnila et al., 2006). In comparison to the building in Finland, the cumulative energy demand of the office building in USA was 34% higher and associated emissions such as CO_2, SO_2, NO_x, and particulate matter were

49%, 84% 61% and 21% higher, respectively. This difference was mainly due to differences in the sources of supply to grid electricity. At the time of the study, Finland had around 45% of its grid electricity from nuclear and hydropower while US (Minnesota- building location) had an 80% share of grid electricity from fossil fuels.

Since the work of Junnila (2003), several other studies evaluated the environmental impacts of whole office buildings. Among these studies, some reported the impacts of the whole building to identify which phase in the building life cycle had a significant influence on the different environmental impacts from office buildings (Asdrubali et al., 2013; Berg et al., 2016; Collinge et al., 2013; Kneifel, 2011; Kofoworola et al., 2008; Scheuer et al., 2003; Wang et al., 2016; Wu et al., 2012); other studies focussed on the environmental impacts of building materials and components to identify alternatives to minimize environmental impacts (Chau et al., 2007; Kua et al., 2012; Robertson et al., 2012; Taborianski et al., 2012; Xing et al., 2008). Robertson et al.(2012) showed that designing buildings with laminated timber instead of concrete structures contributes to reductions in initial embodied impacts for ozone depletion (− 40%), human health effects (− 35%), eutrophication (− 32%), water use (− 30%), air pollutants (− 30%), eco-toxicity (− 21%), smog formation (− 21%), and acidification (− 14%), but marginally increases impacts to abiotic depletion of fossil fuels (+ 6%). However, the influence of operational energy on the life cycle greenhouse gas emissions (CO_2, SO_2, NO_x, and particulate matter) contributes approximately 45-50 % (Berg et al., 2016; Kofoworola et al., 2008; Wu et al., 2012) to 85 - 95% (Asdrubali et al., 2013; Scheuer et al., 2003). Therefore, the studies emphasized the need to adopt energy efficiency measures and use LCA to resolve environmental trade-offs (Scheuer et al., 2003; Wu et al., 2012). Except Collinge et al. (2013), none of the studies evaluated the impacts from refurbishment. The case study building examined by Collinge et al. (2013) had data on a recently undertaken major refurbishment. This refurbishment was not particularly aimed at energy efficiency. It included major upgrade of all mechanical systems; replacement of all the windows and floor coverings; roof replacement and numerous interior space renovations. The study showed that the emissions from refurbishment contributed to approximately 5-10 % of the total impacts to eco-toxicity and human toxicity (carcinogenic and non-carcinogenic).

Most of the reported studies recommended or evaluated options to improve the energy and environmental performance of office buildings which are discussed below. The three main opportunities to improve the environmental performance of the building was identified as energy conservation in building operation (section 2.6.1); improvements in material production and supply (section 2.6.2); and material recycling after demolition (section 2.6.3).

2.6.1 Energy conservation in operation

Kofoworola et al. (2008) and Wu et al. (2012) identified that the energy for heating, cooling and air-conditioning office buildings was high as the indoor room temperature was set too low (18-24°C) in summers and too high (28-30°C) in winters in hot tropical climates of Thailand and China, respectively. These studies recommended a standard indoor room set point temperature of 26°C to avoid increasing the energy load for air conditioning. Kofoworola et al. (2008) calculated that this no-cost energy conservation measure could reduce 10.2% global warming potential and 5.3% acidification potential each year. However to substantially reduce the energy consumption of a building it is recommended to adopt energy efficient building designs which comply with current or improved building standards.

In a research on different office building types across US, Kneifel (2011) showed that *"conventional energy efficiency technologies in an integrated design framework can decrease energy use by 15–20% on average in new commercial buildings, and over 35% for some building types and locations. These energy reductions also reduce a building's energy-related carbon footprint by 10–33%."* In general, energy reduction was lower in high-rise office buildings compared to low-rise buildings. High-rise office building designs in this study had large glazing areas (windows) on the façade. Due to this, the energy loss from the windows increases while eliminating the benefits obtained from increased wall insulation. LCA performed on a office building in Pergia, Italy by Asdrubali et al. (2013) showed similar results and pointed out that the conventional measures such as increase in thermal insulation produce less appreciable energy and environmental impact reduction in office buildings in comparison with residential buildings. Optimization of the window-to-wall ratio and the energy requirements for equipment and lighting use contribute to around 8 % reduction in environmental impacts. Use of photovoltaic system as a source of energy for building operation reduces around 12 % impact throughout the entire life cycle, even though it slightly increases the initial embodied impacts. Collinge et al. (2013) calculated the influence of future changes in fuel mix and the efficiency of the electricity mix on the lifecycle environmental impacts of the building. The emissions from changes in electric power generation contributes to reductions in acidification (− 17%), photochemical ozone (− 16%), human health respiratory effects (− 15%), eutrophication (− 14%), carcinogens (− 5%), abiotic depletion of fossil fuels (− 4%), non-carcinogens (− 3%), eco-toxicity (− 3%), and global warming potential (− 2%).

2.6.2 Environmental improvement in material production

As discussed, the reported LCA studies show that office buildings with a timber structure have lower embodied energy and potential climate change impact compared to buildings with concrete or steel structures. The potential impacts from timber are mainly associated with the adhesives used and paints or other chemicals used during periodic maintenance. It is, however, important to note that steel and concrete are the conventional materials used to develop office building structures-particularly for high-rise buildings (Suzuki et al., 1998; Wu et al., 2012). Xing et al. (2008) compared the environmental impacts of concrete and steel structures of office buildings in China respectively. The study showed the associated environmental emissions to manufacture and demolish steel structures was 25% and 50% lower than concrete, respectively. However, the average heat transfer coefficient of steel-framed building is higher than that of concrete-framed building due to the higher thermal conductivity of steel. Therefore the operational energy consumption of air conditioning in the use phase of steel-framed building is higher than for concrete building. This results in higher life-cycle energy consumption and environmental impacts of the steel-framed building. Therefore, energy efficiency improvements should be prioritised in steel-framed building designs to reduce its environmental impact.

For concrete frame buildings, Robertson et al. (2012) showed that substituting 20% of the cement with blast furnace slag or fly ash for the production of concrete shows an improvement of 1% – 2% with respect to the concrete-framed design for four impact categories: climate change, photochemical oxidant formation, eutrophication, and abiotic fossil fuel depletion.

With respect to non-structural components of a building, Chau et al. (2007) and Taborianski et al. (2012) showed the significant contribution of electrical fittings and façade materials, respectively. Chau et al. (2007) found that copper power cables and copper used in electric conductors can contribute 25% of the environmental impacts associated with human health, ecosystem quality and resource depletion. Despite the insignificant amount (by mass) of copper used per m^2 of construction, these materials have a substantial impact on the total environmental impact of a building. The authors further indicated that greater efforts should be made by building designers towards reducing the quantities of material used and/or improving product lifespan, maintenance needs, reuse, and recyclability of these materials or substituting these materials with alternatives which incur smaller environmental impacts. Taborianski et al. (2012) showed that façades on office buildings using structural glazing and glass emit the most greenhouse gases throughout their life cycle, followed by ceramic brick façades covered with compound aluminum panels, and brick façades with plaster coating. Office building façades made with concrete block and mortar emit less greenhouse gases. This is because this type of façade provides a better thermal barrier than structural glazing façade and materials used to produce this façade require less energy compared to ceramic bricks and compound aluminum panels.

Besides the use of alternative materials or building components, Wu et al. (2012) pointed out that to improve the environmental impacts from construction materials the government and businesses need to make policies to improve the manufacturing sector. This could be done by economic investment for adopting novel and efficient technology to implement cleaner production.

2.6.3 Material recycling

Several studies commented on the increasing importance of the end-of life treatment of construction materials as well as a building's use stage waste (Asdrubali et al., 2013; Kua et al., 2012; Scheuer et al., 2003; Wang et al., 2016; Wu et al., 2012; Xing et al., 2008). However, only one of the reported studies had quantified benefits of material recycling after the end of life of materials. A reason for this could be because the studies modelled the input materials with a certain proportion of recycled material. Use of recycled materials was modelled assuming no environmental burdens, therefore reporting the end-of-life benefits of recycling could be misleading due to double counting of environmental benefits (Scheuer et al., 2003; Xing et al., 2008). This issue has also been highlighted in the building standards EN 15 978 and EN 15 804; therefore care should be taken to report recycling or reuse benefits. It is recommended that the recycling or reuse benefits should be reported separately from the total life cycle impacts.

Berg et al. (2016) reported the recycling benefits contributed to only 1-2% reductions to the lifecycle impacts of office buildings operating for 60 years in New Zealand. Scheuer et al. (2003) commented that although most of the construction materials were recyclable or re-usable, the accuracy for modelling recycling benefits was highly dependent on local waste treatment facilities, recycling policies and markets. For example, Kua et al. (2012) showed that general waste produced in commercial buildings in Singapore is mainly directed towards waste incineration. This waste includes wastes inert wastes (plastics, wall boards, some metals) and sewage waste. Incineration of general wastes from commercial buildings can increase the life cycle greenhouse gas emissions of commercial buildings by 10-20 %. Asdrubali et al. (2013) noted that the embodied energy and emissions of certain building components such as glazing with metal cladding is very high, but they can be easily disassembled for recycling. Therefore it is useful to show the environmental benefits associated with recovery of these materials. This indicates the need to holistically address the issues of waste reduction, sorting, collection and recycling of wastes associated with buildings.

2.7 LCA of refurbishment for energy efficiency in office buildings

In comparison to LCA of whole office buildings, the number of LCA studies that evaluate energy efficiency refurbishment of office buildings is limited. Moreover, studies were conducted only from 2008 onwards. The reported studies can broadly be divided into two types: studies that investigate the environmental impacts of multiple refurbishment measures for energy efficiency (section 2.7.1), and studies that investigate the environmental impacts of individual building components refurbished for energy efficiency (section 2.7.2).

2.7.1 Environmental impacts of multiple refurbishment measures

Rønning et al. (2008) investigated whether refurbishment was better than demolition and rebuild of an existing office buildings in Norway. The project aimed to reduce the energy consumption of the existing building by 80%. Multiple energy efficiency measures such as alteration of façade elements and technical equipment were considered. The study showed that the life cycle greenhouse gas emissions of the refurbished building operating for 60 years would be 40% higher than demolition and rebuilding of a new office. This was mainly because the existing structure was considered to have low adaptability with the suggested efficiency measures. Therefore, the study concluded that rebuild was a more favourable strategy compared to refurbishment in the specific building with respect to greenhouse gas emissions. Ardente et al. (2011) pointed out that optimum refurbishment measures and associated energy benefits are different based on building use and location. The authors analysed the six public buildings with different uses- office buildings in Lithuania (Vilinus) and UK (Plymouth); community centres in Czech Republic

(Brno) and Denmark (Copenhagen); a nursing home in Germany (Stuttgart) and a church in Norway (Gol). Except the building in UK, buildings adopted multiple refurbishment measures optimized for the building use and location. These measures were insulation of roofs and façades (all locations), installation of low-e windows (all locations), efficient heating and ventilation units (Germany, Denmark and Czech Republic) and lighting (Norway and Germany) and installation of photovoltaic panels (Czech Republic, Norway, Denmark and Germany). The building complex in UK only installed local wind turbines to substitute the energy demand with a renewable source. For each building, the refurbishment measures contributed to approximately 50% of annual energy saving, except for UK. The annual energy saving benefits gained at the building site in UK with windmills was reported as merely 2%. Environmental benefits in other environmental categories such as global warming, ozone depletion, acidification and eutrophication were closely correlated with the energy savings. The study also calculated the carbon emission payback. It was shown that photovoltaics had the highest payback period of 4-6 years among other refurbishment measures except in Denmark, where refurbishment of the additional insulation and low-e windows had a payback period of 32 and 12 years respectively.

A similar study was conducted by Wallhagen et al. (2011) on an office building in Sweden. The authors showed that besides the refurbishment measures the source of electricity supply and the required / assumed service life of the building had the greatest influence on the environmental performance of the building. A refurbished building performs approximately 50% better than an existing building. If the refurbished building is supplied mainly with renewable electricity (around 90-100%) for building operation the life cycle impact of the building would be 82-88% lower than the same building supplied with electricity generated from fossil fuels. The authors also showed that the relative impact of the building materials on the life cycle impact increases as the impact of operational energy reduces. Moreover, the relative impact from building materials of a refurbished building can vary from 93% - 59% when the service life varies from 10-100 years.

2.7.2 Environmental impacts of single building component refurbishment

With respect to studies on the refurbishment of individual building components, most of the studies were directed towards the refurbishment of the building façade or façade elements (e.g. insulation, solar shading). In general the façade designs of existing commercial buildings consist of curtain walls. Curtain wall is a non-structural (non-load bearing) building component which can be connected to the structural components of the building using lightweight metallic components (e.g. aluminium) (Perino et al., 2015). Glass is usually preferred as the curtain wall on modern high-rise buildings. It is a great advantage as it allows natural light to reach deeper within the building in addition it adds to a building's aesthetic value (Perino et al., 2015; Pomponi et al., 2015). With respect to energy efficient curtain wall designs, architects are developing double skin façades that can incorporate a range of functions such as- solar shading, natural ventilation and thermal insulation (Harrison et al., 2003; Pomponi et al., 2015). The double skin façade consists of a pair of glass separated by an air cavity. The inner layer of glass and the air cavity act as insulating elements. Solar shading can be incorporated on the outer glass as a coating.

Pomponi et al. (2015) analysed 128 double skin facades configurations based on a combination of parameters for choice of glass coating, air cavity width, the place of manufacture and façade orientation. The study showed that double skin façades are 98% more energy efficient and contribute to an 85% reduction greenhouse gas emissions compared to conventional curtain walls. In particular, air cavity width had a strong influence on the environmental impact. Narrow air cavities (400 mm) contribute to lower impact compared to wide air cavity (1000 mm). This is because façades with wide cavities require a higher amount of construction materials thus increasing the embodied energy and carbon. Additionally, the cavity opens when the inside air reaches the threshold temperature. A larger amount of cold air enters from outside which increases the energy demand for air conditioning. In U.K (location of the case study) south oriented façades were more energy efficient; and façade elements manufactured in Europe had slightly lower impacts compared to materials manufactured in China. All elements used for curtain wall construction (mainly glass and metallic frame) have high embodied impacts. Pomponi et al. (2015) showed that recycling after disposal contributes to 14-20 % benefits relative to the total embodied impact. Wadel et al. (2013) and Perino et al. (2015) investigated the effectiveness of alternative designs which could reduce the environmental impact of similar glazing systems. In particular the improvement strategies suggested by Wadel et al. (2013) were to extend the service life of the glazing system from 25 to 50 years and design for easy disassembly. Both methods could reduce the embodied impacts of a glazing system by approximately 30%. Perino et al. (2015) analysed the increased use of bio-based (timber) materials on the curtain wall panels instead of metallic components (usually aluminium). This strategy could reduce impacts up to 90% for global warming, 60% for acidification and photochemical oxidation, 16% for eutrophication and 2% for ozone depletion.

Huang et al. (2012) analysed the CO_2 emissions associated with refurbishing an existing office buildings in Hong Kong with external solar shadings. External overhang solar shading devices could reduce 45% of the building's energy demand for cooling. Interestingly, this study highlighted that the emissions associated with installing the overhang solar shading surpassed its benefits. The annual CO_2 emission reduced from application of the shading system was 37.6 ton CO_2, while life cycle CO_2 emission of solar shading was 2400 ton CO_2. The payback period of the shading system was calculated as about 63.8 years. The authors commented that the benefits from exterior solar shading were diminished mainly because of the building location. Hong Kong is located within a humid subtropical climate zone, and encounters a number of, tropical storms or typhoons. Therefore, the design of external building structures needs additional material to make the structure strong enough to withstand extreme weather conditions. Biswas et al. (2016) analysed the life cycle impact of adding insulation on existing office buildings in Houston and Chicago. CO_2 emissions associated with four insulation materials was analysed - polyisocyanurate foam (with pentane), polyurethane, extruded polystyrene and aerogel. This study highlighted that although adding insulation material contributes to reduction in CO_2 emissions associated with energy efficiency of existing office buildings; addition of insulation to existing buildings is associated with substantial emissions. For a 25 year operation period, emissions from adding insulation to the roof and walls of existing buildings contributes to 19% and 42% of life cycle impacts in Chicago and Houston, respectively. With respect to the insulation materials extruded polystyrene had the lowest impact to global warming potential followed by polyisocyanurate. This was mainly because the blowing agents used for the manufacture of these materials had low global warming potential.

Two studies were identified that focussed on refurbishment of technical equipment in office buildings, only. Principi et al. (2014) performed a comparative analysis of compact fluorescent (CFL) and Light Emitting Diode (LED) luminaires used for general lighting for the office. The study shows that LED luminaires which are highly energy efficient compared to CFL luminaires reduce the potential climate change impact by 41 - 50%. Similar benefits were noted in other impact categories such as freshwater eco-toxicity and human toxicity (carcinogenic and non-carcinogenic). The study also assessed alternative waste treatment scenarios including recycling, incineration and landfilling but concluded none of these scenarios substantially influenced the results. On the other hand Techato et al. (2009), analysed the hazardous waste produced from refurbishing existing buildings with energy efficient air-conditioners and fluorescent lamps. The study mainly focussed on the waste treatment of the discarded fluorescent lamps and air conditioner parts which are recycled or incinerated. This equipment contains hazardous wastes such as mercury and halocarbons. The study reports that a small 36W fluorescent lamp contributes 0.11 g hazardous waste, 1.1 µg radioactive waste, 0.6 mg slag–ash, and 16 mg bulk waste. A 3.5 kWh air-conditioner contributes to 0.11 kg hazardous waste, 200 mg radioactive waste, 10 g slag–ash and 0.58 kg bulk waste. The authors comment that hazardous waste treatment requires special processing plants or special deposit for hazardous waste. Although the reported quantities are small for single items, the rise of such refurbishments will consequently increase the amount of hazardous wastes therefore due consideration is required to plan appropriate waste management strategies.

2.8 Conclusion

This review has discussed the use of LCA in the building sector to assess the environmental impacts of office buildings and energy efficiency refurbishments in office buildings. Existing LCA studies on this topic were identified from 1994 onwards, and the methodological choices and key findings of the selected studies were evaluated. Most existing studies have focussed on the environmental impacts of whole office buildings as compared to energy efficiency refurbishments in office buildings. In existing studies, the environmental performance of whole buildings is largely dependent of structural or load bearing elements. The impacts of refurbishment, on the other hand, were found to be dependent on non-structural elements (glazing elements, curtain wall, insulation, etc.) and the benefits associated with reductions in operational energy demand. It is interesting to note that, while energy efficient designs contributed to substantial environmental benefits for whole buildings or new building design, the benefits associated with energy efficiency refurbishment were variable. The environmental impacts of refurbishment were reported to be potentially higher depending on the increase in material requirements, and constraints in adapting existing buildings to the required energy efficient building designs. The reviewed studies also highlight the influence of building size, location and service life of the building as important parameters that influence the overall building performance.

The research gaps identified have been summarized below:

- While whole building LCA studies in recent years have provided a more comprehensive environmental assessment, most of the studies of refurbished buildings have focussed mainly on the assessment of greenhouse gas emissions and energy demand. Therefore, there is a need to perform more comprehensive environmental assessment of energy efficiency refurbishments.
- Most LCA studies on refurbishment have been conducted from 2008 onwards, and most of the case studies have been located in Europe. Moreover, no LCA studies on energy efficiency refurbishments were based on New Zealand specific case studies. Given that external factors such as climate and building location are important parameters that influence the LCA results there is a need to perform LCA on New Zealand specific studies to support national policies.
- From a methodological perspective, the use of consequential LCA modelling is missing in both whole office building and energy efficiency refurbishment based LCA studies.
- Most studies recommend the adoption of waste recycling to reduce embodied impacts of buildings. However, only two of the studies quantified the environmental benefits associated with waste material recovery. Therefore, to evaluate whether recycling and re-use of construction waste is useful, there is a need to quantify the benefits.

In conclusion, the findings from the studies reviewed in this chapter indicate that LCA is a useful tool to support decisions on building design, construction process and refurbishment measures. However, this review also points towards the limited work on the application of LCA on office building refurbishment and other gaps in knowledge with respect to this topic.

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Chapter 3 – Evaluating the influence of service life and electricity supply on the environmental performance of a refurbished office building – an attributional study

Abstract

The purpose of this study was to determine the environmental impacts associated with a deep energy efficiency refurbishment using life cycle assessment. A prototypical refurbished model of an office building located in Auckland, New Zealand was used as a case study. The refurbishment included major changes to the building envelope with additional insulation, modified wall-window ratio, solar shading as well as technical replacement of the lighting and HVAC system. The study included identification of environmental hot spots of a deep energy refurbishment, and consideration of the effect of different electricity mixes in New Zealand on the total environmental impact of the refurbished building when compared to the un-refurbished existing building over different operation periods. An environmental payback period was calculated for each impact category. The results of this study indicate that deep energy refurbishment is associated with significant environmental impacts mainly due to the use of energy-intensive construction materials. However, the refurbishment yields net reductions in most impact categories if the building has a longer operational period. The environmental impacts of a building's operation are mainly associated with New Zealand's electricity generated from coal. As future scenarios of New Zealand's electricity mix have a reduced share of electricity generated from coal, the environmental benefits of avoided electricity consumption are also reduced. The study concludes that measures to promote energy efficiency refurbishment in office buildings where a significant proportion of the operational energy is provided from renewable energy sources, should be carefully considered because they may not reduce overall environmental impacts.

3.1 Introduction

Energy use in the building sector contributed 33 % of total global energy use in 2010 (Ürge-Vorsatz et al., 2012); 60 % of this was associated with operational energy use, corresponding to nearly 9 Gt of CO_2 eq emissions (Lucon & Ürge-Vorsatz, 2014; UNEP, 2007a). Operational energy use in buildings is projected to double by 2050 with a concomitant increase in associated emissions (Urge-Vorsatz et al., 2013). Currently energy use in commercial buildings is estimated to be increasing at a 2.5 % higher rate than the rate of increase in residential buildings (UNEP, 2009). Unsurprisingly, refurbishment for energy efficiency during building operation has been identified as a key strategy to reduce environmental problems associated with energy use in buildings. Research conducted by International Energy Agency's Energy in Buildings and Communities Program (IEA EBC) Task 47 (IEA EBC, 2014) identified refurbishment measures that address the challenges related to energy use for heating, cooling, ventilation and lighting in commercial buildings. To initiate a fundamental shift towards more energy efficient commercial buildings, the IEA study recommended a combination of refurbishment measures including: the large scale transformation of the façade with modification of the Wall to Window Ratio (WWR); adding insulation and exterior shading systems; and upgrading or replacing the equipment for HVAC and lighting with improved, effective and efficient options such as heat pumps and LED lighting. Such a "*major building refurbishment project in which site energy use intensity, including plug loads, has been reduced by at least 50% from the pre-renovation baseline*" is described as a deep energy refurbishment (IEA EBC, 2015).

New Zealand's energy policy includes the goal to reduce its total greenhouse gas emissions in 2030 by 30 % compared with 2005 levels (Ministry for the Environment, 2016) and its energy related greenhouse gas emissions in 2050 by 50% compared with 1990 levels (Ministry of Economic Development, 2011). To achieve these targets, government policies promote adoption of energy efficiency measures, energy conservation, and use of energy from renewables (EECA, 2013). As reported in 2013, 15.9 % of New Zealand's greenhouse gas emissions were associated with electricity generation, and 10.7 % were associated with production, processing and transformation of fossil fuels such as natural gas and coal (Ministry of Business Innovation and Employment 2014). In New Zealand's buildings, electricity is the largest energy type used followed by natural gas. Commercial buildings use 16% of New Zealand's total electricity and 7% of total natural gas, and energy use in commercial office buildings is reportedly higher than in other types of commercial buildings (Amitrano et al., 2014b). Indeed, nearly 38 % of the energy-related emissions in New Zealand's cities are due to the heating and cooling needs of commercial buildings (NABERS NZ, 2016). A recent study showed that a deep energy refurbishment of a typical office building in New Zealand could reduce its operational energy consumption by 60 % (Cory, 2016). However, before broad scale implementation of such refurbishment activities, there is a need to evaluate the indirect effects as these activities are potentially energy and environmentally cost-intensive (Antti et al., 2012; Hernandez, 2013; Urge-Vorsatz et al., 2013).

Moreover, the environmental benefits of energy efficiency measures in buildings are also associated with the off-setting of direct emissions related to operational energy use. The share of electricity and heat generated from renewable energy sources in the New Zealand's electricity grid increased from 75 % in 2013 to 81 % in 2015, and the reduction in electricity generated from gas and coal fired plants resulted in a 19 % decrease in direct emissions from electricity generation (Ministry for the Environment, 2016; Ministry of Business Innovation and Employment 2014). New Zealand aims to generate 90 % of its electricity from renewable sources by 2025 (MBIE, 2012; Ministry for the Environment, 2016). With an increasing share of renewables in the national grid mix, the net environmental benefits of a deep energy refurbishment could be in doubt in New Zealand.

Life Cycle Assessment (LCA) is a standardized environmental assessment tool commonly used in the building sector to evaluate environmental impacts in both the early design stages and for completed building construction projects, including studies focused on implementing different energy efficiency measures. Over 120 LCA studies on energy efficiency measures in buildings have been reviewed in two recent papers by Cabeza et al. (2014) and Chastas et al. (2016). However, the majority of these studies evaluated residential buildings rather than commercial buildings. Out of those studies focused on commercial office buildings, some studies have developed optimized energy efficiency refurbishment solutions using energy modelling but are solely focussed on the environmental benefits or burdens of the building's operational energy performance (Ascione et al., 2013; Pisello et al., 2016; Rysanek & Choudhary, 2013). Other studies have evaluated the environmental impact of specific building components. For example, Taborianski et al. (2012), Wadel et al. (2013), Pomponi et al. (2015), and Perino et al. (2015) compared refurbishment of different façade elements of office buildings, while Techato et al. (2009) and Principi et al. (2014) analysed refurbishment with different Heating Ventilation and Air-Conditioning (HVAC) and lighting systems in office buildings.

However, there is still a lack of research on the environmental evaluation of office building refurbishments that include a comprehensive range of refurbishment measures for both façade and technical elements (as occurs in deep energy refurbishment).

Another issue in building LCA studies is the unequal distribution of case studies analysed globally. According to Cabeza et al. (2014), the highest numbers of comprehensive building LCA case studies are from Europe or North America as opposed to other regions of the world. Moreover, in most LCA case studies of commercial buildings analysed outside Europe and North America, the focus is only on embodied energy and energy-related emissions (mainly CO_2 emissions) (Buchanan et al., 1994; Huang et al., 2012; Kofoworola et al., 2008; Kofoworola & Gheewala, 2009; Suzuki et al., 1998; Treloar et al., 2001; Wang et al., 2016). Furthermore, LCA inventory databases usually include just European or global average data (such as ecoinvent); use of these datasets in LCA case studies in other regions of the world might lead to inaccurate estimation of results and therefore necessitates the need to develop location and context specific inventory data (Nebel, 2009; Sinha et al., 2016). Thus there is a need to develop a comprehensive and representative inventory for building case studies, and to evaluate environmental impacts associated with construction and buildings, in different regions of the world.

This study is a part of a whole building, whole-of-life framework project that is developing knowledge and resources to facilitate use of LCA in the New Zealand construction sector (Dowdell, 2013). Existing LCA case studies from the New Zealand construction sector have primarily assessed the embodied energy and carbon footprint of residential buildings and associated construction materials (Alcorn, 2010; Stephen et al., 2009). The primary aim of this study is to evaluate the different environmental impacts of a deep energy refurbishment for a typical office building in New Zealand using a prototypical model of a refurbished office building. More specifically, the objectives of this study are to a) identify the environmental hot-spots related to a deep energy refurbishment, b) identify the effects of the building's operating timespan and the associated electricity use on the cumulative impact of the refurbished building compared to the un-refurbished building, and c) calculate an environmental payback period for each impact category.

3.2 Methodology

3.2.1 Case study description

The building chosen for the case study is an eight-storey office building with a total floor area of 5841 m^2 located in Auckland, New Zealand. The prototype models of this reference building representing the existing and refurbished construction had previously been developed in a study on potential energy efficiency measures required to yield a 60 % reduction in energy consumption in comparison with the pre-refurbished building, using the EnergyPlus energy simulation modelling tool (Cory, 2016). Building characteristics of the existing building and the refurbished building prototype are listed in Table 3.1. The existing building is a reinforced concrete structure with an insulated wall having a thermal resistance value of R= 3.6 m^2 K/W and a non-insulated concrete roof. All existing windows are single glazed with no provision for solar shading. A centralized natural gas boiler and electric chiller power the space conditioning. Grid electricity is used for ventilation, lighting and plug loads.

The energy efficiency measures modelled for the refurbished building prototype were: provision of additional insulation to building envelope (wall and roof); optimization of the WWR; alteration of windows to an advanced glazing system and with a frame to enable natural ventilation; addition of solar shading to the North, East and West façades to avoid passive solar heat gain; change of the air conditioning system (heating and cooling) from a natural gas operated boiler and electric chiller to electric heat pumps; and replacement of existing compact fluorescent lamps with LED luminaires.

Table 3.1 - Building Characteristics - existing and refurbished building (Cory, 2016)

<table>
<tr><td rowspan="2"></td><td colspan="2">Existing Building</td><td colspan="2">Refurbished Building</td></tr>
<tr><td>Area (m^2)</td><td>R- value (m^2 K/W)</td><td>Area (m^2)</td><td>R- value (m^2 K/W)</td></tr>
<tr><td>Cladded Area (External Walls)</td><td>1021</td><td>3.6</td><td>1734*</td><td>5.8</td></tr>
<tr><td>Glazed Area (Windows)</td><td>2113</td><td>0.172</td><td>1400*</td><td>0.625</td></tr>
<tr><td>Roof</td><td>730</td><td>2.9</td><td>730</td><td>3.65</td></tr>
<tr><td>Window to Wall Ratio (WWR)</td><td colspan="2">0.67</td><td colspan="2">0.45</td></tr>
<tr><td>Annual Energy Consumption (kWh)</td><td colspan="2">394994</td><td colspan="2">157998</td></tr>
<tr><td>External wall type</td><td colspan="2">- 100 mm concrete wall.
- 124 mm internal polystyrene insulation supported with timber joists.
- 12 mm plasterboard covering 0.15 mm vapour barrier.</td><td colspan="2">- All external (non-bearing structural) wall components replaced.
- 100 mm pre-cast concrete wall with larger surface area installed.
- 200 mm insulation supported with timber joists installed.
- Plasterboard and vapour-barrier replaced.
- Paint applied on refurbished walls</td></tr>
<tr><td>Roof type</td><td colspan="2">- 100 mm concrete roof
- Without insulation</td><td colspan="2">- Cold roof construction on existing flat concrete roof [41]
- 124 mm insulation added supported with timber joists
- 1.5 mm external waterproof butyl membrane added.
- 12 mm particle board sheathing added.</td></tr>
<tr><td>Window type</td><td colspan="2">- clear single glazed with aluminium frame
- covers 67 per cent of façade area</td><td colspan="2">- Low-e double glazed argon filled with aluminium frame
- covers 45 per cent of façade area</td></tr>
<tr><td>Space Conditioning</td><td colspan="2">- Natural Gas Boiler-80% efficiency
- Electric Chiller- COP 2.5</td><td colspan="2">- Air-Water Heat pumps (30 kW each) - COP 4.0</td></tr>
<tr><td>Heat and Air distribution system</td><td colspan="2">- Radiators
- Air ventilation ducts</td><td colspan="2">- Under floor heat distribution system with 600 mm raised floor [42]
- Air ventilation ducts unchanged</td></tr>
<tr><td>Lighting</td><td colspan="2">- Compact fluorescent lamp
- Luminous efficacy- 60 lm/W
- Power- 3.81 W/m^2</td><td colspan="2">- LED A19 luminaires
- Luminous efficacy- 83 lm/W
- Power- 2.81 W/m^2</td></tr>
<tr><td>Solar Shading</td><td colspan="2">Absent</td><td colspan="2">Shading on- north, east & west façades</td></tr>
<tr><td>Internal walls</td><td colspan="4">Assumed to be unmodified in both building prototypes
Not included in this study</td></tr>
<tr><td>Office fit-outs</td><td colspan="4">Not specified in the building prototypes
Not included in this study</td></tr>
</table>

*wall area increases as window area is reduced (the total façade area remains the same)

3.2.2 Functional unit and system boundaries

The functional unit for this study was defined as "1 m^2 floor area of the refurbished building prototype which has achieved 60 % reduction in annual energy consumption compared to its previous annual energy consumption." This functional unit (i.e. m^2 floor area/year) is also recommended by CEN TC 350 (EeBGuide Project, 2012) which provides guidance for LCA of energy efficient buildings.

Guidelines from the building standard EN 15 978 (EN 15978, 2011) were used to define system boundaries for building refurbishment (see figure 3.1). To evaluate the life cycle impacts of refurbishment, the following processes were included in the system: raw material extraction and processing, product manufacture, product transport to the construction site and construction process, waste treatment of demolished material produced during refurbishment, and the building's operational energy use and periodic maintenance. The building components excluded from the study were existing structural components, internal walls and office fit-outs. Figure 3.1 shows the processes assessed in the system.

Twelve environmental impact categories were selected for the assessment. The CML impact assessment method was used to analyse Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photo-chemical Oxidation Potential (PCOP), Acidification Potential (AP), Eutrophication Potential (EP) and Abiotic Depletion (resources and fossil fuels (AD_r and AD_{ff})). These are the environmental impact categories recommended for use by EN 15978. Furthermore, the UseTox method was used for Human toxicity carcinogenic (HT-carc), Human toxicity non-carcinogenic (HT-non carc) and Eco-toxicity freshwater ($ET_{freshwater}$). The ILCD 2011+ and ReCiPe (H) method was used for Particulate Matter Formation (PMF) and Ionizing Radiation (IR) respectively. These categories and methods were recommended for use by the New Zealand whole building whole of life framework project (Dowdell, 2014).

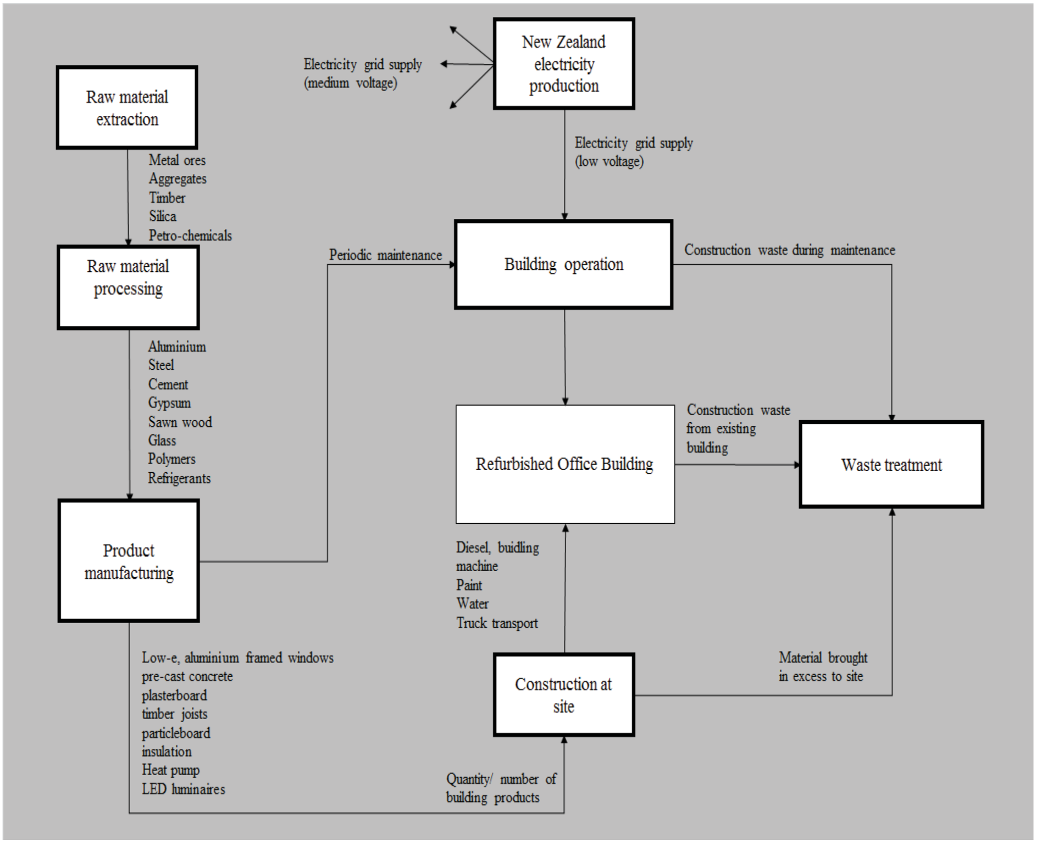

Figure 3.1 The activities and flows associated with materials and energy modelled in this study for building refurbishment and subsequent operational use.

3.2.3 Data acquisition for inventory analysis

The amounts of materials required for the refurbishment as well as generation of waste materials from the existing structure were estimated and measured using the CAD software SketchUp, which provides graphical representation of the EnergyPlus energy simulation models with building geometry and construction details (Lammers, 2011). Estimating material quantities based on energy models developed in CAD software is a recognised data collection method in building LCA when bills of quantities or the finalized detailed design of a building are unavailable (Malmqvist et al., 2011). Previous studies that have compared LCA results using data from early design models with LCA results using data collected from a detailed bill of quantities, have concluded that this simplified approach is sufficiently accurate to aid decision making for building energy refurbishment (Berg, 2014; Malmqvist et al., 2011; Oregi et al., 2015).

Since the information provided by the models used in the building design (as seen in table 3.1) was not detailed enough to compile a life cycle inventory of materials and construction processes, additional assumptions and estimations were made based on technical documentation, scientific literature, and information in the ecoinvent database (ecoinvent, 2013b). The identified gaps in information and subsequent assumptions are described in sections 3.2.3.1 to 3.2.3.6. Table 3.3 presents an overview of the inventory developed for this case study.

3.2.3.1 Building façade elements

The material composition of specific façade elements such as wall, roof and windows is similar for the existing building and the refurbished building prototype. The quantities of materials added and discarded from the building were estimated based on material density, height, length and width specified in the model. The wall and roof are made of concrete, insulation and plasterboard covering or sheathing. Other elements to support and protect the insulation material such as timber joists and vapour barrier are included based on technical requirements for concrete construction provided by the Building Research Association of New Zealand (BRANZ, 2013).

In both buildings the glazing system covers 80 % of the window area. The low-e double glazed consisting of two 4mm sheets of flat glass with a 16mm gap in between filled with argon gas. The exterior glass has a low emissivity coat to reduce heat transfer (Sinha & Kutnar, 2012). The single glazed window in the existing building was assumed to simply consist of one 4mm flat glass sheet. The aluminium window frame covers 20 % of the window area (Byars & Arasteh, 1992; Weir & Muneer, 1998) which consists of extruded aluminium, steel, polyamide and high density plastic (Sinha et al., 2012).

The refurbished building prototype specifies solar heat gain coefficient for the window area on the north, east and west façades, suggesting an effective solar shading system that excludes afternoon summer sun but allows afternoon winter sun. Different shading equipment can be installed such as fixed overhangs or movable louvres depending on the level of shading required on different façades but these details were not given in the model. On the basis of recommendations for shading design in New Zealand by BRANZ (Level, 2015b), it was estimated that:

i. The north façade has a fixed overhang above each window. The dimensions of the overhang were calculated using the shading width and window height factors based on the sun path diagram given for Auckland (Level, 2015a).

ii. The east and west façade has adjustable louvres. It is difficult to have fixed shades to the east and west façades as they receive low morning and afternoon sun (Level, 2015b). Adjustable louvre systems are available as standard manufactured units with pre-assembled mullions and metal clips. The dimensions of the louvre system and the mullions were obtained from the technical specifications provided by louvre manufacturers in New Zealand (LouvreTec, 2015). It was assumed that all solar shadings were made of aluminium, as it is a common choice of shading system in commercial buildings in New Zealand.

3.2.3.2 Technical components

Besides the technical information on the HVAC system, there was no information on its material components or infrastructure required to install it. Heat pumps and ventilation units mainly consist of metals (such as, steel and copper) for the structure, elastomers for tube insulation and refrigerants to store and transport heat. The capacity of a single air source heat pump with a COP of 4.0 ranges between 10 to 30 kW (Caduff et al., 2014). Therefore, the relative material and energy of ecoinvent unit processes for a 10 kW air- water heat pump and heat distribution equipment for 150 m^2 of floor area were scaled for the case study using the following modifications:

i. The manufacturing of a 10 kW heat pump was scaled up by a factor of 1.8 as recommended by Caduff et al. (2014, p. 405) to represent a 30 kW heat pump mass and output capacity. The number of heat pump units was estimated, assuming each heat pump is used for 150 m^2 of floor area.

ii. The raw material inputs for the heat distribution system were scaled relative to the floor space i.e. 150 m^2 as modelled in ecoinvent v3.

The materials discarded from the gas boiler and heat distributing radiators in the existing building prototype were estimated in a similar way based on data provided in ecoinvent unit process for 10 kW gas boiler and an LCA study on alternative heating units (Sørnes, 2011).

The mechanical ventilation system included a heat recovery unit with a ventilation rate of 10 l/s per person. The components of the ventilation system were estimated from the ecoinvent unit process for annual operation of centralized mechanical ventilation functioning at 720 m^3/hour (200 l/s). The components for air distribution (ducts) were excluded from the ventilation system because if the ductwork is periodically maintained, it will be retained during deep energy refurbishment (Alderson, 2009).

For lighting, the model used for the refurbished building prototype specifies the average power per m^2 and the luminous efficacy of each lamp (i.e. the ratio of the luminous flux output to the power input). The number of lamps required for the building was calculated by multiplying the total floor area by the ratio of the average power for lighting per m^2, this was divided by the luminous efficacy of each lamp. A cradle to gate LCA study on LED and compact fluorescent luminaires was used to obtain the data for materials and energy required for the production of each lamp (Principi et al., 2014). The data from this study was relevant as it is based on the recent technology for both types of luminaires used for lighting offices; it included the material requirements for all components of the lamp, including ballasts, fasteners, electrical connections and the light source.

3.2.3.3 Construction activities related to refurbishment

The energy required for demolition and reconstruction of the façade wall was estimated as 36 MJ/m^2 wall area (Gustavsson et al., 2010; Kuikka, 2012) and 0.151 MJ/ kg of material lifted over every 6 metres (Bowick et al., 2014). It was assumed that the new façade and glazing components would be washed and painted as part of finishing construction work. The amount of paint (2 coats) and water required was estimated according to maintenance data collated by Dowdell et al. (2016). A one-way transportation distance of 20 km was calculated using generic distances from gate of last fabrication or manufacturing process to the construction site, and approximate quantities of construction waste due to over-ordering and waste treatment scenarios were also based on data collated by BRANZ (Dowdell et al., 2016).

3.2.3.4 Inventory for construction materials and energy

Currently there is a lack of country-specific recent, comprehensive life cycle inventory data for New Zealand. The ecoinvent V3 database was used in this study. Although this database is not representative for New Zealand, it provides well documented, up to date information with exhaustive coverage of the products and materials considered in this study. The ecoinvent data were supplemented or modified with additional information collected from production processes for construction materials and components used by the construction industry in New Zealand (and specifically for aluminium, iron and steel, cement, glass, insulation and fabricated building components (window frames, solar shading, pre-cast concrete walls). In summary, the main modifications were:

1. Use of manufacture-specific details for material inputs, where available (for example, secondary treatment of aluminium and steel products or share of recycled content for materials produced in New Zealand) or use of data in internationally published Environmental Product Declaration (EPD) for pre-fabricated building products (pre-cast concrete, vapour barrier and roof membrane).
2. Use of New Zealand electricity production for total electricity supplied for production of all products and components produced in New Zealand. This excludes technical equipment for heat pumps and LED luminaires as these are imported (Bakshi et al., 2013; Ministry for the Environment (NZ), 2009); for these, a global average electricity mix was used.
3. Modification of direct greenhouse gas emissions from ecoinvent's generic inventory based on data provided in the National Greenhouse Gas Inventory for New Zealand (UN FCCC, 2014) for construction materials manufactured in New Zealand.
4. Modification of dioxin emissions for waste treatment at recycling plants (metal scrap production) based on Graham and Alistair (2011).

The inventory was modelled using an attributional approach. The background system was based on the 'Allocation, ecoinvent default' also referred as 'Allocation, at the point of substitution' model (ecoinvent, 2013b). In principle, the attributional modelling approach gives benefits for use of recycled content in different materials and components; but no benefits are given for the provision of any recyclable materials at disposal to avoid double-counting (Frischknecht, 2010; Schrijvers et al., 2016). In addition, the applied background system models waste or recycled materials as by-products of the previous cycle and therefore uses system expansion to allocate a fraction of impact from the waste treatment activities (based on physical allocation) before the material is discarded or available for use (ecoinvent, 2013a). It is considered most consistent in the application of allocation in attributional LCA (Schrijvers et al., 2016; Wernet & Moreno Ruiz, 2015). Therefore, the recycled content of materials used in this study bear a fraction of the burdens from previous recycling activities in the background system.

3.2.3.5 Building operation

The refurbished building was assumed to maintain the 60 % reduction in annual operational energy use for 25 years before the need for component replacement or remodelling. This lifetime was based on the assumption that most refurbished components such as heat pumps or low-e windows have an effective lifetime of 25 years (Balaras et al., 2004; Juan et al., 2010). As well as the base case of 25 years, an alternative extended operational period of an additional 25 years was modelled in a sensitivity analysis. For this longer time period (i.e. 50 years), to ensure that the refurbished building prototype maintained its desired energy performance (as given in the functional unit), the model included replacement of the heat pumps and LED lamps after 25 years (Greening & Azapagic, 2012; Principi et al., 2014) and surface coating required maintenance for low-e windows (Howard, 2007). Similarly, the model for the existing building included replacement of the gas boiler and CFL lamps every 25 years and 6 years respectively. The façade components were assumed to remain unchanged.

The cumulative environmental impact of the building was calculated by adding the environmental impacts associated with energy use over the operational period of the refurbished building to the environmental impacts embodied in the refurbishment process. This was compared to the cumulative environmental impact of the building's energy use and maintenance, if the building was un-refurbished. Additionally, an environmental payback period was calculated for each impact category. Payback period is the time taken to compensate the initial embodied impact of refurbishment with the reduction in impact due to annual energy savings. It was calculated using the formula suggested by the Environment and Resource Efficiency Plan (EREP) (2008) as given in Eq 1:

$$Payback\ period\ (years) = \frac{Total\ environmental\ impact\ of\ refurbishment}{Net\ annual\ savings\ (reduction\ in\ environmental\ impact\ per\ year)} \quad \text{Eq 1}$$

where the net annual saving was the avoided environmental impact due to reduced energy consumption of the refurbished building each year.

3.2.3.6 Inventory for electricity mix and potential scenarios

Electricity in New Zealand is generated from a large share of renewables (such as hydropower, geothermal and wind) in combination with fossil fuels. The grid mix is variable depending on resource cost, availability and climatic conditions. In this study, three scenarios with different grid mixes were used. Scenario I was representative of the electricity mix in 2013 as given in the annual energy statistical report (MBIE, 2015). In future, New Zealand aims to reduce the share of electricity generated from coal, and two potential future scenarios are predicted based on implementation of renewable energy technologies or low-cost availability of fossil fuels (MBIE, 2012; Ministry of Economic Development, 2011). The proportions of different sources supplying electricity for each of the scenarios are given in Table 3.2. The inventory for New Zealand's electricity generation was obtained from Sacayon (Sacayon Madrigal, 2016).

Table 3.2 Scenarios used to represent the New Zealand Grid electricity mix

Technology	Scenario I 2013 electricity grid mix	Scenario II Mixed renewables	Scenario III Low cost fossil fuel
Coal	7%	3%	2%
Natural Gas	19%	16%	32%
Hydro	54%	45%	44%
Wind	5%	14%	4%
Geothermal	14%	21%	18%
Biomass	1%	1%	1%

Table 3.3 Inventory data for refurbishment activities and annual building operation for case study building

Materials Used		Unit	Materials discarded (wastes)		Unit
Wall	**1734**	**m^2**		**1021**	**m^2**
Precast concrete [a]	411	tons	Waste Concrete [b]	242	tons
Polystyrene insulation [b]	9.5	tons	Waste plastic [b]	5.7	tons
Plasterboard [b]	16.6	tons	Waste wood [b]	18.2	tons
Timber joists [b]	44.1	tons	Waste plasterboard [b]	14.5	tons
Vapour barrier, polyethylene [a]	0.2	tons			
Roof	**730**	**m^2**		**730**	**m^2**
Sheathing, particleboard [b]	5.6	tons	Waste particleboard [b]	5.6	tons
Polystyrene insulation [b]	2.5	tons	Waste plastic [b]	1.0	tons
Roof membrane, plastics (PVC, PE) [a]	0.9	tons			
Timber joists [b]	13	tons			
Vapour barrier, polyethylene [a]	0.1	tons			
Window (low-e, Al framed, double glazed) [b, c]	**1400**	**m^2**	***(Al framed, single glazed)*** [b]	**2113**	**m^2**
Aluminium, wrought alloy [b]	11	tons	Aluminium scrap [b]	12.0	tons
Glass, float glass [b]	22	tons	Waste glass [b]	48.1	tons
Solar shading (louvres and overhangs) [c]					
Aluminium [b]	1.8	tons			
Heat Pump [c]	**39**	**p**	**Gas boiler and chiller** [b]	**1**	**p**
Refrigerant R134a	0.2	tons	Aluminium scrap [b]	0.5	tons
Copper	1.5	tons	Copper scrap [b]	0.21	tons
Lubricating oil	0.1	tons	Steel scrap [b]	0.01	tons
Steel, low alloyed	1.4	tons			
Steel, reinforcing	5.3	tons			
HVAC distribution system [c]	**5841**	**m^2**	**Radiators** [c]	**5841**	**m^2**
Aluminium, wrought alloy [b]	3.3	tons	Steel scrap [b]	8.4	tons
Aluminium, cast alloy [b]	1.6	tons	Waste plastics [b]	0.7	tons
Tube insulation	0.7	tons			
PVC	0.1	tons			
Polystyrene [b]	2.6	tons			
Polyethylene	3.9	tons			
Portland cement [b]	35.0	tons			
Sand [b]	18.1	tons			
Ventilation units [b]	149.77	m^2a			
Lighting (No. Of LED luminaires) [c]	**198**	**p**	***(No. of Compact florescent lights)*** [c]	**371**	**p**
Aluminium	0.28	tons	Steel scrap [b]	0.012	tons
Polycarbonate	0.07	tons	Waste plastics [b]	0.241	tons
Light emitting diode	0.012	tons	Hazardous waste [b]	0.017	tons
Copper wiring	0.007	tons	Inert waste [b]	0.228	tons
Printed wiring board	0.036	tons			
Silicone	0.002	tons			

Construction at site		***Unit***
Diesel, used for on -site construction plant e.g. cranes [c]	7380	MJ
Paint [c]	296	kg
Water [c]	6495	m^3
Freight, truck [c]	197888	tkm
Freight, ship [c]	264587	tkm
Annual energy consumption [b, c]		***Unit***
After refurbishment	157998	kWh
Before refurbishment	394994	kWh
Avoided annual energy consumption	236996	kWh
Maintenance (every 25 years) [c]		
Heat Pump (Refurbished building)	39	p
Lighting (Refurbished building)	197	p
Gas boiler (Non Refurbished building)	1	p
Lighting (Non Refurbished building)	1484	p
Paint	925	kg

Data sources: a international EPDs; b ecoinvent v3; c literature. Data was modified with NZ specific information. See supporting information SI-1 for further details on ecoinvent processes**.**

3.3 Results

This section presents the detailed results of the environmental impacts related to the deep energy refurbishment (section 3.3.1). Section 3.3.2 gives a comparative analysis of the results for the cumulative impact of the refurbished building and the existing building operating for 25 and 50 years using different electricity mix scenarios. Section 3.3.3 shows the environmental payback periods for the different impact categories.

3.3.1 Environmental impacts of refurbishment

Figure 3.2 presents the detailed results for the refurbishment of the building, split into the different refurbished building components and construction activities. The relative contributions of the different refurbished components are similar for eight out of twelve impact categories (GWP, PCOP, AP, EP, AD_{ff}, HT- carc, PMF and IR). For these categories, the highest contributing refurbished components are the windows (28-37 %), followed by the wall (12-32%), the heat pump (11-20%) and the heat distribution system (9-15%) while the least contributing component is the lighting system (1-5 %), followed by the roof (1-7 %) and solar shading (4-6%). The contributions to these categories are mainly related to metal content, especially aluminium as seen in the case of the windows, distribution system, solar shading and lighting system. With regard to the other refurbished components which do not contain aluminium, the largest contributing aspects are the materials with the most energy intensive production processes (for example, cement and reinforcing steel in concrete walls, refrigerant and steel in heat pump, and plastics for membrane and insulation in the roof). In the remaining four impact categories (ODP, AD_r, HT- non carc and $ET_{freshwater}$), the heat pump makes a significant contribution to all the results. Refrigerant used in the heat pump contributes 98% of the total ODP result while the use of copper contributes 43% of the AD_r, 47% of the HT non-carc, and 10% of the $ET_{freshwater}$ results.

The total contribution of construction site activities is low (about 2-6%) compared with the refurbished components; however, these activities contribute to 14% of the IR, 13% of the PMF, 11% of the AD_{ff} and 8% of the AP results. The contribution to these four impacts is mainly associated with fuel use (diesel for building machine and freight transport). With regard to waste treatment, this life cycle stage makes the biggest relative contribution to the $ET_{freshwater}$ (76 %) and AD_r, (33 %) results due to loss of metals during sorting, collection and cleaning of materials for scrap production.

Impact category	Unit	impact per m^2*yr
GWP	kg CO_2 eq	110.49
ODP	kg CFC-11 e	3.93E-04
PCOP	kg C_2H_4 eq	4.95E-02
AP	kg SO_2 eq	6.38E-01
EP	kg PO^{4---} eq	3.62E-01
AD_r	kg Sb eq	1.41E-03
AD_{ff}	MJ	1106.24
HT-carc	CTUh	3.64E-05
HT-non carc	CTUh	8.48E-05
$ET_{freshwater}$	CTUe	8831.81
PMF	kg PM2.5 eq	7.74E-02
IR	kBq U^{235} eq	5.29

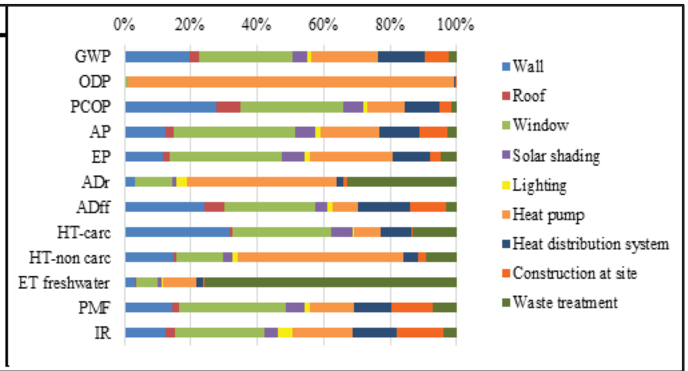

Figure 3.2 The impact assessment results for refurbished building (year 0) showing the relative contributions of the different refurbished components, construction activities and waste treatment.

3.3.2 Cumulative environmental impact

An overview of the cumulative impact of the refurbished building compared to the cumulative impact of the existing building if it remains un-refurbished and operating for either 25 or 50 years is given in Figure 3.3 (a and b), assuming different electricity grid mix scenarios. The results are presented in absolute values.

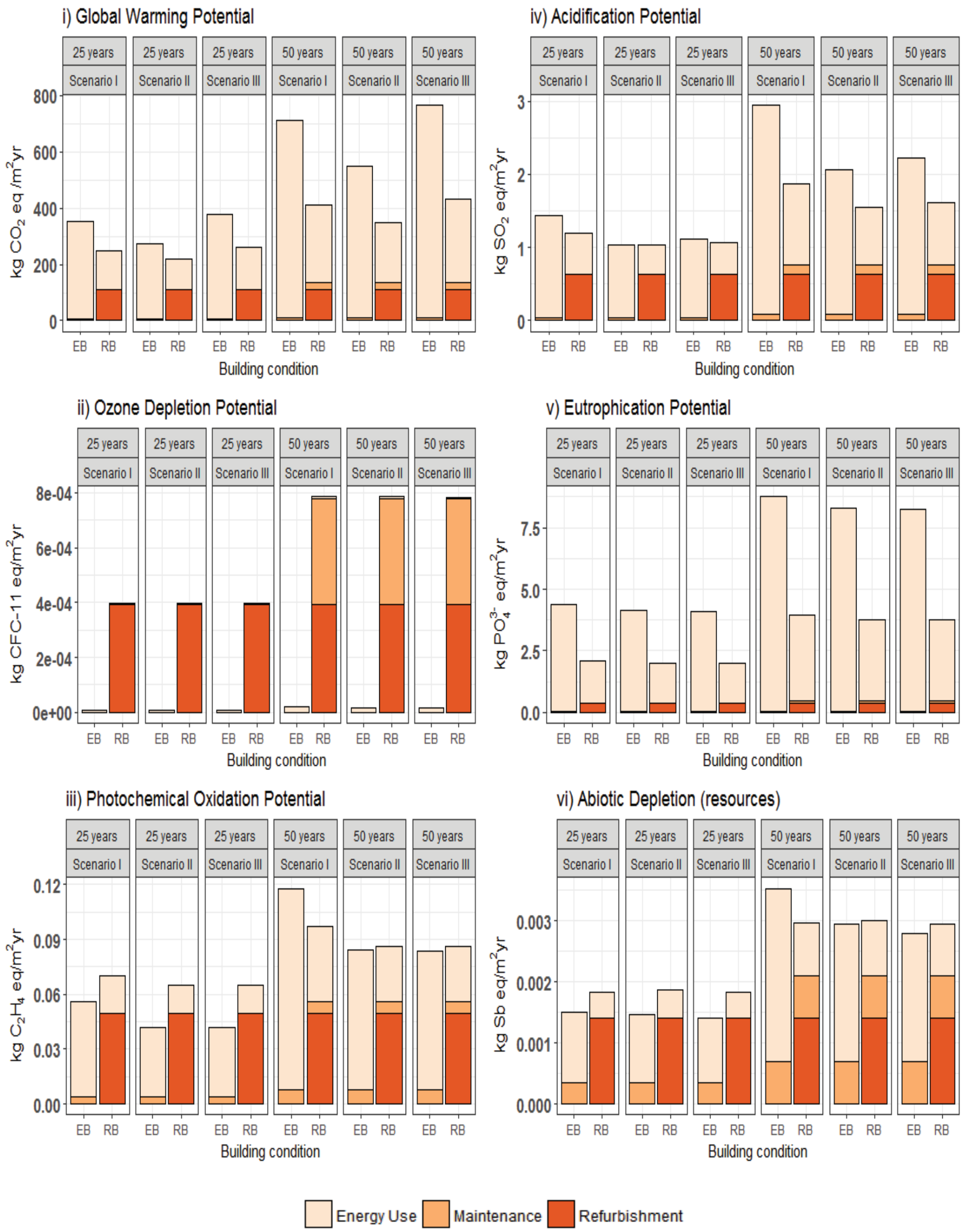

Figure 3.3.a) Cumulative impact assessment results for the refurbished building (RB) and existing building (EB) operating for 25 or 50 years using different electricity grid mix scenarios; where Scenario I represents 2013 electricity grid mix, Scenario II represents mixed renewables electricity grid mix and Scenario III represents Low cost fossil fuel electricity grid mix .

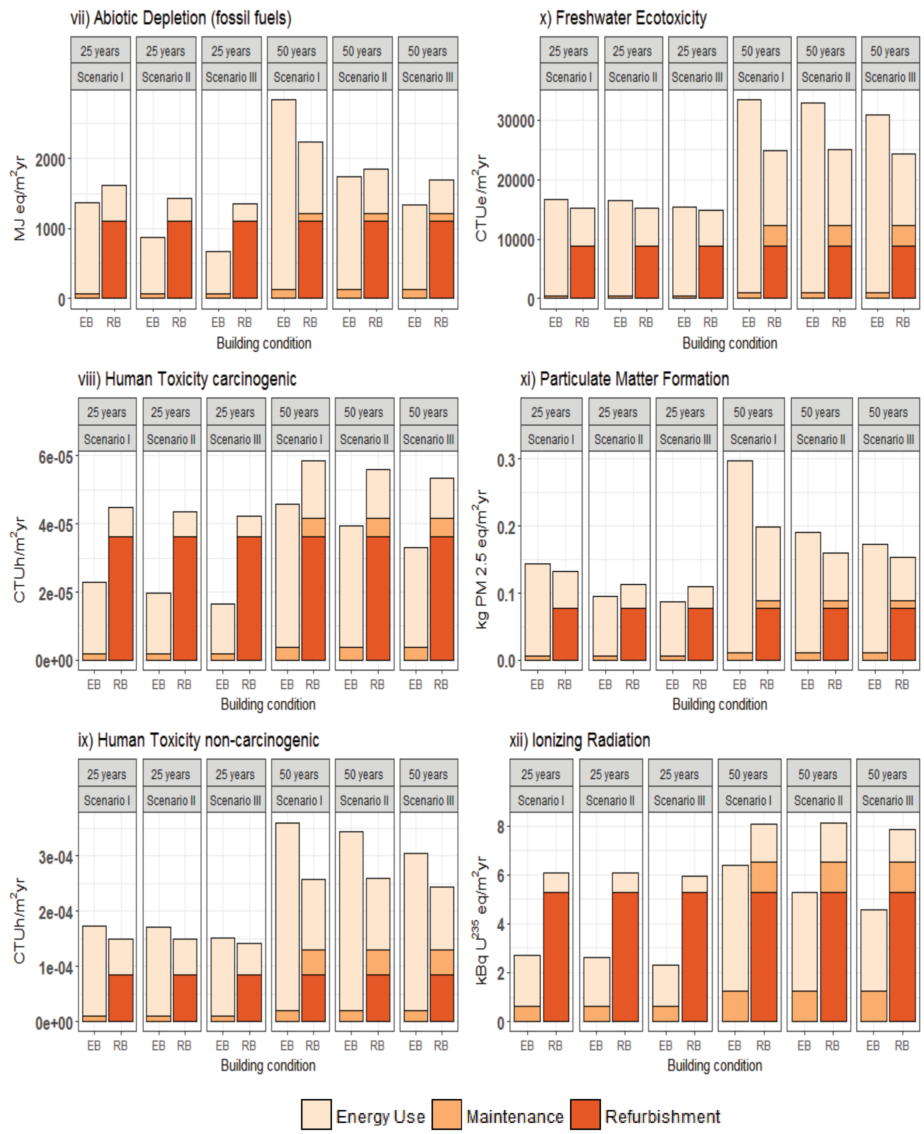

Figure 3.3 b) Cumulative impact assessment results for the refurbished building (RB) and existing building (EB) are operating for 25 or 50 years using different electricity grid mix scenarios; where Scenario I represents 2013 electricity grid mix, Scenario II represents mixed renewables electricity grid mix and Scenario III represents Low cost fossil fuel electricity grid mix.

Based on the values in Figure 3.3 (a and b), the refurbished building has lower cumulative impacts across all scenarios and both timespans for four out of twelve impact categories (GWP, EP, HT-non carc and $ET_{freshwater}$), and further this is also true for two other impact categories (AP and PMF) with one or two exceptions. The contribution to these impacts is largely dominated by electricity use and is therefore determined by the source of energy for electricity generation in each scenario.

For four out of twelve impact categories (ODP, AD_r, HT-carc and IR), the refurbished building has higher impacts across all three scenarios and for both timespans and this is also true for two other impact categories (PCOP and AD_{ff},) with one exception. The relative contribution to these impacts is mainly from refurbishment. It is interesting to note that the ODP impact is almost entirely due to the refurbishment of the building across all scenarios in both timespans. As explained in section 3.1, the ODP impact is related to refrigerants used in the heat pump. This impact doubles for the 50 year period due to replacement of a new heat pump for maintenance. Similar to ODP, the replacement of heating and lighting appliances for maintenance increases the impacts to AD_r, HT-carc and IR in the 50 year period.

The results also indicate that, as expected, within each impact category the cumulative impact increases for both the refurbished and the existing building when comparing the 25 with the 50 year timespan. Furthermore, the ranking of the three scenarios within either of the operational time periods remains similar. Both the existing and the refurbished buildings in scenario I have the highest results for eight out of twelve impact categories (PCOP, AP, EP, AD_r, AD_{ff}, HT-carc, HT- non carc and PMF), while the contribution to two of the impact categories ($ET_{freshwater}$ and IR) is marginally similar to scenario II. The scenario II results are lowest for the GWP and AP impact categories. The results of scenario II compared to scenario III are higher for seven impact categories (AD_r, AD_{ff}, HT-carc, HT- non carc, $ET_{freshwater}$, PMF and IR) and marginally similar for the PCOP and EP impact categories. The scenario III results are highest for the GWP impact category.

3.3.3 Environmental Payback

The net benefits of energy efficiency refurbishment are largely dependent on the avoided environmental impacts due to reduced electricity consumption. This was evaluated using the environmental payback period metric. Table 3.4 shows environmental payback period for each impact category in the three scenarios. If the operation of the building is considered in all three scenarios, it can be seen that the payback period is less than or equal to 25 years for four impact categories (GWP, EP, HT-non carc, and $ET_{freshwater}$); the payback period is less than or equal to 50 years for six impact categories (additionally AP and PMF). For ODP, IR and HT-carc (scenario III), the payback period is over 100 years; effectively for these impact categories there is no payback period because the building would either be demolished or re-modelled within this time period.

Table 3.4 Payback period of the deep energy refurbishment for the case study using different electricity grid mix scenarios

Payback period (years)	GWP	ODP	POCP	AP	EP	AD_r	AD_{ff}	HT-carc	HT-non carc	$ET_{freshwater}$	PMF	IR
Scenario I	13	>100	40	19	3	55	36	72	22	23	24	>100
Scenario II	17	>100	54	27	4	53	57	85	22	23	36	>100
Scenario III	12	>100	55	25	4	57	76	>100	25	25	40	>100

The shortest and the longest payback periods for GWP are the low cost fossil fuel scenario III (12 years) and mixed renewable energy scenario II (17 years) respectively. It is interesting to note that, although scenario III has the shortest payback period for GWP, it has the longest payback period in most other impact categories compared with scenario I and II. The shortest payback period is for EP (3-4 years across all scenarios) while the longest payback period is for HT-carc (72 and 85 years in scenarios I and II).

In summary, and as expected, the results for most impact categories indicate that a longer operation period for the refurbished building is advantageous to offset a higher proportion of the environmental impacts associated with refurbishment of an existing building. However, there is no environmental payback within 50 years for at least one scenario for ODP, PCOP, AD_r, AD_{ff}, HT-carc, and IR. Arguably the benefits of the refurbished building are highest in scenario I as it has the shortest payback period for eight out of the twelve categories (PCOP, AP, EP, AD_{ff}, HT-carc, HT-non carc, $ET_{freshwater}$). Scenario II has the shortest payback period for AD_r (and is the same as scenario I for HT-non carc and $ET_{\text{freshwater}}$), and has shorter environmental payback periods compared to scenario III for all impact categories except GWP and AP) (and is the same as scenario III for EP). Scenario III has the shortest payback period for just the GWP result.

3.4 Discussion

This section discusses the major environmental hot spots related to the impacts from deep energy refurbishment (section 3.4.1) followed by a discussion on how relevant is a deep refurbishment with respect to avoiding impacts from New Zealand's electricity grid mix (section 3.4.2), and a comparison of results with existing LCA studies on refurbishment (section 3.4.3).

3.4.1 Environmental hotspots in building refurbishment

The impact assessment results indicate that the materials with the most energy intensive production make a significant contribution to most environmental impact categories. The major hotspots associated with GWP were aluminium used in window frames, solar shading, heat distribution system and LED luminaires; and reinforcing steel and cement in pre-cast concrete walls. These contributions are mainly from the use of fossil fuel in aluminium smelting, steel production, and in clinker production for cement.

The greenhouse gas (GHG) emission factor for primary aluminium production in New Zealand is only 9.85 kg CO_2 eq/kg (UN FCCC, 2014) compared to the global average 16.5 kg CO_2 eq/ kg primary aluminium (Jones, 2014). New Zealand's reinforcing steel production from scrap steel is 0.69 kg CO_2 eq/ kg compared to a global average of 0.9 kg CO_2 eq/ kg calculated by (World Steel Association, 2011). The impact of these locally produced materials is lower than the global average for processes that require significant amount of electricity relative to fuels for energy, due to the relatively high share of renewable energy in New Zealand's grid electricity. Around 50 % of the cement used in New Zealand is imported from South East Asia (Statistics NZ, 2015). The source for cement used for concrete production in this study was representative of the average of New Zealand production and imports. The GHG emission factor calculated for pre-cast concrete in this study is 0.19 kg CO_2 eq/ kg of concrete which is in the range of 0.17- 0.22 kg CO_2 eq/ kg of equivalent pre-cast concrete produced in Malaysia where there is a higher share of fossil fuel use in production (Omar et al., 2014).

Refrigerant used in heat pumps contribute 14 % to the GWP and 98 % to the ODP results. The refrigerant used for heat pumps in this study is HFC 134a which is among the permitted and commonly used refrigerant types used in New Zealand for air conditioning systems (Bowen, 2016). It has a GWP potential of 1430 kg CO_2 eq/ kg (IPCC, 2007) and ODP potential of 0.009 kg CFC-11 eq per kg (Bovea et al., 2007). The refrigerant HFC134a itself does not contribute to ozone depletion, but its production may emit small amounts of ozone depleting substances (Bovea et al., 2007; Saner et al., 2010). Johnson (2011) showed that if the refrigerants are leaked even once during the heat pump's lifetime, this could push up the GWP impact of the heat pump by 11–13%. Since, January 2013, New Zealand has enforced strict laws and guidelines to manage careful disposal of refrigerants in equipment during maintenance and end-of-life treatment (Bowen, 2016; NZ Environmental Protection, 2012). Therefore in this study the impact from HFC 134a in the atmosphere was associated only with heat pump production.

Impacts to PCOP were associated with carbon monoxide (CO) and pentane emissions from aluminium smelting and foam blowing of insulation respectively.

Other GHG emissions related to fossil fuel use such as sulphur dioxide (SO_2), nitrogen oxides (NO_x) and particulate matter (<2.5µm) emissions, are the main contributing emissions for the AP, EP and PMF categories respectively while the use of coal, petroleum and natural gas contributes to AD_{ff}. Thus the major hotspots associated with these categories are similar to GWP.

With regard to HT-carc, the hotspots are associated with the steel and aluminium used in the walls and windows. The contribution is related to release of chromium VI emissions to water from landfilling of slag and dust wastes from electric arc steel production, and red mud wastes from mining bauxite used for aluminium production. Moreover, secondary metal processing is the fourth-highest contributor of dioxin and furan emissions to land in New Zealand (Graham et al., 2011), which also contribute to this category. The heat pump also contributes significantly to HT-non carc and AD_r, which is related to copper used in heat pumps. Copper mining contributes to zinc and arsenic emissions as well as loss in ores. Hotspots from waste treatment are particularly relevant for $ET_{freshwater}$ and AD_r. This is due to losses of metal scrap (especially copper) during recycling of steel or aluminium. Copper is a typical alloying element in both ferrous and non-ferrous metals which is often lost when recycling metals for upgraded quality (Nakamura et al., 2012).

The IR impacts are mainly related to use of nuclear energy in the grid mix. Although New Zealand does not have any nuclear energy production, the impact is contributed from materials produced overseas and imported to New Zealand such as post-consumer metal scrap, polymers for insulation production, and finished technical equipment (LED luminaires and heat pumps). Another aspect contributing to IR emissions is the release of low level radioactive waste during crude oil extraction (Smith et al., 2003); therefore fuel use in transport and construction activities at site is a significant contributor to this category.

3.4.2 Relevance of deep energy refurbishment in offsetting environmental impacts from New Zealand's electricity grid mix

The results presented in Table 3.4 indicate that the refurbished building has a lower net environmental impact in eight out of twelve impact categories if the building operates with the same efficiency for 50 years after refurbishment in scenario I. The environmental benefits of the refurbished building are associated with GWP, PCOP, EP, AP, AD_{ff}, HT non-carc, ET $_{freshwater,}$ and PMF.

The environmental impacts of New Zealand's electricity are largely related to the share of different fossil fuels as shown in a comprehensive LCA study on New Zealand's grid electricity in 2013 (Sacayon Madrigal, 2016). The share of electricity generated from coal contributes more than 30-70 % of the PCOP, AP, ET, HT and AD_{ff} results. The share of electricity from natural gas contributes 50 % to the GWP and between 20- 30 % of the AD_{ff}, AP and PCOP results. The share of electricity from biomass (mainly biogas) contributes 70% of the EP result. The contribution to the impact category results from other electricity generation sources is negligible. In future scenarios of electricity generation in New Zealand, the share of electricity generated from coal is expected to decrease, therefore the benefits of energy efficiency refurbishment are reduced in the impact categories affected by electricity from coal generation. This is particularly visible in the PCOP, AP, AD_{ff} and PMF results in both scenarios II and III (Table 3.4).

Surprisingly, the environmental impacts of the refurbished building in scenario II (which has a larger share of renewables) are marginally higher than scenario III (which has a higher share of natural gas in combination with other renewable energy) in six out of twelve impact categories (Figure 3.3). These differences can be explained by the share of electricity generated from coal which dominates the contribution to most of the impact categories. The share of electricity generated from coal is marginally higher in scenario II compared with scenario III, therefore the impacts from scenario II are higher than scenario III except for GWP and AP. This is further confirmed by the results of the environmental payback period calculated for each impact category (Table 3.4). The differences for GWP and AP can be explained by the higher share of natural gas for electricity production in scenario III.

It is important to note that New Zealand's electricity mix makes a negligible contribution to the ODP and relatively low contribution to the HT-carc and IR results (Figure 3.3) therefore the payback periods are much longer than the usual operational lifetime of a building (Table 3.4). These three impacts therefore constitute the major trade-offs of the deep energy refurbishment. In addition, even if the building stays in use for at least 50 years, AD_r, and PCOP and AD_{ff} (in Scenario II and III), will be the other environmental trade-offs.

3.4.3 Comparison of results with existing studies

In positioning this study in the context of existing studies which have modelled refurbishment from early design models, the impact category GWP was chosen for consideration as it was the most reported impact category. The GWP impact calculated for the building refurbishment is 110 kg CO_2 eq/ m^2 yr and the cumulative impact of the building over a 50 year period is 409 kg CO_2 eq/ m^2 yr, 350 kg CO_2 eq/ m^2 yr, and 432 kg CO_2 eq/ m^2 yr for current, increased renewable, and low cost fossil fuel use electricity grid mix scenarios respectively. In comparison with existing LCA studies which have modelled refurbishment in early building design, these values are very high as seen in the results by Passer et al. (2016) who calculated 15-45 kg CO_2 eq/ m^2 yr for deep energy refurbishment of residential buildings operating for 60 years or Wallhagen et al. (2011) calculated 3.1- 5.2 kg CO_2 eq/ m^2 yr in 12 different office buildings each with a different refurbishment scenario in Sweden. However, the case study results are much closer to impacts calculated for the large façade refurbishments studied by Pomponi et al. (2015) who calculated 250 -368 kg CO_2 eq/ m^2 yr of office building operating for a 50 year lifetime in U.K.; or Ferreira (2015) who calculated 149 kg CO_2 eq/ m^2 floor area for a large scale refurbishment of a multi-storey building in Portugal with site specific data.

Despite these differences, it is important to note that the results are in line with existing literature on individual building components. For example, for façade elements the impact of double glazed aluminium framed windows calculated here was 129 kg CO_2 eq/m^2 glazed facade area in comparison to 195 kg CO_2 eq/m^2 glazed façade area for aluminium framed curtain wall systems for commercial buildings in China calculated by Han et al. (2015); the impact calculated for expanded polystyrene insulation is 3.4 kg CO_2 eq/ kg insulation compared to 2 kg CO_2 eq/ kg as calculated by Nicolae and George-Vlad (2015). The impact of aluminium solar shading is 16.3 t CO_2 eq/ ton material compared to 18.3 t CO_2 eq/ ton aluminium as calculated by Huang et al. (2012). For technical systems, the total impact of the HVAC system (heat pump including distribution system) is 37 kg CO_2 eq/ m^2 floor area compared to the carbon footprint of air source heat pumps as calculated by Johnson (2011) which is 27-38 kg CO_2 eq/ m^2 floor area. For lighting system, the impact of each LED luminaire was calculated as 39 kg CO_2 eq compared to 22 kg CO_2 eq/ LED luminaire as calculated in the cradle to gate boundaries by Principi et al. (2014). With respect to the contribution of construction activities at the site and waste treatment, the GWP impact calculated contributed 9 % of the total GWP impact from refurbishment and this is close to the 12 % contribution calculated by Ferreira (2015) who evaluated the partial demolition and construction during refurbishment of a real building case study. For the façade area, the impacts are 26.9 kg CO_2 eq and 8.65 kg CO_2 eq/ m^2 façade area in this study compared with 35.2 kg CO_2 eq and 4.08 kg CO_2 eq/ façade area calculated by Han et al. (2015).

Moreover, although the results of the environmental payback calculated in previous studies are different; their conclusions support the results of this case study. For example, Ardente et al. (2011) calculated a GWP payback period ranging between 0.6-31 years depending on the components refurbished, and suggested that façade refurbishments with low-e windows and added insulation will have a longer payback period. Similarly, Antti et al. (2012) and Passer et al. (2016) calculated payback periods of large scale energy efficiency refurbishment between 20-25 years for Finnish and Swedish case studies respectively, where Antti et al. (2012) also showed that the payback period for refurbishment was marginally shorter if the electricity grid mix had a higher share of fossil fuel based production.

As pointed out by both Wallhagen et al. (2011) and Pomponi et al. (2015), the possible difference in results could largely depend on the availability of primary data collected specific to the case study. However, the wide variation in results can also be explained due to the variability in refurbishment strategies, involving different building components and electricity mixes for production of construction materials and operation of the building. Therefore they cannot be used for a direct comparison.

3.4.4 Limitations and Future Work

The findings of this study are somewhat limited as the results are mainly relevant for this case study. For example, the results cannot be generalized for other buildings which use different construction materials and refurbishment strategies. LCA studies (Blengini, 2009; Bribián et al., 2011; Sandin et al., 2014; Stacey, 2015) on comparable building construction have shown that promoting the use of resource management strategies such as eco-innovation, use of local materials or increasing the share of construction waste recovery, re-use and recycling could significantly reduce the total environmental impacts. It would be useful to investigate the effects of these strategies at an early design phase to develop strategies that could effectively minimize the total environmental impacts associated with a deep energy refurbishment.

Another limiting factor in conducting an LCA of an early design model is in completeness with respect to accounting for impacts from the additional components likely to be refurbished during a large scale energy efficiency refurbishment (such as office fit-outs). Studies (Alderson, 2009; Cole et al., 1996; Yohanis et al., 2002) have shown that interior fit outs of office buildings such as partitions, finishes, floorings, fittings, furniture and equipment can contribute 12-15% to the initial embodied impacts. Interior refurbishments are driven by building occupancy (e.g.

change in tenants or office churn rates) and typically recur every 5-7 years; as a result, they eventually outweigh the initial embodied impacts associated with refurbishment of the building structure (Forsythe & Wilkinson, 2015). However, the type and number of interior fit-outs of office buildings greatly vary and are therefore difficult to quantify in early design models (and therefore not included in this study). Inclusion of details about typical recurring interior refurbishments would increase the quality and accuracy of LCAs performed on early building designs.

One of the most important findings to emerge from this study was that the cumulative environmental impact of a building is largely driven by the share of different fossil fuels in the energy mix for energy used to produce the refurbished building components and to operate the building. Huijbregts et al. (2010) highlighted the strong correlation between most impact categories chosen in this study (GWP, AD, AP, EUP, PCOP, ODP and HT) and Cumulative Energy Demand (CED) indicators (comprising use of non-renewable and renewable energy resources); they recommended CED indicators as good screening indicators for the overall life cycle environmental impacts of many commodities including construction materials. Frischknecht et al. (2015) recommended that the inclusion of CED indicators in building performance analysis as this could help stakeholders (e.g. architects, developers and engineers) to quantify the amounts of different energy resources used within the life cycle of a building, and policymakers to quantify the regional (e.g. city or country) consumption or need for energy resources. Including the CED indicators in this study or similar early design models could extend the potential of such studies to better inform and influence energy strategies that narrowly focus only on efficiency targets. This should be considered in future work.

3.5 Conclusion

This study assessed the environmental performance of a deep energy refurbishment of a typical office building located in New Zealand and its subsequent operation using LCA. The results highlighted both environmental burdens and benefits associated with deep energy refurbishment. Reduction in operational energy consumption with the adoption of energy efficiency refurbishment contributes in reducing environmental impacts caused by greenhouse gas emissions. However, the adoption of energy efficiency refurbishment contributes to significant increases in environmental impacts influenced by resource depletion and non-greenhouse gas emissions. In general, the results indicate that the environmental impacts associated with a deep energy refurbishment are associated with the use of energy intensive materials used in the building façade and HVAC, especially windows and heat pump. The overall environmental performance of the refurbished building is influenced by the electricity grid mix as this mix determines the magnitude of the impact reduction associated with avoided electricity consumption. The study further indicated that the maximum impact reductions associated with avoided electricity consumption are incurred when the energy sources for grid electricity generation include a relatively high share of coal-based electricity generation. Given that coal-based electricity generation in New Zealand will decline in future as is expected in current predictions by the Ministry for the Environment (MBIE, 2012), it will be more difficult to compensate the impacts associated with refurbishment in future. It will therefore be necessary to maintain a long service life of >25 years for the refurbished building to compensate for most of the environmental burdens associated with refurbishment when the electricity is sourced mainly from renewable sources.

In conclusion, this study supports the effectiveness of deep energy refurbishments of office buildings in New Zealand in order to mitigate climate change. Unlike most existing studies that have mainly evaluated the impact carbon footprint or GHG-related impacts of the early design phase of buildings, this study assessed the comprehensive environmental impacts of refurbishment activities. It highlights the trade-offs against some other environmental impacts, and the benefits of longer operation periods after the refurbishment has taken place. The implications of these results might be relevant when assessing deep energy refurbishments as a mitigation strategy in other countries with larger shares of electricity generated from renewable electricity. Although the generalizability of these results is subject to certain limitations, given the limited number of comprehensive LCA studies related to New Zealand's building sector, the data collected for this study and the results provide a starting point for New Zealand's building engineers and architects to give further consideration to alternative material options or refurbishment strategies when considering energy efficiency improvements. In future work it will be important to consider the uncertainties related to other types and frequency of refurbishments to increase the validity and effectiveness of the results.

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Chapter 4- Evaluating the influence of resource and waste management on the environmental performance of a refurbished office building – a consequential study

Abstract

Large scale building refurbishments are likely to become more common in New Zealand's building sector, and therefore it is relevant to assess the environmental impacts associated with these activities. The aim of this study was to investigate the environmental impacts arising from the increase in demand for building refurbishments in New Zealand using consequential Life Cycle Assessment (LCA). The study focused on the identification of resource constraints and marginal suppliers of construction materials using market information specific to New Zealand. Building refurbishment strategies related to waste minimization at construction sites and use of recycled materials at production sites were compared. According to the results, increasing the rates of construction waste recovery and re-use at site can reduce the overall environmental impact of a building refurbishment by 15- 25 % compared to use of construction materials with recycled content which only reduces the environmental impacts by approximately 5%. The net impact results were sensitive to the quality of recyclable material, location of the marginal supplier and marginal energy source. The study recommends stakeholders involved during early building design to focus on material sourcing and quality; and practical solutions to increase material recoverability at site e.g. planning for efficient on-site management for waste disaggregation, recovery and re-use.

4.1 Introduction

With increasing awareness about the environmental impacts related to the operational energy use of buildings, most OECD countries have prioritised adoption of energy efficiency strategies for the existing building stock (IEA, 2014). This has led to increased attention to construction activities as well, which use energy-intensive materials and generate large quantities of solid waste (UNEP, 2014). Whilst energy efficiency and renewable energy use in the operation of buildings is addressed by existing policies in OECD countries (IEA, 2014), better construction practices and sourcing of building construction materials (including extraction, production and waste management of these materials) is also required to reduce environmental impacts (Herczeg et al., 2014). This could reduce the life cycle energy consumption and GHG emissions by 42% and 35% respectively, and 50% of the extracted materials used in the building sector, and could even save up to 30% of water in some regions, as reported in a study by the European Commission (European Commission, 2011).

The New Zealand Government's Energy Efficiency and Conservation Strategy for 2011-2021 identify transformation of the country's commercial buildings as a key strategy to improve energy security, and promote efficient energy use (Ministry of Economic Development, 2011). This strategy is mainly focussed on realising low energy use during building operation through the adoption of solutions such as well-designed building façades, and efficient air-conditioning and lighting systems (Amitrano et al., 2014). Besides contributing to improved energy security and reduced environmental impacts, reduction in operational energy has been shown to add market value to recent commercial building developments in New Zealand (Jewell, 2014; NABERS NZ, 2016). Currently in New Zealand, existing buildings outnumber new buildings by 50 to 1 (BRANZ, 2013; Isaacs & Hills, 2013). Therefore, national building policies have identified refurbishment as a potential strategy to improve the existing building stock as well as an opportunity to meet global greenhouse gas emission targets by the adoption of recommended energy efficiency solutions (Bedford et al., 2016). Indeed, the consented building refurbishments of commercial buildings in New Zealand for 2011 and 2013 exceeded a total expenditure of 3.9 and 4.4 billion NZ$ respectively for each year (Whats On, 2013).

Construction activity in New Zealand is growing and is expected to continue in the next few years with particularly rapid development in the commercial building sector (Chaney, 2012; SafeSmart Access NZ, 2015; Statistics NZ, 2015a). New Zealand's

Green Building Council (NZGBC) claims that, although awareness of sustainable and green building designs has increased, strategies that prioritise material procurement and waste management that potentially reduce environment impacts have been slow to percolate into the construction sector (Craven, 2015). In Chapter 3 it was identified that large scale energy efficiency refurbishment was a substantial contributor to the overall environmental performance of buildings in New Zealand. Most of these impacts were related to the construction materials with energy intensive production. Indeed, use of conventional building materials with high embodied energy still dominates the New Zealand's construction sector (Crampton, 2015), and approximately 1.7 million tonnes of construction waste is generated each year, which is nearly 50% of the total waste generated in New Zealand (BRANZ, 2014; Inglis, 2012). In general, large scale deployment of energy efficiency refurbishments will also be coupled with high levels of resource consumption and waste generation.

The aim of this study is to investigate the environmental impacts of an increase in construction activities arising from energy efficiency refurbishments in New Zealand. In particular, it addresses the following research questions: (a) What are the potential environmental impacts of an increase in resource demand associated with energy efficiency refurbishments? And, (b) Can material procurement and construction waste management strategies reduce these environmental impacts at the same time as delivering the benefits of more energy efficient buildings?

The study builds on previous research in Chapter 3 which used attributional Life Cycle Assessment to evaluate a large energy efficiency refurbishment of an office building. However, in contrast to the study in Chapter 3, and in order to address the research questions above, this study utilizes the consequential modelling approach to identify the expected change in activities linked to the refurbishment processes (ISO, 2012).

4.1.1 Use of Consequential LCA modelling in the building sector

LCA is used for the comprehensive evaluation of environmental impacts related to activities and products, including construction activities and buildings. There are two major modelling choices in LCA: attributional and consequential (Finnveden et al., 2009). In attributional modelling, all relevant energy and material inputs are based on status quo (or average) supply data to quantify the environmental impacts of a specific construction (Ekvall et al., 2016; Ekvall & Weidema, 2004). This approach uses allocation factors to partition the impacts between by-products and recycled materials. Attributional modelling is the most common approach used in building sector LCAs (Cabeza et al., 2014; Peuportier et al., 2011). It is particularly useful to identify environmental hot spots in materials or life stages of specific buildings, and to optimize building designs (Blom et al., 2010; Junnila et al., 2006; Kofoworola & Gheewala, 2008; Scheuer et al., 2003). In consequential modelling, the focus is on the environmental impacts of discrete effects on production and supply due to changes in demand for construction (Gustavsson et al., 2015). Consequential modelling is used to identify a) the unconstrained (or marginal) suppliers in the studied system that can increase production if there is an increase in demand for a product or process, and b) products and processes which will be substituted in other systems (system expansion) due to additional production of by-products (Ekvall & Weidema, 2004). Although a well-founded methodology exists in the literature for consequential modelling (Ekvall, 2000; Ekvall & Weidema, 2004; Schmidt, 2008; Weidema, 2003b), the application of consequential LCA in the building sector was initially limited - but has been increasing in recent years. Examples of application of consequential LCA in the building sector can be found regarding the use of different heating systems (Rinne & Syri, 2013); the substitutability of different building materials, components and designs (Buyle et al., 2016; Kua & Kamath, 2014, Kua & Lu, 2016); and the promotion of policies for re-use or recycling of construction related demolition and waste (Kua, 2015; Sandin et al., 2014; Vieira & Horvath, 2008). Another common objective in each of the above mentioned studies is the comparison between using the consequential and attributional modelling approach to calculate the environmental impact of a building or a construction material. Whilst the variance in the results using the two modelling approaches in each of these studies was related to uncertainties in modelling assumptions and data, the choice between the modelling approaches was not as critical as expected (Vieira & Horvath, 2008). Yang (2016) and Buyle et al. (2016) suggested that the consequential approach was complementary to the attributional approach and a useful addition to inform policy makers on effects of different types of available decisions. Consequential LCA adds a future-oriented perspective to a study, and is therefore considered a useful methodological approach to assess transformation strategies (Earles & Halog, 2011; Gustavsson et al., 2015; Paulik & Hertwich, 2016).

Vieira and Horvath (2008) identified that the limited use of consequential LCA in the building sector was probably due to the fact that identifying marginal technologies and suppliers for all building construction materials can be challenging.

It is interesting to note that LCA case studies on buildings often use substitution - which is most often associated with consequential modelling in LCA - to model the avoided burdens of recovered construction and demolition waste but do not specify the use of marginal or average data (Blengini & Di Carlo, 2010; Chau et al., 2016; Kucukvar et al., 2016). The lack of consistency and transparency in the modelling approach may also be traced back to the use of earlier versions of the ecoinvent database which was based on attributional modelling, and is commonly used as the generic background database in process-based LCA studies (Peuportier et al., 2011). The development of consequential datasets in the ecoinvent v3 database in 2013 has reduced the uncertainty related to choice of generic background datasets used in consequential modelling (ecoinvent, 2013). In addition the ecoinvent database is geographically differentiated i.e. it provides generic data on numerous products and processes in different geographic locations. This has increased the ability of modellers to choose geographically delimited, unconstrained technologies and suppliers to global or regional markets (ecoinvent, 2013; Weidema, 2016). However, the ecoinvent database still lacks New Zealand specific background data (Kellenberger, 2007; Nebel, 2009). Therefore the use of a consequential modelling approach in a New Zealand specific LCA study requires the use of domestic market information, and use of the recommended guidelines by Weidema (2003b) for market delimitation (i.e. market limits/constraints) and substitution, in order to approximate the marginal effects of a change in demand.

4.2 Methodology

The methodological approach used in this study was based on the guidelines presented by Weidema (2003b). The functional unit for the study was defined as demand for refurbishment and subsequent use of 1 m^2 gross floor area in an office building. Refurbishment is defined as '*modifications and improvements to an existing building or its parts to bring it up to an acceptable condition*' (EN 15 978, 2011). This study specifically analysed a major refurbishment as defined by Leifer (2003) that included complete remodelling and upgrading of the façade, and replacing and modernising the Heating, Ventilation and Air-Conditioning (HVAC) and lighting systems. The guidelines from the building standard EN 15 978 were used to define the system boundaries for building refurbishment (see figure 4.1). The processes included in the system were: raw material extraction and processing, product manufacture; product transportation to the construction site and construction process; and transportation and waste management of demolished material produced during refurbishment (EN 15978, 2011).

4.2.1 Base case and scenarios

A standard set of energy efficiency measures recommended to reduce the operational energy consumption for New Zealand's existing commercial buildings by 60 per cent was assessed (Cory, 2016). The reference building used for this study was an office building located in Auckland. The refurbishment measures adopted in the building were: large scale transformation of the façade with increased insulation to building envelope (wall and roof); optimization of the Wall to Window Ratio (WWR); alteration of windows to an advanced glazing system and with a frame to enable natural ventilation; addition of solar shading to the North, East and West façades to avoid passive solar heat gain; change of the air conditioning system (heating and cooling) from a natural gas operated boiler and electric chiller to electric heat pumps; and replacement of existing compact fluorescent lamps with LED luminaires. Two prototypical models of this reference building, representing the existing and the refurbished constructions were also developed by Cory (2016) using the EnergyPlus energy simulation modelling tool (EnergyPlus 8.6.0, 2015) and the corresponding graphical interface OpenStudio SketchUp (Lammers, 2011). The building prototypes modelled in the EnergyPlus and SketchUp softwares provided the construction details and building geometry respectively. The refurbished and exiting building prototypes were used to estimate the material quantities required for refurbishment and produced as waste respectively. As there were no changes to the structural components of the building (i.e. foundation, load-bearing walls), they were not included in the study. Moreover, only the building components associated with the energy efficiency measures were included in the models; therefore, internal fit-outs (such as, office furniture, internal finishes to floors and ceilings) were excluded from this study. Details on calculations and assumptions made to determine the material quantities from the prototype models can be found in Chapter 3 (Sections 3.2.3.1-3.2.3.4). A summary of the reference building's specifications and associated refurbishment measures is given in Table 4.1.

Table 4.1 Specifications of the existing and refurbished building and related refurbishment measures

	Existing Building		Refurbished Building		Refurbishment measures
	Area (m^2)	R- value [a] (m^2 K/W)	Area (m^2)	R- value (m^2 K/W)	
External Walls	1021	3.6	1734[b]	5.8	Non-bearing concrete walls replaced and adjusted to increase wall area. Overall insulation increased.
Windows	2113	0.172	1400 [b]	0.625	Large clear non insulated aluminium framed windows replaced with smaller low-e double glazed aluminium framed windows. Solar shading added.
Roof	730	2.9	730	3.65	Overall insulation increased with required waterproofing.
Heating	Natural gas boiler, electric chiller and radiators		Air source heat pumps, Under floor distribution system		Equipment replaced. Additional cement-based flooring added over floor distribution system
Lighting	Compact fluorescent lighting		LED lighting		Luminaires replaced

[a] R-Value is defined as a measure of thermal resistance for materials or assemblies of materials (such as walls, windows and roofs) (Desjarlais, 2008); [b] The ratio of wall to window area changes (the total façade area remains the same)

The base case was termed as the Business As Usual (BAU) scenario in which there were no specific conditions for waste recovery or material procurement. Data on conventional construction practices in New Zealand with respect to current waste recovery rates, generic transportation distances in New Zealand from last manufacturer or supplier, and typical values for energy required for construction sites (as compiled by Dowdell et al. (2016)) were used. Three other scenarios were developed to represent different waste handling and material procurement strategies for the refurbishment:

- ***Scenario 1: Best practice construction waste management which minimizes waste generation through re-use and recycling.*** This scenario was based on Resource Efficiency in the Building and Related Industries (REBRI) guidelines in New Zealand (BRANZ, 2014). REBRI's main focus is on reducing the quantity of building material wastes generated at construction and demolition sites that would be sent to landfill. The "best practice" for waste minimization by increasing waste recovery rates for recycling and reuse for construction materials (also compiled by Dowdell et al. (2016)) were used. The data were based on waste management case studies in New Zealand between 2009 and 2014. In comparison to the conventional practice, Dowdell et al. (2016) reported examples where higher waste recovery rates have been achieved for concrete, metals, timber, glass, plasterboard, particleboard and other plastics. Moreover, the proportion of materials such as plasterboard, particleboard, planed timber and insulation that could be re-used at site was also provided.

- ***Scenario 2: Reduced demand from primary production of construction materials by using substituted materials.*** This scenario was developed to investigate the influence of alternative material procurement. Alternative materials used for insulation and concrete production were modelled. Whilst most of New Zealand's construction industry still practices traditional material procurement strategies and management (Samarasinghe, 2014), dominant manufacturers of insulation and concrete products have increasingly considered the use of alternative raw materials to the conventional use of polystyrene polymers for insulation and Portland cement for concrete production respectively (Autex, 2016; CCANZ, 2015). These measures are developed to potentially create a market for recoverable waste as well as reduce the environmental and economic cost of primary raw material (Autex, 2016; CCANZ, 2015). Polyester fibres from recycled PET bottles and granulated iron blast furnace slag from national steel production are used to substitute primary materials in insulation and concrete production respectively. The proportion of polyester fibres bottles from recycled fibres was based on the value presented in the sustainability report of Autex (2016), while the maximum proportion of blast furnace slag that could be used while maintaining the required functionality and durability of pre-cast concrete production was based on the value presented in technical guidelines by Holcim NZ (2011).
- ***Scenario 3: Both best practice waste management (Scenario 1) and sustainable material procurement (Scenario 2).***

  The above mentioned strategies were combined in this scenario which was developed to quantify the environmental implications if both the measures were adopted during refurbishment. .

A summary of the three scenarios is given in Figure 4.1.

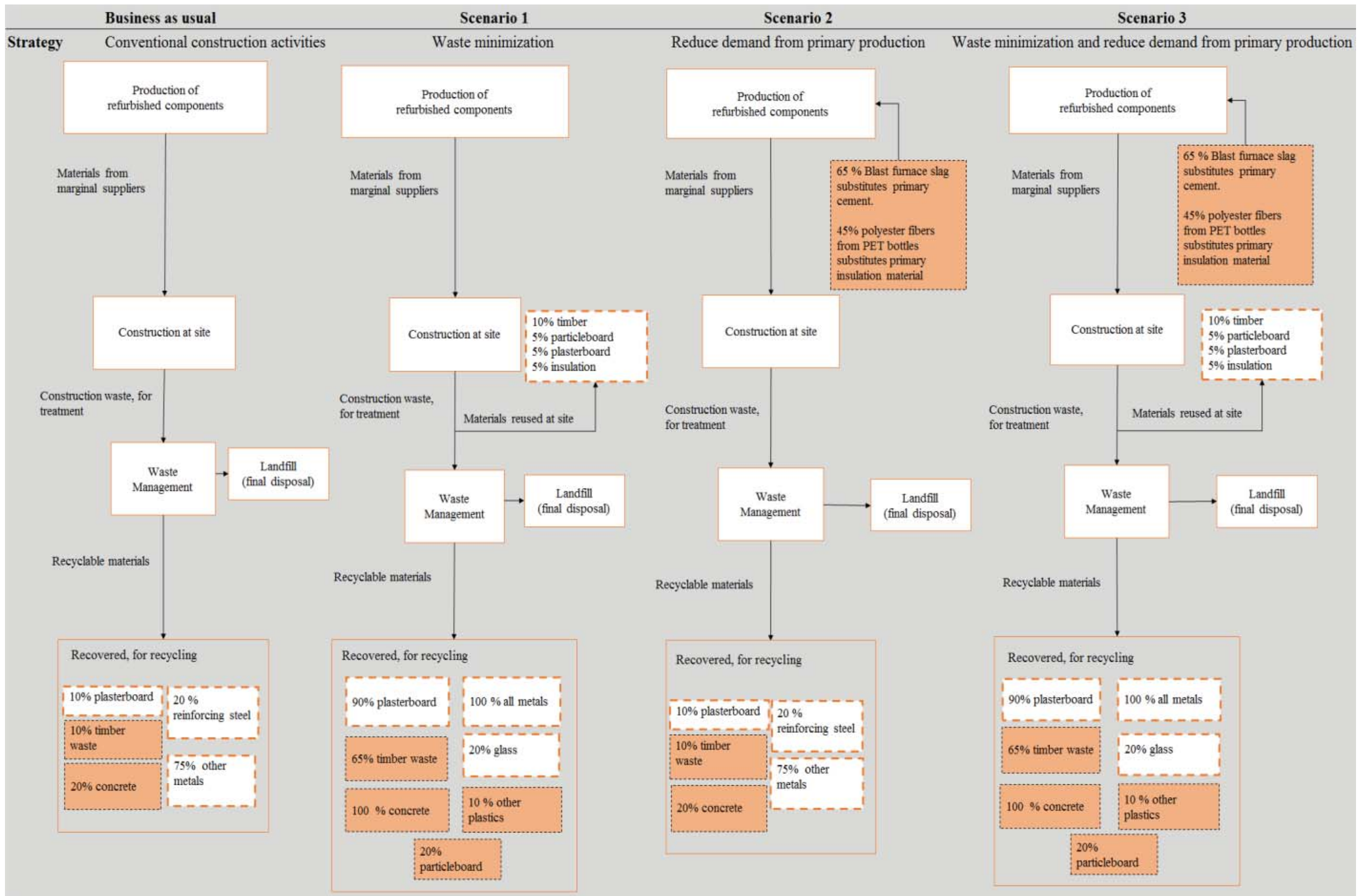

Figure 4.1The system boundary, base case and the three scenarios assessed in the LCA study. Each scenario highlights the share of materials recycled or re-used. The white boxes correspond to the activities in the system boundary and the arrows correspond to material flows. The orange dotted boxes correspond to the recovered materials that avoid burdens from primary production (for example, recovered metals sent for recycling avoid burdens related to primary production of metals) and the orange shaded boxes correspond to the avoided burdens from final disposal of the recovered material (for example, recovery of timber waste used as wood chips for landscaping or fuel does not avoid primary timber production for construction but corresponds to avoided burdens from landfilling of wood waste)

4.2.2 Inventory analysis

In consequential modelling, the inventory is developed based on how the flows and activities are affected by a change in demand for a product or process. This study assumes an increase in demand for refurbishment in each scenario, which leads to the increase in demand for raw materials and energy required for production of refurbished components; and waste management of construction waste available at site. The foreground processes included all the activities and flows as shown in Figure 4.1. The marginal suppliers of construction materials and energy required for the refurbishment were identified (see section 4.2.2.1). Moreover, substitution was applied to the production and use of recyclable/ re-usable materials (see section 4.2.2.2). The ecoinvent v3 database, consequential version, was used to model background processes (ecoinvent, 2013). For the detailed inventory of the refurbished building in each scenario in the supporting information (SI 2, see section I).

4.2.2.1 Identification of marginal suppliers

The identification of marginal suppliers was based on the guidelines for stepwise market-based system delimitation (Weidema, 2003a). In summary, the ability of suppliers to respond to a marginal increase in demand may be constrained by shortage of resources, the high financial cost of production, use of redundant technology, and/or regulatory policies (European Commission, 2013; Weidema, 2003a). A marginal supplier is identified as the most competitive with a steady increase or constant trend that is unaffected by such constraints (Schmidt & Thrane, 2009; Weidema, 2003a, 2003b).

4.2.2.1.1 Marginal supply of construction materials and products

Market information on annual domestic production and trade data for New Zealand for different construction materials was gathered from New Zealand Statistics (2015b), international survey report (USGS, 2013), international commodity trade statistic (UN COMTRADE, 2015), and industry annual reports (Bluescope steel, 2015; Fletcher Building NZ, 2015). In New Zealand's industrial sector, the share of production and fabrication activities related to pre-fabricated building components (e.g., the production of pre-cast concrete or the fabrication of aluminum to produce window frames or solar shading) has increased in proportion to the increase in demand from the New Zealand's building sector (Fletcher Building NZ, 2015; Ministry of Business Innovation and Employment 2013). However, a decline in the domestic production of some key construction materials (e.g., aluminium, cement) has been reported due to financial constraints related to the increase in cost of resource inputs (USGS, 2013). Therefore, the increase in demand for constrained materials and products in the domestic market were modeled using imports from 2008-2015. By default it was assumed that materials/products with a low value-to-weight ratio are traded in the regional market (i.e. close geographic locations, for example Australia, South East Asian countries and China were considered as the regional market for New Zealand) to reduce freight costs (e.g., glass, aggregates), and materials/products with a high value-to-weight ratio are traded in the global market where freight costs do not affect the value of the product (e.g., metals, electric equipment) as suggested by Weidema (2003a). Therefore, the marginal suppliers in the regional market were identified using simple linear regression on the 2008-2015 import trends from Statistics New Zealand (2015b). If there was a constraint in the domestic production of globally traded materials/products (e.g., aluminium, plastics), the global marginal supplier was identified from existing studies which provide the current and future trends in production of these materials (Galiè & Trabucchi, 2014; Schmidt & Thrane, 2009). If market information was insufficient from the suggested sources, ecoinvent processes with consequential modeling were used as these include the generic life cycle inventories for global marginal suppliers of all resources. Table 4.2 shows the list of identified marginal suppliers used in the model.

Table 4.2 Marginal suppliers of construction materials and products

Material	Market	Marginal suppliers	Comment
Aluminium	Global	China (60 %), CIS Russia (22 %) and Middle East (18 %)[a]	New Zealand aluminium production capacity is 360,000 tons annually of which nearly 87 % is exported. Due to increase in production costs and global drop in aluminium prices there has been a sharp decline in national production since 2011(MBIE, 2012; USGS, 2013).
Steel	Global	New Zealand (100 %)	New Zealand steel production capacity is 650, 000 tons annually which primarily supplies the domestic market. Domestic production capacity has steadily increased over the years due to abundance of iron sand ore on the West coast (Bluescope steel, 2015; USGS, 2013; World Steel Association, 2015).
Portland Cement	Regional	South East Asia (72 %) and China (28 %)[b,*]	One of New Zealand's dominant cement producers shut down their manufacturing in 2016 due to financial constraints and high energy costs. New Zealand is now investing in infrastructure to facilitate cement import from overseas (Scanlon, 2016; USGS, 2013).
Aggregates (Sand, Gravel)	Regional	New Zealand (100 %)	Mining for aggregates has steadily increased by nearly 10 % over the last eight years (USGS, 2013).
Float Glass	Regional	China (45 %), Middle East (43 %) and New Zealand (12 %)[b,*]	New Zealand is mainly dependent on float glass imports. However there has been a recent investment in domestic production since 2015 (Galloway, 2012; Metro Glass ltd, 2015).
Sawn timber	Regional	New Zealand (100 %)	New Zealand sawn timber production capacity is 4,050, 000 cubic metres which is sufficient for both domestic consumption and exports (FAO, 2011)
Particleboard	Regional	New Zealand (100 %)	New Zealand particleboard production capacity is 240, 000 cubic metres which is sufficient for both domestic consumption and exports (FAO, 2011).
Gypsum	Regional	Australia (100 %)	New Zealand has no exploitable gypsum reserve and imports over 300, 000 tons of gypsum from Australia. As gypsum is a low unit cost product, future supplies will likely continue from Australia (Sansbury & Boyle, 2001; USGS, 2013)
Expandable polystyrene Polyethylene Polyvinylchloride (PVC)	Global	Middle East (77 %) and USA (23 %)[c]	New Zealand imports all raw materials for plastic manufacturing (Plastics NZ, 2011).
LED luminaires Heat pumps	Global	RoW (66 %) and Europe (33 %)[d]	There are no large scale regional manufacturers of electrical appliances such as commercial lamps and heat pumps, and so the supply is dependent on imports (Bakshi et al., 2013; Ministry for the Environment (NZ), 2009).

Source: [a]Schmidt and Thrane (2009), [b] Statistics NZ (2015b), [c]Galiè and Trabucchi (2014), [d]ecoinvent (2013); *Derived from import trends given in SI 2 section II

4.2.2.1.2 Marginal supply of energy

Each of the modeled activities has an energy input sourced from electricity and/or fossil fuels. The geographic market for grid electricity is regional (Weidema, 2003a), i.e. transmission and trade of grid electricity is limited by location therefore the marginal source of electricity production varies in different countries or regions. Table 4.3 shows the marginal electricity supply for each of the material and product suppliers identified in Table 4.2. The marginal electricity supply for New Zealand was identified using the method suggested by Schmidt et al. (2011). The business-as-usual approach in this method assumed the increase in share of sources for electricity production to be similar to the recent past. Thus the marginal electricity supply for New Zealand was based on differences in the share of sources for electricity production between 2008 and 2015 as reported by Ministry of Business, Innovation and Environment (MBIE) for New Zealand (MBIE, 2015). Similarly the marginal electricity supply for regions South East Asia and the Middle East was identified based on the electricity production reported in IAE reports for the respective regions (IEA, 2013a, 2013b). The geographic market for fossil fuels is global (Weidema, 2003a), therefore the marginal supply of energy directly sourced from fossil fuels such as diesel and natural gas was modeled as given in ecoinvent v3's consequential database.

Table 4.3 Marginal electricity supply of identified material and product suppliers

Technology	New Zealand[a*]	South East Asia[2]	Middle East[b]	China[c]	CIS (Russia)[d]	Australia[d]	North America[d]	Europe[d]	RoW[d]
				(in %)					
Coal	-	36	-	76.4	7.5	86	62.4	79.5	48.5
Oil	-	1	40	0.8	0.3	-	-	-	-
Natural Gas	6	53	60	-	8.6	6	1	-	0.7
Nuclear	-	-	-	2.3	3.1	-	1.4	-	12
Hydro	16	9	-	20	80	6	35.2	7.9	37.4
Geothermal	38	-	-	-	-	-	-	-	0.23
Wind	40	1	-	0.5	-	2	-	12.6	1.11

Source :[a]MBIE (2015) [b]IEA (2013a), [c]IEA (2013b), [d] ecoinvent (2013)

* The inventory for New Zealand's different electricity production sources was obtained from Sacayon Madrigal (2016).

4.2.2.2 Substitution and avoided burdens

In consequential modelling, substitution is applied to model the environmental burdens avoided due to the availability of by-products. In general, there is no distinction between the modelling approach applied to by-products, waste, and recyclable materials (Weidema, 2015; Weidema, 2003a). If a by-product is not utilized or there is no demand for it, this implies that any additional amount produced would be sent to final disposal and thus can be described as waste. If the by product is a recyclable material and is recycled into a new product or material, primary production of this product or material is avoided, i.e. the recycled product/material substitutes the primary one. The substitution ratio can be up to 1:1 if the recycled and the primary product/material are functionally equivalent. If the recyclable material is not functionally equivalent to the primary product/material, the burdens avoided are related to final waste treatment. Recycling efficiency varies for different materials; the recycling efficiency for different types of metal scrap is reported in Table 4.4.

Table 4.4 Summary of modelling assumptions for secondary materials produced from the recovery of demolition waste or used to substitute primary materials during refurbishment and associated avoided burdens.

Materials for waste treatment	Secondary material after recycling	Substitution ratio	Recycling efficiency (%)	Avoided burdens from*
Aluminium scrap	Aluminium	1:1	98 [a]	Primary aluminium production from alumina
Steel scrap	Steel	1:1	90 [b]	Primary steel production from pig iron
Copper scrap	Copper	1:1	64 [c]	Primary copper production from copper ore
Glass	Glass cullet	1:1	-	Primary glass production from sand
Concrete	Aggregates and steel	1:<1 and 1:1	70 for reinforcing steel [b]	Aggregates sent to landfill and primary steel production
Blast furnace slag	Granulated slag cement	1:<1		Blast furnace slag sent to landfill
Timber, for recycling	Wood chips for landscaping or fuel	1:<1	-	Wood chips sent to landfill
Timber, reused at site	Planed sawn wood	1:1	-	Primary sawn wood production from forestry processes
Plasterboard, for recycling	Gypsum	1:1	-	Primary gypsum production
Plasterboard, reused at site	Plasterboard	1:1	-	Primary plasterboard production from gypsum
Particleboard, for recycling	Wood chips for landscaping or fuel	1:<1	-	Wood chips sent to landfill
Particleboard, reused at site	Particleboard	1:1	-	Primary particleboard production
Insulation, reused at site	Polystyrene insulation	1:1	-	Primary insulation production from polystyrene polymers
Other plastics, recycled	Plastic polymers	1:<1	-	Inert waste sent to landfill
Insulation fibers, recycled PET bottles	Polyester insulation	1:<1	-	Inert waste sent to landfill

Source: [a] IAI (2009), [b]AISI (2014),[c] Ruhrberg (2006)
*** Total avoided primary material =Recovery rate x Recycling efficiency (Rigamonti et al., 2009)**

4.2.3 Impact Assessment

Characterised results at midpoint were calculated with the CML impact assessment method for Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photo-chemical Oxidation Potential (POCP), Acidification Potential (AP), Eutrophication Potential (EP) and Abiotic Depletion (resources and fossil fuels (AD_r and AD_{ff})). Instead, Human toxicity carcinogenic (HT-carc), Human toxicity non-carcinogenic (HT-non carc) and Eco-toxicity freshwater ($ET_{freshwater}$) results were calculated using the UseTox method. The impacts on Particulate Matter Formation (PMF) and Ionizing Radiation (IR) were calculated using the ILCD 2011+ and ReCiPe (H) method respectively. These categories and methods were recommended for use by the New Zealand whole building whole of life framework project (Dowdell, 2014).

4.2.4 Sensitivity analysis

To limit uncertainties and increase robustness of the study, a number of sensitivity analyses were performed based upon modification of the recycling efficiency, marginal suppliers mix based on trading partners, and prospective electricity mix:

- Recycling efficiency (S1_RER): the recycling efficiency of aluminium was set to 70 %, steel was set to 78 %, reinforcing steel was set to 67 % and copper was set to 53 % as reported in UNEP (2011).
- Marginal suppliers (S2_TP): the marginal supply of construction materials dominated by imports was modified. Based on the marginal suppliers identified in Table 4.2, it was assumed that each material/product was supplied from a single supplier and the choice of supplier was restricted to the top trading partners for imports to New Zealand. Since 2012, China has been the largest principle trading partner for imports to New Zealand followed by Australia, USA, Japan and the European Union (Statistics NZ, 2015b; Treasury NZ, 2015).

  The marginal supply for aluminium, Portland cement and float glass was only from China; gypsum was from Australia; and mixed plastics and electrical equipment were from USA and the European Union respectively. The remaining construction materials were considered to be sourced from New Zealand which was identified as the dominant marginal supplier (Table 4.2).
- Prospective electricity mixes (S2_TP(el)): for the marginal suppliers identified in the second sensitivity analysis, the marginal electricity supply was re-calculated based on differences in the share of sources for electricity

production between 2015 and the IEA projected 2020 scenario (see SI 2, section II table 2.3). This scenario assumes that the countries have adopted a low carbon electricity grid mix (IEA, 2013b).

4.3 Results

4.3.1 Contribution analysis

Figures 4.2 (a and b) presents the contribution analysis of refurbished components and associated activities for building refurbishment, and the net value for the twelve environmental impact categories in each of the four scenarios. The production of refurbished components contributes over 90 % of the total results (in all scenarios) in ten out of twelve impact categories in all four scenarios. Among these, the refurbished façade components (insulated flat roof, pre-cast concrete walls, double glazed windows and solar shading devices) make ≥ 50 % contribution to six impact categories (GWP , POCP, EP, AD_{ff}, HT carc and PMF). The refurbished heating and lighting components (heat pumps, heat distribution system and LED luminaries) make ≥ 50 % contribution to four impact categories (ODP, HT non carc, AD_{r}, and $ET_{freshwater}$). The contribution of the refurbished façade and the heating and lighting components is similar for the impact categories AP (≈ 47 %) and IR (≈ 25 %). Transport of materials to site and construction at site together make a noticeable contribution to IR (≈ 54 %) and AD_{ff} (≈ 15 %); negligible contributions to (≤ 10 %) to six impact categories (GWP, POCP, AP, EP, HT non carc and PMF); and no contribution to the other four impact categories (ODP, AD_{r}, HT carc and $ET_{freshwater}$). Waste management includes impacts from energy for demolition, transport of construction waste to treatment site, sorting, recycling processes and benefits from avoided primary production or final disposal. The avoided waste reduces the total impact for ten categories (GWP, POCP, AP, EP, AD_{r}, AD_{ff}, HT carc, HT non carc, PMF and IR) by at least 20 %. However, this activity has negligible benefits for ODP (< 1 %), and makes a large contribution to $ET_{freshwater}$ (≥ 250 %). The absolute characterized impact results per kg of material and products used for refurbishment and per kg of material recycled, re-used or used for alternative production are given in SI 2 section IV (tables SI-2.4 and SI-2.8 respectively).

4.3.2 Scenario analysis

The net impact results indicate that the three scenarios that are supposed to provide environmental benefits i.e. reduced environmental impacts due to improved waste management and sustainable material procurement (or both), show better results than the BAU for six out of the twelve impacts (GWP, POCP, AP, AD_{ff} , PMF and IR). For ODP, there is no difference in the results for any scenario. For $ET_{freshwater}$, scenarios 1 and 3 have the highest net impact followed by scenario 2 compared with BAU; the main contribution is from increased recycling during waste treatment. For EP, scenarios 2 and 3 have higher impacts for EP compared with BAU and scenario 1; the main contribution is from refurbished façade elements. For AD_r, HT carc and HT non carc scenarios 1 and 3 have a lower impact compared to BAU but scenario 2 impact has no difference compared to BAU.

Due to the benefits of waste minimization, the net impacts for scenario 1 compared with the BAU scenario are 15-25 % lower for GWP, AD_{ff}, HT carc, PMF and IR; 8-12 % lower for POCP, AP, EP, AD_r and HT non carc; and 56 % higher for $ET_{freshwater}$. Alternative procurement in scenario 2 compared with the BAU scenario yields negligible benefits (≤ 5 %) for GWP, POCP, AP, AD_{ff}, PMF and IR; and 10 % higher impacts for EP. Although avoiding the final disposal of plastic and blast furnace slag to landfill also reduces impacts (see SI table S-2.8), it is insufficient to substantially offset the net impact of the refurbishment.

For the combined waste minimization and alternative procurement scenario (scenario 3) compared with the BAU scenario the net results are 20-30 % lower for GWP, POCP, AD_{ff} and IR; 8-16 % lower for AP, AD_r, HT carc, HT non carc; and 68 % and 10 % higher for $ET_{freshwater}$ and EP respectively.

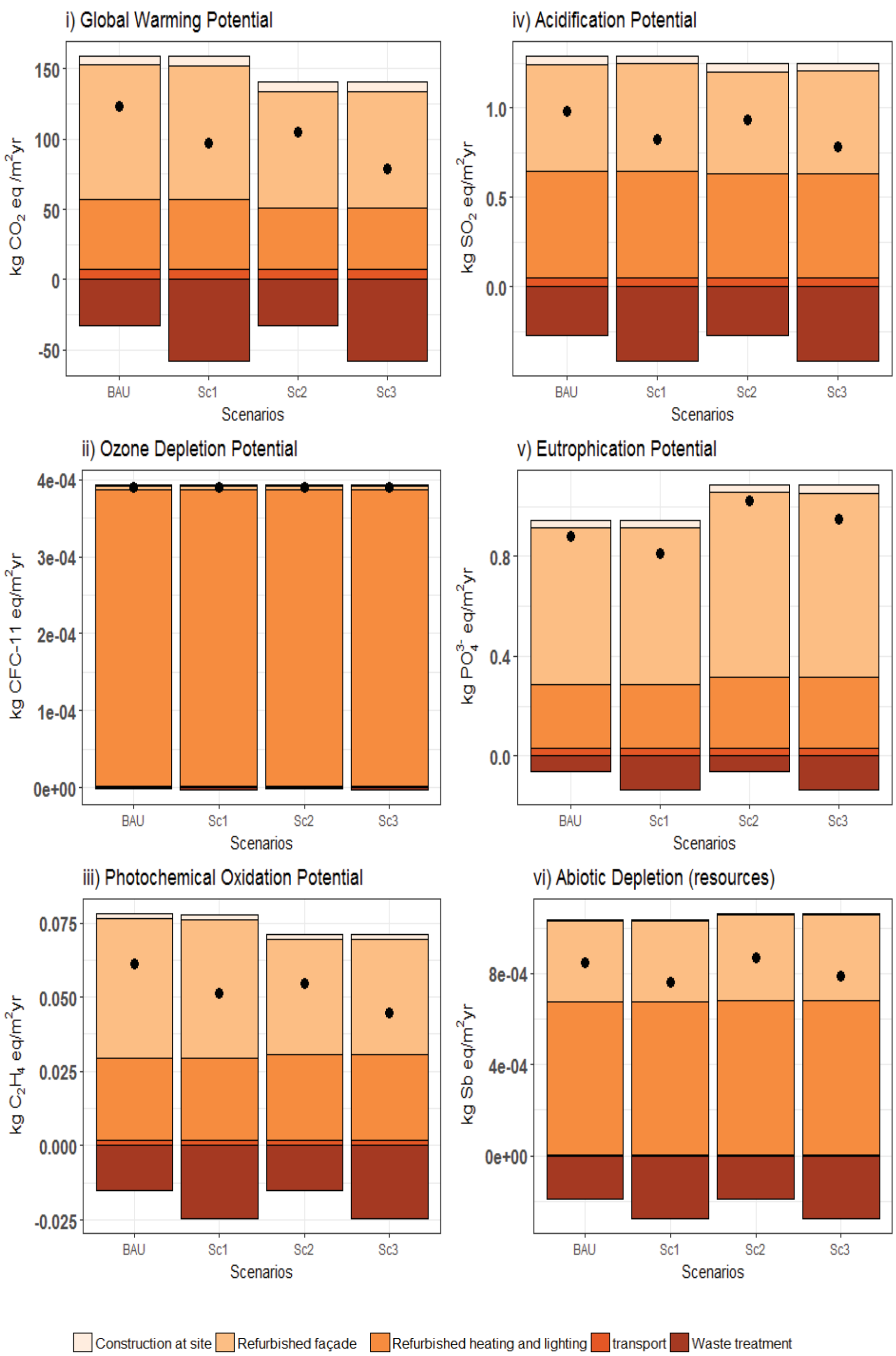

Figure 4.2-a) Impact assessment results for the building refurbishment in Business As Usual scenario (BAU), waste minimization scenario (Sc1), alternative material procurement scenario (Sc2) and combination of waste minimization and alternative material procurement scenario (Sc3). The dot marked in each bar indicates the net impact in each scenario.

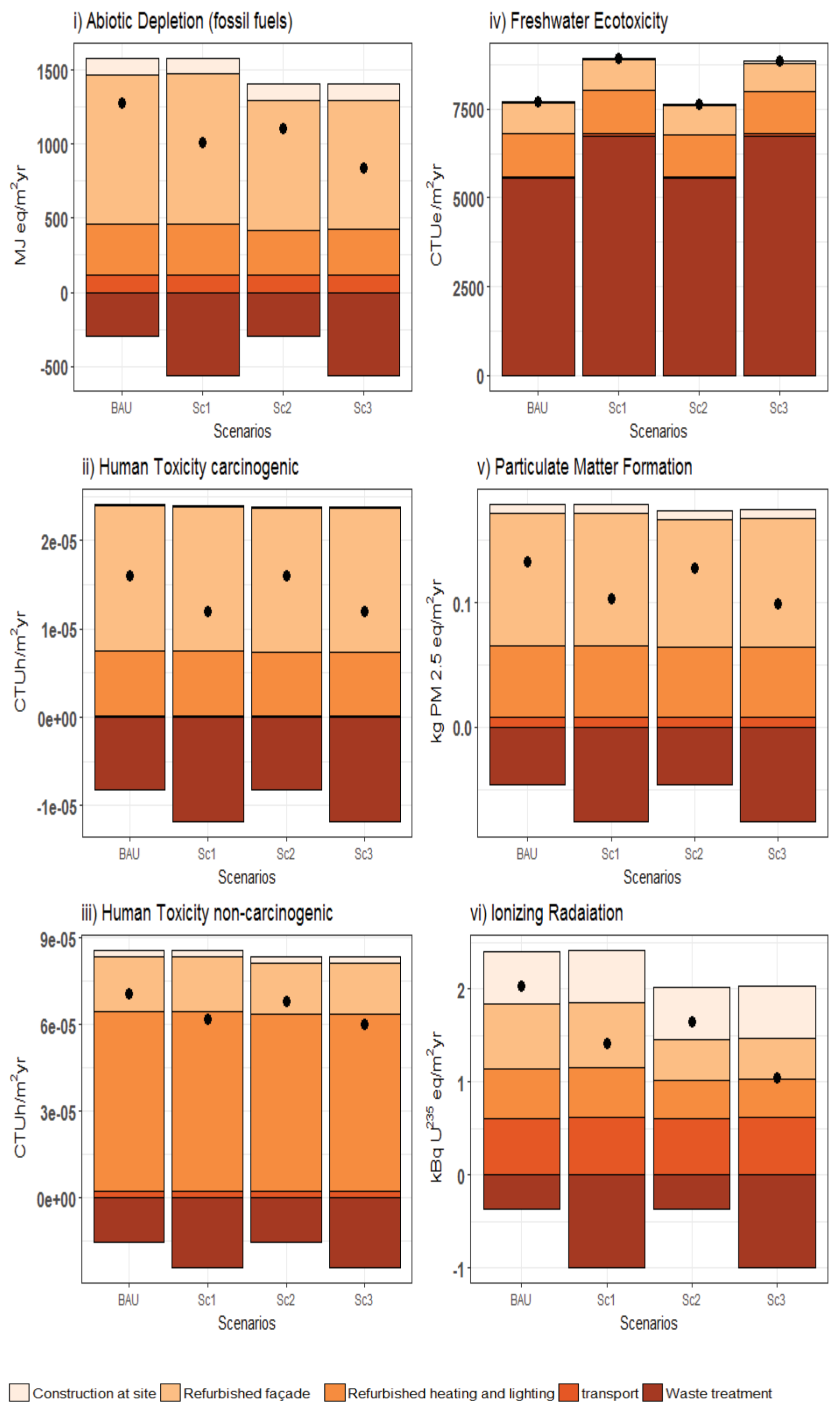

Figure 4.2-b) Impact assessment results for the building refurbishment in Business As Usual scenario (BAU), waste minimization scenario (Sc1), alternative material procurement scenario (Sc2) and combination of waste minimization and alternative material procurement scenario (Sc3). The dot marked in each bar indicates the net impact in each scenario.

4.3.3 Sensitivity analysis

Figures 4.3 (a and b) presents the sensitivity of the net impact results to the recycling efficiency, specific marginal suppliers, and potential change in electricity grid mix in each scenario. The net impact results are sensitive to changes in the three parameters modified for the analysis, but the modification of the parameters does not affect the ranking of net impact results of the scenarios. The impacts of BAU and Scenario 3 are highest and lowest in most impact categories respectively as indicated in section 4.3.1. Moreover, the net results for ODP remained the same across all the scenarios for all three parameters considered in the sensitivity analysis. The absolute characterized impact results with respect to the sensitivity analysis in each scenario are given in SI 2 (section IV, table 2.4).

A decrease in the recycling efficiency of metals (S1_ RER) leads to a 10- 20 % increase to nine of the impact categories (GWP, POCP, AP, AD_{ff}, AD_{r}, HT carc, HT non carc, PMF and IR) compared with the results in section 4.3.1. Limited or negligible changes were observed in the remaining impact categories (≤ 5 %).

If the marginal suppliers are limited to the top New Zealand trading partners (S2_TP), the impacts increase compared with the results in section 4.3.1 for PMF (≈ 50 %) , AP (≈ 23 %), GWP and POCP (≈ 5-15 % in both categories). There is also a major decrease in IR (≥ 100 %). In the alternative electricity grid mix considered for each of the top trading partners (S3_TP(el)), there is a major decrease in the results in each scenario for PMF (≈ 50- 70 %), GWP, POCP, AP and AD_{ff} (≈ 30- 40 % in all categories); at the same time, there is a major increase in IR (≥ 600 %) and smaller increases in AD_{r} and $ET_{freshwater}$ (≈ 4- 8 % in both categories). The results for EP, HT carc and HT non-carc (≤ 1 %) are not sensitive to the change in electricity grid mix. The absolute characterized impact results per kg of material and products with respect to the trading partners required are given in SI 2 (section IV, tables 2.6 and 2.7).

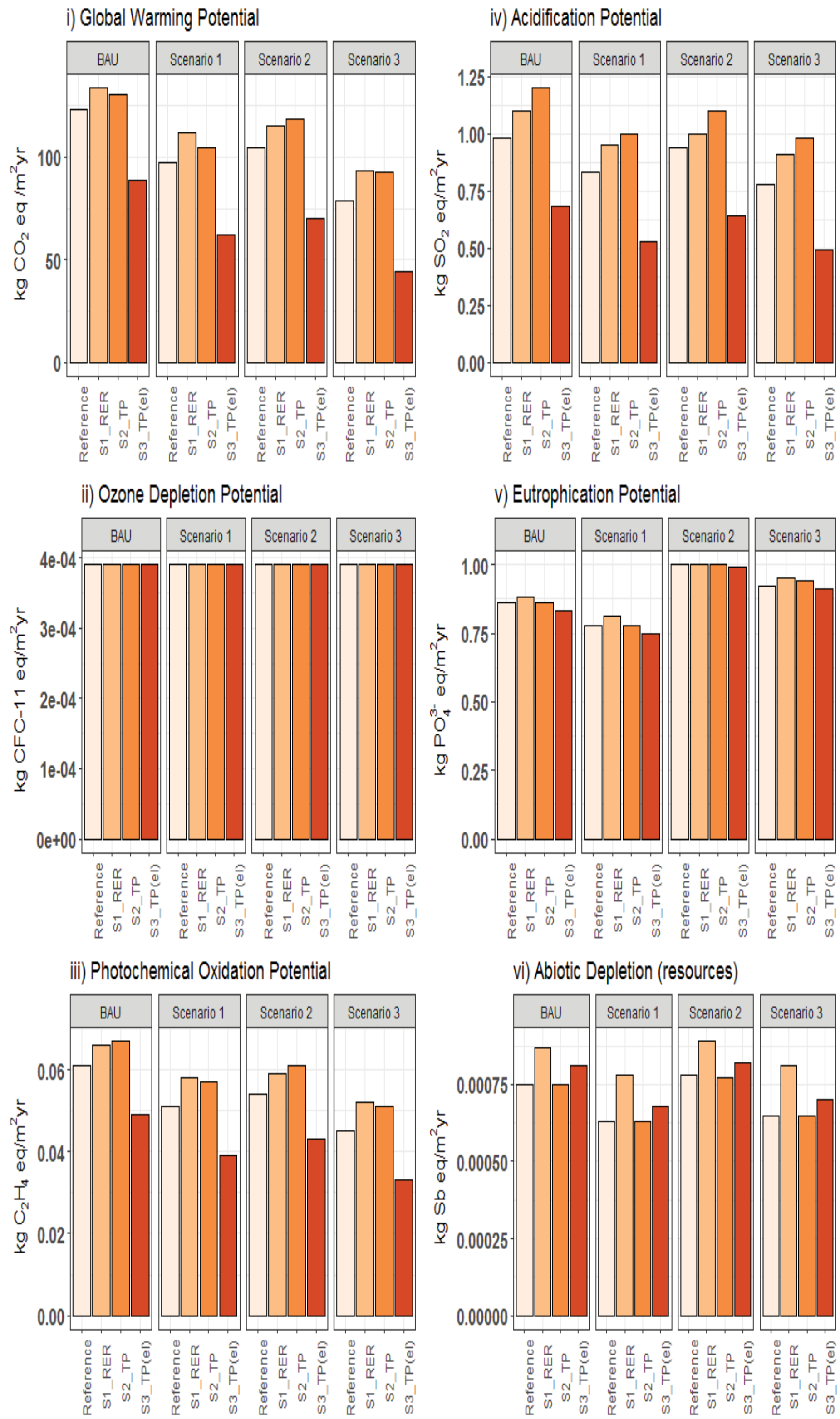

Figure 4.3-a) Net impact results (per functional unit) in each scenario for sensitivity analysis of a) recycling efficiency (S1_ RER), b) specific marginal suppliers (S2_ TP) and c) potential change in electricity grid mix of specific marginal suppliers (S3_ TP(el)).

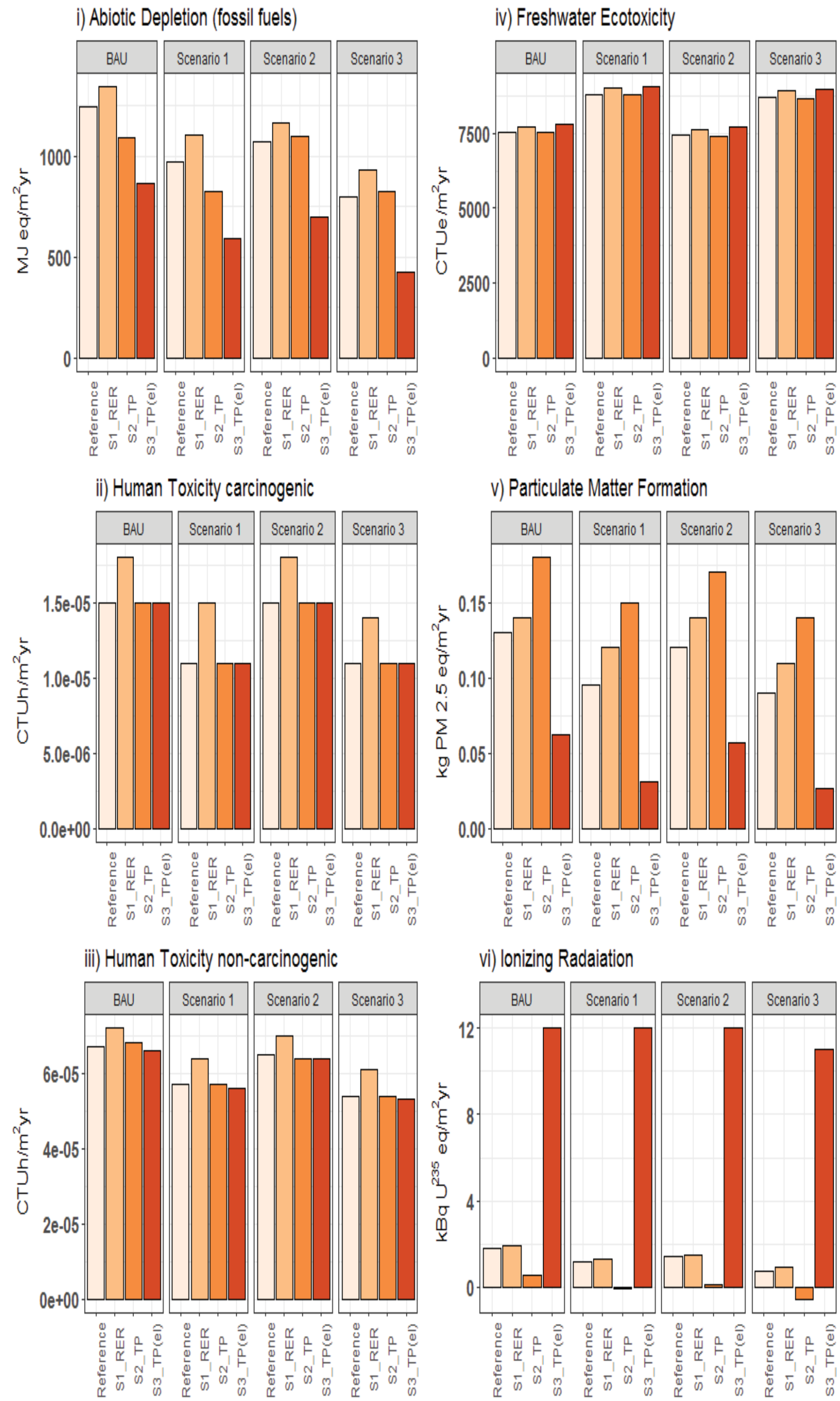

Figure 4.3-b) Net impact results (per functional unit) in each scenario for sensitivity analysis of a) recycling efficiency (S1_ RER), b) specific marginal suppliers (S2_ TP) and c) potential change in electricity grid mix of specific marginal suppliers (S3_ TP(el)).

4.4 Discussion

4.4.1 Contribution Analysis

The largest contribution to most impact category results for the refurbished façade components is from the aluminium used in window frames and shading devices, followed by reinforced concrete walls which make a high contribution to EP; float glass units for windows makes a contribution to HT non carc and polystyrene insulation makes contributions to POCP and AD_{ff}. The largest contribution to the results from the heating and lighting elements is also from metals, particularly copper and aluminium production. Impacts from copper production make a particularly high contribution to HT non carc, AD_{r} and $ET_{freshwater}$; while aluminium production contributes to all these categories. Use of refrigerant HFC 134a in heat pumps was the single highest contributor to ODP. All impacts related to transportation and constructions at site are associated with fuel use. Most benefits related to waste management are associated with aluminium recycling; followed by steel and copper recycling. However, metal recycling contributes to $ET_{freshwater}$. Recycling of other materials such as glass, concrete and timber also provides additional benefits by reducing impacts for GWP, POCP, AP, EP, AD_{r}, AD_{ff}, PMF and IR (see SI table S-4.8).

The impact of materials that require energy intensive production (e.g. aluminium, steel, cement) is determined by the energy source at the site of production. For example: the marginal energy source of the identified suppliers of primary aluminium is mainly from coal (China), oil and natural gas (Middle East) or nuclear and hydro power (Russia). The high proportion of fossil fuel use makes a significant contribution to GWP, POCP, AP, AD_{ff} and PMF; the impact to IR is contributed from the marginal electricity sourced from nuclear power plants in CIS Russia. Impacts from pre-cast concrete production were associated with both Portland cement and reinforcing steel production. Identified marginal suppliers for cement (China and South East Asia) have a high share of fossil fuel in their electricity mix considered for production which contributes to GWP. New Zealand was identified as the marginal supplier for steel; here steel is produced from a basic oxygen furnace with primary inputs of pig iron (extracted from iron sands) and liquid oxygen. The process is highly energy intensive and results in 4.2 kg CO_2 eq/ kg compared to 2.0 kg CO_2 eq/ kg of global average primary steel production (World Steel Association, 2011). Waste gas from the production of liquid oxygen required for steel production contains nitrogen which was the main contributor to EP. While the demand for other materials such as insulation and float glass production is also dominated by imports, energy use during production has a smaller contribution to the associated environmental impacts. Polystyrene polymers produced from fossil fuels contribute to AD_{ff}, and pentane emissions used to expand the polymers (foam blowing) is a prominent volatile organic compound (VOC) which contributes to POCP. Impacts from polyester insulation to POCP, EP, AD_r, and HT carc arise from organic chemicals such as ethylene glycol and terephthalic acid used during production. The contribution to HT non carc from float glass production is associated with the use of crystalline soda ash. The impacts from copper production are mainly related to mining and smelting which leads to leachate wastes and loss of heavy metals which are key agents in toxicity pollution (Ayres et al., 2013; Nriagu, 1989) and resource depletion (Northey et al., 2014). The refrigerant HFC 134a itself does not contribute to ODP but its production involves the emission of other chlorinated hydrocarbons (Saner et al., 2010).

The major hotspots identified in the contribution analysis were also similar to those identified in a previous LCA performed on the same case study using attributional modelling (Ghose et al., 2017); however, the net impacts calculated in this study for the BAU scenario were substantially different (see SI 2 table 2.9) for GWP, AP, AD_r, AD_{ff}, HT carc, PMF and IR as these categories were influenced by the identified marginal suppliers and substitution of recyclable and re-used materials. While the attributional modelling focused on the status quo of current suppliers of construction materials in New Zealand, the consequential modelling identified resource constraints and marginal suppliers and therefore focuses on future trends in the building sector. The results of the contribution analysis with respect to the activities considered in this study are also similar to the findings of Blengini (2009) and Thormark (2001). The findings of both studies on the LCA of low energy buildings indicated the significant contribution of façade elements to the overall results.

4.4.2 Scenario Analysis

The scenario analysis results indicated that in general waste minimization measures (scenario 1) had higher benefits compared to resource efficiency measures (scenario 2) and BAU. Current waste minimization measures in New Zealand primarily focus on recovery of metallic wastes which have high market demand and value. This study additionally quantifies the additional benefits related to recovery and re-use of non-metallic wastes (for example, glass, concrete, timber, plastics), which form the bulk of the construction waste sent to landfills in New Zealand (BRANZ, 2014). Moreover, the re-use of construction waste specifically at the building site decreases the demand for primary production, and thus directly avoids environmental burdens from primary production (Weidema, 2014).

As shown in the scenario 2 results, use of materials with low market demand in alternative material production (blast furnace slag and discarded PET bottles) avoids the impacts related to landfilling. Benefits were mainly associated with the use of blast furnace slag; while the use of polyester insulation containing recycled fibres from discarded PET bottles actually increased the contribution to EP arising from use of organic chemicals such as ethylene glycol and terephthalic acid during polyester production.

Scenario 3 shows substantial benefits of combined resource efficiency and waste minimization measures to reduce the burdens in most impact categories compared to BAU. Lack of local recycling facilities, limited communication with staff at site, unavailability of separate waste bins, and additional primary costs are some of the current challenges associated with limited recovery of construction materials from construction sites in New Zealand (Inglis, 2012; Napier, 2014). For example, feasibility studies on non-metallic waste recovery suggest the need for additional investments for effective supervision and planning at construction sites, which is still lacking for the bulk of construction activities in New Zealand (Hanne & Boyle, 2001; Sansbury & Boyle, 2001). Moreover, a tendency to continue with the cheap conventional materials is a major obstacle to the use of alternative construction materials (Samarasinghe, 2014).

4.4.3 Sensitivity Analysis

With respect to the sensitivity of the net results to a decrease in recycling efficiency, the impacts increase in scenarios with higher metal recovery rates (scenarios 1 and 3). Material recovery rate and recycling efficiency are the two main factors that determine the benefits of recycling (Graedel & Reuter, 2011; Intini & Kühtz, 2011). For example, in this study assuming a low recovery rate (75 %) but a high recycling efficiency (98 %) per kg aluminium scrap will result in the avoidance of 0.74 kg of primary aluminium production; in comparison, a high recovery rate (100 %) but a low recycling efficiency (70 %) per kg aluminium scrap will avoid 0.70 kg of primary aluminium production. Metal alloys or coatings used in specific building components (e.g. aluminium in window frames) could affect the recycling efficiency (Gilmer, 2005; Stacey, 2015). Poor quality of recovered material affects its recyclability, hence another obstacle to the availability of secondary material to substitute primary production (Horvath, 2004; Vieira & Horvath, 2008).

The study also highlights the sensitivity of the results to the choice of marginal suppliers and primarily the policies on energy production for the material production. The contribution to most impact categories was largely dominated by the share of coal used as the marginal source of electricity for the production of construction materials. If coal is phased out, the overall impact for GWP, PCOP, AP, AD_{ff} and PMF is reduced. However, the marginal source of electricity from nuclear power and other renewables (e.g. wind and geothermal) will contribute to IR and AD_r. The high sensitivity to the source of electricity production are in line with findings of Buyle et al. (2016) and Srinivasan et al. (2012) which also highlighted how alternative energy used for production influences the total environmental impact of building materials.

4.4.4 Limitations

Limitations of this study were related to data quality and availability. At the time of this study, the data quality with respect to non-GHG emissions in New Zealand was limited and generic data from ecoinvent was used. Availability of New Zealand specific data could have increased the quality of the results. For instance, New Zealand's Ministry of Environment is striving to develop data on emissions from New Zealand landfills (Ministry for the Environment, 2015). Availability of this data might have indicated additional benefits or trade-offs of avoiding final disposal to landfill. Moreover, the reference case was restricted to a single building to maintain the consistency in the physical characteristics and functionality of the building as comparisons of buildings are often difficult as each building is characteristically different (Leipziger, 2013). Applying the same methodological approach to substantially different types of buildings, such as buildings constructed largely from bio-based materials such as timber, could show different results. With respect to the methodology, there is a consensus on the general methodology and application of consequential LCA for policy making (Ekvall et al., 2016), but the appropriate method for identification of marginal suppliers is still a contested topic (Mathiesen et al., 2009; Suh & Yang, 2014). Recent work by Pizzol & Scotti (2016) discusses current challenges in the identification of marginal suppliers, and proposes the use of international trade databases (for example, UN COMTRADE (2015) and FAO (2011)) and a trade network analysis as a potential approach to increase the robustness of the process for identifying marginal suppliers.

4.5 Conclusion

This study investigated the environmental impacts of large scale energy efficiency refurbishment and the best practice measures that will reduce the overall impacts of this type of refurbishment. Regarding the environmental impacts associated with increase in resource demand, this study corroborates the ideas of Horvath (2004) who highlighted that, although major construction material resources may be plentiful globally, construction material constraints at a regional level are a major concern. Thus the potential environmental impact of the refurbishment depends on where materials such as aluminium and cement are imported from and the energy used to produce them. This is because these materials require energy intensive production and the associated environmental impacts are dominated by the energy sources (particularly fossil fuels) used during production. In addition, the results highlight the need for policymakers and stakeholders to focus on waste management to compensate for the impacts of increasing construction activity related to refurbishment.

The outcome of this study can assist both policy makers and stakeholders in the building sector, and LCA practitioners. Utilization of information on local or regional constraints in the modelling can provide insightful information for policy makers and stakeholders to support avoidance of problem shifting in future policies. To the knowledge of the authors of this study, shortages and constraints in the availability of materials have not been considered in existing LCA case studies of New Zealand buildings. The information on marginal suppliers of major construction materials provided in this study could therefore be used for the assessment of refurbishment or new construction for other building types in New Zealand in future. In future it might be possible to extend the knowledge from this study to economic and social implications using other methods such as Life Cycle Sustainability Assessment (LCSA) when appropriate data are available.

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Chapter 5- Refurbishment of office buildings in New Zealand: identifying priorities for reducing environmental impacts

Abstract

In recent years the building sector has highlighted the importance of efficient operational energy and resource management in minimizing the environmental impacts of buildings. However, differences in building-specific properties (building location, size, construction material, etc.) pose a major challenge in development of generic policy related to this topic. This study investigated the relationship between efficient energy and resource management, building specific characteristics and life cycle-based environmental impacts of deep energy retrofits of office buildings. Life Cycle Assessment (LCA) was performed for 119 refurbished office building prototypes in New Zealand. Each building was assessed under four scenarios: i) business-as-usual, ii) use of on-site photo-voltaic (PV) panels, iii) electricity supply from a renewable energy grid, and iv) best practice construction activities adopted at site. The influence of fifteen building-specific characteristics in combination with each scenario was evaluated. The study used regression analysis, more specifically Kruskal-Wallis and General Additive Modelling (GAM), to support interpretation of the LCA results. All the chosen strategies can significantly contribute to climate change mitigation as compared to business-as-usual. In general, policies on increasing renewable energy sources supplying national grid electricity can substantially reduce most of the impacts related to buildings. Better construction practices should be prioritised over on-site PV installation as use of PV panels significantly increases the environmental impacts related to use of resources. With respect to the building characteristics, in large buildings efficient HVAC and smaller wall to window ratio are beneficial features while in small buildings, the choice of façade materials with low embodied impacts should be prioritised. These findings can support policy makers to prioritise strategies to improve the environmental performance of typical office buildings in New Zealand and in regions with similar building construction and climate.

5.1. Introduction

Large scale refurbishment of buildings with multiple energy efficiency measures is regarded as an important strategy for reducing energy demand and mitigating climate change. Numerous studies have highlighted that energy efficiency improvements to office buildings can lower future environmental impacts as a result of reduced operational energy use (Asadi et al., 2012; Ascione et al., 2014; Carletti et al., 2014b; Doran et al., 2009). However, refurbishment activities can also contribute between 2 and 55% of the total impacts over the refurbished building's total service life across environmental indicators such as global warming potential, atmospheric acidification and eco-toxicity, depending on the quantities of material flows and the frequency of these activities (Grant et al., 2014; Grant & Ries, 2013; Juan et al., 2010). Therefore, as well as focusing on reducing the operational energy consumption in the building sector, it is important to also consider the wider range of environmental impacts associated with the refurbishment activities themselves (Moschetti & Brattebø, 2016).

Life Cycle Assessment (LCA) is a key analytical tool widely utilized in the building sector to quantify the environmental impacts of different building components, construction activities and whole buildings. Several studies have assessed the comprehensive environmental impacts of discrete refurbishment such as adding insulation (Nicolae et al., 2015); modification of wall to window ratio (Su & Zhang, 2010); adoption of multiple glazed windows (Citherlet et al., 2000; Salazar & Sowlati, 2008b) and solar shading (Babaizadeh et al., 2015; Carletti et al., 2014b); modification of heating and ventilation units (Greening et al., 2012; Mattinen et al., 2015; Rinne & Syri, 2013); lighting systems (Principi et al., 2014; Tähkämö et al., 2013); and the adoption of on-site energy production from photovoltaic plants (Balcombe et al., 2015; Bush et al., 2014). Studies that have focused on the environmental performance of buildings in which several energy efficiency measures have been adopted reported the overarching influence of electricity mix (Al-Ghamdi et al., 2015; Heeren et al., 2015) and construction activities related to materials supply and waste management (Bhochhibhoya et al., 2016; Blengini et al., 2010a; Srinivasan et al., 2012).

However, LCA modelling results may vary considerably depending on factors such as the geographical location and the technology type of the inventoried processes (Reap et al., 2008). Al-Ghamdi et al. (2015) evaluated the life cycle impacts of a reference 43000 ft^2 (3995 m^2) office building situated in 400 locations worldwide; they showed that there was considerable variation in the environmental performance of the same building in different locations. Similarly, Babaizadeh et al. (2015) evaluated the environmental and economic performance of solar shadings, highlighting the variability in environmental benefits related to shading material and design depending on building location. Also, relatively few LCA studies have explored the environmental performance of large scale refurbishments of whole buildings (Buyle et al., 2014; Pomponi et al., 2015; Rønning et al., 2008; Vilches et al., 2017). Moreover, most of these studies are usually limited to an assessment of embodied energy and global warming potential of a single case study building. As the environmental performance of buildings is influenced by several factors such as electricity mix, thermal inertia, choice of heating system or construction materials, building size and location (Babaizadeh et al., 2015; Grant et al., 2016; Heeren et al., 2015), it is difficult to generalize the outcomes of an LCA study made on a single building. Scenario analysis and sensitivity analysis are commonly adopted techniques to assess the robustness of the results (Wei et al., 2015). Statistical methods have been suggested to more accurately deal with uncertainty in LCA (Lloyd & Ries, 2007). Stochastic modelling performed by Monte Carlo simulations has been adopted in numerous studies to deal with inaccuracies in data (Huijbregts et al., 2001). Inferential statistical modelling such as correlation and regression analysis increases the predictive power of LCA results, and is thus recommended to help in decision making (Grant et al., 2016). Regression analysis was used by Atkas and Bilec (2012) to estimate the service life of building products for LCA, by including technical and social factors. Berger and Finkbeiner (2011) used correlation analysis to identify dependencies between environmental indicators. Lasvaux et al. (2016) used principal component analysis to help in identifying the effect of impact assessment methods for construction materials (Lasvaux et al., 2016). And Heeren et al. (2015) used multivariate correlation and Monte Carlo simulations to determine the most influential factors affecting the life cycle inventory and environmental impacts of buildings in Switzerland among twenty eight parameters related to building construction, energy load and external conditions.

The desirability of reducing operational energy consumption in New Zealand's commercial office buildings has been highlighted by Amitrano et al. (2014b). In pursuit of this objective, a comprehensive set of refurbishment measures were developed and recommended to reduce the operational energy consumption of typical office buildings based on their energy demand, size and location by Cory and colleagues (Cory, 2016; Cory et al., 2015). However, a subsequent detailed environmental assessment of all these measures adopted in a typical multi-storied office building in Auckland, New Zealand, revealed the environmental benefits were sensitive to external factors such as electricity mix and resource management as shown in chapters 3 and 4. Building on these findings, this study expands the assessment to consider multiple office buildings of different sizes, refurbished using alternative construction materials at different locations in New Zealand. In particular, this study explores how different potential policies concerning operational energy and resource management influence the environmental performance of refurbished office buildings in New Zealand.

In addition, the study uses regression models to estimate how the suggested refurbishment measures and building characteristics allow predicting the environmental performance in each scenario.

The findings of this study aim to generate additional information to support the effectiveness of future policies and refurbishment measures for typical office buildings in New Zealand and and in regions with similar building construction and climate.

5.2. Methodology

In this study, the influence of three different policy interventions on the potential environmental impacts of 119 office buildings operating for 25 years after refurbishment was assessed. All the buildings were modelled as having adopted large scale refurbishment measures leading to at least a 60 per cent reduction in operational energy consumption. A Business-As-Usual (BAU) scenario was defined in which all refurbished buildings were supplied with grid electricity. The marginal share of energy sources used to generate grid electricity was assumed to be similar to past years (21 % non-renewable and 79 % renewable)[4].

The three potential policy interventions were:

- Installation of photovoltaic panels on the roof of each refurbished building to enable on-site renewable energy generation (scenario PV) (Bedford et al., 2016). If the energy demand of a refurbished building is greater than the electricity produced at site, the additional energy demand is supplied with grid electricity as modelled in the BAU scenario.

[4] Based on the change in electricity production from 2000-2013 (MBIE, 2014). Method used to calculate marginal energy sources is based on Schmidt et al. (2011)

- Increase in the marginal share of renewables supplying grid electricity (Bedford et al., 2016). Therefore the refurbished buildings operated with more than 90 per cent of renewables[5] supplying the grid (scenario RE).

- Widespread adoption of best practice construction methods, where all raw materials required for refurbishment were supplied specifically from manufacturing sites using renewable energy; in addition, the final disposal of construction and demolition waste produced at construction sites was directed away from landfills by maximizing recovery, re-use and recycling of materials (Ghose et al., 2017; International Resource Panel, 2017; Srinivasan et al., 2012) (scenario Best Construction Practice (BCP)) In this scenario, operational energy consumed in buildings is supplied with grid electricity as modelled in BAU scenario.

The study involved two main steps. Firstly, the environmental impacts related to refurbishment and subsequent operational energy consumption was calculated using Life Cycle Assessment (LCA). Secondly, inferential statistical analysis, specifically generalized regression analysis, was used to determine the relationships between the potential environmental impacts and the respective influence of the selected policies, refurbishment measures and building characteristics.

The primary data were obtained from a study by Cory (2016) who had developed prototypical building refurbishment models based on construction and energy consumption details of seventeen existing buildings in New Zealand. He also simulated the operational energy consumption in seven different regions representative of typical climatic conditions found in New Zealand. A total of 119 (=17 x 7) refurbished building prototypes were available using all the possible building-region combinations. The study recommended a standard set of refurbishment measures that would reduce the operational energy consumption of these buildings by at least 60 per cent in each region. These refurbishment measures were: large scale transformation of the façade with increased insulation to building envelope (wall and roof); optimization of the Wall to Window Ratio (WWR); replacement of window types; addition of solar shading to avoid passive solar heat gain; change of the air conditioning system (heating and cooling) from a natural gas operated boiler and electric chiller to electric heat pumps; and replacement of existing compact fluorescent lamps with LED luminaires. The data for operational

[5] Based on suggested change in electricity production from 2010-2040 (MBIE, 2012)

energy consumption of the refurbished building prototypes were simulated for both refurbished buildings with PV installed, and refurbished buildings without PV installed.

5.2.1 LCA modelling

To investigate the environmental performance of each refurbished office building, LCA was performed based on the requirements and guidance in the building standard EN 15 978. The processes included in the system boundary were: raw material extraction and processing, product manufacture; product transportation to the construction site and construction process; and transportation and waste management of demolished material produced during refurbishment; and the annual operational energy use (EN 15978, 2011). The functional unit was determined as 1 m^2 gross floor area of the refurbished building prototype with a ≥ 60 per cent reduction in annual energy consumption compared to its pre-refurbishment annual energy consumption.

The prototypical models provided by Cory (2016) were developed in the EnergyPlus energy simulation tool (EnergyPlus 8.6.0, 2015) and a corresponding graphical interface OpenStudio SketchUp (Lammers, 2011) which provided the required data on operational energy consumption, construction details and building geometry. The energy simulation for the prototypical models was based on the real energy use in commercial buildings derived from the Building Energy End use Study (BEES) performed by the Building Research Association in New Zealand (BRANZ). Use of data measured from real buildings reduces the uncertainties associated with energy modelling, particularly relating to the lack of information and assumptions (Cory et al., 2015). This improves the reliability of the energy simulation results from the prototypical models.

The suggested refurbishment measures required a large scale transformation, also referred to as "deep energy refurbishment", of the existing building to improve its energy performance (IEA EBC, 2015). Therefore it was assumed that the existing façade (non-load bearing external walls and windows) and technical equipment for Heating, Ventilation and Air-Conditioning (HVAC) (boilers, chillers and radiators) and lighting (compact fluorescent luminaires) were removed, demolished and sent for waste treatment. The façade components of the refurbished building were assumed to be re-constructed with pre-fabricated components such as external (non-load bearing) walls, insulation (for external wall and roof), wall boards, windows with advanced glazing and solar shading for the façade. The technical equipment for

HVAC and lighting systems were replaced with air source heat pumps and LED luminaires respectively. However, the prototypical models did not provide details on internal walls, floors and load-bearing construction and hence these were not modelled in this study.

Using the data on building geometry, construction, and energy consumption, life cycle inventories were developed for all 119 buildings for each of the four scenarios (BAU, PV, RE and BCP) thus providing a sample size of 476 buildings (= 119 x 4). Fifteen independent variables were identified for each refurbished building based on the individual building characteristics and refurbished measures (see Table 5.1). Details on estimating material quantities from building geometry can be found in chapter 3 (sections 3.2.3.1- 3.2.3.3). Data on supply of raw material and finished products required for refurbishment were obtained from statistical agencies (Statistics NZ, 2015; UN COMTRADE, 2015; USGS, 2013) Transportation distances and modes varied with respect to material type, site of production and construction. Total transportation was calculated based on typical distances and modes of transport provided by Dowdell et al. (2016). Assumptions on the share of demolished materials recovered from construction site were also based on data provided by Dowdell et al. (2016) for conventional and best practice construction measures in New Zealand. Data on the current and predicted energy sources used for grid electricity production for New Zealand was obtained from (MBIE, 2012, 2015). The predicted energy sources used to produce grid electricity assumes an increase in the share of renewable sources such as wind and geothermal (MBIE, 2012; NZ Ministry of Economic Development, 2011). Emissions related to electricity and materials produced in New Zealand were obtained from Sacayon Madrigal (2016) and (Ministry for the Environment, 2015; Sinclair Knight Merz, 2004; UN FCCC, 2014) respectively. The inventory was developed using consequential modelling i.e. the emissions were calculated for processes that responded to a change in demand. In this study, the change in demand was assumed to be an increase in demand for energy efficiency refurbishments. Details on the modelling procedure used to identify marginal supply of materials and energy, and the substitution procedure of recycled or re-used materials, can be found in chapter 4. (sections 4.2.2.1- 4.2.2.2). The inventory for background processes was based on the consequential version of the ecoinvent v3 database (ecoinvent, 2013c). Data specific to the building characteristics, refurbished measures and energy is provided in the supporting information (SI-3a).

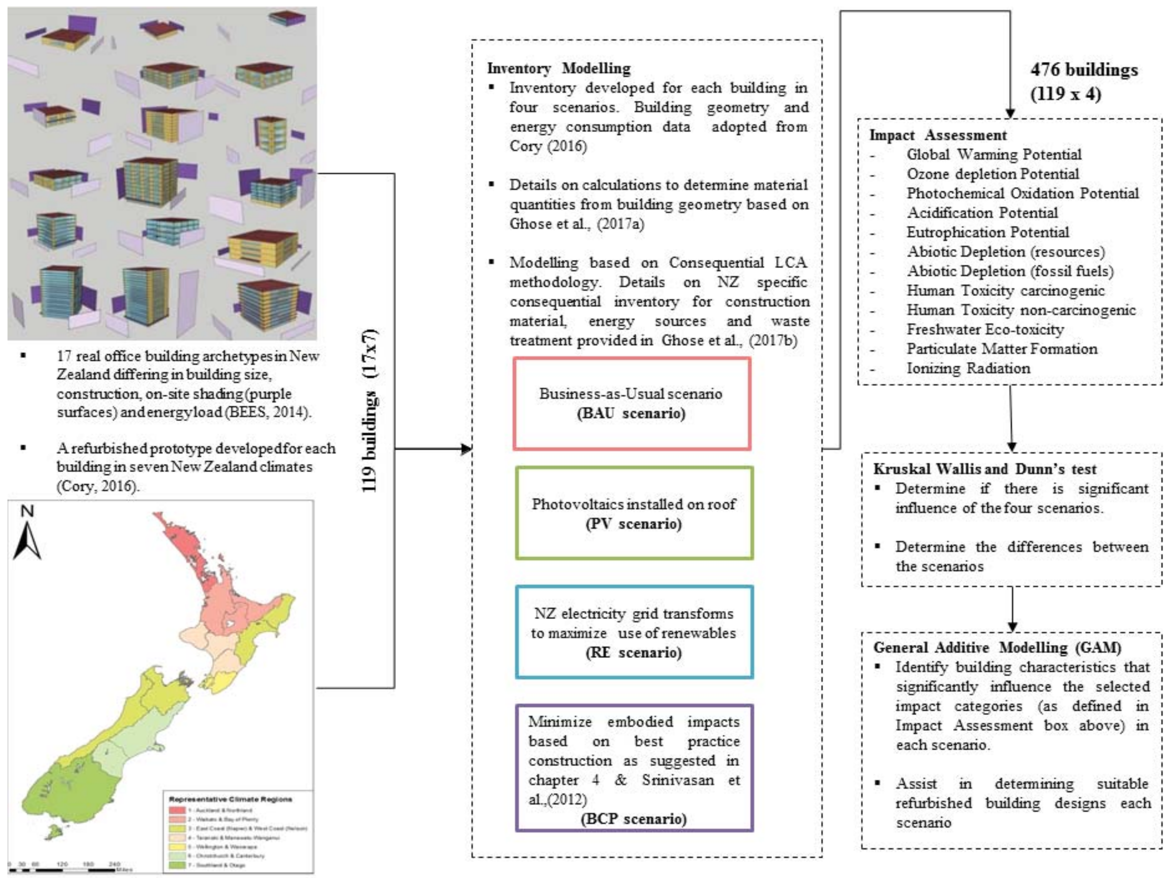

Figure 5.1 Schematic representation of the methodology adopted in this study. The left side of the diagram shows the data adopted from existing studies in New Zealand which investigated the energy demand of existing buildings and developed refurbishment strategies for them. The central part of the diagram shows that this study builds on New Zealand specific inventories developed by previous LCA case studies and adopts them for four scenarios. This study further uses inferential statistical methods to infer the effects of policies and building characteristics on twelve different impact categories.

Table 5.1 Summary of building characteristics which were considered as predictor variables in the GAM modelling to test their influence on the environmental impact.

Building characteristics	Unit	Comment
i) Gross Floor Area (GFA)	m^2	Total floor area for different buildings ranging from approx. 200- 33,000 m^2. Does not change after refurbishment.
ii) Location	-	Selected seven regions 1) Auckland & Northland 2) Hamilton & Waikato, 3) East & West Coast (including Napier and Nelson), 4) Manawatu & Taranaki, 5) Wellington & Wairarapa 6) Christchurch & Canterbury 7) Otago & Southland
iii) Roof Area	m^2	All buildings adopted a flat roof construction. This is not modified after refurbishment.
iv) Storeys	Nos.	Determines the height of the building. This is not modified after refurbishment.
v) Shading factors	-	Factors determined by position of mid-summer and mid-winter sun and are specific based on the location of the building. Used to calculate the width of the solar shading overhangs on the North façade.
vi) Façade material	-	Depending on the building size, façades were installed with: 1) Bricks (GFA <649 m^2), 2) concrete blocks (GFA 650-1499 m^2), 3) fibre cement (GFA 1500-3499 m^2) and 4) reinforced concrete (GFA >3500 m^2) Type of façade material assumed to remain the same after refurbishment in different building types.
vii) Window-Wall ratio (WWR)	-	Ratio of the total window area to the total façade area. Modified based on building size and location
viii) Window type	-	Refurbished buildings were installed with aluminium framed windows that were: 1) single glazed, 2) clear double glazed, 3) double glazed with Low Emissivity (low-e) or 4) tinted double glazed with low-e windows
ix) R-value (wall)	m^2 K/W	Thermal resistivity of the external walls. Modified based on building characteristics.
x) R-value (roof)	m^2 K/W	Thermal resistivity of the roof. Modified based on building characteristics.
xi) Heat pumps	Nos.	Number of heat pumps installed in the refurbished building.
xii) LED luminaires	Nos.	Number of LED luminaires installed in the refurbished building.
xiii) Energy for heating and cooling	kWh	Annual energy consumed in refurbished buildings for heating and cooling.
xiv) Energy for lighting and equipment use	kWh	Annual energy consumed in refurbished buildings for lighting and equipment use.
xv) Transport	tkm	Total transport related to the refurbishment process to and from the site of construction.

Twelve impact categories were selected to assess the environmental impacts of building refurbishment of all buildings in each scenario. These impact categories and impact assessment methods were suggested by BRANZ based on recommendations in EN15 978 (Dowdell, 2014). The CML impact assessment method was used to analyze Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photo-chemical Oxidation Potential (PCOP), Acidification Potential (AP), Eutrophication Potential (EP) and Abiotic Depletion (resources and fossil fuels (AD_r and AD_{ff})). The UseTox method was used for Human toxicity carcinogenic (HT-carc), Human toxicity non-carcinogenic (HT-non carc) and Eco-toxicity freshwater ($ET_{freshwater}$). The ILCD 2011+ and ReCiPe (H) methods were used for Particulate Matter Formation (PMF) and Ionizing Radiation (IR) respectively.

5.2.2 Statistical Analysis

This study focussed on the use of inferential statistical modelling, specifically the Kruskal-Wallis test, in a preliminary stage, and General Additive Model (GAM) in a second stage. Classical regression analyses typically assume normality, linearity and homoscedasticity of the underlying data. In this study the underlying data violated the Shapiro-Wilk test for normal distribution, i.e. the residuals were not normally distributed. The Kruskal Wallis test is the non-parametric alternative method for one-way Analysis Of Variance (ANOVA), i.e. unlike ANOVA, it does not assume the normal distribution of the residuals of the sample (Theodorsson-Norheim, 1986). This method together with a post hoc Dunn's test were utilized to identify the effect of the defined scenarios on the selected environmental impact category results, and to compare the calculated means for the scenarios for each impact category. GAM is a generalized version of General Linear regression Models (GLM) (Guisan et al., 2002) used in this study to estimate the environmental impact based on the independent variables related to refurbishment. This modelling approach is particularly helpful to handle non-linearity in the data (see Box 1 for details).

Box 5.1| General Additive Modelling

GAM is an alternative regression modelling method that identifies the appropriate transformation of the data to maximize the relationship between the dependent and independent variables without assuming normality or linearity of the underlying data (Hastie & Tibshirani, 1990; Wood, 2006). The basic model for linear regression is:

$$\mathbb{E}(y) = \mu \qquad \text{Eq 1}$$

$$g(\mu) = \beta_0 + f_1(X_1) + f_2(X_2) + \cdots + f_n(X_n) \qquad \text{Eq 2}$$

Where Y is the observed outcome, or dependent variable, the environmental impact here, $\mathbb{E}(y)$, or μ is the mean of the distribution of this outcome (from the exponential family), and g is the so-called link function classically used in GLMs to incorporate the dependency of μ on the independent variables X_i's. In this case, g is the identity function. β_0 is the intercept and $f_1, \ldots, f_n$ are the univariate representation which allows to decompose the multivariate dependency of the continuous $g(\mu)$ to the X_i's (superposition theorem).

In classical GLMs, the X_i's are multiplied by the coefficients (β's) and summed, giving the linear predictor $X\beta$ which provides the expected values in a linear regression model (Clark, 2016). In the case that the predictor variables are non-linear, GAM models use a series of smoothers 'f' from a chosen family of functions to fit the data locally; the model copes with a wide range of response shapes, in particular non-normal or non-linear.

An alpha level of .05=5% was used for all statistical tests. The implementation of all statistical modelling was performed using R (R Core Team, 2017).

5.2.2.1 Model selection

Several different GAM models were tested for each impact category. In this study only the results of the best fit model were reported (see SI-3). A backward stepwise procedure (Derksen & Keselman, 1992) was used to perform variable selection. Firstly, two complete models (See Equations 1 & 2) are developed that included all the independent variables (building characteristics and scenarios). In Equation 1 no interaction was considered between the building characteristics and the scenarios. In

Equation 2, interaction terms were considered i.e. consider the effect of a building characteristic in a specific scenario.

$$\mu = \beta_0 + f_1(x_1) + f_2(x_2) + \cdots + f_n(x_n) + f_\gamma(\gamma_1) + f_\gamma(\gamma_2) + \cdots + f_\gamma(\gamma_i) \qquad \text{Eq3}$$

$$\mu = \beta_0 + f_1(\gamma_1 x_1) + f_1(\gamma_2 x_1) + f_2(\gamma_1 x_2) + f_2(\gamma_2 x_2) + \cdots + f_n(\gamma_i . x_n) \qquad \text{Eq4}$$

Where,

μ and $\beta_0, f_1, \ldots f_n$ are as shown in Equation 2. $x_1 \ldots x_n$ are the considered fifteen (n=15) independent variables as indicated in Table 1. $\gamma_1 \ldots \gamma_i$ are the independent variables representing the four (*i*=4) tested scenarios (BAU, PV, RE, BCP), such that when $\gamma_1 = 1;\ \gamma_2 = \gamma_i = 0$.

Two successive rules were applied to build and compare several parsimonious models with a subset of the independent variables determined by the backward stepwise selection procedure:

1) Only independent variables which were identified as significant ($p<0.05$) predictors of the impact category with or without interaction were retained in the model.

2) If two or more variables were highly collinear (rho ≥ 0.95)[6], only one of these variables was included as long as removing the others did not reduce the adjusted R^2 value of the model.

As all parsimonious models were nested in the complete models[7] (Equations 3 & 4), an ANOVA F-test was used to determine if the parsimonious models predict (fit) as well as or better than the complete model. Further the Akaike Information Criterion (AIC; the smaller, the better the model, Akaike (1974)) of the models was used to select the best predictive GAM model.

[6] Determined based on Spearman's rank correlation or 'rho' is a nonparametric measure of correlation and does not consider the underlying distribution of the data.

[7] The parsimonious models are constructed using a subset of the variables of the complete model

5.3 Results

Section 5.3.1 reports the results of the preliminary one-way Kruskal-Wallis and the post hoc TukeyHSD test. Section 5.3.2 is concerned with GAM results for each impact category.

5.3.1 Kruskal-Wallis and post hoc Dunn test results

The Kruskal-Wallis results showed that there was a statistically significant difference (*p<0.001)* between the scenarios in all impact categories. Figures 5.2a and 5.2b show the comparison between the four scenarios (BAU, PV, RE and BCP) based on the impact of all buildings (n=119) in each scenario. The figures also report the summary from the Kruskal-Wallis results for all twelve impact categories. Based on the Kruskal-Wallis test, a significant effect of the scenarios was detected for all impact categories except $ET_{freshwater}$ (H (3) =5.78, p=1.22e-01). Furthermore, based on the Kruskal-Wallis and Dunn test results, it was clear that with respect to GWP (H (3) = 24.684, p=1.798e-05), refurbished buildings in the PV, RE and BCP scenarios have significantly lower impacts compared to buildings in the BAU scenario.

5.3.1.1 Buildings in BAU compared to other scenarios

The life cycle impact of buildings installed with PV was significantly lower for six categories (GWP, PCOP, AP, ADff, HT carc, PMF); significantly higher for three categories (ODP, AD_r and IR); and non-significant for three categories (EP, HT non carc and $ET_{freshwater}$) as compared to that of refurbished buildings in BAU. The life cycle impact of buildings connected to the renewable electricity grid had significantly lower impact for all categories except two categories (AD_r and IR, where p-value=>0.05) as compared to buildings in BAU scenario. In the scenario with buildings adopting best construction practice, the life cycle impact was significantly lower for six categories (GWP, PCOP, AP, ADff, HT carc, PMF), and significantly higher for IR, as compared to buildings in BAU, and not significantly different for the remaining five impact categories (ODP, EP, AD_r, HT non carc, $ET_{freshwater}$).

5.3.1.2 Comparison of buildings in RE, PV and BCP scenarios

The impacts of the buildings in the RE scenario are significantly lower for seven categories as compared to buildings in the PV scenario (ODP, EP, AD_r, AD_{ff}, HT carc, HT non carc and IR) and BCP scenario (AP, EP, AD_{ff}, HT carc, HT non carc, $ET_{freshwater}$ and IR). Moreover, the impacts of the buildings in the PV scenario are significantly higher for three categories (ODP, AD_r and PMF); significantly lower for three categories (AP, PCOP and IR); and not significantly different for the six remaining categories as compared to buildings in the BCP scenario.

In summary, the results indicated that refurbished buildings in the RE scenario had the least environmental impact compared to buildings in all other scenarios for most impact categories; while the benefits from buildings in PV and BCP scenarios are similar as compared to buildings in the BAU scenario. Additional details on significant differences between scenarios based on the post hoc Dunn's test are provided in the supporting information (SI-3b).

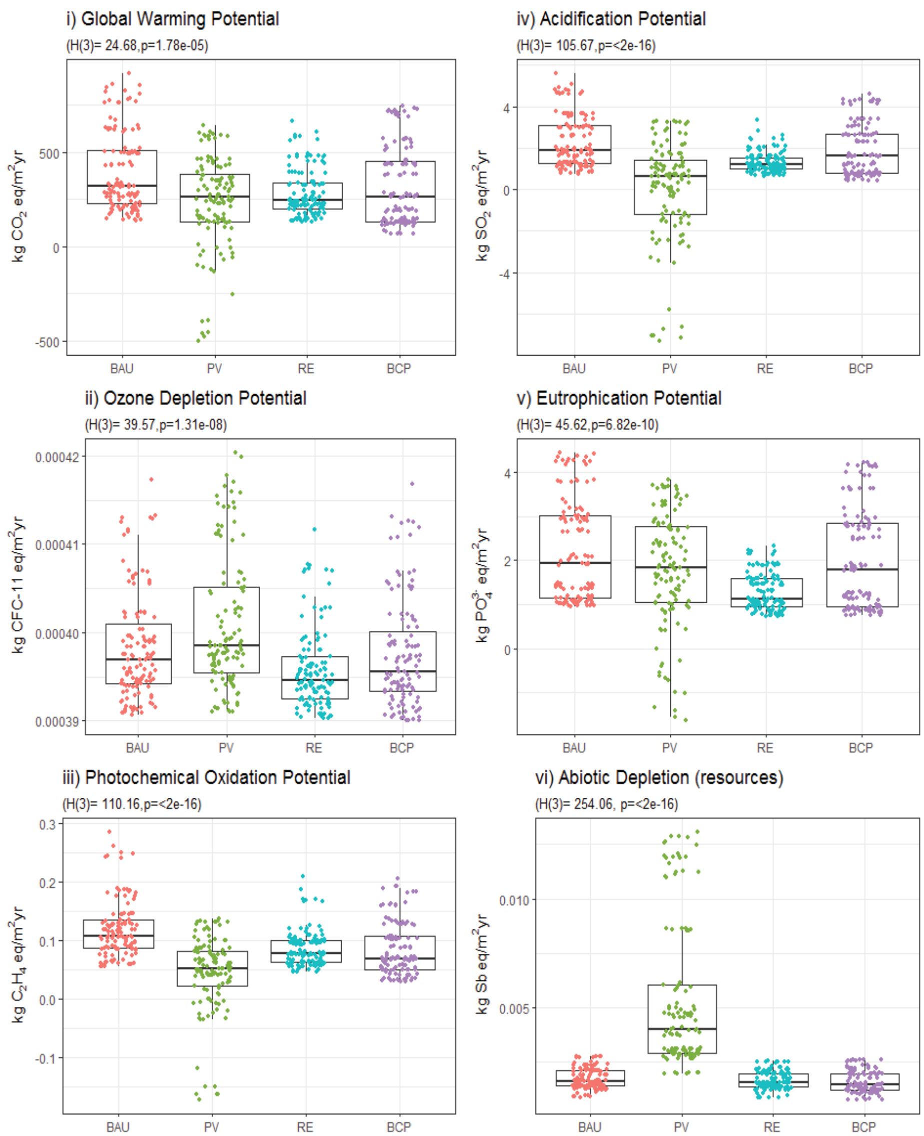

Figure 5.2 a The comparative results per functional unit for the four scenarios: Refurbishment undertaken Business as usual (BAU), Refurbished buildings installed with photovoltaics (PV), Refurbished buildings supplied with grid electricity generated from renewable energy sources (RE), and Refurbishment undertaken using best construction practices at site (BCP). Boxplots are used to show the assessed environmental performance of all buildings in each scenario (n=119 in each scenario). The line that divides each box shows the median, the box spans the inter-quartile range (25–75% of the data) with the whiskers that span to the minimal and maximal values in the data. The sample size in each scenario is also depicted by coloured dots. Each dot is representative of the impact of a building in the specific scenario.

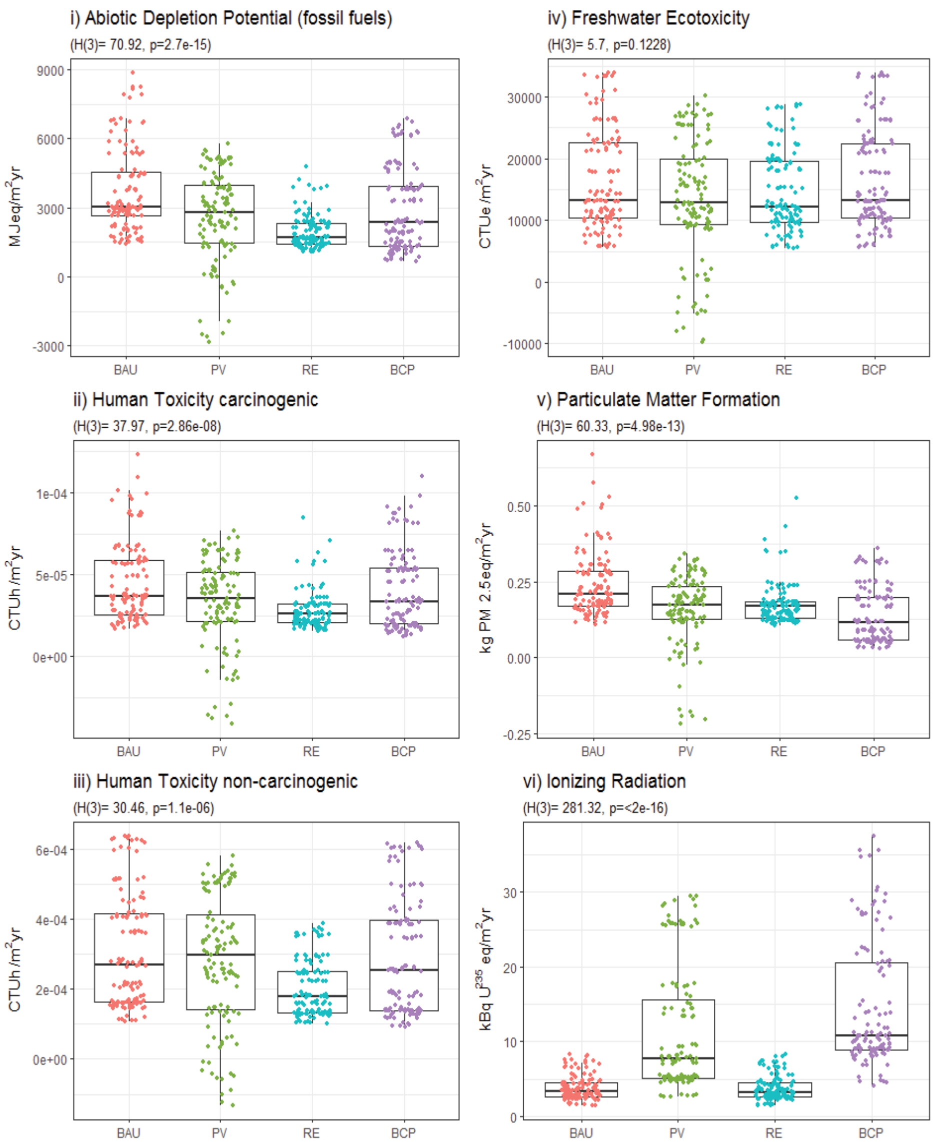

Figure 5.2 b The comparative results per functional unit for the four scenarios: Refurbishment undertaken Business as usual (BAU), Refurbished buildings installed with photovoltaics (PV), Refurbished buildings supplied with grid electricity generated from renewable energy sources (RE), and Refurbishment undertaken using best construction practices at site (BCP). Boxplots are used to show the assessed environmental performance of all buildings in each scenario (n=119 in each scenario). The line that divides each box shows the median, the box spans the inter-quartile range (25–75% of the data) with the whiskers that span to the minimal and maximal values in the data. The sample size in each scenario is also depicted by coloured dots. Each dot is representative of the impact of a building in the specific scenario.

5.3.2 GAM results

In the best fit GAM models, the interaction of the building characteristics with scenarios (as shown in Equation 2) was identified as an essential component as compared to the individual effect of the variables. In general, nine out of fifteen building characteristics (façade material, R-value (wall), storeys, roof area, WWR, Window type, number of heat pumps installed, annual energy consumption and building location) were identified as potential predictors of the environmental impacts. Their significance was further determined based on their interactions with the scenarios. Building characteristics such as shading factors, thermal resistivity of the roof and total transport were non- significant predictors for all impact categories and were hence removed from the model. GFA of the buildings, number of heat pumps and LED luminaires installed were highly collinear. Only the variable for number of heat pumps installed was included; unlike the previous two parameters, removing this variable reduced the adjusted R^2 value of the model. The significance of the different independent (predictor) variables is discussed below, and the detailed results from each model are provided in the supporting information (SI-3c).

Façade material used and annual operational energy used (kWh) were identified as having a significant effect on the building's refurbishment impact in all scenarios and impact categories. Façade materials installed in smaller buildings (brick and concrete blocks) lead to significantly higher impacts compared to materials used in large buildings fibre cement and reinforced concrete) in all scenarios. An increase in the annual operational energy use (kWh) in the BAU and BCP scenarios significantly increases all twelve impact category results irrespective of the function related to energy use i.e. space heating/cooling or equipment use. In all four scenarios, increasing the window to wall ratio (WWR) significantly increases the impact while the increase in number of heat pumps significantly decreases the impact in nine impact categories (GWP, ODP, PCOP, AP, EP, AD_{ff}, HT carc, $ET_{freshwater}$ and PMF). The influence of all other parameters related to building construction (such as thermal resistivity of wall, number of storeys, roof area and type of window installed) was limited to two or three scenarios. An increase in thermal resistivity of the wall in the BAU and BCP scenarios significantly reduces the impact in five impact categories (GWP, ODP, AP, EP and HT non cancer). In the PV scenario, an increase in roof area (m^2) and in the number of storeys significantly increases the impact in all impact categories. The significant effect of the type of window installed was variable for the scenarios and impact categories. In general, installation of double glazed windows has a significantly higher impact than single glazed windows; while installation of low-e double glazed windows or tinted low-e double glazed windows significantly reduces the impact in most categories.

Building location significantly influenced the impact in the BAU, PV and BCP scenarios for six impact categories (GWP, ODP, AP, EP, HT non-carc and $ET_{freshwater}$). In general, the impact of refurbished buildings in the southern regions of

New Zealand (Christchurch/Canterbury and Otago/Southland) was significantly higher compared to buildings in other regions.

5.4 Discussion

The results highlight that the potential environmental impacts related to refurbished buildings after each of the three potential policy interventions can be significantly reduced in comparison to refurbished buildings operating in the BAU scenario, although there will still be a few environmental trade-offs depending on the adopted policy. The Kruskal-Wallis and Dunn test results clearly indicated that prioritizing energy supply from renewable electricity grid can significantly reduce the potential environmental impacts of refurbished buildings for most impact categories as compared to the BAU scenario. These results are comparable to findings in previous studies on environmental performance which also highlighted the influence of energy source used for building operation (Bush et al., 2014; Dahlstrøm et al., 2012). In comparison, environmental benefits related to installation of PV or using best construction practices were limited due to additional environmental trade-offs. The GAM results further indicate the significant influence of specific building characteristics on the environmental performance of refurbished buildings in each scenario.

5.4.1 Refurbished buildings in the BAU scenario

With respect to building characteristics in the BAU scenario, the façade material, thermal resistivity of the wall, window to wall ratio, number of heat pumps installed, annual energy consumption and building location were factors significantly influencing the impact of large refurbished buildings. However, the façade materials used in smaller buildings (buildings with GFA $\leq$ 1499 m^2) had a higher contribution than the façade materials used in large buildings for all assessed environmental impacts. A main reason for this is that the quantity of façade materials used per m^2 gross floor area is relatively higher in small buildings. Moreover, among typical façade materials used in New Zealand, concrete blocks have the most energy intensive production followed by clay bricks and reinforced concrete. Concrete blocks and clay bricks are typically used on façades of small building. The higher environmental impact of concrete blocks compared to clay bricks was also reported by Utama et al.(2012); while Kua and Kamath (2014) reported that the impact of bricks was higher than reinforced concrete façades.

The results from the present study also showed a significant increase in all assessed impacts from higher WWR. It contrasts with findings reported by Su et al. (2010) for a study in China, which shows that a higher WWR in combination with low-e double glazed windows reduces the climate change impact by 9 to 15 per cent. An increase in WWR means higher building energy loads due to solar heat gain and the heat conduction through the walls and windows (Cory, 2016; Yong et al., 2017). Byrd and Leardini (2011) strongly argued in favour of smaller WWR in large office buildings to reduce the electricity consumption of office buildings in New Zealand. Buildings with smaller WWR installed – and with operable windows - can improve indoor air quality and provide natural cooling as compared to buildings with a high WWR which need to be sealed and continuously air conditioned with an uninterrupted electricity supply to remain habitable. Incidentally, significant energy savings have been reported by introducing natural ventilation to occupied office spaces instead of relying on traditional closed off HVAC systems in New Zealand office buildings (Baird, 2014; Cory, 2016). However, it has been argued that natural ventilation is not always possible, especially in densely populated areas where there might be significant outdoor noise, air pollution, or where the ambient temperatures are much hotter or colder than air temperature guidelines. Under such conditions, an alternative controlled HVAC system is preferable (Gates, 2013).

This study also showed that an increased number of heat pumps results in a significant reduction in the total impact of the buildings. The number of heat pumps installed is strongly correlated with both the number of efficient lighting appliances and the gross floor area of the building. This is because the total number of these appliances was calculated based on the air conditioning and lighting requirement per m^2 floor area. Therefore, larger buildings with efficient HVAC (heat pumps) and lighting have a better environmental performance than smaller buildings with the same technologies installed. Indeed, Cory (2016) identified that upgrading equipment for HVAC and lighting was more effective in larger buildings than in smaller refurbished ones which had lower HVAC and lighting energy demands compared to large buildings. Energy demand of buildings with a large floor area was dominated by internal load (mainly heat produced from equipment use) while buildings with a small floor area are more affected by the ambient conditions (Gates, 2013). This finding supports the installation of HVAC in large buildings that are primarily located in densely populated areas, where natural ventilation might not always be preferable.

Refurbished buildings located in Christchurch and the Canterbury area had significantly higher impacts compared to other New Zealand locations which could largely be attributed to the additional material and energy requirements of the buildings in this region. The average climatic conditions in Canterbury are extreme with hotter summers and colder winters in comparison with more temperate regions of New Zealand (Britten, 2000). Most buildings in this region had a higher requirement for thermal resistivity of building envelope with respect to wall, roof and window as the total annual energy consumption was higher compared with other regions in New Zealand (Cory et al., 2012).

5.4.2 Refurbished buildings in the PV scenario

Use of PV as a refurbishment strategy for buildings increases the availability of renewable energy to meet a building's operational energy demand. The supply of electricity from on-site rooftop PV has a good alignment with demand, i.e. greater demand for electricity during office working hours aligns well with PV derived generation (Fu et al., 2015; Pikas et al., 2014). However, the magnitude of environmental savings (compared to BAU) is reduced due to resource requirements and site conditions.

Production of PV panels contributes to environmental impacts of the refurbished buildings in this scenario. For example, halogenated emissions, such as tetrafluoroethylene, used in PV cell manufacture contribute to ODP results (Balcombe et al., 2015). The use of antimony in batteries used for inverters and silver in the metal coating used on the solar cells contribute to AD_r and the share of nuclear power used in the manufacturing of PV contributes to IR (Balcombe et al., 2015). With respect to building characteristics, roof area installed with PV and the number of storeys of a building were significant contributors to all impact categories. Cory (2016) indicated that roof area is inversely proportional to building height; therefore PV may not be suitable for high-rise buildings as the smaller roof area will not generate sufficient energy to offset the building's operational energy consumption. Conversely, it is worth noting that low rise buildings may be significantly overshadowed by high rise buildings, especially in major cities which have a high proportion of high rise buildings. This study also showed that PV will not be environmentally viable for buildings located in areas with limited sunshine hours as the limited energy generation would not compensate for the impacts embodied in the production, delivery and installation of these PV units.

More specifically the results showed that the installation of PV is not beneficial if the total roof area is less than 50 % of GFA and or the buildings are located in Southland and Canterbury.

5.4.3 Refurbished buildings in RE scenario

If there is investment to increase the proportion of renewable energy source for New Zealand's grid electricity generation (as recommended by MBIE (2012, 2015)), the assessed environmental performance of refurbished buildings is better in the RE scenario compared to buildings in the PV or BCP scenario. New Zealand has maintained investment in renewable electricity production between 2000 and 2015 (MBIE, 2015). However, depending on market demand and climatic conditions, the source of electricity production fluctuates, and maintaining sufficient energy production which combines fossil fuel and renewable based energy is required (Sise, 2016).

In this study, the use of consequential LCA modelling to develop the inventory helps to identify impacts related to marginal electricity supply. A large share of electricity generated to supply base load in New Zealand is from hydro-electricity (IEA, 2010; NZ Ministry of Economic Development, 2011). But meeting the increase in electricity demand between 2000 and 2013, and compensating for years with low rainfall, means that the marginal electricity sources that meet peak demand are currently based on a combination of coal, wind and geothermal based electricity production with an emission factor of 0.278 kg CO_2 eq/kWh (Cory, 2016; IEA, 2010). If the investment in renewable electricity sources increases and coal power is phased out, the marginal electricity supply will be mainly from a combination of natural gas, geothermal and wind-based energy with an emission factor of 0.159 kg CO_2 eq/kWh (MBIE, 2012). As the impact associated with operational energy is reduced, it takes a correspondingly longer time to compensate for the embodied environmental impacts of refurbishment (as shown in chapter 3). Nevertheless, the results of this study emphasize the need to increase the share of electricity supplied from renewables to reduce the environmental impact of refurbished buildings.

While the source of energy supply significantly influences the assessed environmental impact of the buildings, most building characteristics (annual energy consumption, thermal resistivity of the wall, roof area, number of storeys, building location) show no significance in this scenario. This finding supports the argument that most environmental impacts of a building are primarily determined by the source of energy supply (Heeren et al., 2015; Khasreen et al., 2009) irrespective of building size, design, thermal performance and location.

5.4.4 Refurbished buildings in the BCP scenario

With respect to building characteristics in the BCP scenario, the significance of all independent variables except two variables (number of storeys, type of window installed) were identical to the BAU scenario. The assessed embodied impacts related to construction and refurbished components are low in this scenario. Therefore, unlike in the BAU scenario, an increase in number of storeys does not significantly affect the impact for PMF. Installation of clear and tinted double glazed low-e double glazed windows in this scenario significantly reduces the impact for GWP, PCOP, AP, EP, AD_{ff}, HT carc, HT non-carc and PMF but increases the impact for IR.

The contribution of low-e double glazed windows to environmental impacts was sensitive to the material used for the window frame and the energy used to produce the materials (Asif et al., 2005). The impact for IR was related to the use of nuclear power in the production of imported aluminium used to produce window frames in New Zealand. Imported aluminium was considered in this study as the production of aluminium in New Zealand was subject to constraints (USGS, 2013) (see Chapter 4, table 4.2). The case study results in chapter 4 indicated that the adoption of better construction practices, such as increased recycling and re-use of materials, reduces the total impact for most categories (GWP, POCP, AP, EP, AD_r, AD_{ff}, HT carc, HT non carc and PMF) by at least 15-20 %. Furthermore, if the construction materials are sourced from regions where a high share of renewable energy is used for material production, the impacts for GWP, POCP, AP and AD*ff* reduce by approximately 30-40 % in all categories; at the same time, there is an increase of over 100 % in IR. Except for PMF and IR, most of the reductions related to energy use for material production might be substantial with respect to reducing the embodied impacts in building construction, but not that significant when considered across the building life cycle as indicated in the current study. However, the results also highlight that buildings in this scenario contribute to significant reductions in impact categories related to resource use, such as AD_r and ODP, as compared to buildings installed with PV.

5.4.5 Limitations and future work

It is important to note that the assumptions and parameters considered in the study are primarily valid for buildings with similar construction and location. For instance, besides clay bricks, timber, natural stone and sheet metal are other typical façade materials used in small, low-rise buildings in New Zealand (Russell & Ingham, 2010), and these were not considered in this study. Different façade materials affect the total embodied impacts and the energy required for heating and cooling (Heeren et al., 2015). Similarly, all buildings in this study have conventional flat roof design and construction. Developments in roof construction have identified refurbishment technologies related to green roof construction beneficial for increasing the thermal resistivity of roofs and reduction in environmental impact (Castleton et al., 2010; Kosareo & Ries, 2007). As the study also indicated the benefits of renewable energy supply, it would be worth investigating the performance of non-refurbished buildings versus refurbished buildings if the electricity generation from renewables increases, as suggested in the RE scenario.

Additional factors which are important in determining the performance of a well performing building such as occupant comfort, indoor air quality, fire safety (Baird, 2014) were not included in this study. Therefore, future work could focus on multiple parameters and categories related to material selection and building design.

5.5 Conclusion

The present study assessed the environmental impacts of refurbished buildings in New Zealand in four different scenarios using life cycle assessment. Besides the influence of the scenarios, this study used inferential and predictive statistical models to assess the influence of individual building characteristics (such as façade material, thermal resistivity, wall to window ratio, building location) on the results. The main conclusions based on the results of this study are:

a) With respect to policies:
    - Prioritizing policies on increased use of renewable energy sources for grid electricity generation can significantly reduce the potential impacts of refurbished buildings as compared with policies on installation of PV or better construction practices.
    - Prioritizing policies on installation of PV or better construction practices have similar environmental benefits; however, prioritizing policies on installation of PV significantly increases those impacts that are related to resource demand.

b) With respect to building characteristics:

- In large buildings, efficient HVAC, lighting and smaller WWR should be prioritised.
- In small buildings, the choice of façade materials with low embodied impacts should be prioritised.
- If on- site PV is installed, it should be prioritised in low-rise buildings with large roof areas.

c) With respect to regions of New Zealand:

- Refurbishment of buildings in the across North Island of New Zealand (which includes Auckland, Waikato, Wellington, Manawatu and Napier) should be prioritised.
- If on- site PV is installed, it should be prioritised in regions with long sunshine hours.

These findings can help policy makers and individual building stakeholders to prioritise strategies to improve the environmental performance of typical office buildings in New Zealand. In general, better data quality and larger sample sizes are important to increase the confidence in the findings of statistical models (Grant et al., 2016; Heeren et al., 2015). This study used New Zealand specific data currently available with respect to inventory modelling to maintain data quality (Cory, 2016; Dowdell et al., 2016), and a total sample size of 476 buildings; this sample size is substantially higher than in earlier published studies on building LCA which are typically limited to a smaller number of case studies (Cabeza et al., 2014; Grant et al., 2016). In order to consider the validity of these findings to a broader range of buildings, it will be important to consider additional parameters related to use of alternative construction materials and building functions for future work.

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Chapter 6- Comprehensive environmental impact assessment of New Zealand's office building stock

Abstract

The aim of this study is to estimate the potential environmental impacts associated with adopting energy efficiency refurbishments on the entire existing office building stock in New Zealand. Additionally, a second objective was to identify the potential contribution of the refurbished office building stock in relation to New Zealand's 2050 greenhouse gas (GHG) emissions reduction target. For this purpose, the study used Life Cycle Assessment (LCA) in conjunction with stock aggregation modelling. The impacts of the building stock were calculated for i) non- refurbished building stock, ii) refurbished building stock, iii) refurbished building stock adopting resource and waste management measures and iv) refurbished building stock installed with photo-voltaics. The results show that refurbishment of the existing office building stock can potentially reduce 50 – 70 % of the environmental impacts associated with the non-refurbished building stock. The major environmental trade-offs associated with refurbished buildings are associated with ozone depletion potential, resource depletion and ionizing radiation. Energy sources for grid electricity generation play an important role in determining the overall environmental performance of the building stock. The results also highlight the achievability of New Zealand's 2050 target with respect to reducing GHG emissions in the office building sector. In general, increasing the share of renewable energy supply from grid electricity or utilizing on-site PV reduces the total impact of buildings. However, use of on-site PV increases resource demand which contributes to impacts such as human toxicity and abiotic depletion. Prioritizing the refurbishment of the building stock by adopting efficient resource use and waste management measures can contribute to substantial reductions in the environmental impacts of the building stock without increasing pressures on resource depletion. Moreover, prioritizing refurbishment activities in major cities and/or in large buildings can also help in more effective GHG reduction. These results can guide policy makers interested in adopting energy efficiency in commercial buildings as a GHG emission reduction measure but not at the cost of increases in other environmental impacts.

6.1 Introduction

By 2050, New Zealand aims to reduce its greenhouse gas (GHG) emissions by 50 % compared to 1990 emissions (Bedford et al., 2016). In its commitment to achieve this target, the New Zealand Energy Strategy (2017 – 2022) prioritises investment in energy efficiency in conjunction with increasing renewable electricity generation (EECA, 2017a). As a key strategy to enable the business sector to contribute towards this target, the Government is planning to support nationwide improvement in the energy efficiency of commercial buildings (Chaney, 2012; EECA, 2017a; MBIE, 2012). Commercial buildings in New Zealand account for approximately 16 % of New Zealand's annual energy consumption (Amitrano et al., 2014b).

The Energy Efficiency and Conservation Authority (EECA) estimates that commercial buildings could reduce energy demand by 20 % by using energy more efficiently (EECA, 2017b). However, a recent study has shown that. the annual operational primary energy demand[8] of commercial buildings could be reduced by more than 60% by adopting multiple energy efficiency measures (Cory, 2016). In addition, use of on-site photo-voltaic (PV) power generation (for example) can offset most of the remaining operational energy demand from the electricity grid (Cory, 2016). Such a building is referred to a Nearly Zero Energy (NZE) building (Chastas et al., 2016; Peterson et al., 2015).

Refurbishing an existing building with multiple energy efficiency measures such that the energy demand of a building is substantially reduced is referred to as a deep energy refurbishment (IEA EBC, 2014). Studies that have evaluated the performance of refurbished energy efficient buildings (with or without the use of PV) have reported large savings on operational energy use and associated costs (Alajmi, 2012; Ardente et al., 2011; Chidiac et al., 2011; Clinton Foundation, 2013). However, it is vital to note that the adoption of multiple energy efficiency measures on the existing building stock is not a straightforward strategy for reduction in GHG emissions. As buildings move from conventional design to low energy or Nearly-Zero Energy (NZE) buildings, the energy and GHG emissions embodied in the refurbishment materials make an increasing contribution to the overall environmental impacts of these buildings (Berggren et al., 2013; Weißenberger et al., 2014). In an extensive review on life cycle energy use of energy efficient buildings, Chastas et al. (2016) reviewed 90 case studies and identified that embodied energy in low energy and

[8] Primary energy is the energy form not subjected to any conversion or transformation process. Primary energy demand also includes the efficiency losses by converting the coal, gas and oil into electricity.

NZE buildings contributes 26% –57% and 74% –100% respectively of the total primary energy demand for a building operated for 50-100 years. The substantial gap in the share of embodied energy between a low energy and NZE building indicates the importance of the technologies used to achieve greater energy efficiency in buildings. At the same time, it is important also to consider improvement in construction activities associated for achieving energy efficient buildings. For example, Blengini (2009) reported that an increase in recycling of construction waste could reduce 29% and 18% of the life cycle energy and GHG emissions, respectively of low-energy buildings.

In New Zealand, energy efficiency in buildings is not a target in itself but a strategy towards the long term goal of climate change mitigation (Bedford et al., 2016). For climate change mitigation, it is necessary to ensure refurbishment activities don't lead to a net increase in climate change impacts even if the resulting building is more energy efficient. Furthermore, it would be beneficial if refurbishment is not at the expense of increases in other types of environmental impacts. An increase in construction activities for refurbishment also increases the pressure on resource use which is often not quantified when solely focusing on energy related targets (Thema et al., 2017). To ensure the fulfilment of a climate change mitigation without many trade-offs it is necessary to calculate both GHG and non-GHG related environmental impacts (Thema et al., 2017; Urge-Vorsatz et al., 2013; Vorstaz et al., 2007)

Life Cycle Assessment (LCA) can be used to perform a comprehensive environmental assessment of the building life cycle. Existing LCA studies typically focus on a single or small group of buildings (Cabeza et al., 2014; Vilches et al., 2017). At a larger scale, the stock aggregation method can be used to approximate the performance of a building stock using environmental assessments of representative building prototypes or a subset of the stock (Moffatt, 2001). Also referred to as a 'bottom up' approach, this method in combination with LCA assists policy-makers at varying scales (IEA, 2001). First, it provides information on how the performance of specific measures could affect the entire building stock if adopted on a large scale. Second, it provides policy-makers (local or national) with a larger database on building energy, resource use and environmental effects. For example, Heeren et al. (2013) used a stock aggregation method to demonstrate that adopting specified efficiency measures in Zurich's building stock could reduce 85 % of the GHG emissions from the city's building sector by 2050. Pauliuk and Müller (2014) used a stock aggregation method to analyse the effect of different mitigation strategies on GHG emissions from the Norwegian residential stock. This study showed that if the entire Norwegian residential building stock was refurbished to a low energy building standard, the emission reduction corresponding to the Norwegian building sector's contribution to climate change was not substantial. This was because Norway's residential building energy standards currently mandate regulations to control space heating but not for other energy-related applications (e.g. energy for hot water generation, appliances and lighting). The study argues that, with increase in population and technological dependence, there will be an exponential increase in energy consumption by 2050. Therefore, to substantially reduce the energy demand in future, strategies for energy reduction must be coupled with lifestyle changes. It has also been noted that, whilst the stock aggregation method has been widely used to assess changes in energy demand and the associated GHG emissions, its use in evaluating the impacts for non-GHG related environmental impacts has been limited (Heeren et al., 2013; Mastrucci et al., 2017a).

In New Zealand, the stock aggregation approach was used by Cory (2016) to determine if the existing office building stock could be transformed to a NZE building stock by adopting deep energy refurbishment with or without PV. As New Zealand's aim to improve the energy efficiency of existing buildings is also a climate change mitigation strategy (Bedford et al., 2016), Cory's study specifically defined NZE building stock as, "*A community of buildings which have a greatly reduced demand for energy and only consume energy from the country's existing GHG free renewable electricity.*" Currently nearly 45 % of the operational primary energy demand for the commercial building sector is supplied from non-renewable energy sources; this includes energy supplied from grid electricity and natural gas use at site. Cory showed that adopting a set of energy efficiency measures on the existing building stock could reduce 45 % of the operational primary energy demand and thus offset all the associated non-renewable CO_2 emitting energy currently consumed by the existing stock. Cory concluded that the existing commercial building stock could be transformed into a NZE building stock by adopting deep energy refurbishment. However, the study did not address certain key aspects related to refurbishment when considering it from a wider environmental sustainability perspective:

- Other environmental impacts associated with New Zealand's electricity production (in addition to primary energy use and climate change impacts).
- The environmental impacts of indirect energy and resources used in undertaking the suggested refurbishment measures. Energy and GHG emissions embodied in refurbishment were not considered.

- The effect of prospective changes to energy sources for grid electricity generation (and therefore associated environmental impacts). The mix of different energy sources for electricity will change over time due to changes in resource availability, technology costs and/or policy responses to climate change mitigation (MBIE, 2012). This was not considered in the study[9].
- The potential contribution of energy efficient commercial building stock to New Zealand's GHG reduction target.

This study therefore aims to offer a wider analysis of the environmental impacts of refurbishment of New Zealand's office building stock. Office buildings have the highest energy consumption intensity per unit floor area ($kWh/m^2.yr$) compared to other commercial building types in New Zealand (Amitrano et al., 2014b). This can be at least partly attributed to the fact that approximately 80 % of the total office floor area was constructed pre-2000 (Cory, 2016). Since then the mandatory requirements on energy performance of buildings have been upgraded in the New Zealand building code (NZS 4243, 2007a, 2007b). Although there are no specific requirements for existing buildings to upgrade to the new standards, existing office building owners may need to consider these measures in order to remain competitive in the commercial retail market. Therefore, a large proportion of the office building stock is likely to undertake refurbishment with energy efficiency upgrades.

In this context, this study aims to answer the following research questions:

1) What are the potential environmental impacts associated with the adoption of deep energy refurbishment of the existing office building stock?
2) What are the potential environmental impacts or benefits associated with operation of the refurbished office building stock in comparison to non-refurbishment of the entire office building stock, in New Zealand between 2017 and 2050?
3) How do strategies such as resource and waste management or the installation of PV influence the performance of refurbished buildings?
4) How do prospective changes to energy sources for New Zealand's electricity generation affect the potential impacts of the refurbished office building stock used between 2017 and 2050?
5) What is the potential contribution of the refurbished office building stock in relation to New Zealand's 2050 GHG reduction target? And what is the

[9] The proportion of energy sources for electricity generation was representative of past years 2006 – 2012, where the increase in energy demand was supplemented from non-renewable energy sources.

environmental payback period of refurbishing the building stock with respect to GHG emissions?

6.2 Methodology

The methodological approach for stock aggregation adopted in this study was similar to the procedure suggested by Moffatt (2001) where the performance of a representative set of building prototypes are used to estimate the characteristics of an entire building stock. This study builds on the data and results of Cory (2016) and chapter 5 which analysed the energy and environmental performance of building prototypes in New Zealand respectively. Data on New Zealand's existing office building stock was obtained from New Zealand's Building Energy End-Use Study (BEES) (BEES, 2013).

6.2.1 New Zealand specific office building prototypes

6.2.1.1 Building characteristics and Energy simulation

Cory (2016) used details on building construction and energy loads of seventeen real office buildings (collected by (BEES, 2013) and representative climatic conditions in seven regions across New Zealand to simulate the annual operational energy consumption for 119 (17 x7) existing office buildings (see Figure 6.1). Cory further developed refurbished prototypes for each building adopting a standard set of energy efficiency measures to reduce the annual operational energy consumption. These measures were: increased insulation on building envelope (wall and roof); optimization of the Wall to Window Ratio (WWR); replacement of windows depending on the glazing types; addition of solar shading to avoid passive solar heat gain; change of the air conditioning system (heating and cooling) from a natural gas operated boiler and electric chiller to electric heat pumps; and replacement of existing compact fluorescent lamps with LED luminaires. Energy performance of the refurbished buildings was simulated under two conditions: with and without the use of Photo Voltaic (PV) panels installed at the building site.

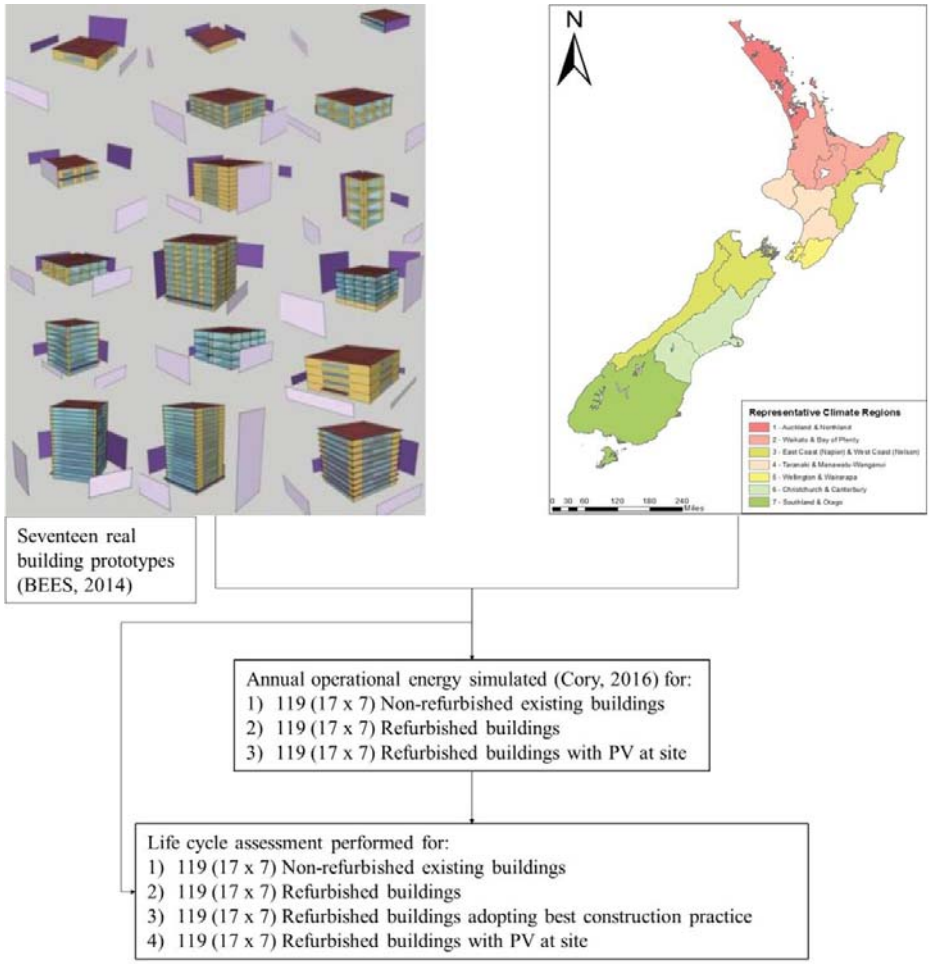

Figure 6.1 Representative office building prototypes and seven regions across New Zealand used by Cory (2016) to simulate the annual energy consumption and determine energy efficiency refurbishment measures. This information was used to calculate environmental impacts for each prototype using LCA. Each prototype represents a real building based on both internal and external factors such as building dimensions and surrounding structures/buildings (in purple) respectively. The climate regions were developed by Cory (2016) based on aggregation of geographic regions in New Zealand with similar climatic conditions.

6.2.1.2 Life cycle assessment of building prototypes

The adoption of energy efficiency refurbishment measures suggested by Cory requires a large scale transformation of each building i.e. a deep energy refurbishment (IEA EBC, 2015). Detailed process-based Life Cycle Assessment (LCA) based on the guidelines provided in the building standard EN 15978 (2011), and was performed to calculate the environmental impacts for each of the refurbished building prototypes developed by Cory (2016). Details on the refurbishment measures and the energy consumption for each building are given in supporting information (SI-3a). The life cycle inventory was based on a consequential modelling approach which has been recommended as a method to support policies on climate change mitigation (Brandão et al., 2014; Plevin et al., 2014). The inventory included environmental emissions embodied in construction products and processes related to building refurbishment, maintenance and annual energy consumption. Details on calculations related to quantifying materials, energy and emissions associated with refurbishment, waste management, building operation and maintenance based on the building prototypes, and more specifically on the consequential modelling approach adopted in developing the inventory, are given in chapter 3 (sections 3.2.2.1-3.2.2.3) and chapter 4 (sections 4.2.2.1-4.2.2.2) respectively. The results for twelve environmental impact categories (see Table 6.1) were reported per m^2 of total floor area of each building prototype.

Table 6.1 Environmental impact categories and related impact assessment methods used to report results in this study (as suggested by Dowdell (2014))

Environmental Impact Categories	Abbreviation	Unit	Impact Assessment Method
Global Warming Potential*	GWP	kg CO_2 eq	CML 2001
Ozone Depletion Potential*	ODP	kg CFC-11 eq	
Photochemical Oxidation Potential*	PCOP	kg C_2H_4 eq	
Acidification Potential*	AP	kg SO_2 eq	
Eutrophication Potential*	EP	kg PO_4^{3-} eq	
Abiotic Depletion (resources)*	AD_r	kg Sb eq	
Abiotic Depletion (fossil fuels)*	AD_{ff}	MJ	
Human Toxicity (carcinogenic)	HT carc	CTUh	UseTox
Human Toxicity (non-carcinogenic)	HT non carc	CTUh	
Eco-toxicity (freshwater)	$ET_{freshwater}$	CTUe	
Particulate Matter Formation	PMF	kg PM2.5 eq	ILCD 2011+
Ionizing Radiation	IR	kBq U^{235} eq	ReCiPe (H)

6.2.1.3 New Zealand's Electricity grid scenarios

In chapters 3 and 5 it was identified that the environmental performance of the buildings was sensitive to the energy sources of the national electricity grid. On average, 80 % of New Zealand's electricity generation was from renewable energy sources in 2014. The increasing demand for electricity from 1990-2013 was accommodated by investments in electricity generation from coal, wind and geothermal power; these can also be referred as the marginal energy sources. However, New Zealand is seeking to decarbonise the grid electricity by phasing out the use of coal for electricity production by 2040 (MBIE, 2012, 2015). Therefore, an alternative scenario has been considered in this study where investment in electricity generation from renewable energy sources increases in the future (MBIE, 2012; Smith, 2017).

Thus the environmental impacts related to building operation have been calculated for two scenarios:

- Energy sources for New Zealand's electricity grid remains mostly unchanged compared with production in previous years **- Business as usual (BAU) scenario**
- Share of renewable energy source for New Zealand's electricity production increases **- Renewable Energy (RE) scenario**

Table 6.2 shows the share of marginal sources of electricity and the environmental impacts related to 1 kWh of low voltage electricity produced in both scenarios.

Table 6.2 Marginal sources of electricity production in New Zealand and the environmental impacts associated with 1 kWh of low voltage electricity produced.

Energy Source*		**BAU scenario**	**RE scenario**
Coal		21%	-
Natural Gas		-	6%
Hydro		-	16%
Wind		30%	40%
Geothermal		49%	38%
Total		100%	100%
Impact Categories	**Unit**	**BAU**	**RE**
GWP	kg CO_2 eq	0.28	0.16
ODP	kg CFC-11 eq	7.10E-09	4.46E-09
PCOP	kg C_2H_4 eq	5.89E-05	2.31E-05
AP	kg SO_2 eq	1.65E-03	5.83E-04
EP	kg PO_4^{3-} eq	1.58E-03	5.94E-04
AD_r	kg Sb eq	6.83E-07	5.87E-07
AD_{ff}	MJ	2.38	0.47
HT carc	CTUh	2.91E-08	1.08E-08
HT non carc	CTUh	2.21E-07	1.07E-07
$ET_{freshwater}$	CTUe	11.76	9.65
PMF	kg PM2.5 eq	1.21E-04	5.28E-05
IR	kBq U^{235} eq	1.13E-03	1.08E-03

*Marginal energy sources for 1) BAU based on 2013 New Zealand electricity production and 2) RE scenario based on prospective investments for electricity production for 2040 (MBIE, 2012).

6.2.1.4 Environmental impact of building prototypes up to 2050

For the BAU and RE scenarios, the potential environmental impacts up to 2050 were calculated for a building prototype under each one of four specific conditions:

1) Non Refurbished building (nRb)
2) Refurbished building (Rb)

3) Refurbished building adopting best construction practice (Rb BCP) as suggested in chapter 5
4) Refurbished building with PV installed on site (Rb PV)

using equations 1 and 2

$$b_{eb}^{x} = I_{rb}^{x} + I_{m}^{x} \quad \text{Eq1}$$

$$b_{en}^{x} = el^{x} \times y \times I_{sc}^{el} \quad \text{Eq2}$$

Where,

b_{eb}^{x} is the potential impact embodied in materials and construction of a specific building prototype under a specific condition x.

x refers to the condition of the building: nRb, Rb, Rb BCP or Rb PV

I_{rb}^{x} is the total impact from refurbishment per m^2 total floor area of a particular building. For a non-refurbished building this was assumed as zero.

I_{m}^{x} is the total impact from periodic maintenance per m^2 total floor area of a particular building. All technical equipment was assumed to be replaced every 25 years. In the case of PV, inverters were replaced every 5 years.

b_{en}^{x} is the potential impact of a given building operating under a specific condition x between 2017 and 2050 (35 years) under a given scenario.

el^{x} is the annual energy consumption (kWh) of a given building operating under one of the 4 conditions (nRb, Rb, Rb BCP or Rb PV) as simulated by Cory (2016).

y is the number of years of building operation. For this study this was assumed to be 35 years assuming the year of refurbishment as 2017 and the building is operated up to 2050 (and including the impacts in 2017 and 2050).

I_{sc}^{el} is the impact associated with 1 kWh of low voltage electricity under a given scenario (BAU or RE) as given in Table 6.2.

6.2.2 New Zealand's office building stock

New Zealand's office building stock consists of approximately 5698 buildings with a total floor area estimated to be 6.9 million m^2; this is 28 % of New Zealand's total commercial building floor area (BEES, 2014). The entire office building stock was divided into building size groups in the seven representative locations as identified by Cory (2016) (see Table 6.3). It can be seen that the highest concentration of office building floor area based on location is located in Auckland, followed by Wellington and Christchurch which account for 42, 21 and 12 % of the total office building stock respectively. Based on building size, there are a high number of small office buildings (Group 1) but these account for only 15 % of the total office building stock floor area, while the largest office buildings (Group 5) consists of a smaller number of buildings but account for 28 % of the total office building stock floor area.

Table 6.3 Total floor area of office buildings in New Zealand based on size and location (Cory, 2016; Isaacs et al., 2013)

	Building Groups (based on total floor area of buildings)					Total
Approximate number of office buildings in New Zealand (nos.)	**3,709**	**997**	**547**	**314**	**131**	**5698**
Building Location	**Group 1 (5- 649 m²)**	**Group 2 (650 -1499 m²)**	**Group 3 (1500 - 3499 m²)**	**Group 4 (3500 - 8999 m²)**	**Group 5 (≥ 9000 m2)**	**Total floor area (in each location) (m²)**
Auckland/ Northland (m²)	262,942	378,937	521,604	817,808	946,341	**2,297,631**
Waikato/ Bay of Plenty (m²)	210,123	165,386	128,490	141,276	33,740	**679,015**
East Coast/ Napier/ Nelson/ West Coast(m²)	121,779	74,158	52,480	28,498	9,640	**286,554**
Taranaki/ Manawatu (m²)	161,550	106,883	83,298	81,502	51,567	**484,801**
Wellington/ Wairarapa (m²)	68,217	67,713	161,388	397,629	759,808	**1,454,755**
Chirstchurch/ Canterbury (m²)	134,850	120,061	205,095	187,510	155,605	**803,120**
Southland/ Otago (m²)	97,654	79,530	73,087	37,301	21,670	**309,243**
Total floor area (in each group) (m²)	**1,057,115**	**992,668**	**1,225,442**	**1,691,524**	**1,978,371**	**6,945,120**

6.2.2.1 Stock Aggregation Analysis

This process has two steps: firstly, a simple multiplication of the prototype building's environmental performance by the proportion of buildings it represents (i.e. the building stock in a specific region and building size group) and, secondly, a summation of the results for each region and building size group. The environmental performance of New Zealand's whole building stock was calculated for each impact category and for a total of 35 years (between 2017 and 2050) using Equations 3, 4, 5 (i and ii) and 6 for both the BAU and RE scenarios.

$$\overline{B^{x}_{g\times r}} = \frac{\sum_{i=1}^{n} b^{x}}{n} \text{ ; } where\ b^{x} \in g \qquad \text{Eq 3}$$

$$I^{x}_{g\times r} = \overline{B^{x}_{g\times r}} \times P_{g\times r} \qquad \text{Eq 4}$$

$$I^{x}_{G} = \sum_{i=1}^{7} I^{x}_{g\times r} \qquad \text{Eq 5 (i)}$$

$$I^{x}_{R} = \sum_{i=1}^{5} I^{x}_{g\times r} \qquad \text{Eq 5 (ii)}$$

$$I^{x}_{W} = \sum_{i=1}^{5} I^{x}_{G} = \sum_{i=1}^{7} I^{x}_{R} \qquad \text{Eq 6}$$

where,

$\overline{B^{x}_{g\times r}}$ is the average environmental impact of buildings in each group for a specific region in a specific condition x (nRb, Rb, Rb BCP, or Rb-PV).

b^x is either the embodied impact or the impacts associated with energy consumption in each building as calculated in equations 1 and 2.

g is one of the five building size groups (see Table 6.3)

r is one of the seven regions across New Zealand (see Table 6.3)

n is the number of buildings analysed in this study for each group in a given region

$I^x_{g \times r}$ is the aggregated environmental impact of all of the buildings in a specific group g and region r

$P_{g \times r}$ is the total office building floor area in a specific group g and region r

I^x_G is the aggregated environmental impact of all of the buildings in a specific group across all regions

I^x_R is the aggregated environmental impact of all of the buildings in a specific region across all groups

I^x_W is the aggregated environmental impact of the whole office building stock under a specific condition. To identify the contribution of impact embodied in construction and energy use respectively I^x_W was calculated separately and then combined to estimate the total impact (See figure 6.2).

6.2.2.2 Accounting for New Zealand's 2050 GHG emission target

Based on the Paris Agreement (United Nations, 2015), New Zealand's 2050 target aims at 50 per cent reduction of the overall GHG emissions compared to 1990 levels, and there are no other targets or benchmarks for the building sector specifically. Use of a sectoral approach as a way to break down national targets has been used by Schmidt et al. (2008) and Pauliuk et al. (2014) to assess specific mitigation strategies and inform associated stakeholders within a specific sector. In this study, the total GHG emissions from the office building stock in 1990 were used as a benchmark for measuring future reductions in GHG emissions[10]. In 1990, GHG emissions

[10] This is a valid assumption as approximately 50 % of the office floor area was constructed before 1980 (Cory, 2016) (see Supporting Information (SI) fig 1 for details).

associated with the office building stock's energy use for electricity and heating[11] were approximately 124 kt CO_2 eq[12].

GWP is a common unit of measure to compile a national GHG inventory (EPA, 2016). The GWP in 2050 was calculated based on potential GHG emissions associated with operational energy consumption of the building stock in 2050. The stock aggregated values for GWP in 2050 were compared to the GWP from 1990 using Equation 7.

$$\Delta I_{2050-1990} = \left(\frac{I^{x}_{W(GWP\ in\ 2050)} - I_{(GWP\ in\ 1990)}}{I_{(GWP\ in\ 1990)}} \right) X100 \qquad \text{Eq7}$$

where,

$\Delta I_{2050-1990}$ (calculated in %) is the change in GWP from 1990 to 2050 from New Zealand's commercial office building sector normalised against energy sector emissions in 1990.

$I^{x}_{W(GWP\ in\ 2050)}$ is the GWP associated with the energy use of New Zealand's office building stock in 2050.

$I_{(GWP\ in\ 1990)}$ is the GWP associated with the energy use of New Zealand's commercial building stock in 1990 (reported as 124 kt CO_2 eq).

$I^{x}_{W(GWP\ in\ 2050)}$ was also calculated to identify the GWP of the whole building stock if a smaller proportion of building stock was prioritised for refurbishment based on building location or size (see Box 1 for details).

Additionally, the environmental payback period of refurbishing the whole building stock was calculated (see Box 2 for details).

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[11] In 1990, the total GHG emissions from energy use for electricity and heating were around 3364 kt CO_2 eq (MBIE, 2016a). 19 % of the energy generation was from non-renewable sources (17 % natural gas and 2 % coal) and 81 % was from renewable sources (75% hydropower and 6 % geo thermal) (MBIE, 2016a).

[12]Assuming approximately 16% of emissions from energy use for electricity and heating were from the commercial building sector (Amitrano et al., 2014b), and 23 % of the emissions of the commercial building sector were from the office building stock (Cory, 2016), the total GHG emissions from the office building stock were 124 kt CO_2 eq.

Box 1. GWP of the whole office building stock when refurbishment is undertaken only for specific regions or specific building groups

Prioritising a smaller proportion of the building stock based on building location or size might be easier to direct policies given the high economic and resource requirements for construction activities. To identify the GWP reduction potential of the whole office building stock if a smaller proportion of building stock was refurbished based on location and size $I^{x}_{W(GWP\ in\ 2050)}$ in Eq 7 was substituted with $I^{Rb^r}_{W(GWP\ in\ 2050)}$ and $I^{Rb^g}_{W(GWP\ in\ 2050)}$ as given in equations B1 (a) and B1 (b) respectively.

$$I^{Rb^r}_{W(GWP\ in\ 2050)} = \sum_{i=1}^{r} I^{Rb}_{R(GWP\ in\ 2050)} + \sum_{i=1}^{7-r} I^{nRb}_{R(GWP\ in\ 2050)} \quad \text{Eq B1(a)}$$

$$I^{Rb^g}_{W(GWP\ in\ 2050)} = \sum_{i=1}^{g} I^{Rb}_{G(GWP\ in\ 2050)} + \sum_{i=1}^{5-g} I^{nRb}_{G(GWP\ in\ 2050)} \quad \text{Eq B2 (b)}$$

where,

$I^{Rb^r}_{W(GWP\ in\ 2050)}$ is the aggregated GWP of the whole office building stock if only buildings in a specific region/regions are refurbished in 2050. This was calculated to represent the situation where refurbishment is limited to one or more regions which include major cities (Auckland, Wellington and Christchurch)

$\sum_{i=1}^{r} I^{Rb}_{R(GWP\ in\ 2050)}$ is the GWP of refurbished buildings across all groups in a specific region in 2050.

$\sum_{i=1}^{7-r} I^{nRb}_{R(GWP\ in\ 2050)}$ is the GWP of non-refurbished buildings across all groups in remaining regions in 2050.

$I^{Rb^g}_{W(GWP\ in\ 2050)}$ is the aggregated GWP of the whole office building stock if only buildings in a specific group/ groups are refurbished in 2050.

$\sum_{i=1}^{g} I^{Rb}_{G(GWP\ in\ 2050)}$ is the GWP of refurbished buildings across all regions in a specific group in 2050.

$\sum_{i=1}^{5-g} I^{nRb}_{G(GWP\ in\ 2050)}$ is the GWP of non-refurbished buildings across all regions in remaining groups in 2050. This is calculated to represent the situation where refurbishment is limited to the buildings with a total floor area under 3500 m^2 (groups 1-3) or over 3500 m^2 (groups 4-5).

Box 2. Environmental (GWP) Payback Period of building refurbishment

The environmental payback period with respect to GWP (also referred to as carbon payback period) is a measure of the time required by the refurbished building stock to compensate the embodied emissions with its energy savings (Marimuthu & Kirubakaran, 2013). The payback period was calculated for GWP using Eq B2:

$$Payback\ period = \frac{I^{Rb}_{W(GWP\ embodied)}}{I^{nRb}_{W(GWP\ annual\ energy\ use)} - I^{Rb}_{W(GWP\ annual\ energy\ use)}} \quad \text{Eq B2}$$

where,

$I^{Rb}_{W(GWP\ embodied)}$ is the aggregated GWP of the whole refurbished office building stock embodied in refurbishment for three building conditions (Rb, Rb BCP, Rb PV).

$I^{nRb}_{W(GWP\ annual\ energy\ use)}$ is the aggregated GWP of the whole non refurbished office building stock associated with annual energy consumption

$I^{Rb}_{W(GWP\ annual\ energy\ use)}$ is the aggregated GWP of the whole refurbished office building stock associated with annual energy consumption for buildings operating in one of the three building conditions (Rb, Rb BCP, Rb PV).

The values for $I^{Rb}_{W(GWP\ embodied)}$ and $I^{Rb}_{W(GWP\ annual\ energy\ use)}$were also calculated when refurbishment is undertaken only for specific regions or specific building groups similar to calculations for $I^{x}_{W(GWP\ in\ 2050)}$ as given in Box 1.

6.3 Results

6.3.1 Environmental performance of New Zealand's office building stock

Figures 6.2(a) and (b) show the stock aggregation results for New Zealand's entire office building stock operating under the four given conditions (nRb, Rb, Rb BCP and Rb PV) in BAU and RE scenarios for all twelve impact categories. For each building condition, the results also show the share of impacts embodied in construction and operational energy consumption.

In general the stock aggregation results show that the potential impact of the building stock in the BAU scenario is high compared to the RE scenario mainly because the impacts related to operational energy consumption reduce sharply in the latter scenario. This difference is particularly noticeable for the un-refurbished building stock (nRb), since a large share of the impacts from these buildings is from emissions embodied in operational energy use.

In the BAU scenario, all the refurbished buildings (Rb, Rb BCP and Rb PV) have lower potential impact compared to non-refurbished buildings (nRb) in all categories except ODP and IR. Refurbished buildings that adopt best construction practices (Rb BCP) have lower potential impact compared to refurbished buildings (Rb) in all other categories except ODP and IR. Refurbished buildings with PV (Rb PV) have the lowest potential impact in all categories except AD_r and IR. In both these impact categories, refurbished buildings with PV (Rb PV) have the highest potential impacts.

In the RE scenario, refurbished buildings in any condition still have a lower potential environmental impact than non-refurbished buildings for GWP, AP, $ET_{freshwater}$ and HT carc. However, the environmental performance of refurbished buildings with PV (Rb PV) is weaker as compared to its performance in BAU scenario. Indeed, Rb PV has a higher potential impact for EP, AD_r, AD_{ff}, PMF and IR compared to the three other building conditions in the RE scenario whilst it has a higher potential impact for just AD_r and IR in the BAU scenario. It is worth noting that Rb PV still has the lowest potential impact for GWP, PCOP, AP and $ET_{freshwater}$ compared to the three other building conditions in the RE scenario. On the other hand, Rb BCP has the lowest potential impacts for EP, AD_r, AD_{ff}, HT carc, HT non carc and PMF compared to the three other building conditions in the RE scenario.

6.3.2 Environmental performance based on building location and building size groups

The aggregated environmental impacts of the building stock in Auckland are the highest followed by the building stock in Wellington and Christchurch for all impact categories in both the BAU and RE scenarios (see SI 4b fig. i and ii). This is mainly because these three locations have the highest share of the total office floor area in New Zealand.

With respect to aggregated impacts based on building size groups, the largest buildings (group 5) and smallest buildings (group 1) have the highest and least impact in all impact categories respectively for the non-refurbished and refurbished stock without PV (i.e. nRb, Rb and Rb BCP). This trend also remains similar for refurbished buildings with PV except in two categories (AD_r and IR) where the impacts are highest for small buildings (group 1) in both scenarios (see SI 4c fig. i and ii).

Integrating these two sets of results, the medium to large sized building stock (groups 3 - 5) in the regions with major cities (Auckland, Wellington and Christchurch) have the highest impacts. In the remaining four regions (Waikato, Taranaki, East &West coasts and Southland), the highest impacts are mostly from the small building stock (groups 1- 2). This is because the buildings in these groups account for a higher share of the total office floor area in these locations.

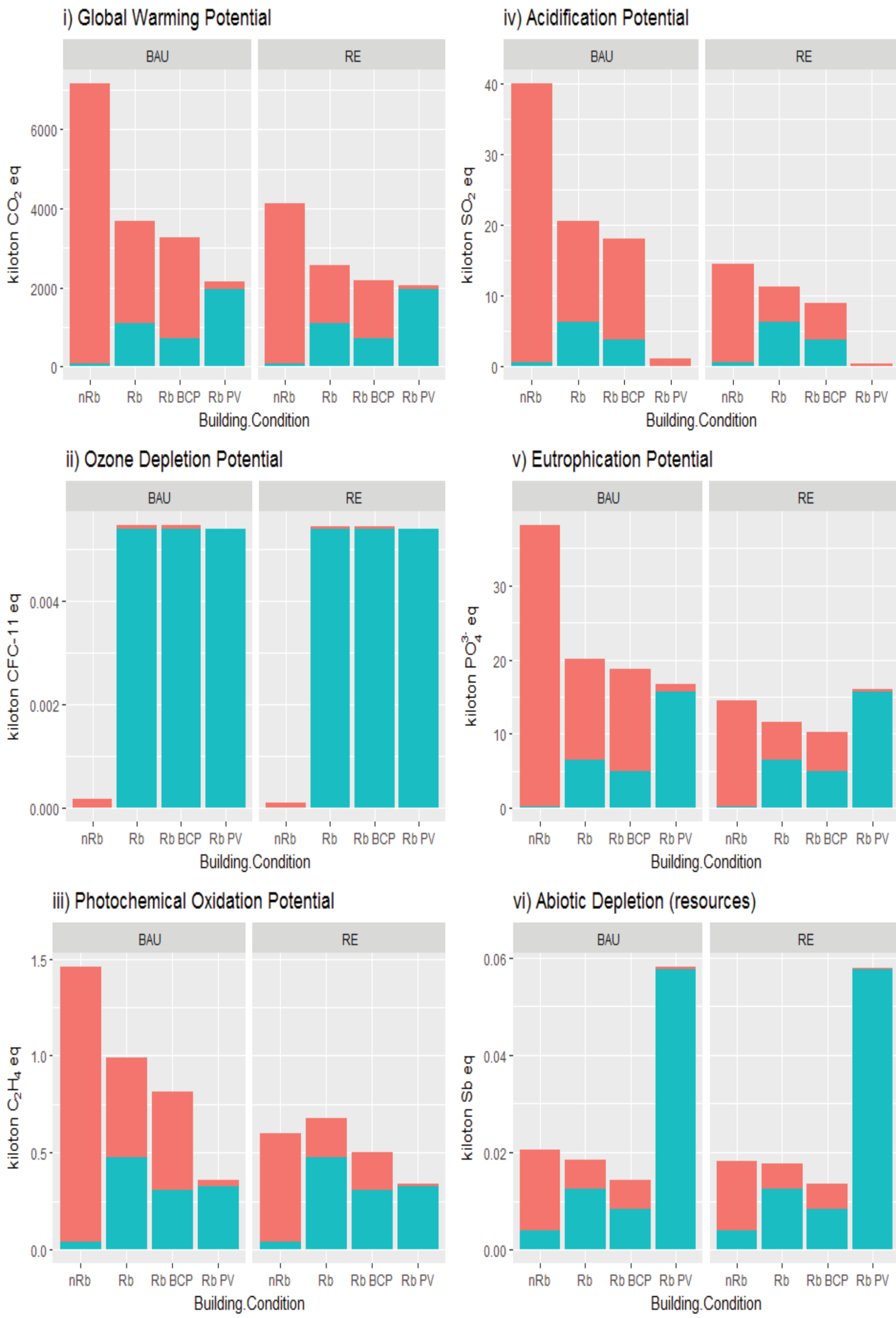

Figure 6.2 (a) The stock aggregated impact assessment results from 2017 - 2050 for buildings in four different conditions (nRb, Rb, Rb BCP, Rb PV) and two scenarios (BAU & RE) are shown for : i) Global warming potential, ii) Ozone depletion potential, iii) Photochemical oxidation potential, iv) Acidification potential, v) Eutrophication potential, vi) Abiotic depletion (resources) . The blue and red shaded areas represent the impacts embodied in construction and operational energy consumption respectively.

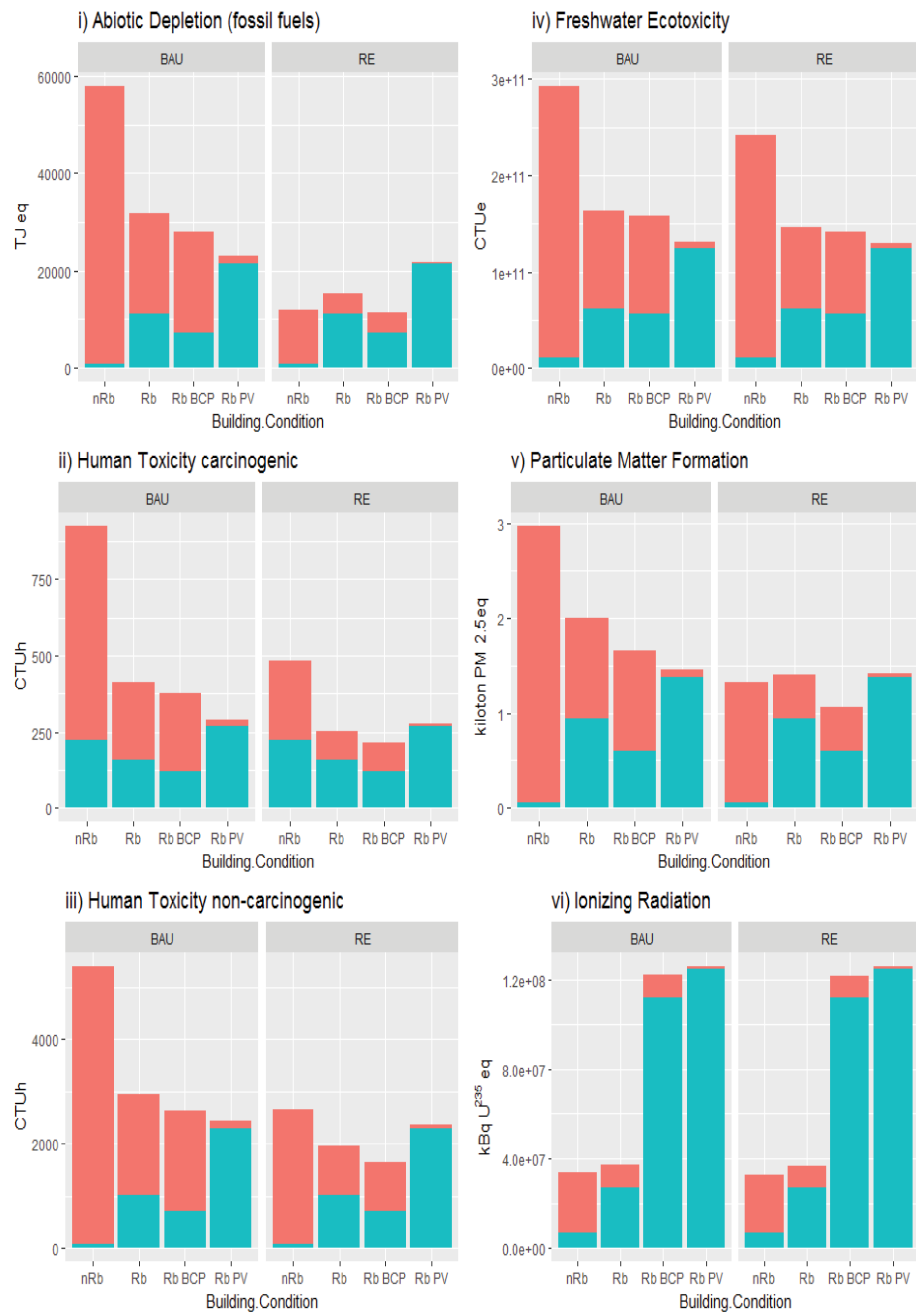

Figure 6.2 (b) The stock aggregated impact assessment results from 2017 - 2050 for buildings in four different conditions (nRb, Rb, Rb BCP, Rb PV) and two scenarios (BAU & RE) are shown for :i) Abiotic depletion (fossil fuels) ii) Human toxicity (carcinogenic) iii) Human toxicity (non-carcinogenic) iv) Ecotoxicity (freshwater) v) Particulate matter formation and vi) Ionizing radiation. The blue and red shaded areas represent the impacts embodied in construction and operational energy consumption respectively.

6.3.3 Target 2050 - New Zealand's office building stock

Table 6.4 shows the change in the stock aggregated GWP in 2050 compared to 1990 levels for buildings in all four conditions (nRb, Rb, Rb BCP Rb PV) and two scenarios (BAU, RE) if the whole building stock is refurbished. The results indicate that if the entire building stock is refurbished without PV (Rb and Rb BCP) it is possible to reduce the GWP impact in 2050 by 40 – 60 % in comparison to the office building stock in 1990. In 2050, the emissions will only be associated with the energy demand of the building stock and therefore the GWP associated with annual energy consumption of the refurbished building stock Rb and Rb BCP are same. Impact reductions over 95 % are possible for the refurbished office building stock with on-site PV. GWP is higher in the RE scenario compared to BAU for building stock in any condition. Rb BCP has the shortest payback period for both the BAU and RE scenarios due to the reduced embodied emissions associated with refurbishment, The payback period for refurbishing in the BAU scenario is lower than in the RE scenario for all refurbishment conditions.

Figure 6.3 shows that, by 2050, the cumulative GWP associated with nRb are approximately 7150 and 4200 kt CO_2 eq in the BAU and RE scenarios respectively. Approximately 50 and 40 % the emissions are avoided if the building stock is refurbished without PV (Rb and Rb BCP); and 70 and 50 % of the impacts are avoided if the building stock is refurbished with PV in the BAU and RE scenarios respectively.

The GWP from refurbished buildings peak two times: in the year of construction and in year 25 when building components are replaced (see Figure 6.3). The emissions from the refurbished building stock with PV in year of construction are the highest compared to buildings refurbished without PV (Rb and Rb BCP). Refurbished buildings adopting best construction practice (Rb BCP) have 25 % and 51 % less contribution to GWP in year 1 compared to Rb and Rb PV, respectively. In the year of maintenance and replacement, the GWP increase by 25 % compared for Rb PV; and about 12 and 10 % for Rb and Rb BCP, respectively.

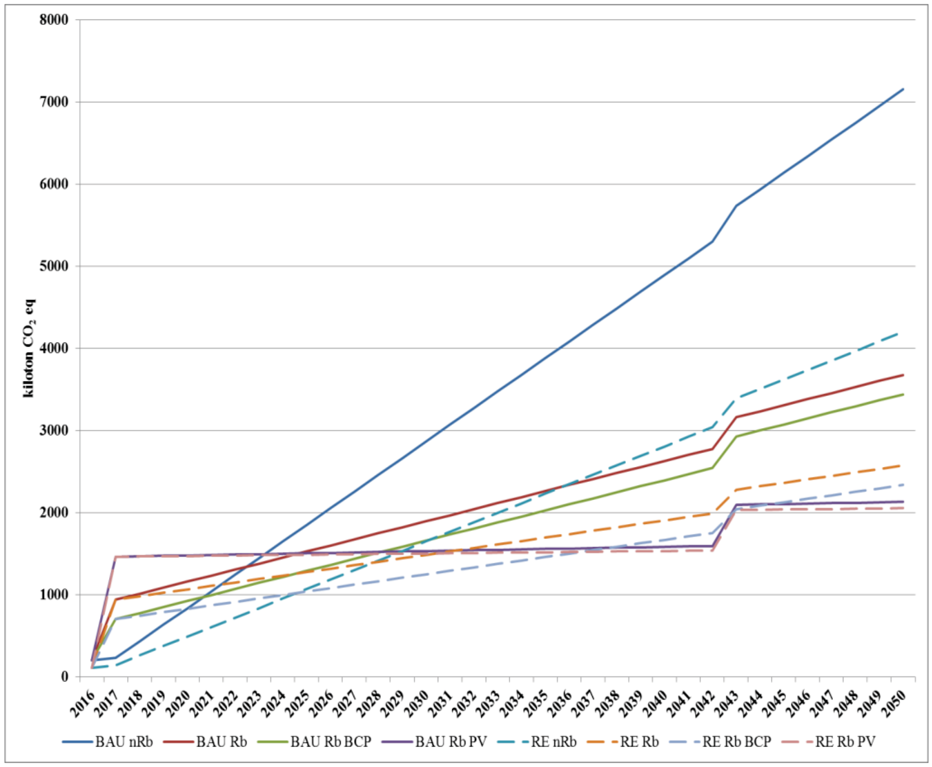

Figure 6.3 Cumulative GWP between 2017 to 2050 for buildings in four different conditions (nRb, Rb, Rb BCP, Rb PV) and two scenarios (BAU & RE). The solid lines and dotted lines are representative of the GHG emissions of the whole building stock in BAU and RE scenarios.

6.3.4 Targeting refurbishment towards specific building stock

The results in tables 6.5 and 6.6 show the GWP of the whole office building stock with respect to the 2050 target, if the refurbishment of the building stock in one or more regions with major cities is prioritised. Substantial reductions in GWP is possible only if the building stock is refurbished in two or more regions with major cities particularly in the RE scenario. This is because the three major cities in New Zealand have over 65 % of the existing office building stock. In the RE scenario, refurbishing the building stock in all three cities with or without PV can reduce 50-70 % of GWP from the whole building stock compared with 1990. Substantial reductions in GWP is possible only if refurbishments are prioritised in Auckland or Wellington in comparison to Christchurch in the RE scenario. GWP reduction in the BAU scenario is possible only if the building stock is refurbished with PV in Auckland in combination with one or more other cities. It is also worth noting that the payback period of refurbishing the building stock in Wellington is shorter compared to other major cities. This is because the annual operational energy savings in Wellington are high compared to the emissions embodied in refurbishment of the building stock in this region.

Table 6.4 GWP in 2050 of whole office building stock with respect to New Zealand's 2050 target. The '+' and '-' signs indicate the increase and decrease in GWP as compared to 1990 emissions, respectively.

		$I_{W(GWP\ in\ 2050)}$	Target 2050	Payback period
		kt CO_2 eq	$\Delta I_{2050-1990}$	yr.
BAU	nRb	203	+ 64 %	
	Rb	73	- 41 %	7
	Rb BCP	73	- 41 %	5
	Rb PV	5	- 96 %	7
RE	nRb	116	- 6 %	
	Rb	42	- 66 %	13
	Rb BCP	42	- 66 %	10
	Rb PV	3	- 98 %	13

Table 6.5 GWP in 2050 of whole office building stock with respect to 2050 target- if buildings in specific regions are refurbished. The '+' and '-' signs indicate the increase and decrease in GWP as compared to 1990 emissions, respectively.

		AKL*	Target 2050	Payback period	WLG*	Target 2050	Payback period	CHC*	Target 2050	Payback period
		kt CO_2 eq	$\Delta I_{2050-1990}$	yr.	kt CO_2 eq	$\Delta I_{2050-1990}$	yr.	kt CO_2 eq	$\Delta I_{2050-1990}$	yr.
BAU	Rb	151	+ 22%	8	150	+ 21%	4	185	+ 50%	8
	Rb BCP	151	+ 22%	5	150	+ 21%	2	185	+ 50%	5
	Rb PV	126	+ 2%	9	141	+ 14%	5	178	+ 43%	10
RE	Rb	86	- 30%	15	86	-31%	7	106	- 14%	13
	Rb BCP	86	- 30%	9	86	-31%	4	106	- 14%	9
	Rb PV	72	- 42%	16	81	-35%	8	102	- 18%	17

* AKL- Auckland/Northland, WLG- Wellington/Wairarapa, CHC- Christchurch/Canterbury

Table 6.6 GWP in 2050 of whole office building stock with respect to 2050 target- if buildings in two or more major cities and adjoining regions are refurbished. The '+' and '-' signs indicate the increase and decrease in GWP as compared to 1990 emissions, respectively.

		AKL+ WLG	Target 2050	Payback period	WLG+ CHC	Target 2050	Payback period	AKL+ CHC	Target 2050	Payback period	3 major cities[#]	Target 2050	Payback period
		kt CO_2 eq	$\Delta I_{2050-1990}$	yr.	kt CO_2 eq	$\Delta I_{2050-1990}$	yr.	kt CO_2 eq	$\Delta I_{2050-1990}$	yr.	kt CO_2 eq	$\Delta I_{2050-1990}$	yr.
BAU	Rb	125	+ 1%	8	159	+ 28%	5	134	+ 8%	8	108	- 13%	8
	Rb BCP	125	+ 1%	5	159	+ 28%	5	134	+ 8%	5	108	- 13%	5
	Rb PV	90	-27%	9	142	+ 15%	9	101	-19%	9	65	- 47%	9
RE	Rb	71	- 42%	14	91	-27%	13	77	-38%	14	61	- 50%	14
	Rb BCP	71	- 42%	9	91	-27%	8	77	-38%	9	61	- 50%	9
	Rb PV	52	- 58%	16	81	-34%	15	58	-54%	16	37	- 70%	16

[#] Performance of entire office building stock when buildings are refurbished buildings in all three cities/ regions (AKL + WLG + CHC)

Table 6.7 GWP in 2050 of whole office building stock with respect to 2050 target- if buildings of specific sizes are refurbished. The '+' and '-' signs indicate the increase and decrease in GWP as compared to 1990 emissions, respectively.

		Buildings <3500	Target 2050	Payback period	Buildings >3500	Target 2050	Payback period
		kt CO_2 eq	$\Delta I_{2050-1990}$	yr.	kt CO_2 eq	$\Delta I_{2050-1990}$	yr.
BAU	Rb	141	+ 14%	10	135	+ 9%	7
	Rb BCP	141	+ 14%	7	135	+ 9%	4
	Rb PV	90	- 28%	12	118	- 5%	7
RE	Rb	80	- 35%	18	77	- 37%	12
	Rb BCP	80	- 35%	12	77	- 37%	7
	Rb PV	51	- 59%	21	68	- 45%	12

The results in table 6.7 show the GWP with respect to the 2050 target, if the refurbishment of buildings of a specific size is prioritised. In general, GWP reduction is higher in the RE scenario. Refurbishment of medium to large sized buildings (**Buildings >3500m^2)** contribute to higher GWP compared to refurbishment of small sized buildings (**Buildings <3500m^2)** except if refurbished buildings installed with PV. Small sized buildings (**Buildings <3500m^2)** refurbished with PV contribute to higher GWP reductions compared to medium to large sized refurbished buildings (**Buildings >3500m^2)** with PV.

In New Zealand, the total floor area of large office buildings is approximately 53 % of the total building stock. Therefore, the share of annual energy savings is higher when buildings are refurbished without PV (Rb and Rb BCP). For refurbished buildings with PV, Cory (2016) noted that small buildings in New Zealand are typically low rise with a large roof area as compared to multi-storeyed buildings. Given that these buildings also have large area for on-site electricity production and a relatively small annual energy demand it enables them to off-set energy demand from the electricity grid. This is not possible in large multi-storey buildings which do not have the sufficient roof area to offset all their energy demand with on-site electricity generation.
However, it is important to note that the payback period for refurbishing large buildings is lower than refurbishing small buildings irrespective of the refurbished building condition. This is because of the large energy savings and low material intensity per m^2 for large buildings.

6.4 Discussion

The results highlight that refurbishment of existing office buildings can contribute to substantial reductions in most impact categories for the whole building stock. However, energy sources for grid electricity generation play an important role in determining the overall environmental performance of the building stock. In this section, the results are discussed with respect to the role of electricity supply, impacts embodied in the refurbishment process, and the potential role of refurbishment in climate change mitigation from the existing office building sector.

6.4.1 Role of electricity supply

As refurbished buildings substantially reduce the operational energy demand, they also reduce all impacts associated with the electricity supply. The majority of environmental impacts from New Zealand's energy supply are associated with electricity generated from coal which contribute to both GHG and non-GHG related impact categories (in particular, GWP, PCOP, AP, $ET_{freshwater}$, HT carc, HT non carc, and AD_{ff}) (Sacayon Madrigal, 2016). In the BAU scenario, around 21 % of the marginal electricity generation is from coal. Operational energy consumption of refurbished buildings in this scenario contributes 50 – 70 % of the environmental impacts in this scenario. In the RE scenario, as electricity generation from coal is phased out, the environmental impact per kWh of electricity is reduced (see Table 6.2) and, together with the increased share of renewable electricity supply to the buildings, contributes to a reduction in GWP and other energy-related impact categories (in particular, AP, PCOP, and PMF) compared with the BAU scenario. This change in electricity mix contributes around a 30 % reduction in the energy-related impacts associated with refurbished buildings without PV (Rb, Rb BCP) as compared to the BAU scenario. Figure 6.3 and Table 6.4 show that this change can even contribute to GHG mitigation from the non-refurbished building stock. However, this strategy makes little difference to the performance of refurbished buildings installed with PV with respect to GWP. This is mainly because refurbished buildings with PV already have approximately 90 % of their energy demand supplied from on-site electricity generation.

Adoption of deep energy refurbishment across the whole office building stock can contribute to substantial impacts in categories not influenced by a building's energy consumption; this is particularly the case for ODP, AD_r and IR as shown in Figures 6.2 (a and b) and for refurbished buildings installed with PV. Increased reliance on technological requirements (e.g. LED luminaires, PV panels) does raise concerns that the climate change mitigation can come at the cost of increases in other environmental impacts associated with increased resource consumption for manufacture of these technologies (Pauliuk et al., 2014). Indeed, the International Resource Panel (2017) has reported that by 2050, low-carbon technologies will require approximately 1.5 billion tonnes of metal resources for infrastructure and wiring.

6.4.2 Impacts embodied in refurbishment

Most impacts associated with the refurbished building stock are related to emissions embodied in refurbished building components such as aluminium framed windows, façade materials, heat pumps and PV as indicated in chapters 3 and 5. For refurbished buildings without PV (Rb, Rb BCP) approximately 30-50 % of the impacts are embodied in refurbished building components for most categories and 99 % for ODP. Building components which are made of materials that require energy intensive production (such as aluminium, steel, cement or bricks) have a high contribution to GWP, AP, EP, AD_{ff}, HT carc, PMF and IR. Impacts to PCOP and ODP are due to emissions from insulation production and refrigerant use in heat pumps respectively. Installation of PV panels increases the embodied impacts in all categories except (ODP, AP and PCOP) by over 50 %. Most impacts from PV are related to the silicon wafer panel production, followed by the materials (mainly aluminium and steel) required to mount the PV on the roof. Moreover, PV and other technical equipment for heating and lighting require speciality metal alloys, especially from copper. These contribute substantially to AD_r, HT non carc and $ET_{freshwater}$.

Maximizing construction waste recycling and recovery can reduce 20-30 % of the embodied impacts associated with refurbishment. In addition if the resources are also sourced from production sites using renewable energy nearly 40 % of the energy related impact categories (in particular, GWP, POCP, AP, AD_{ff} and PMF) can be reduced, with a marginal increase in IR. Reducing the embodied impact of refurbishment is particularly advantageous in the RE scenario, where the overall impact of the refurbished building is dominated by the embodied emissions.

6.4.3 Refurbishment and 2050 GHG mitigation target

Undoubtedly the refurbishment of existing office buildings (with or without PV) can contribute substantially to 2050 GHG emission mitigation from the office building sector in New Zealand. However, the results also highlighted that it was especially important to prioritise renewable electricity supply for a substantial reduction in emissions. The results of this study are largely in line with findings of existing LCA studies on refurbished buildings, which have also reported reductions in GHGs despite the initial increase in embodied emissions (Ardente et al., 2011; Azzouz et al., 2017; Passer et al., 2016).

The shorter payback period in the BAU scenario as compared to the RE scenario indicates the desirability of prioritizing energy efficiency refurbishment strategies in the short term, given that it is planned to transform New Zealand's electricity generation to a 100 % renewables grid by 2050 (Smith, 2017).

It is also important to note that emissions embodied in refurbished components spike the GHG emissions in the year of construction and replacement. Antti et al. (2012) noted that the rise in GHG emissions due to large construction projects should be highlighted because emissions occurring in the short term could be more harmful to the climate than the benefits related to subsequent energy efficiency that accrue over longer periods. Prioritizing the reduction in embodied GHG emissions by investing in best construction practices could help overcome this challenge given the benefits of a short payback period.

Refurbishing the whole building stock can be challenging due to escalating costs and construction delays which are considered the major barriers for the adoption of deep energy refurbishment in commercial office buildings (Bennet & Halvitigala, 2013) . Policymakers could prioritise refurbishment of specific parts of the building stock based on location or size as it may be more cost-effective and efficient (see sections 4.3.1 and 4.3.2). This measure could also be useful to limit the share of non-energy related environmental impacts associated with refurbishing buildings.

6.4.3.1 Targeting GHG mitigation with specific location

Regarding location, the major cities in New Zealand have the highest concentration of the existing office building stock. In general, prioritizing the refurbishment of buildings in Auckland in combination with one or more other major cities gives the largest benefits. Currently, the regional councils in Auckland, Wellington and Christchurch are involved in long term visionary projects aimed at developing as models for future cities (Auckland Council, 2014; Christchurch City Council, 2015; Wellington City Council, 2015). Given the benefits associated with energy efficiency refurbishment of existing buildings shown in this study, these actions could be prioritised by policy makers in regional councils to contribute to New Zealand's 2050 GHG mitigation target.

Refurbishing buildings with PV is more beneficial in Auckland with high solar irradiance compared to other major cities in New Zealand (Cory, 2016). Meanwhile, the results in this study also indicated that it might be worth refurbishing buildings in Wellington as compared to Christchurch although both cities have harsh climatic conditions. This is due to the type of buildings in the two cities. Wellington has a high share of multi-storey large buildings which provide large energy savings with relatively low material inputs per m^2 floor area.

6.4.3.2 Targeting GHG mitigation towards buildings of specific sizes

Regarding size, in general the refurbishment of large buildings (>3500 m^2) contributes to higher reductions in GHG emissions compared to small to medium sized buildings (<3500 m^2) except for buildings installed with PV. On the other hand, it is worth noting that the total number of large buildings (>3500 m^2) is only 445, which cover 53 % of the total existing office floor area. This contributes to large annual energy savings with limited resource cost. Moreover, it might be easier for policy makers to target the refurbishment of a smaller number of buildings which can easily compensate the embodied emissions given the short payback period as well as contribute to substantial GHG emissions over the long term.

6.4.4 Limitations and future work

There is great interest in the use of stock aggregation models to investigate the potential for reduction in energy demand and GHG emissions associated with the existing building stock. Studies in New Zealand have used this approach to primarily report the benefits related to reduction in operational energy demand and/or GHG emissions due to refurbishment (Becken et al., 2001; Cory et al., 2015; Garde et al., 2015). In comparison, this study presents a comprehensive environmental analysis by including the emissions embodied in construction and extending the analysis to multiple environmental categories. The results support the fact that increasing the share of renewables in New Zealand's electricity grid reduces emissions related to the building sector and this is a vital measure in moving towards the 2050 target (NZBCSD, 2016; Smith, 2017). As the benefits of on-site PV are mainly limited to regions with high solar irradiance, it is worth investigating the environmental effects of installing centralised versus on-site rooftop solar power generation in these areas. There is a level of simplification adopted in the modelling approach applied to this study. The construction and energy load of the entire office building stock was assumed to be similar to a representative sample. Building stock aggregation models can be enhanced by the adoption of Geographic Information Systems (GIS) (Mastrucci et al., 2017a). This approach allows detailed analysis of individual buildings in the stock and the total environmental impact is calculated by aggregating individual results at the stock level. This type of modelling is excessively demanding to perform analysis on national level building stock but has been used to increase the model resolution for stock aggregation in individual cities (Garcia-Perez et al., 2017; Mastrucci et al., 2017b). Given that this study has identified the benefits of refurbishing the building stock in major cities, GIS-integration targeted in these locations could further help to improve the quality of the analysis.

Moreover, this study has not considered the economic or social dimension associated with transformation of the building stock. These two factors are important to be considered to identify potential barriers for effective policy making and implementation. Deep energy refurbishments have a high capital cost, which can be a major barrier to promote such policy incentives (Bennet et al., 2013; Perrett, 2011). Miller et al. (2015) reported the high sensitivity of energy cost savings from use of PV due to location-specific production and retail tariff. Thus suggesting large scale deployment in New Zealand's commercial sector is still not economically viable. In future, combining this study with life cycle cost benefit analysis of refurbishing the building stock could enable policy makers to address both environmental and economic aspects of this mitigation strategy. This model could be further improved by considering exogenous stock drivers such as population rate and per capita use of office building stock, and rate of new construction or demolition. Integrating these factors would allow the development of a more sophisticated dynamic model to assess the future impacts of the existing stock (Pauliuk et al., 2014). Some studies have also recommended the need to include social and economic rebound effects to enhance the quality of information from such models (Heeren et al., 2013). However, Mastrucci et al. (2017a) argued against the development of computationally complex models as it could increase complications especially when using Monte Carlo based uncertainty propagation and stochastic sensitivity analyses. Instead where possible it is suggested to rely on simplified models which are also enable relatively quick calculations.

6.5 Conclusion

This study presents a comprehensive environmental assessment of New Zealand's office building stock using a stock aggregation approach based on LCA results of prototypical office buildings. The results of the study provide the following insights if the existing stock remains in operation up to 2050:

1. Refurbishment of the existing office building stock can substantially reduce most of the environmental impacts compared with the non-refurbished buildings, especially for impact categories affected by operational energy use.
2. Energy sources for grid electricity generation plays an important role in determining the overall environmental performance of the building stock. A renewable energy mix contributes to largest environmental benefits.
3. Substantial environmental emissions are embodied in materials and components associated with refurbishment which lead to an increase in all environmental impact categories in the year of refurbishment.
4. Although combining refurbishment with the addition of PV reduce the operational energy demand of the refurbished building it contributes to increase in embodied emissions. PV panel production increases environmental impacts associated with resource depletion and non-greenhouse gas emissions.
5. Adopting best available resource and waste management measures during refurbishment can contribute to substantial benefits across most environmental categories, and these are greater than the benefits of installing and using on-site PV.

The results also highlight the achievability of New Zealand's 2050 target with respect to reducing GHG emissions from the office building sector. Invariably substantial reductions in GHG emissions are possible if the the share of renewable electricity supplied is increased from the grid. However, efforts to reduce the GHG emissions from the office building stock must also consider the emissions embodied in refurbishment as these can be substantial.

The study indicates the immediate need to adopt energy efficiency strategies because the greatest reductions in environmental impacts arise from reducing operational electricity use generated from the current electricity mix rather than a future electricity mix comprising a larger share of renewable sources. Prioritizing the refurbishment of large buildings (> 3500 m2) or buildings located in major cities (Auckland, Wellington and Christchurch) can help in substantial GHG reduction without increasing the embodied impact of the entire building stock, and can contribute to limiting environmental trade-offs in other impact categories. These insights could help policy makers who are interested in supporting energy efficiency of commercial buildings from an environmental sustainability perspective.

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7 General Discussion

7.1 Introduction

Refurbishment of existing office buildings with multiple energy efficiency measures can substantially reduce the growing energy demand for space heating, cooling and lighting in New Zealand (Cory, 2016; EECA, 2017a). Reductions in energy demand also have the potential to reduce greenhouse gas emissions (GHGs) and other environmental impacts associated with energy consumption (Thema et al., 2017). However, large scale energy efficiency refurbishments require substantial upfront investment in infrastructure (International Resource Panel, 2017). The resources used and energy requirements for this initial investment also contribute to a range of environmental impacts. It is therefore important to assess the initial environmental impacts of energy efficiency investment in addition to the potential environmental benefits in future in order to support more informed and robust decision making on refurbishment of office buildings.

The objective of this research was to assess multiple environmental impacts associated with deep energy refurbishments of existing office buildings in New Zealand and, in particular, to identify strategies that could minimize the environmental impacts and maximize the environmental benefits. The environmental impacts and benefits were assessed using Life Cycle Assessment (LCA) for typical office buildings in New Zealand as shown in chapters 3 – 6. This chapter discusses the influence of study design in each of the previous four chapters (section 7.2), the key findings (section 7.3), the policy implications (section 7.4), limitations with implications for future work (section 7.5); and finally the main outcomes of this research (section 7.6)

7.2 Influence of study design

Assessment of the environmental impacts associated with large scale energy efficiency refurbishment in office buildings using LCA was an element of commonality in the previous four chapters (3 – 6). However, the study design adopted in each chapter was different. In this section the influence of the study design in the four chapters will be discussed with specific focus on how it influenced the development of the succeeding chapters. Table 7.1 provides a summary of the study design adopted in each of chapters 3 to 6. It is worth noting that the research for all four chapters was conducted sequentially. Therefore the data, results and key findings of the preceding chapters helped develop the subsequent chapters. Each chapter also addressed specific research questions and objectives. The research objectives determined the methodology employed and the key parameters chosen for further analysis (see Table 7.1).

All the building prototypes used in this research were obtained from a single source (Cory, 2016). In total, Cory (2016) developed 119 refurbished building prototypes based on construction details of 17 existing office buildings and their energy performance based on the seven regions in New Zealand. Each building prototype was representative of the construction and energy performance of a typical office building operating in a specific region in New Zealand. Moreover, all building prototypes adopted the same energy efficiency measures suggested for a deep energy refurbishment. These measures were: 1) large scale transformation of the façade with increased insulation to building envelope (wall and roof); 2) optimization of the Wall to Window Ratio (WWR); 3) replacement of window types; 4) addition of solar shading to avoid passive solar heat gain; 5) change of the air conditioning system (heating and cooling) from a natural gas operated boiler; and 6) electric chiller to electric heat pumps, and replacement of existing compact fluorescent lamps with LED luminaires. The specific differences with respect to building construction of different building prototypes were mainly the choice of façade material used, thermal resistivity of the building envelope, ventilation rate, luminous efficacy of lighting equipment, and the building geometry (building height, total floor area, window area, number of windows, shaded façade area). All other parameters were calculated based on this information.

In this research a systematic approach was adopted. In chapter 3 the fundamental calculations required to estimate the material quantities from the construction details and building geometries were developed to establish the LCA model. The LCA model was adapted to the consequential modelling approach in chapter 4, which was then used in succeeding chapters. This enabled the focus in chapters 5 and 6 to be on the influence of key strategies that could affect the future environmental performance of the buildings.

A key difference among the four chapters was the **sample size** (or the number of buildings analysed.). In Chapters 3 and 4 the environmental impact of a typical office building in Auckland was used, since this is a region with the highest concentration of office buildings in New Zealand. In Chapter 5, the environmental impacts of all 119 refurbished building prototypes were evaluated in four different scenarios. Finally in Chapter 6, the environmental impacts of the 119 buildings were scaled up to represent the potential impact of the existing New Zealand office building stock which consists of approximately 5700 buildings.

Other differences in the study design were related to the inventory modelling approach (section 7.2.1), life cycle stages included (section 7.2.2), and additional methodological approaches adopted (section 7.2.3).

7.2.1. Inventory modelling

In LCA there are two main inventory modelling approaches: attributional and consequential. In this research both attributional and consequential modelling approaches were used. Attributional modelling was used in chapter 3 and consequential modelling was used in chapters 4, 5 and 6 respectively. Although it is still a topic of debate as to which of these two modelling approaches is better suited for supporting decision making (Brandão et al., 2014; Plevin et al., 2014; Suh et al., 2014), there is growing consensus that both methods generate relevant environmental information and should be used in a complementary manner (Chobtang, 2016; Yang, 2016). Use of the two different approaches depends on the goal and scope of the analysis. For example, attributional LCA can be recommended to assess the environmental impacts of a product/process based on the current situation, while consequential modelling approach is used to assess the environmental impacts based on the change in demand for a product/process (Chobtang, 2016).

Attributional LCA was used in chapter 3 to identify hot spots associated with a deep energy refurbishment based on the current average supply of construction materials and energy. In particular, the environmental impacts of each refurbished component and the construction activities associated with refurbishment were evaluated. The results revealed that the highest impact for a majority of categories was associated with the use of construction materials which have energy intensive production processes; the contributions of transportation and construction at site were minimal. The consequential LCA was used to evaluate the environmental impacts due to the increase in demand for construction activities related to energy efficiency refurbishments. This study showed that the supply of certain construction materials which require energy intensive production such as aluminium and cement might be constrained if there was an increase in demand for large energy efficiency refurbishments in New Zealand. Thus the environmental impacts of these construction materials will depend on where these are imported from and the energy used to produce them. For example, if energy intensive materials are supplied in regions with a high share of renewable electricity generation the environmental impact of these materials is substantially lower for environmental impacts which are mainly influenced by energy sources.

Consequential modelling identifies the consequences of changes in consumption as opposed to non-consumption of a product (Weidema, 2015); and therefore identifies marginal or net effects of a change in demand to model future scenarios. Consequential modelling is recommended as a more appropriate approach in informing policy development because it accounts for market mechanisms and avoided burdens associated with the utilization of by-products (or waste) (Brandão et al., 2014; De Camillis et al., 2013). In chapter 4, the consequential inventory was developed based on identified marginal suppliers of key construction materials and energy in New Zealand. This background inventory was used for the research presented in chapters 5 and 6 which was focussed on evaluating the efficacy of alternative policies on refurbishing multiple buildings.

7.2.2 Life Cycle Stages

Refurbishment consists of a deconstruction (removal of building components to be changed) and a re-construction (installation of new refurbished components). In this thesis the environmental performance of refurbishment was based on the Module B5 in EN 15 978 which provides the standardized guidelines on the life cycle stages to be assessed to determine the impact of building refurbishment (EN 15978, 2011). This includes the production, transport, construction at site and end of life treatment of all materials and building components discarded and installed during the process.

As the primary aim of refurbishment is to improve the performance of buildings compared to its current condition (EeBGuide Project, 2012), LCA studies on energy efficiency refurbishments broaden the scope of the research to include the use stage (this includes operational energy use and building maintenance) and the impacts associated with energy consumption pre- refurbishment as a benchmark for comparison (Vilches et al., 2017). Except for chapter 4, the use stage was included in the research described in the remaining chapters (3, 5 and 6). The inclusion or exclusion of life cycle stages was based on the primary objective of the case. For example, in chapter 3, it was identified that embodied emissions associated with refurbishment can contribute 30 – 70% of the potential environmental impacts associated with a refurbished building operating for 25 years. Therefore in chapter 4, the focus of the research was to determine the effect of resource and waste management strategies as a means to reduce the environmental impacts embodied in the refurbishment process of a building; the subsequent use phase of the refurbished building was excluded as it was not the focus of the study.

Maintenance of the refurbished components was included only when the operation of a building was considered for over 25 years (chapter 3 and 6). This time frame was used as it represented the average time before replacement of the refurbished building components, particularly for the technical equipment – HVAC, LED lamps and PV panels (Balaras et al., 2004; Juan et al., 2010; Principi et al., 2014).

7.2.3 Analytical approaches adopted to strengthen LCA results

In each chapter additional analytical approaches (such as sensitivity analysis, regression analysis, stock aggregation) were used to increase the reliability and interpretability of LCA results.

Sensitivity and/or scenario analysis are ways to minimize and quantify uncertainty in LCA (Huijbregts et al., 2001). This approach was adopted in all four chapters for the same reason. Sensitivity analysis is particularly recommended to enhance the quality of consequential LCA analysis (Zamagni et al., 2012). Consequential LCA modelling is considered more accurate to assess future scenarios as it models the system based on the potential change in demand (Brandão et al., 2014). However, uncertainties are inherent to identification of future scenarios. The uncertainty in consequential modelling can be addressed with sensitivity analysis as this helps to present the magnitude of the possible ranges in future scenarios (Zamagni et al., 2012). The influence of future electricity mix (chapter 3, 4 and 6), recycling efficiency and choice of marginal supplier (chapter 4) were considered using sensitivity analysis. Scenario analysis was used to highlight the influence of key strategic issues such as the influence of building lifetime (in chapter 3); strategies for waste and resource management (chapter 4); and adoption of best practice construction measures or installation of PV panels (in chapters 5 and 6).

In chapters 3 and 6, **the environmental payback period** was calculated for each impact category. Hesser et al. (2017) identified that integrating the concept of payback period with LCA is essential in order to define the scope of further research in a target-oriented way. Moreover, calculation of payback periods based on environmental performance in different scenarios is an additional way of communicating the potential magnitude of environmental performance of refurbished buildings.

In chapter 5, **regression analysis** was used to estimate how the suggested refurbishment measures and building characteristics allow prediction of the environmental performance of refurbished buildings in each scenario. The use of **inferential statistics** such as correlation and regression provides useful information with respect to the strength and statistical significance of the variables influencing the environmental impact (Grant et al., 2016; Pushkar, 2016). It also increases the predictive capacity of the studied system on the impacts analysed (Grant et al., 2016).

In chapter 6, **building stock aggregation** was used to estimate the potential environmental performance of the entire existing office building stock in New Zealand. Although this method is frequently used to model energy demand of a building stock, it has seldom been applied in conjunction with assessment of environmental impacts (Heeren et al., 2013; Österbring et al., 2014). Besides estimating the potential impact from energy and resource use of refurbishing the whole building stock, the approach also enables estimation of the potential contribution that can be made towards achievement of New Zealand's 2050 Paris Agreement target using deep energy refurbishment of office buildings.

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Table7.1 A summary and comparison of the study design adopted in chapters 3 - 6

	chapter 3	chapter 4	chapter 5	chapter 6
Sample size (No. of Buildings)	1	1	119	5698
Inventory modelling approach	Attributional	Consequential	Consequential	Consequential
Additional methodological approach	•Scenario and sensitivity analysis • Environmental Payback period	• Scenario and sensitivity analysis	• Scenario analysis •Regression analysis - Kruskal Wallis and Dunn's test - General Additive Modelling (GAM)	• Stock Aggregation analysis • Scenario and sensitivity analysis • Environmental Payback period
Life cycle stages included:				
• Refurbished components (material extraction, manufacturing)	✓	✓	✓	✓
• Construction activities (transport, on-site energy use)	✓	✓	✓	✓
• Waste treatment	✓	✓	✓	✓
• Operational energy use	✓	n.a.	✓	✓
• Maintenance of building components	✓	✓	n.a.	✓
Comparison with environmental performance of non-refurbished building prototype/s	✓	n.a.	n.a.	✓
Influence of :				
• Renewable (de-carbonized) grid electricity supply	✓	✓	✓	✓
• On-site Photo-voltaic (PV)	n.a.	n.a.	✓	✓
• Building lifetime	✓	n.a.	n.a.	n.a.
• Building size	n.a.	n.a.	✓	✓
• Building location	n.a.	n.a.	✓	✓
• Other building characteristics (No. of storeys, Technical equipment installed)	n.a.	n.a.	✓	n.a.
• Construction waste and resource management	n.a.	✓	✓	✓
• Waste recovery and recycling efficiencies	n.a	✓	n.a.	n.a.

Here ✓ represents factors that were specifically modelled in the chapter to address the over-arching research questions; and 'n.a.' represents not applicable to that chapter.

7.3 Key findings

In this section the key findings of the research presented in chapters 3 to 6 will be discussed. More specifically, the section highlights the environmental hotspots associated with refurbishment (section 7.3.1), the influence of electricity supply (section 7.3.2), resource and waste management (section 7.3.3) and other building characteristics (including building size and location) (section 7.3.4). Finally strategies and scenarios assessed in this research which contribute to maximum environmental benefits at minimal environmental cost has been summarized (section 7.3.5)

7. 3. 1. Environmental Hotspots

The majority of existing LCA studies on commercial buildings have shown that refurbishment of office or other non-residential buildings contributes to only 2-10 % of the total life cycle environmental impacts of a building operating for 50 - 60 years (Vilches et al., 2017). Moreover, these studies have primarily focussed on the life cycle energy demand and GHG emissions. However, the results of this research shows that the embodied emissions of a refurbished building operating for 25 years in New Zealand could contribute 30 – 70 % of the results for the energy and GHG emission related impact categories (GWP, AP, EP, $AD_{ff,}$ PCOP and PMF) and 70 – 99 % of the non-energy related impact categories (ODP, AD_r, HT carc, HT non carc, $ET_{freshwater}$ and IR) (chapter 3-6).

In chapter 3, it was demonstrated that all refurbished building components considered in this research reduce the future energy consumption and the associated environmental impacts of the analysed building. The environmental benefits associated with refurbishment as compared to non-refurbishment are evident for most environmental impact categories. However, it was also clear that some of the refurbished components could generate substantial environmental impacts in categories not influenced by the energy demand of the building. For example, use of refrigerants in heat pumps can contribute substantially to ODP and the release of pentane emissions during the foam blowing of insulation contributes to PCOP. Overall the results revealed that the highest contribution for a majority of categories was associated with the use of construction materials with an energy intensive production - notably the use of aluminium in double glazed window frames. The results also showed the high contribution of the use of copper in technical equipment such as heat pumps and luminaries to AD_r, HT non carc and $ET_{freshwater}$. The results highlighted the role of waste recycling in contributing to AD_r and $ET_{freshwater}$ due to losses of metal scrap (especially copper which is present in alloys) during recycling of steel or aluminium. However, waste recycling also contributes to reduction of 10 - 25% of the impacts in all categories except ODP and $ET_{freshwater}$.

The contribution of refurbished components remained similar also when the impact of refurbishment was analysed using consequential modelling in chapter 4. This was the same for chapters 5 and 6 except in the scenario where the installation of on-site photo voltaic panels was considered. The share of embodied impacts from photo voltaic panels was approximately 30 – 50% for all categories except AP and PCOP. This is because the production of PV panels is substantially energy and resource intensive (International Resource Panel, 2017). Additionally, the contribution of emissions from transport of construction material to site and construction activities at site is minimal (1 - 5%), except to IR. The contribution to IR is mainly associated with fuel use (diesel for building machine and freight transport). Crude oil extraction from fracking in certain regions releases naturally occurring radionuclides, which settle out as radioactive waste at extraction sites (Ferrar, 2017; US EPA, 2000).

The environmental hotspots identified in this research are in line with existing LCA studies on refurbishment of the building facade (Pomponi et al., 2015); the refurbishment of specific building components such as windows (Carletti et al., 2014a), solar shading (Babaizadeh et al., 2015), insulation (Nicolae et al., 2015), HVAC (Blom et al., 2010; Rinne et al., 2013), LED luminaires (Principi et al., 2014) or PV (Fu et al., 2015); or effects of construction waste recovery (Bernstad Saraiva et al., 2017; Blengini & Garbarino, 2010b). However, the benefit of this research is that it assesses the environmental impacts of refurbished buildings that have adopted multiple energy efficiency strategies. This is, in fact, the most likely situation if the strategic aim is to reduce the building operational energy consumption after refurbishment by over 50 % (IEA EBC, 2015; Zhai et al., 2011).

7. 3 .2. Influence of electricity supply

The results highlighted the strong influence of grid electricity in determining the results in all categories except ODP, AD_r and IR. For instance, the results in chapters 3, 5 and 6 indicated that increase in renewable electricity generation reduces the environmental impact of building operation. These benefits are mostly associated with the reduction in emissions associated with electricity generation from coal production. Interestingly, and perhaps not entirely surprisingly, the results in chapters 3 and 6 indicated that the environmental payback period of a deep energy refurbishment increases as the electricity supply from renewable sources increases.

For refurbished buildings installed with PV, the energy-related environment impacts associated with operational electricity consumption are negligible. The environmental impacts and subsequent payback period for refurbished buildings installed with on-site PV is higher than buildings refurbished without PV when the grid electricity supply from renewables increases. This is because as the GHG or other emissions associated with annual energy savings decrease, it becomes challenging to compensate the emissions embodied in refurbishment. Nevertheless, the importance of reducing the operational energy consumption cannot be neglected. As shown in chapter 6, the environmental impact of the refurbished building stock is still low compared to the non-refurbished building stock when the electricity is supplied from renewable electricity grid.

The efficacy of an energy efficiency strategy for environmental impact reduction depends on both energy demand and supply management. The New Zealand government currently targets to have 90% of the grid electricity generation from renewable sources by 2025 (Ministry for the Environment, 2016). Therefore, environmental emissions from grid electricity generation in New Zealand, like most countries, will potentially decrease by years 2030 and 2050 due to climate change mitigation activities aimed at bringing the country into line with the IPCC 2-degree Celsius scenario (IEA, 2017; MBIE, 2012; United Nations, 2015). As a result, the International Resource Panel (2017) has highlighted that technologies that reduce GHG emissions or other impacts in 2010 may not necessarily do the same in future. Given the payback period of deep energy refurbishment of New Zealand's building stock is shorter if it is undertaken now rather than in future, the results of this research support of acting sooner rather than later to deploy large scale energy efficiency measures.

7. 3 .3. Influence of waste and resource management

Energy efficiency refurbishments can substantially reduce the energy consumption of existing office buildings in New Zealand, but they have a high resource demand that could contribute to non-energy related environmental impacts. Escalating resource demand coupled with constrained resource availability in a region, drives the need to understand the environmental implications of potential resource flows from waste recovery (UNEP, 2011) and international trade flows (O'Brien-Malone, 2015).

The research in chapter 4 highlighted the environmental issues associated with increase in demand for key construction materials required for deep energy refurbishments with particular focus on resource and waste management strategies. The study highlighted that increasing construction waste recovery for recycling or re-use contributed to 15 - 25 % environmental impact reductions. The study also highlighted the importance of material quality and energy source for material production which contribute to determining the environmental impacts embodied in refurbishment. Benefits associated with construction waste recovery were mainly associated with waste metal recovery. Poor quality of metal recovered affects the recycling efficiency of the recovered metal and subsequently increases the environmental impacts. Prioritizing the source of constrained construction materials, such as aluminium which require energy intensive production, from regions where the marginal energy used for production is mainly from renewable energy sources. Use of renewable grid electricity reduces 20 - 40% of the embodied impacts to GWP, AP, POCP AD_{ff} and PMF but increases the impacts to IR. Increase in impacts to IR is mainly from imported products manufactured with a proportion of nuclear-supplied grid electricity generation which is expected to increase along with renewable sources as fossil fuel based electricity is phased out. Given that New Zealand's main trading partner is China, and China is aggressively transforming their electricity production to use more solar and nuclear power over the next years (Mathews & Tan, 2013), the impacts associated with energy intensive materials sourced from there are likely to shift as shown in this study. Moreover, it is worth noting that if the material with an energy intensive production cannot be sourced from regions/ manufacturers using grid electricity, then the use of alternative materials should be preferred. For example, cement contributes to 20-25% of the environmental impacts associated with concrete. Clinker production for cement requires heat which typically comes from coal; using concrete with cement-replacement materials such as blast furnace slag can reduce environmental impacts by approximately 90-95 % of the environmental impacts associated with cement (see SI 2, tables 5, 7 and 8 for absolute impacts per kg construction material).

In general, the results showed that maximizing the construction waste recovery for re-use and recycling, and the use of materials produced using renewable energy sources, can nearly halve the impacts embodied in refurbishment for all categories except IR. The importance of minimizing the embodied impact of energy efficient buildings by increasing construction waste recovery and prioritizing material production from renewable sources has also been highlighted by Blengini et al. (2010a), and Srinivasan et al. (2012) respectively.

In chapters 5 and 6, minimizing the embodied impacts of refurbishment was considered in the best construction practice scenario. The chapter 5 results highlight that environmental benefits in this scenario were similar to the benefits associated with refurbished buildings installed with PV for most of the energy related impact categories (such as GWP, PCOP, AP, AD_{ff}, HT carc, PMF). Moreover, refurbished buildings adopting resource and waste management have substantially lower impacts for abiotic resource depletion as compared to refurbished building with PV. Reducing the embodied impacts also reduces the payback period associated with large scale deployment of deep energy refurbishment which is advantageous for the climate change mitigation strategy (as shown in chapter 6).

7. 3 .4 Influence of building characteristics

The results in all the chapters show that, although energy efficiency refurbishment activities could help reduce energy demand and associated environmental impacts of New Zealand's existing office building stock, they also contribute to other environmental impacts (mainly related to ODP, AD_r, HT carc, HT non carc, $ET_{freshwater}$ and IR). Whilst these other impacts may be considered less significant than impacts such as climate change, a multi-attribute analysis of refurbishment strategies based on building characteristics such as building lifetime (7.3.4.1), building size (7.3.4.2), and location (7.3.4.3) can support balanced decisions that additionally help reduce or compensate for some of these impacts (as shown in Chapter 3, 5 and 6).

7. 3 .4. 1 Building Lifetime

The environmental payback periods calculated in chapter 3 indicated the importance of maintaining a longer operational period of ≥ 50 years for the refurbished building to compensate for most of the environmental impacts. Moreover, for certain environmental impact categories, the refurbishment activities cannot be compensated by the avoided impacts over any feasible time period for the refurbished building. This is an important new insight as most existing studies evaluate the payback period only in terms of potential climate change impact (kg CO_2 eq) (Hesser et al., 2017; Mahlia et al., 2011; Petrović Bećirović & Vasić, 2013) and thus overlook other environmental impacts. As energy efficiency and sustainable refurbishment are gaining momentum to maintain the existing office building stock's market value, it is also important to note that sometimes office buildings are refurbished as often as every 8 - 10 years (Forsynthe, 2007; Yohanis et al., 2002).

The results in chapter 3 indicated that environmental payback periods of energy efficiency refurbishments are longer than typical renovation cycles for many impact categories. Moreover, the benefits from energy savings are low if the share of electricity generated from non-renewable sources reduces. This indicates the need to limit the embodied impact of a building in order to maximise the substantial environmental benefits associated with energy savings over a building's life cycle. Frequent reoccurrence of structural or mechanical refurbishments could potentially cancel out their potential environmental benefits. This also demonstrates the need to introduce flexibility in the building design that can cater for different needs of building users; or design building components for easy disassembly for recovery and re-use (Wadel et al., 2013).

7. 3 .4. 2 Building size

The results in chapter 5 showed that small buildings (buildings with GFA ≤ 1499 m^2) had a higher embodied impact from refurbishment (per m^2) compared to large buildings (buildings with GFA ≥ 3499 m^2). This was because the quantity of materials used per m^2 gross floor area is relatively high in small buildings as compared to large buildings. In comparison, the environmental impacts of large buildings (buildings with GFA ≥ 3499 m^2) were dominated by energy demand for equipment use (Cory, 2016).

In chapter 6, the results indicated that prioritizing the refurbishment of existing large building stock (buildings with GFA ≥ 3500 m^2) could reduce 37 - 45 % of the greenhouse gas emissions to help contribute to meeting New Zealand's 2050 climate mitigation target from the existing office building sector. In addition to limiting other embodied emissions associated with other impact categories. Existing large building stock (GFA ≥ 3500 m^2) consists of only 445 buildings which cover 53 % of the total existing office floor area, as compared to over 5000 small buildings (GFA ≤ 3499 m^2) which cover 47 % of the total existing office floor are. Prioritizing energy efficiency in a smaller proportion of the building stock which yields substantial energy savings for the whole office building stock has two benefits. Firstly, it is easier to manage and therefore leads to effective policy implementation; secondly, it requires fewer resources and thus reduces the payback period required to compensate the initial emissions embodied in refurbishment.

7. 3 .4. 3 Buildings in different location

With respect to regions of New Zealand, refurbishing buildings in the South Island of New Zealand, mainly in Christchurch and Canterbury, and in Otago and Southland, had higher environmental impacts as compared to refurbishing buildings in the North Island (chapter 5). Canterbury and Southland, typically have hotter summers and colder winters in comparison with more temperate regions of New Zealand (Britten, 2000). Therefore, buildings in these regions have a higher requirement for thermal resistivity of the building envelope with respect to wall, roof and windows as the total annual energy consumption was higher compared with other regions in New Zealand (Cory et al., 2012) and therefore also required additional construction materials as compared to buildings in North Island. Chapter 5 results also indicated that, in general it was not beneficial to install PV panels to buildings in this region as compared to regions in North Island due to shorter sunshine hours. The findings in chapter 5 were also highlighted in chapter 6 where the impact of the whole existing office building stock was considered. More specifically the results in chapter 6 show that the environmental benefits for buildings installed with PV was higher for the building stock in Auckland as compared to the building stock in Christchurch.

In addition, the results in chapter 6 showed the benefits of prioritizing the refurbishment of the existing office building stock in regions with major cities. Refurbishment of the existing building stock in Auckland accounts for 33 % of the existing office floor area in New Zealand; it is also the largest share of existing office floor area compared to other regions in New Zealand. Refurbishment of the existing building stock in Wellington, which accounts for 20 % of the office floor area in New Zealand, has the shortest payback period compared to refurbishment of buildings in other major cities such as Auckland and Christchurch. The reason is that the building stock in Wellington has a larger proportion of large buildings (GFA ≥ 3500 m^2); as discussed in section 7. 3. 4. 2, refurbishment of large buildings leads to higher annual energy savings as compared to the quantity of materials used per m^2 gross floor area.

The comprehensive environmental impacts and benefits associated with building size and location have not previously been addressed in LCA studies on buildings in New Zealand. However, it is worth noting that substantial benefits related to energy savings from a small number of large buildings has also been highlighted by Cory (2016).

7.3.5 Maximizing net environmental benefits

This research quantified the environmental impacts of refurbishment and subsequently assessed strategies that could reduce the total environmental impact of energy efficient refurbishment. In general, the findings indicated that the overall environmental performance of non-refurbished or refurbished buildings is better if the grid electricity supplied to these buildings is generated from renewable energy sources. However, the results also highlighted that both non-refurbished buildings and refurbished buildings were associated with certain environmental trade-offs. These findings might be difficult to interpret by policy makers interested in adopting measures for climate change mitigation at minimum environmental costs.

Using the key findings in chapter 6[13] a heat map was developed (Figure 7.1) to show the strategies that could potentially maximize environmental benefits from the office building stock at minimal environmental cost. In chapters 3 and 6 it was identified that the environmental trade-offs associated with refurbishment are relatively larger when most of the grid electricity is from renewable sources. This is because the relative contribution of environmental emissions from grid electricity reduces if the use fossil fuels reduce. Given that New Zealand's electricity grid is likely to use more renewable energy sources in future (MBIE, 2012; Sise, 2016; Smith, 2017), only results from the renewable electricity scenario were used to generate the heat map. The impacts of the refurbished building stock were normalized with the environmental impact associated with the non-refurbished building stock. Three strategies were considered: 1) refurbishment of the entire building stock, 2) refurbishment of the building stock in only the three major cities (Auckland, Wellington and Christchurch), and 3) refurbishment of only the large office buildings (≥3500 m^2 total floor area). The heat map intuitively shows the environmental performance of the building stock based on the building condition using a colour scale. Colour hues towards red, yellow and green imply the high, moderate and low contribution to an impact category respectively.

With respect to the overall environmental performance of the building stock, the results highlight the environmental impacts from refurbished buildings as compared to non-refurbished building stock. The environmental impacts are particularly high for non-refurbished building stock and refurbished building stock with PV. However, based on the overall environmental performance of existing building stock, energy efficiency refurbishment should be prioritized especially with the adoption of measures for resource and waste management. The results highlighted that instead of refurbishing the entire existing building stock, prioritizing refurbishment of limited number of buildings with respect to the building location or

[13] In chapter 6, the influence of all strategies related to electricity supply and building condition were addressed to evaluate the environmental performance of the existing office building stock

building size can be helpful in limiting other environmental impacts in addition to contributing towards a climate change mitigation target. Applicability of the key findings for developing policies at national and building level is further elaborated in section 7.4.

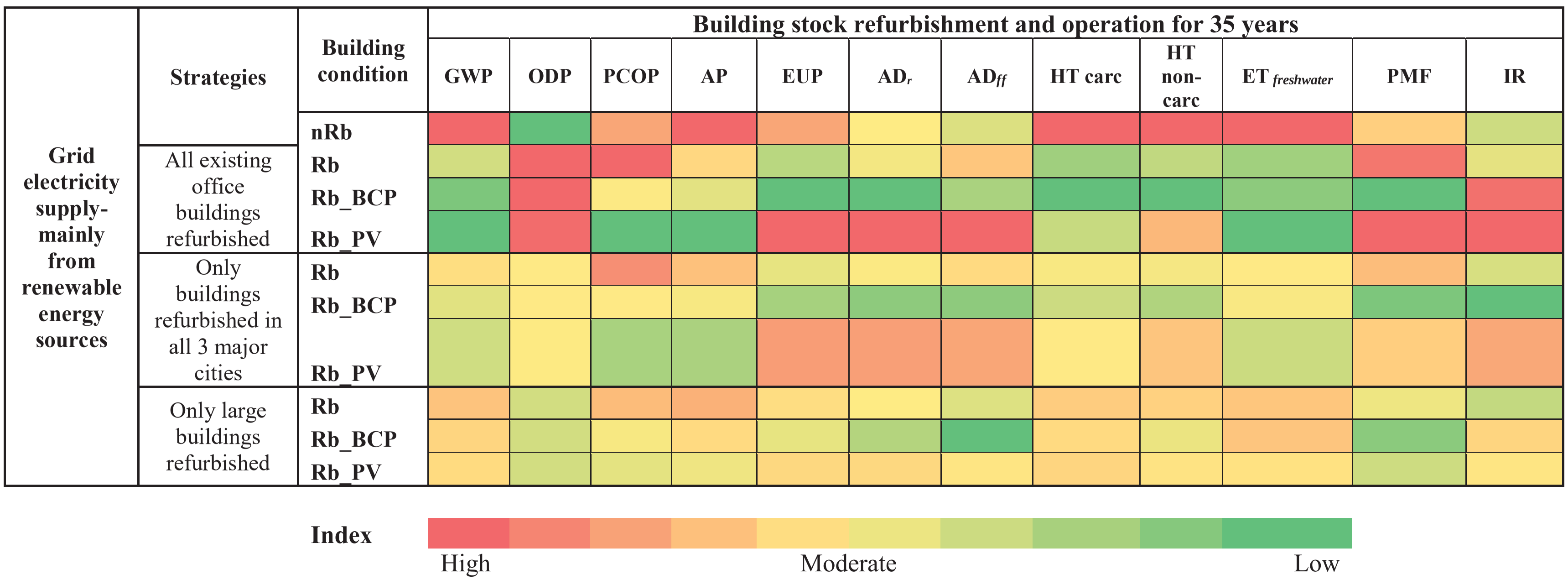

Figure 7.1 Heat map built to represent the influence of building condition and strategies for building refurbishment on the overall environmental performance of New Zealand's existing office building stock. Here nRb represents non refurbished building stock, Rb refurbished building stock, Rb_BCP represents refurbished building stock adopting best construction practice and Rb_PV represents refurbished buildings installed with PV. Colour hues towards red, yellow and green imply the high, moderate and low contribution to the impact category.

7.4 Applicability of results to policy makers

The final goal of this research was to use the key findings to support policy making in the development of environmentally sustainable, energy-efficient building stock in New Zealand. Although, the findings of this research are specific for commercial office buildings, they can also be used to inform policymaking for buildings with similar construction located in New Zealand, and indeed in other countries with similar climatic conditions. All the results indicated that deep energy refurbishment of buildings can substantially reduce the environmental impacts associated with non-refurbished building stock; however, the environmental performance could be optimised if specific policies are prioritised. Suggestions for policies based on the key findings of this research can support policy makers at national (sections 7.4.1 – 7.4.4) and building level (sections 7.4.5 – 7.4.7).

7.4.1 National policy: prioritise renewable grid electricity generation

The analyses in this research strongly suggest that energy efficiency improvements and renewable (low-carbon) electricity supply are both important as a climate change mitigation strategy as well as reducing other environmental impacts. However, in general, renewable electricity supply from the centralized national electricity grid is preferable to the installation of on-site PV panels for refurbished buildings as shown in chapters 5 and 6. Although installation and use of PV panels as a refurbishment strategy could reduce approximately 80 % of the grid electricity demand of refurbished buildings and associated emissions, it nearly doubles the environmental pressures on natural resources such as abiotic depletion of resources, eutrophication, carcinogenic and non-carcinogenic toxicity. In contrast, New Zealand is already investing in the 90 % decarbonisation of grid electricity generation (Ministry for the Environment, 2016) which will contribute to environmental impact reduction for all buildings in all impact categories except ozone depletion as shown in chapter 6. The International Resource Panel (2017), has pointed out the need for informed decision-making about energy technologies and infrastructure to avoid new environmental issues.

7.4.2 National policy: prioritise deep energy refurbishment of existing building stock as an immediate climate change mitigation strategy

It is important to accelerate the deployment of energy efficiency refurbishment in the short term in order to compensate for initial climate change and other potential impacts in order to accrue environmental benefits with annual energy savings in the short term. As there will be a gradual decarbonisation of grid electricity generation in future, compensation for embodied emissions becomes more challenging and will take a longer time as the emissions associated with annual energy savings reduce in future.

7.4.3 National policy: prioritise services that support segregation and recycling of construction wastes

Currently nearly 50 % of dry waste in landfills is associated with construction (Inglis, 2012). Existing studies on construction and demolition wastes have identified the lack of collection, separation and recycling facilities in close proximity to construction sites as a barrier to waste management (Inglis, 2012; Jaques & Hindley, 2013). This study highlighted the benefits of maximizing construction waste recovery to reduce the environmental impacts of refurbished buildings as well as reducing the payback period of refurbishment. Given the importance of maximizing construction waste recovery, policy makers could prioritise facilities such as provision of clearly labelled containers for separation and collection of construction waste from site. Such facilities could be provided by city or regional councils.

7.4.4 National policy: prioritise refurbishment strategies based on building size and location

This research highlighted the environmental benefits associated with refurbishing a subset of the building stock which could provide substantial energy savings whilst minimising embodied emissions. This strategy is particularly relevant when pursuing specific climate mitigation targets but at the same time seeking to minimise other environmental impacts. The results specifically highlighted the substantial benefits associated with refurbishing large buildings (GFA $\geq$ 3500 m^2) and/or refurbishing buildings in major cities (specifically in Auckland and Wellington), in the context of reducing greenhouse gas emissions from the existing office building sector in order to meet New Zealand's 2050 target for climate change mitigation.

7.4.5 Building Level: prioritise construction waste and resource management

Construction waste and resource management strategies should be considered during the building design stage. If a construction material/product supply is not constrained/not manufactured in New Zealand, stakeholders should prioritise supply from producers using an increased share of renewable energy. This can be done by using certified Environmental Product Declarations (EPDs) which provide environmental impacts arising from manufacture and source(s) of energy, or prioritising supply from manufacturers actively focussed on reducing the environmental impacts associated with their products. Recycling and re-use of construction waste materials may require some additional effort and planning beyond the design stage. For example, investment in training of construction personnel to handle on-site material separation could increase waste recovery (Hanne & Boyle, 2001).

7.4.6 Building Level: prioritise longer operational period of refurbished buildings with maintenance

Environmental benefits associated with energy efficiency refurbishments will be reduced if the refurbished building does not maintain the energy performance of the building. Moreover, any additional need for significant structural or mechanical refurbishments could even nullify the net environmental benefits. Therefore, building facility managers should ensure periodic maintenance of the refurbished components.

7.4.7 Building Level: prioritise refurbishment strategies based on building design, size and location

According to the results of this research, stakeholders of large buildings (GFA ≥ 3500 m^2) should focus on reducing the internal energy demand and should prioritise the use of efficient technologies for HVAC and lighting; and incorporate building designs with smaller WWR. Stakeholders of small buildings (GFA ≤ 3499 m^2) should focus on using façade materials with low embodied impacts due to the high material requirement per m^2 of refurbished buildings. If on-site PV installation is considered, it should be prioritised only for low-rise buildings with large roof area, located in regions with high sunshine hours.

7.5 Limitations and future work

In this section, limitations with respect to the selected case studies (section 7.5.1) and methodologies (section 7.5.2) are discussed along with suggestions for future work.

7.5.1 Limitations - case studies

The main limitation of case study led research is its ability to generalise research conclusions beyond the specific case study building to a larger sample (Creswell, 2009). The construction and energy performance of individual buildings can be quite variable which makes it challenging to generalize the results of a single or a few buildings to the entire building stock. A larger sample size is always preferable to improve the quality and validity of the results, which is also the strength of the work conducted in chapters 5 and 6.

In general, energy modelling of building designs is based on assumptions of building energy standards or codes. Although this approach is adopted internationally, Cory et al. (2015) has strongly argued that such assumptions add to uncertainty in energy modelling. Instead, using the actual energy demand of real office buildings provides "good engineering judgement" which significantly improves the quality of the energy modelling when compared to using energy demand assumptions as suggested in national energy building codes. The data for this thesis was based on prototypical refurbished models of real buildings in New Zealand which were considered to have a low uncertainty with respect to energy performance (Cory, 2016). Moreover, Berg (2014) and Wallhagen et al. (2011) have shown that use of LCA based on material quantities calculated from early building design prototypes is an effective way to benchmark the potential environmental impacts of a building.

This research made assumptions on the choice of construction materials and products based on the most common types of materials and products used in New Zealand (Dowdell et al., 2016). Although different façade materials were considered for buildings of different sizes, it is likely that in reality there is a wider choice of materials available for many of the refurbished components. For example, material for insulation can be produced from glass fibre, minerals, polyester, or even aerogels (Bribián et al., 2011; Chau et al., 2007); window frames and solar shading could be from timber or plastic based products (Asif et al., 2002); heat source of heat pumps can be from air and ground (Rinne et al., 2013); and the luminous efficacy of LED luminaires (Principi et al., 2014; Tähkämö et al., 2013) and capacity of PV panels (Gerbinet et al., 2014) could be variable. Therefore, this work could be further expanded by considering the variability in material and product choices in New Zealand.

Another limiting factor of this research was with respect to accounting for impacts from the additional components likely to be refurbished during a large scale energy efficiency refurbishment mainly related to interior office fit-outs. Interior refurbishments are driven by building occupancy (e.g. change in tenants or office churn rates) and typically recur every 5-7 years; as a result, they eventually outweigh the initial embodied impacts associated with refurbishment of the building structure (Forsynthe, 2007). Inclusion of details about typical recurring interior refurbishments would increase the quality and accuracy of LCAs performed on early building designs.

Another potential improvement of this research could be investigating the potential rebound effect of energy efficiency refurbishments in office buildings. Energy efficiency improvements can lead to increased consumption of energy or other services (referred to as direct or indirect rebound effects, respectively) (Font Vivanco & van der Voet, 2014; Hertwich, 2005) which has the potential to nullify the environmental benefits achieved by the energy efficiency strategy. Therefore, consideration of potential rebound effects for energy and environmental assessment of energy efficiency measures can help to support more robust policy making and should be considered in future work.

7.5.2 Limitations - methodology

With respect to the LCA methodology, certain limitations were related to data availability; modelling choices with respect to inventory analysis; and interpretation of multiple environmental impact categories. This section describes the limitations with respect to the methodology adopted in this research with suggestions for future work.

As far as possible, consistent and context appropriate data was used for this research. However, currently available data on manufacturing processes for construction materials is largely calculated based on international data (from ecoinvent) rather than data sourced directly from New Zealand specific manufacturers. In most cases the internationally available data was modified with New Zealand-specific information about fuel mix, transportation distances and national reporting on emissions (mainly GHG emissions, other emissions were included if available). Despite these limitations associated with data availability, the key findings of this research are expected to remain unchanged if more New Zealand-specific data become available. This is mainly because the total environmental impact of the refurbished buildings was dominated by the source of grid electricity supply. GHG emissions associated with grid electricity supply are annually reported by New Zealand’s Ministry of Environment (2016) and are therefore New Zealand-specific. However, at the time of this research, the data quality with respect to non-GHG emissions in New Zealand was limited and generic data from ecoinvent were used. The future availability of manufacturer-specific data could increase the quality of the results for other impact categories such as human toxicity (carcinogenic and non-carcinogenic), freshwater eco-toxicity, abiotic depletion and ionizing radiation.

With respect to the choice of system boundaries, this research only assessed the embodied impacts of products and processes associated with refurbishment based on the building LCA guidelines provided in EN 15 978. In addition, the emissions were calculated based on the refurbished building's subsequent energy use based on different service life periods in Chapter 3, 5 and 6. Within the estimated service life, processes for maintenance and replacement of building's refurbished components were also considered. In general, it was assumed that the technical equipment for air-conditioning (heat pumps), lighting (LED lamps) and PV panels would need replacement after 25 years to maintain the required energy efficiency of the refurbished buildings. Service life periods for individual façade components (such as, windows and solar shadings) were not considered. It was assumed that these components would be retained for the entire lifetime of the refurbished building with regular maintenance. As identified in Chapter 3, the cumulative environmental performance of a building is highly sensitive to the service life of the building. It could be argued that, with regular maintenance, individual façade components such as windows or solar shading have a residual service life i.e. remaining useful life which could be longer than the assumed service life of the refurbished building. Also, depending upon the component's contribution to building's energy performance, visual appearance, design, and durability, these components could be re-used (Venkatesan et al., 2006; Vohora & Marston, 2011) and thus even avoid additional environmental impacts. However, estimating the residual service life of façade components requires sophisticated data (Venkatesan et al., 2006) which was not available at the time of this research. Future work on the development of a database on estimates of residual life of individual building components with respect to New Zealand conditions could serve as a benchmark for estimating actual service life of buildings (Vohora et al., 2011).

All LCA calculations performed in this research were process-based LCA calculations based on current requirements, recommendations and guidance on methodology for attributional and consequential LCA (for example, Ekvall et al. (2016a),JRC- IEA (2010a),Weidema (2003)). However, as indicated in chapter 4, the appropriate method for identification of marginal suppliers is still a contested topic (Suh et al., 2014). In this research, the uncertainty in identification of marginal suppliers was minimized using sensitivity analysis. However, Pizzol & Scotti (2016) have proposed a new methodology requiring the use of international trade databases (for example, UN COMTRADE (2015)) and a trade network analysis as a potential approach to increase the robustness of the process for identifying marginal suppliers. This could be considered for future work.

In addition to this, combining the process-based analysis with an input-output database which is referred to as hybrid LCA reduces the truncation errors in LCA i.e. errors caused by omission of upstream or downstream processes by setting system boundaries (Lenzen, 2000). Studies that have used the hybrid modelling approach recommended it as a more holistic tool to analyse the environmental impacts of construction, particularly to account for the impacts from the capital-intensive construction service sector (Antti et al., 2012; Bawden & Williams, 2015; Bilec et al., 2006; Treloar et al., 2001). This approach was not considered in the initial stages of this research because the New Zealand specific IO tables at that time were outdated (Alcorn, 2003, 2010). However, with recent developments in up-to-date New Zealand specific and multi-regional input output databases (Motu, 2017; Wood et al., 2015), it will be possible to use this modelling approach to investigate if it significantly affects the results and conclusions of this research.

As indicated in the previous sections a high level of detail on individual building constructions and energy performance and information on region specific market improves the quality of the analysis. However, it is both data and time intensive to perform such an analysis for a large number of buildings or for the whole building stock. Detailed environmental evaluation of the building stock can be enhanced through use of Geographic Information Systems (GIS) (Mastrucci et al., 2017b). If the objective is to calculate the impacts of the entire building stock this type of analysis is also data and time intensive (Garcia-Perez et al., 2017; Mastrucci et al., 2017a). Based on the key findings of this research, this method could be used specifically for large buildings or the building stock in major cities to improve the efficiency of the analysis.

With respect to the impact assessment methods, this research developed a comprehensive environmental assessment of refurbishment and reported twelve different environmental impact category results. However, it might be argued that the magnitude or relevance of some of the impact categories is low compared with other categories. For example, the contribution of office refurbishment (due to use of refrigerants in heat pumps) to the absolute ozone depletion potential impact (either globally or in New Zealand) is likely to be very small relative to the absolute contributions to most other impact category results. Moreover, based on Montreal Protocol there has been a massive improvement globally to adopt measures to reduce the release of ozone depleting elements (Nelson, 2017). New Zealand has phased out the import of all ozone depleting substances in accordance with this protocol since 1996 and therefore it might be argued that it is not relevant to consider it(Ministry for the Environment, 2017). Similarly, ionizing radiation impacts might be less relevant for policy makers in New Zealand because these impacts are largely associated with activities in other countries that are unlikely to be influenced by decision-makers in New Zealand. Normalisation (comparing the impacts to reference scores) is conventionally used in LCA to address the relative significance of different impact category results. Several impact assessment methods such as CML, ReCiPe or ILCD midpoint provide normalisation reference sets covering different regions and years (for example, World 2000, Canada 32008, Europe 2000) (Goedkoop et al., 2016). However, no such verified normalisation reference has been developed for New Zealand or Australasia. This should be considered for future work.

7.6 Conclusions

In conclusion, this research investigated the environmental impacts of large energy efficiency refurbishments using LCA. This methodological approach is particularly advantageous as it provided information both on environmental benefits and burdens associated with energy efficiency refurbishments. Identification of environmental benefits helped to determine that the adoption of energy efficiency measures in existing buildings can reduce impacts associated with operational energy use, particularly for global warming potential, acidification potential, eutrophication potential, abiotic depletion of fossil fuels, photochemical oxidation and particulate matter formation. However, the research also highlighted potential environmental trade-offs associated with energy efficiency due to increase in resource demand at the time of refurbishment. The impacts associated with increase in resource demand were abiotic depletion of resources, ozone depletion, human toxicity (carcinogenic and non-carcinogenic), freshwater eco-toxicity and ionizing radiation.

In general, the research supports the adoption of energy efficiency measures in existing buildings but indicates the need to adopt strategies that could potentially reduce the overall environmental impacts of this type of refurbishment. Strategies such as resource and waste management at the site of construction or use of specific refurbishment measures focused on specific building sizes, designs and locations could be adopted to reduce the environmental impact of individual buildings. At national level, strategies such as an increase in renewable energy sources for grid electricity generation or prioritising refurbishment in major cities or refurbishment of large buildings (≥3500 m^2 gross floor area) could reduce the overall environmental impact of upgrading existing buildings.

More specifically, the study addressed five specific research questions (see chapter 1, section 1.5.1). The key findings associated with each research question have been summarized below:

- With respect to the first research question, detailed LCA analysis was performed on office building refurbishments. It was determined that environmental impacts from refurbishment were mainly associated with aluminium framed windows, façade components and heat pumps.
- With respect to the second research question, construction waste and resource management was identified as an important strategy to reduce the overall environmental impacts of refurbished buildings. The research showed that it was important to prioritise recovery and recycling of waste at construction site as compared to use of alternative production strategies for construction materials.
- With respect to the third research question, the research showed that the energy sources for material production and operational energy demand is one of the most important factors that determine the overall environmental impact of the refurbished buildings. The research also showed that energy supply from grid electricity generated from renewable sources should be prioritised over on-site renewable energy production such as roof top PV.
- With respect to the fourth research question, detailed LCA analysis was performed for different office building prototypes in New Zealand that are representative of the diversity of the New Zealand office building stock. The buildings differed based on size, location and construction specifications. The LCA results obtained from these models were used to determine the refurbishment measures that can substantially reduce the environmental impacts of a particular building type. For example, prioritizing efficient HVAC, lighting and smaller WWR in large buildings (≥3500 m^2 GFA), while prioritizing the choice of façade materials with low embodied impacts in small buildings, were identified as specific measures that could reduce impacts of individual buildings.
- With respect to the final research question, the research shows that although energy efficiency refurbishment contributes to the reduction in carbon

emissions, such improvements alone may not make substantial contributions to New Zealand's 2050 climate change mitigation target for this sector. The research further provides supporting evidence of the importance of increasing the renewable sources for national grid electricity generation. The research also highlights the environmental benefits associated with prioritizing refurbishment in a smaller proportion of the whole building stock.

The strength and uniqueness of this research also lies in its study design which includes a combination of multiple well established methodological approaches. The study progressed from the analysis of a single case study to evaluation of potential impacts of the entire existing office building stock. Analysis of a single case study was performed to ensure the data quality and sensitivity of the results to the assumptions considered in inventory development. An additional contribution of this was the detailed LCA inventories developed for recommended building refurbishment measures based on both attributional and consequential modelling approaches. The inventories were calculated using New Zealand specific data using both current and future market scenarios for key construction materials and energy supply.

The consequential LCA model results were complemented with statistical analysis and stock aggregation to evaluate the interaction between the strategies with the building specific characteristics and the potential impact of upgrading the existing office building stock. The transformation of the existing office building stock on a large scale is not trivial. Based on this research, it has been possible to recommend specific strategies for more sustainable energy and resource management in the office building sector. In future work, a similar study design could be replicated to assess the environmental performance of refurbishing buildings with different use (e.g. residential or educational buildings) or building stock in other geographical locations.

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Supporting Information - 1

a) Modified ecoinvent processes for refurbished façade components
b) Modified ecoinvent processes for refurbished heating, ventilation, lighting products and photovoltaics
c) Modified ecoinvent processes for discarded materials, transport and electricity

Note: - For the attributional inventory ecoinvent v3 Alloc Def unit processes were used based on current suppliers of energy and resources. For the consequential inventory ecoinvent v3 Conseq, unit processes were used based on marginal suppliers of energy and resources.

Table S-1(a) Ecoinvent processes used for refurbished façade components

<table>
<tr><th></th><th>Input materials</th><th>Ecoinvent processes</th><th>Modifications (Remarks)</th></tr>
<tr><td>Inputs for refurbished wall and roof</td><td>Portland cement</td><td>Cement, Portland {RoW}| production| Alloc Def/Alloc Def/ Conseq, U</td><td>Cement and clinker inputs Modified with electricity supply sourced from identified current/ marginal suppliers</td></tr>
<tr><td></td><td>Cement substitutes (Blast furnace slag)</td><td>Cement, blast furnace slag 81-95% {RoW}| production| Alloc Def/Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Gravel</td><td>Gravel, crushed {RoW}| production | Alloc Def /Alloc Def/ Conseq, U</td><td>Modified with NZ electricity at medium voltage</td></tr>
<tr><td></td><td>Sand</td><td>Sand {RoW}| gravel and quarry operation | Alloc Def /Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Water</td><td>Tap water {RoW}| market for | Alloc Def/Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Reinforcing steel</td><td>Reinforcing steel {RoW}| production | Alloc Def/Alloc Def/ Conseq, U</td><td>Modified with alloyed steel source from NZ and NZ electricity supply at medium voltage</td></tr>
<tr><td></td><td>Insulation, polystyrene</td><td>Polystyrene foamslab {RoW}| production | Alloc Def /Alloc Def/ Conseq, U</td><td>Modified with source of polymers from identified current/ marginal suppliers; and polymer foaming</td></tr>
<tr><td></td><td>Insulation, polyester (45% recycled PET)</td><td>Polyester foamslab {RoW}| production | Alloc Def/Alloc Def/ Conseq, U</td><td>Modified with NZ electricity at medium voltage and propane emissions as given in UN FCCC inventory of global warming emission in NZ (UN FCCC, 2014)
Waste output of mixed plastics to landfill avoided</td></tr>
<tr><td></td><td>Joists, sawn wood</td><td>Sawn wood, softwood, kiln dried, planed {RoW}| market for | Alloc Def /Alloc Def/ Conseq, U</td><td>Modified with NZ electricity at medium voltage for all sawn wood inputs (in backward sequence till forestry), removed ecoinvent transport entries</td></tr>
<tr><td></td><td>Vapour barrier, polyethylene</td><td>Extrusion, plastic film {RoW}| production | Alloc Def /Alloc Def/ Conseq, U
Polyethylene, low density, granulate {RoW}| production| Alloc Def/Alloc Def/ Conseq, U</td><td>Modified with source of polymers from identified current/marginal suppliers</td></tr>
<tr><td></td><td>Plasterboard</td><td>Gypsum plasterboard {RoW}| market for | Alloc Def /Alloc Def/ Conseq, U</td><td>Modified with source of gypsum from identified current/ marginal suppliers, plasterboard production Modified with NZ electricity at medium voltage</td></tr>
<tr><td></td><td>Sheathing, particleboard</td><td>Particle board, for outdoor use {RoW}| production | Alloc Def/Alloc Def/ Conseq, U</td><td>Modified with NZ electricity at medium voltage</td></tr>
<tr><td>Window (low-e, Al framed, double glazed)</td><td>Aluminium, wrought alloy</td><td>Window frame, aluminium, U=1.6 W/m²K {RoW}| production | Conseq</td><td>Modified with NZ electricity at medium voltage, current/ marginal source for aluminium wrought alloy; and inputs for section bar extrusion and powder coating as provided in Garrett, P. (2010). Streamlined Life Cycle Assessment of aluminium doors and windows. Retrieved from: report provided by Fletcher Aluminium on request</td></tr>
<tr><td></td><td>Insulating low-e glass units, float glass</td><td>Glazing, double, U<1.1 W/m²K {RoW}| production| Alloc Def/Alloc Def/ Conseq, U</td><td>Modified with NZ electricity at medium voltage and current/ marginal source for float glass and aluminium wrought alloy</td></tr>
<tr><td>Solar shading (louvres and overhangs)</td><td>Aluminium, wrought alloy</td><td>Aluminium, wrought alloy {GLO}| market for | Alloc Def /Alloc Def/ Conseq, U</td><td>Aluminium Sun Louvre systems- technical details. Retrieved from http://www.louvretec.co.nz/products/sun-louvres-and-systems/aluminium-louvre-systems.aspx
Quantity of aluminium= Density of aluminium * Volume of overhang (Dimensions for overhang estimated using formulas given in http://www.level.org.nz/passive-design/shading/)
Modified with current/ marginal source for aluminium wrought alloy and current/ marginal electricity of the suppliers</td></tr>
</table>

Table S-1(b) Ecoinvent processes used for refurbished heating, ventilation, lighting products and photovoltaics

<table>
<tr><th></th><th>Input materials</th><th>Ecoinvent processes</th><th>Modifications (Remarks)</th></tr>
<tr><td>**Heat Pump**</td><td></td><td>Heat pump, 30kW {RoW}| production | Alloc Def /Alloc Def/ Conseq, U</td><td rowspan="2">Each ecoinvent heat pump is modelled to heat 150 m² floor area. Ecoinvent extrapolates the data from the manufacturing of a 10 kW heat pump. The data was corrected using a scaling factor of 0.60 as recommended by Caduff et al. (2014, p. 405), to represent the correct relation of a 30 kW heat pump mass and output capacity. These estimations correlate with material estimations for technical equipment as given by Blom et. al (2010) and Johnson (2011). Data for heat distribution system was also calculated based on the same assumptions. Papers Available Caduff (2014) doi:http://dx.doi.org/10.1111/jiec.12122 Blom (2010) doi: http://dx.doi.org/10.1016/j.buildenv.2010.04.012 Johnson (2011)doi: http:/dx.doi.org/10.1016/j.enpol.2010.12.009</td></tr>
<tr><td>**Heat distribution system**</td><td></td><td>Heat distribution, hydronic radiant floor heating, 150m² {RoW}| production | Alloc Def /Alloc Def/ Conseq, U</td></tr>
<tr><td></td><td></td><td>Ventilation of dwellings, central, 1 x 720 m³/h {RoW}| steel ducts, with earth tube heat exchanger | Alloc Def /Alloc Def/ Conseq, U</td><td>The mechanical ventilation system included a heat recovery unit with a ventilation rate of 10 l/s per person (Cory, 2016). Ecoinvent process Modified by removing the input for central unit input. It was assumed the ductwork was retained during deep energy refurbishment as suggested by Alderson (2009), in Technical Preservation Guidelines- HVAC upgrades in historic buildings. Available from: http://www.gsa.gov/graphics/pbs/HVAC.pdf</td></tr>
<tr><td>**Lighting**</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Aluminium, cast alloy</td><td>Aluminium, cast alloy {GLO}| market for | Alloc Def /Alloc Def/ Conseq, U</td><td rowspan="9">Lighting (No. Of LED luminaires)- The number of lamps required for the building was calculated by multiplying the total floor area by the ratio of the average power for lighting per m², this was divided by the luminous efficacy of each lamp. A cradle to gate LCA study on luminaires was used to obtain the data for materials and energy required for the production of each lamp (Principi & Fioretti, 2014). Available from: http://dx.doi.org/10.1016/j.jclepro.2014.07.031</td></tr>
<tr><td></td><td>Steel, low-alloyed</td><td>Steel, low-alloyed {GLO}| market for | Alloc Def /Alloc Def/ Conseq, U</td></tr>
<tr><td></td><td>Copper</td><td>Wire drawing, copper {GLO}| market for | Alloc Def /Alloc Def/ Conseq, U</td></tr>
<tr><td></td><td>Light emitting diode</td><td>Light emitting diode {GLO}| production| Alloc Def /Alloc Def/ Conseq, U</td></tr>
<tr><td></td><td>Printed wiring board</td><td>Printed wiring board, for power supply unit, desktop computer, Pb free {GLO}| market for | Alloc Def /Alloc Def/ Conseq, U</td></tr>
<tr><td></td><td>Polycarbonate</td><td>Polycarbonate {RoW}| production | Alloc Def /Alloc Def/ Conseq, U</td></tr>
<tr><td></td><td>Plastics, (PE, LDPE)</td><td>Packaging film, low density polyethylene {GLO}| market for | Alloc Def /Alloc Def/ Conseq, U</td></tr>
<tr><td></td><td>Packaging, corrugated packaging board</td><td>Corrugated board box {GLO}| market for corrugated board box | Alloc Def /Alloc Def/ Conseq, U</td></tr>
<tr><td></td><td></td><td>Polypropylene, granulate {GLO}| market for | Alloc Def /Alloc Def/ Conseq, U</td></tr>
<tr><td>**Photovoltaics**</td><td>Photovoltaic, flat roof (3kWp)</td><td>Photovoltaic flat-roof installation, 3kWp, single-Si, on roof {NZ}| photovoltaic flat-roof installation, 3kWp, single-Si, on roof | Alloc Def /Alloc Def/ Conseq, U</td><td>Modified with NZ electricity at medium voltage. 1 piece of photovoltaic panel covers 22.1 m² of roof area (as given in ecoinvent). In each refurbished building, the panel pieces were calculated assuming it covered half the roof area.</td></tr>
</table>

Table S-1(c) Ecoinvent processes used for discarded materials, transport and electricity

<table>
<tr><th></th><th>Input materials</th><th>Ecoinvent processes</th><th>Modifications (Remarks)</th></tr>
<tr><td>Transport to site</td><td>Transport, lorry 16-32 tonnes</td><td>Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def/ Conseq, U</td><td>Total of generic one-way transportation distances for each material and finished product based on site of production to construction site (Auckland, NZ) available from www.branz.co.nz</td></tr>
<tr><td></td><td>Transport, oceanic freight</td><td>Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td>Transport to waste treatment from site</td><td>Transport, lorry 7.5-16 tonnes</td><td>Transport, freight, lorry 7.5-16 metric ton, EURO3 {GLO}| transport, freight, lorry 7.5-16 metric ton, EURO3 | Alloc Def/ Conseq, U</td><td>generic one way distance to sorting plant or landfill is 20 km from site assumed</td></tr>
<tr><td>Energy for processes in New Zealand</td><td>Diesel, building machine</td><td>Diesel, burned in building machine {RoW}| processing | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>NZ electricity supplied at low or medium voltage</td><td>Electricity, medium (or low) voltage {NZ}| market for | Alloc Def/ Conseq, U</td><td>Based on detailed inventory from Sacayon Madrigal, Edgar (2016). Assessment of the Life Cycle-Based Environmental Impacts of New Zealand Electricity. (Master of Science), Massey University, New Zealand. Source of electricity generation Modified based on identified marginal electricity production.</td></tr>
<tr><td>Waste treatment of discarded materials</td><td>Aluminium, for recycling</td><td>Aluminium scrap, post-consumer {RoW}| treatment of, by collecting, sorting, cleaning, pressing | Alloc Def/ Conseq, U</td><td>Modified with NZ electricity supplied at medium voltage.</td></tr>
<tr><td></td><td>Aluminium, to landfill</td><td>Waste aluminium {RoW}| treatment of, sanitary landfill | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Steel, for recycling</td><td>Steel and iron (waste treatment) {RoW}| recycling of steel and iron | Alloc Def/ Conseq, U</td><td>Modified with NZ electricity supplied at medium voltage.</td></tr>
<tr><td></td><td>Steel, to landfill</td><td>Scrap steel {CH}| treatment of, inert material landfill | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Copper for recycling</td><td>Copper scrap, sorted, pressed {RoW}| treatment of copper scrap by electrolytic refining | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Copper, to landfill</td><td>Waste copper {RoW}| treatment of, sanitary landfill | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Concrete, to landfill</td><td>Waste concrete {RoW}| treatment of, inert material landfill | Alloc Def/ Conseq, U</td><td>0.054 ton reinforcing steel/ ton concrete</td></tr>
<tr><td></td><td>Concrete, for recycling</td><td>Waste reinforced concrete {CH}| treatment of, recycling | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Reinforcing steel in concrete, for recycling</td><td>Scrap steel {CH}| treatment of, inert material landfill | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Reinforcing steel in concrete, to landfill</td><td>Waste reinforcement steel {RoW}| treatment of, sorting plant | Alloc Def/ Conseq, U</td><td>Modified with NZ electricity supplied at medium voltage.</td></tr>
<tr><td></td><td>Glass, for recycling</td><td>Waste glass sheet {CH}| treatment of, sorting plant | Alloc Def/ Conseq, U</td><td>Modified with NZ electricity supplied at medium voltage.</td></tr>
<tr><td></td><td>Glass, to landfill</td><td>Waste glass sheet {CH}| treatment of, collection for final disposal | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Timber, for recycling</td><td>Waste wood, post-consumer {GLO}| market for | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Timber, to landfill</td><td>Waste wood, untreated {CH}| treatment of, sanitary landfill | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Plastic, for recycling</td><td>Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Plastic, to landfill</td><td>Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, sanitary landfill | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Particleboard, for recycling</td><td>Core board (waste treatment) {GLO}| recycling of core board | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Particleboard, to landfill</td><td>Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Plasterboard, for recycling</td><td>Waste gypsum plasterboard {CH}| treatment of, sorting plant | Alloc Def/ Conseq, U</td><td>Modified with NZ electricity supplied at medium voltage.</td></tr>
<tr><td></td><td>Plasterboard, to landfill</td><td>Waste gypsum plasterboard {CH}| treatment of, collection for final disposal | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Inert waste</td><td>Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Alloc Def/ Conseq, U</td><td></td></tr>
<tr><td></td><td>Hazardous waste</td><td>Hazardous waste, for underground deposit {RoW}| treatment of hazardous waste, underground deposit | Alloc Def/ Conseq, U</td><td></td></tr>
</table>

Supporting Information - 2

I. Detailed inventory for refurbished materials per functional unit in all scenarios

II. Marginal suppliers for cement, float glass and electricity mix (for sensitivity analysis)

III. Details on consequential modelling of waste treatment and recycling

IV. Detailed LCIA results-for sensitivity analysis, absolute impacts of construction materials (per kg) and refurbished product, difference between attributional and consequential modelling results.

Section I. Details on the inventory for refurbished materials per functional unit (1 m² floor area in a refurbished office building). Additional details on ecoinvent processes are given in SI 1.

Table SI-2.1(a) Inventory of refurbished façade components

Refurbished façade components	*Input materials and transport*	BAU	Scenario 1	Scenario 2	Scenario 3	Unit
Precast concrete (non-bearing) wall with internal insulation and plasterboard covering						
	Portland cement	9.18	9.18	2.29	2.29	kg
	Cement substitutes (Blast furnace slag)	-	-	6.88	6.88	kg
	Gravel	17.27	17.27	17.27	17.27	kg
	Sand	29.96	29.96	29.96	29.96	kg
	Water	11.33	11.33	11.33	11.33	kg
	Reinforcing steel	3.78	3.78	3.78	3.78	kg
	Insulation, polystyrene	1.63	1.58	-	-	kg
	Insulation, polyester (45% recycled PET)	-	-	1.49	1.45	kg
	Joists, sawn wood	7.39	7.24	7.39	7.24	kg
	Vapour barrier, polyethylene	0.03	0.03	0.03	0.03	kg
	Plasterboard	2.85	2.71	2.85	2.71	kg
Roof with external insulation and membrane						kg
	Joists, sawn wood	2.23	2.23	2.23	2.23	kg
	Sheathing, particleboard	0.96	0.91	0.96	0.91	kg
	Insulation, polystyrene	0.43	0.43	-	-	kg
	Insulation, polyester (45% recycled PET)	-	-	0.37	0.37	kg
	Roof membrane, plastics (PVC, PE)	0.15	0.15	0.15	0.15	kg
	Vapour barrier, polyethylene	0.02	0.02	0.02	0.02	kg
Window (low-e, Al framed, double glazed)						kg
	Aluminium, wrought alloy	1.88	1.88	1.88	1.88	kg
	Insulating low-e glass units, float glass	3.77	3.77	3.77	3.77	kg
Solar shading (louvres and overhangs)						kg
	Aluminium, wrought alloy	0.31	0.31	0.31	0.31	kg
Transport to site						
	Transport, lorry 16-32 tonnes	17.30	17.11	17.96	17.78	tkm
	Transport, oceanic freight	97.87	97.28	61.56	60.96	tkm
Construction at site						
	Diesel, building machine	1.26	1.26	1.26	1.26	MJ
	Discarded materials (waste) and transport					
	Concrete, to landfill	33.15	-	33.15	-	kg
	Concrete, for recycling	8.29	41.44	8.29	41.44	kg
	Steel, for recycling	0.35	2.07	0.35	2.07	kg
	Insulation, to landfill	0.94	0.90	0.94	0.90	kg
	Timber, to landfill	2.34	0.78	2.34	0.78	kg
	Timber, for recycling	0.62	2.02	0.62	2.02	kg
	Timber, re-used at site	0.16	0.31	0.16	0.31	kg
	Plasterboard, to landfill	2.24	0.12	2.24	0.12	kg
	Plasterboard, for recycling	0.25	2.24	0.25	2.24	kg
	Plasterboard, re-used at site	-	0.12	-	0.12	kg
	Particleboard, to landfill	0.96	0.72	0.96	0.72	kg
	Particleboard, for recycling	-	0.19	-	0.19	kg
	Particleboard, re-used at site	-	0.05	-	0.05	kg
	Roof membrane, (PVC) to landfill	0.59	0.53	0.59	0.53	kg
	Roof membrane, (PVC) for recycling	-	0.06	-	0.06	kg
	Vapour barrier, (PE) to landfill	0.05	0.05	0.05	0.05	kg
	Aluminium, to landfill	0.51	-	0.51	-	kg
	Aluminium, for recycling	1.54	2.05	1.54	2.05	kg
	Float glass, to landfill	8.23	6.59	8.23	6.59	kg
	Float glass, for recycling	-	1.32	-	1.32	kg
Transport to waste treatment site						
	Transport, lorry 16-32 tonnes	1.51	1.54	1.51	1.54	tkm
	Transport, oceanic freight	9.47	20.63	9.47	20.63	tkm

Table SI-2.1(b) Inventory of refurbished Heating, Ventilation and Air-conditioning (HVAC); and lighting components

Refurbished HVAC and lighting components	*Input materials and transport*	BAU	Scenario 1	Scenario 2	Scenario 3	Unit
Heat Pump						
	Refrigerant R134a	0.04	0.04	0.04	0.04	kg
	Copper	0.26	0.26	0.26	0.26	kg
	Lubricating oil	0.02	0.02	0.02	0.02	kg
	Steel, low alloyed	0.24	0.24	0.24	0.24	kg
	PVC	0.01	0.01	0.01	0.01	kg
Heat distribution system						
	Aluminium, wrought alloy	0.56	0.56	0.56	0.56	kg
	Aluminium, cast alloy	0.27	0.27	0.27	0.27	kg
	Steel, reinforcing	0.91	0.91	0.91	0.91	kg
	Tube insulation, Polystyrene	0.56	0.56	0.56	0.56	kg
	PE	0.67	0.67	0.67	0.67	kg
	Portland cement	5.99	5.99	1.50	1.50	kg
	Cement substitutes (Blast furnace slag)	-	-	4.49	4.49	kg
	Sand	3.10	3.10	3.10	3.10	kg
Lighting						
	Aluminium, cast alloy	4.78E-05	4.78E-05	4.78E-05	4.78E-05	kg
	Steel, low-alloyed	2.78E-06	2.78E-06	2.78E-06	2.78E-06	kg
	Copper	1.12E-06	1.12E-06	1.12E-06	1.12E-06	kg
	Light emitting diode	2.03E-06	2.03E-06	2.03E-06	2.03E-06	kg
	Printed wiring board	9.36E-07	9.36E-07	9.36E-07	9.36E-07	kg
	Polycarbonate	1.14E-05	1.14E-05	1.14E-05	1.14E-05	kg
	Plastics, (PE, LDPE)	1.08E-06	1.08E-06	1.08E-06	1.08E-06	kg
	Packaging, corrugated packaging board	2.28E-05	2.28E-05	2.28E-05	2.28E-05	kg
Transport to site						
	Transport, lorry 16-32 tonnes	17.62	17.62	17.62	17.62	tkm
	Transport, oceanic freight	16.66	16.66	16.66	16.66	tkm
	Discarded materials (waste) and transport					
	Aluminium, to landfill	0.02	-	0.02	-	kg
	Aluminium, for recycling	0.07	0.09	0.07	0.09	kg
	Copper, to landfill	0.01	-	0.01	-	kg
	Copper, for recycling	0.03	0.04	0.03	0.04	kg
	Steel, to landfill	0.29	-	0.29	-	kg
	Steel, for recycling	1.15	1.44	1.15	1.44	kg
	Plastic, (mixed) to landfill	0.15	0.13	0.15	0.13	kg
	Plastic, (mixed) for recycling	-	-	-	-	kg
	Hazardous waste, to landfill	0.00	0.00	0.00	0.00	kg
	Inert waste, to landfill	0.04	0.04	0.04	0.04	kg
Transport to waste treatment site						
	Transport, lorry 16-32 tonnes	0.04	0.04	0.04	0.04	tkm
	Transport, oceanic freight	6.23	7.89	6.23	7.89	tkm

Section II Marginal suppliers for cement, float glass and electricity mix (for sensitivity analysis)

Figures SI 2.1(a) and 2.1(b) provide a summary of import trends for Portland cement and Float glass to New Zealand based on the data provided in NZ statistics. The slope of each trend shows the relative annual increase or decrease of imports from different regions. The marginal share of material supply from each supplier calculated was relative to the total annual increase in imports between 2008-2015.

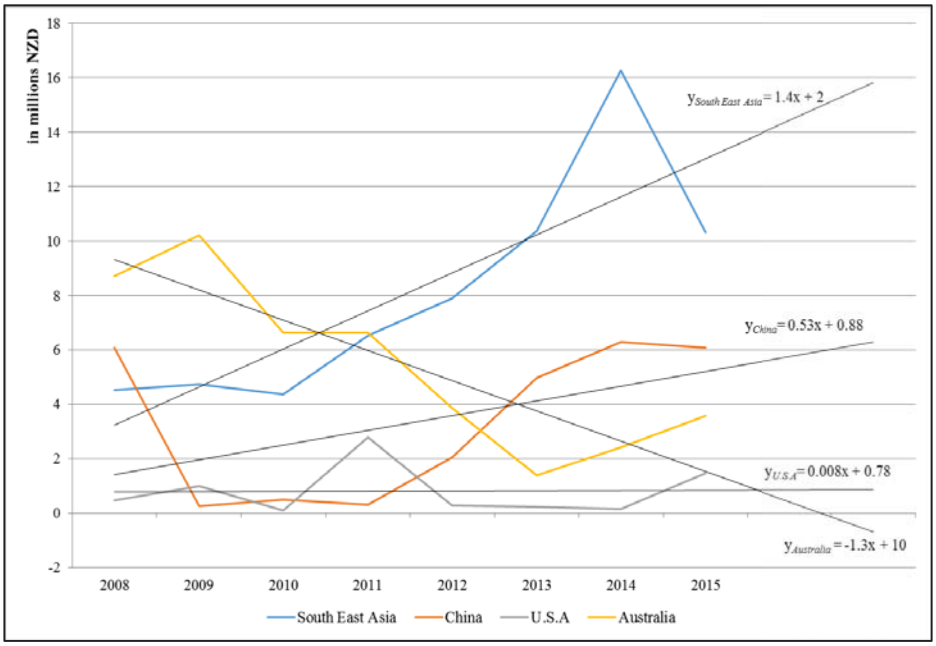

Figure SI 2.1(a) Import trends of major suppliers of Portland cement to New Zealand from 2008-2015

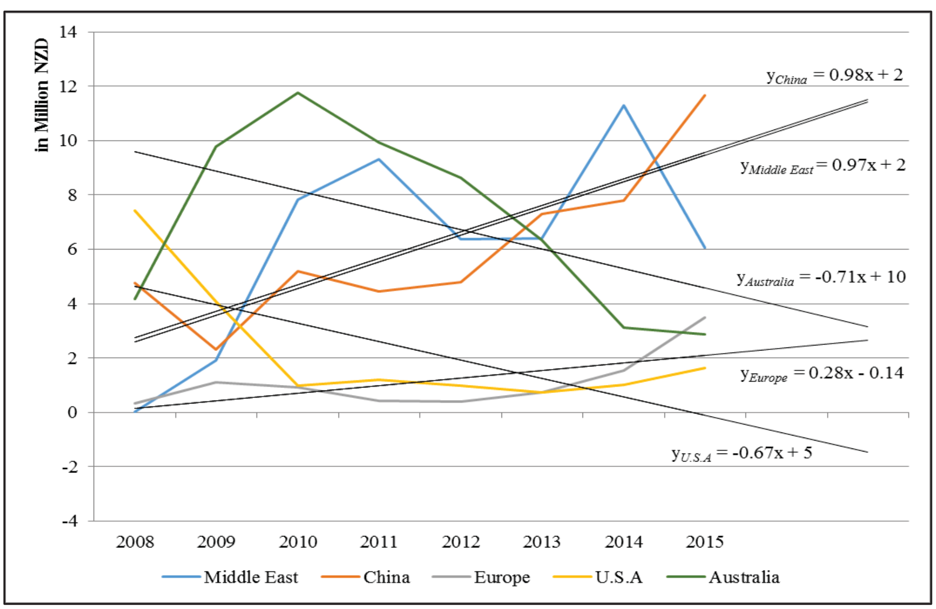

Figure SI 2.1(b) Import trends of major suppliers of insulating units of float glass to New Zealand from 2008-2015

The marginal electricity supply for each region was identified using the consequential future method suggested by Schmidt et al. (2011). The marginal electricity supply was calculated based on differences between electricity capacity and generation for the years 2015 and 2020 (extrapolated for a low carbon scenario) as reported in in IAE reports for the respective regions (IEA, 2010, 2013a, 2013b).

Table SI-2.3 Marginal electricity supply for specific material and product suppliers identified for sensitivity analysis

Section III Consequential modelling of waste treatment and recycling:

An important element in this study was the modelling of avoided environmental burdens from recovered and re-used waste for different construction materials and products. Recycled material is a constrained resource and therefore the input of recycled materials is not credited in consequential LCA. Availability of recycled materials depends on the availability of recyclable waste materials; this could imply the need to produce more waste which is abominable. Recyclable materials with a high demand belong to mature markets (i.e. where supply matches demand) in which all of the material is already recycled, and therefore under these conditions increase in demand for recycled materials cannot be fulfilled (Weidema, 2003a). Indeed, the markets for waste metal scrap are mature i.e. nearly 85-95% of total metal scrap available at present globally is already in use for metal production (Atherton, 2007). Recycling of metal is not dependent on the demand for recycled metal but on the availability and recovery of metal scrap (Atherton, 2007). Crediting the recovery of metal scrap from waste extends a responsibility to stakeholders in the building sector to ensure the availability recyclable scrap and to reduce waste produced at site (Horvath, 2004). On the contrary, increased use of recycled materials from non-metallic wastes (for example, blast furnace slag, timber, plastics) should be credited because these materials belong to non-mature markets where the demand for these materials is not yet constrained by supply (Green Star, 2016). These materials which are currently low in demand also form the bulk of the construction waste sent to landfills (BRANZ, 2014). Therefore the use of these materials reduces waste sent for final disposal and are credited with avoided burdens from waste treatment such as landfilling. The re-use of construction waste specifically at the building site decreases the demand for primary production, and in this situation the avoided environmental burdens from primary production are modeled (Weidema, 2014).

It is worth mentioning that waste treatment using incineration was not included in this study. At present, waste incineration is limited and under-utilized in New Zealand. There are only three waste incineration plants in New Zealand close to Auckland and Christchurch airports; and in New Plymouth (Greater Wellington Regional Council, 2015). Construction waste is not handled at any site as their primary function is to handle aeroplane waste and medical or quarantine waste.

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Section IV Detailed LCIA results

Table SI-2.4 Absolute characterized impact results with respect to the sensitivity analysis per functional unit in each scenario

Impact category	Unit	Base case				Scenario I				Scenario II				Scenario III			
		Reference	RER_S1	TP_S2	TP(el)_S3	Reference	RER_S1	TP_S2	TP(el)_S3	Reference	RER_S1	TP_S2	TP(el)_S3	Reference	RER_S1	TP_S2	TP(el)_S3
GWP	kg CO_2 eq	123.4	133.7	130.8	88.5	97.1	111.8	104.7	62.3	104.8	115.0	118.8	70.3	78.7	93.1	92.7	44.2
ODP	kg CFC-11 eq	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04	3.9E-04
POCP	kg C_2H_4 eq	6.1E-02	6.6E-02	6.7E-02	4.9E-02	5.1E-02	5.8E-02	5.7E-02	3.9E-02	5.4E-02	5.9E-02	6.1E-02	4.3E-02	4.5E-02	5.2E-02	5.1E-02	3.3E-02
AP	kg SO_2 eq	9.8E-01	1.1E+00	1.2E+00	6.8E-01	8.3E-01	9.5E-01	1.0E+00	5.3E-01	9.4E-01	1.0E+00	1.1E+00	6.4E-01	7.8E-01	9.1E-01	9.8E-01	4.9E-01
EP	kg PO_4^{3-} eq	8.6E-01	8.8E-01	8.6E-01	8.3E-01	7.8E-01	8.1E-01	7.8E-01	7.5E-01	1.0E+00	1.0E+00	1.0E+00	9.9E-01	9.2E-01	9.5E-01	9.4E-01	9.1E-01
AD_{rr}	kg Sb eq	7.5E-04	8.7E-04	7.5E-04	8.1E-04	6.3E-04	7.8E-04	6.3E-04	6.8E-04	7.8E-04	8.9E-04	7.7E-04	8.2E-04	6.5E-04	8.1E-04	6.5E-04	7.0E-04
AD_{ff}	MJ	1247.3	1344.0	1094.2	867.5	970.2	1107.3	821.6	590.5	1072.7	1167.3	1100.5	699.0	798.7	933.6	826.5	425.1
HT carc	CTUh	1.5E-05	1.8E-05	1.5E-05	1.5E-05	1.1E-05	1.5E-05	1.1E-05	1.1E-05	1.5E-05	1.8E-05	1.5E-05	1.5E-05	1.1E-05	1.4E-05	1.1E-05	1.1E-05
HT non-carc	CTUh	6.7E-05	7.2E-05	6.8E-05	6.6E-05	5.7E-05	6.4E-05	5.7E-05	5.6E-05	6.5E-05	7.0E-05	6.4E-05	6.4E-05	5.4E-05	6.1E-05	5.4E-05	5.3E-05
$ET_{freshwater}$	CTUe	7540.8	7708.5	7531.3	7794.6	8801.3	9027.7	8792.1	9055.2	7459.5	7624.6	7415.9	7698.3	8720.9	8944.7	8678.1	8959.9
PMF	kg PM2.5 eq	1.3E-01	1.4E-01	1.8E-01	6.2E-02	9.5E-02	1.2E-01	1.5E-01	3.1E-02	1.2E-01	1.4E-01	1.7E-01	5.7E-02	9.0E-02	1.1E-01	1.4E-01	2.6E-02
IR	kBq U^{235} eq	1.8E+00	1.9E+00	5.6E-01	1.2E+01	1.2E+00	1.3E+00	-7.8E-02	1.2E+01	1.4E+00	1.5E+00	8.8E-02	1.2E+01	7.6E-01	9.2E-01	-5.4E-01	1.1E+01

Table SI-2.5 Absolute characterized impact results per kg of material and products used for refurbishment

		Aluminium	Steel	Portland cement	Aggregates	Float Glass	Gypsum	Timber	Particleboard	Polystyrene	Polyester	Polyethylene	Polyvinylchloride	LED luminaires	Heat pumps
		(window frames, heat distribution system)	(Precast concrete walls)			(Windows)	(Wallboards)	(Joists to support insulation)	(roof board)	(insulation)		(Vapour barrier)	(Roof membrane)		
GWP	kg CO_2 eq	21.14	4.15	1.16	0.01	1.13	0.03	0.09	0.29	3.71	2.72	0.37	10.37	0.79	14.53
ODP	kg CFC-11 eq	1.1E-06	1.2E-07	3.0E-08	8.0E-10	1.1E-07	2.2E-09	1.1E-08	1.7E-08	7.4E-08	1.2E-07	3.1E-09	4.9E-07	4.0E-08	2.4E-04
POCP	kg C_2H_4 eq	1.1E-02	1.0E-03	9.9E-05	2.8E-06	4.2E-04	4.8E-06	5.4E-05	1.6E-04	6.7E-03	6.9E-04	8.2E-05	5.4E-03	3.9E-04	4.5E-03
AP	kg SO_2 eq	1.9E-01	7.3E-03	2.5E-03	5.8E-05	1.2E-02	8.3E-06	5.4E-04	1.7E-03	1.3E-02	1.1E-02	1.7E-03	7.3E-02	5.6E-03	8.5E-02
EP	kg PO_4^{3-} eq	3.5E-02	1.2E-01	8.6E-04	8.4E-05	3.5E-03	1.2E-04	6.8E-04	2.9E-03	2.3E-03	1.2E-01	4.5E-04	9.7E-02	-3.4E-02	2.4E-01
AD_r	kg Sb eq	3.6E-05	1.5E-05	3.6E-07	1.9E-07	7.7E-06	2.5E-08	1.0E-06	9.1E-07	6.1E-07	1.8E-05	1.7E-07	2.1E-05	2.6E-05	5.3E-04
AD_{ff}	MJ	215.87	26.22	4.75	0.10	13.94	0.66	1.19	5.77	90.61	69.61	10.72	157.10	8.58	60.94
HT carc	CTUh	5.6E-06	5.5E-07	9.8E-09	9.7E-10	2.5E-08	1.8E-09	8.9E-09	3.8E-08	1.2E-07	1.6E-07	1.6E-08	1.9E-06	1.4E-07	2.0E-06
HT non-carc	CTUh	5.1E-06	1.5E-07	8.9E-08	4.9E-09	3.2E-07	1.1E-08	3.2E-08	2.4E-07	3.2E-07	1.1E-06	2.5E-08	2.4E-06	4.6E-07	4.3E-05
$ET_{freshwater}$	CTUe	245.06	20.49	1.42	0.14	7.73	0.26	1.77	12.35	9.83	30.94	0.94	96.42	13.22	923.11
PMF	kg PM2.5 eq	3.7E-02	2.2E-03	2.3E-04	9.2E-06	9.7E-04	-4.7E-06	6.0E-05	1.7E-04	1.4E-03	1.6E-03	2.2E-04	1.3E-02	9.5E-04	7.8E-03
IR	kBq U^{235} eq	3.5E-01	5.5E-03	1.3E-02	2.6E-04	1.2E-02	-1.7E-02	4.6E-03	-1.0E-02	-8.7E-03	1.4E-01	1.3E-02	2.4E-01	5.3E-02	1.8E-02

Table SI-2.6 Absolute characterized impact results per kg of material and products based on sensitivity analysis TP_S2

		Aluminium	Steel	Portland cement	Aggregates	Float Glass	Gypsum	Timber	Particleboard	Polystyrene	Polyester	Polyethylene	Polyvinylchloride	LED luminaires	Heat pumps
		(window frames, heat distribution system)	(Precast concrete walls)			(Windows)	(Wallboards)	(Joists to support insulation)	(roof board)	(insulation)		(Vapour barrier)	(Roof membrane)		
GWP	kg CO_2 eq	25.69	4.15	1.18	0.01	1.15	0.03	0.09	0.29	3.37	2.60	0.37	11.77	0.17	13.64
ODP	kg CFC-11 eq	5.4E-07	1.2E-07	2.8E-08	8.0E-10	1.1E-07	2.2E-09	1.1E-08	1.7E-08	5.7E-08	1.2E-07	3.1E-09	3.2E-07	8.6E-09	2.4E-04
POCP	kg C_2H_4 eq	1.3E-02	1.0E-03	1.2E-04	2.8E-06	4.3E-04	4.8E-06	5.4E-05	1.6E-04	6.6E-04	6.6E-04	8.2E-05	6.1E-03	8.5E-05	4.4E-03
AP	kg SO_2 eq	2.6E-01	7.3E-03	2.9E-03	5.8E-05	1.2E-02	8.3E-06	5.4E-04	1.7E-03	1.1E-02	1.1E-02	1.7E-03	9.3E-02	1.2E-03	8.5E-02
EP	kg PO_4^{3-} eq	3.7E-02	1.2E-01	8.6E-04	8.4E-05	3.6E-03	1.2E-04	6.8E-04	2.9E-03	1.2E-03	1.3E-01	4.5E-04	9.8E-02	-7.3E-03	2.4E-01
AD_r	kg Sb eq	3.6E-05	1.5E-05	3.6E-07	1.9E-07	7.7E-06	2.5E-08	1.0E-06	9.1E-07	3.5E-07	1.4E-05	1.7E-07	2.1E-05	5.6E-06	5.3E-04
AD_{ff}	MJ	227.31	26.22	4.57	0.10	14.00	0.66	1.19	5.77	85.40	68.20	10.72	160.21	1.89	51.38
HT carc	CTUh	5.6E-06	5.5E-07	9.6E-09	9.7E-10	2.5E-08	1.8E-09	8.9E-09	3.8E-08	1.2E-07	1.4E-07	1.6E-08	2.0E-06	3.2E-08	1.9E-06
HT non-carc	CTUh	5.4E-06	1.5E-07	9.0E-08	4.9E-09	3.2E-07	1.1E-08	3.2E-08	2.4E-07	3.2E-07	8.7E-07	2.5E-08	2.5E-06	1.0E-07	4.3E-05
$ET_{freshwater}$	CTUe	246.10	20.49	1.40	0.14	7.73	0.26	1.77	12.35	9.65	25.29	0.94	97.10	2.90	912.79
PMF	kg PM2.5 eq	5.3E-02	2.2E-03	4.0E-04	9.2E-06	1.1E-03	-4.7E-06	6.0E-05	1.7E-04	1.4E-03	1.4E-03	2.2E-04	1.7E-02	2.1E-04	7.8E-03
IR	kBq U^{235} eq	-3.1E-02	5.5E-03	1.5E-02	2.6E-04	1.2E-02	-1.7E-02	4.6E-03	-1.0E-02	-8.4E-03	1.2E-01	1.3E-02	1.3E-01	1.1E-02	1.1E-01

Table SI-2.7 Absolute characterized impact results per kg of material and products based on sensitivity analysis TP (el) _S3

		Aluminium	Steel	Portland cement	Aggregates	Float Glass	Gypsum	Timber	Particleboard	Polystyrene	Polyester	Polyethylene	Polyvinylchloride	LED luminaires	Heat pumps
		(window frames, heat distribution system)	(Precast concrete walls)			(Windows)	(Wallboards)	(Joists to support insulation)	(roof board)	(insulation)		(Vapour barrier)	(Roof membrane)		
GWP	kg CO_2 eq	10.92	3.24	1.09	0.01	1.09	0.01	0.09	0.23	3.71	2.52	0.37	7.18	0.17	11.48
ODP	kg CFC-11 eq	9.3E-07	1.2E-07	3.0E-08	8.0E-10	1.1E-07	2.8E-09	1.1E-08	1.7E-08	7.3E-08	1.3E-07	3.1E-09	4.5E-07	8.7E-09	2.0E-04
POCP	kg C_2H_4 eq	7.0E-03	1.0E-03	8.2E-05	2.8E-06	4.1E-04	2.6E-06	5.4E-05	1.6E-04	6.7E-03	6.4E-04	8.2E-05	4.3E-03	8.5E-05	3.7E-03
AP	kg SO_2 eq	1.0E-01	7.3E-03	2.0E-03	5.8E-05	1.2E-02	-7.0E-05	5.4E-04	1.7E-03	1.3E-02	1.0E-02	1.7E-03	4.6E-02	1.2E-03	7.2E-02
EP	kg PO_4^{3-} eq	2.8E-02	1.2E-01	8.1E-04	8.4E-05	3.5E-03	-5.0E-05	6.8E-04	2.9E-03	2.3E-03	1.3E-01	4.5E-04	9.5E-02	-7.4E-03	2.0E-01
AD_r	kg Sb eq	5.1E-05	1.5E-05	4.6E-07	1.9E-07	7.8E-06	5.1E-08	1.0E-06	9.1E-07	6.1E-07	1.5E-05	1.7E-07	2.6E-05	5.6E-06	4.4E-04
AD_{ff}	MJ	104.64	26.22	3.83	0.10	13.50	0.37	1.19	5.77	90.60	67.93	10.72	122.37	1.84	43.27
HT carc	CTUh	5.5E-06	5.5E-07	8.9E-09	9.7E-10	2.5E-08	1.8E-09	8.9E-09	3.8E-08	1.2E-07	1.3E-07	1.6E-08	1.9E-06	3.1E-08	1.6E-06
HT non-carc	CTUh	4.9E-06	1.5E-07	8.7E-08	4.9E-09	3.2E-07	1.1E-08	3.2E-08	2.4E-07	3.2E-07	8.5E-07	2.5E-08	2.3E-06	9.9E-08	3.6E-05
$ET_{freshwater}$	CTUe	318.03	20.49	1.88	0.14	8.07	0.26	1.77	12.35	9.65	25.52	0.94	119.33	2.86	775.16
PMF	kg PM2.5 eq	1.8E-02	2.2E-03	1.9E-04	9.2E-06	9.7E-04	2.1E-06	6.0E-05	1.7E-04	1.4E-03	1.4E-03	2.2E-04	6.7E-03	2.1E-04	9.2E-03
IR	kBq U^{235} eq	3.5E+00	5.5E-03	3.7E-02	2.6E-04	1.2E-02	-1.1E-02	4.6E-03	-1.0E-02	-8.4E-03	1.3E-01	1.3E-02	1.2E+00	1.2E-02	1.7E+00

Table SI-2.8 Absolute characterized impact results per kg of material recycled, re-used or used for alternative production

		Aluminium	Steel	Copper	Glass	Concrete	Blast furnace slag	Timber		Plasterboard		Particleboard		Insulation		Other plastics
		recycled	recycled	recycled	recycled	recycled	used for alternative production	reused, at site	recycled	reused, at site	recycled	reused, at site	recycled	reused, at site	PET fibres used for alternative production	recycled
GWP	kg CO_2 eq	-18.8	-0.67	-6.39	-0.98	-0.17	0.038	-0.09	-0.02	-0.11	0.00	-0.29	-0.02	-3.37	-0.06	-0.09
ODP	kg CFC-11 eq	-7.6E-07	-9.0E-09	-2.4E-07	-9.8E-08	-1.9E-09	1.6E-09	-1.1E-08	-1.2E-09	-9.6E-09	1.7E-09	-1.7E-08	-1.2E-09	-5.7E-08	1.2E-09	-3.0E-09
POCP	kg C_2H_4 eq	-9.7E-03	-1.0E-04	-1.5E-02	-3.3E-04	-2.5E-05	3.4E-05	-5.4E-05	-6.9E-06	-2.5E-05	9.5E-04	-1.6E-04	-6.9E-06	-6.6E-04	-1.2E-05	-1.8E-05
AP	kg SO_2 eq	-1.8E-01	-5.7E-04	-3.7E-01	-8.4E-03	-1.1E-04	8.7E-04	-5.4E-04	-3.1E-05	-4.0E-04	2.4E-02	-1.7E-03	-3.1E-05	-1.1E-02	5.3E-05	-8.0E-05
EP	kg PO_4^{3-} eq	-3.6E-02	-5.0E-04	-5.6E-01	-3.6E-03	-1.1E-04	2.4E-04	-6.8E-04	-1.1E-03	-5.7E-04	1.5E-05	-2.9E-03	-1.1E-03	-1.2E-03	-4.3E-03	-4.8E-03
AD_r	kg Sb eq	2.6E-06	-5.81E-08	-6.1E-03	-3.5E-06	-1.2E-08	3.2E-07	-1.0E-06	-6.7E-09	-2.9E-07	2.3E-09	-9.1E-07	-6.7E-09	-3.5E-07	-1.0E-09	-1.7E-08
AD_{ff}	MJ	-186.7	-3.20	-63.45	-12.40	-0.80	0.624	-1.19	-0.11	-1.69	0.15	-5.77	-0.11	-85.41	0.08	-0.28
HT carc	CTUh	-5.3E-06	-1.3E-08	-6.3E-06	-3.0E-08	-3.6E-09	5.92E-10	-8.9E-09	-2.4E-10	-4.7E-09	1.7E-09	-3.8E-08	-2.4E-10	-9.8E-08	-1.0E-09	-4.0E-09
HT non-carc	CTUh	-5.8E-06	-4.3E-08	-2.0E-04	-2.6E-07	-3.8E-08	-1.52E-07	-3.2E-08	-1.6E-08	-5.5E-08	5.8E-08	-2.4E-07	-1.6E-08	-9.0E-08	-2.1E-07	-7.3E-07
$ET_{freshwater}$	CTUe	3249.46	-1.30	-3924.92	-5.63	-0.88	-3.17	-1.77	-0.36	-1.02	0.85	-12.35	-0.36	-5.34	-45.35	-43.53
PMF	kg PM2.5 eq	-3.0E-02	-2.5E-04	-2.4E-02	-1.4E-03	-4.8E-06	4.5E-05	-6.0E-05	-4.7E-06	-6.3E-06	1.2E-03	-1.7E-04	-4.7E-06	-1.3E-03	6.5E-05	-1.2E-05
IR	kBq U^{235} eq	-2.5E-01	2.2E-03	-1.4E+00	-6.0E-02	1.4E-03	1.2E-03	-4.6E-03	-5.3E-04	2.2E-02	4.8E-04	1.0E-02	-5.3E-04	-2.1E-04	-3.8E-05	-1.3E-03

Table SI-2.9 Comparison of the cumulative impact of the refurbishment based on consequential (BAU scenario) and attributional results from Chapter 3

		Consequential (BAU scenario)	Attributional	difference in results Consquential versus Attributional
GWP	kg CO_2 eq	126.35	110.49	13%
ODP	kg CFC-11 eq	3.92E-04	3.93E-04	0%
POCP	kg C_2H_4 eq	5.19E-02	4.95E-02	4%
AP	kg SO_2 eq	7.35E-01	6.38E-01	13%
EP	kg PO_4^{3-} eq	9.47E-01	3.62E-01	62%
AD_r	kg Sb eq	1.11E-03	1.41E-03	-27%
AD_{ff}	MJ	1276.08	1106.24	13%
HT carc	CTUh	1.65E-05	3.64E-05	-120%
HT non-carc	CTUh	8.20E-05	8.48E-05	-3%
$ET_{freshwater}$	CTUe	8162.05	8831.81	-8%
PMF	kg PM2.5 eq	1.17E-01	7.74E-02	34%
IR	kBq U^{235} eq	2.04E+00	5.29E+00	-160%

Supporting Information - 3

a) Details on building characteristics for all 119 (17 x 7) buildings

b) Results of Dunn's test with Bonferroni correction for individual comparisons between the scenarios for each impact category selected for this study.

c) General Additive Model (GAM) results

SI 3 a) Details on building characteristics for all 119 (17 x 7) buildings

Building number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Total floor area (m^2)		599	188	209	1356	742	3555	2310	2675	5861	6019	9436	5841	5172	33636	19840	6028	12888
Storeys (nos.)		1	1	1	2	2	4	4	2	10	5	9	8	4	20	18	4	10
Roof area (m^2)		524	188	209	525	288	688	1271	766	586	752	1048	730	1282	1682	1102	1167	1271
Heat pumps (nos.)		4	1	1	9	5	24	15	18	39	40	63	39	34	224	132	40	86
LED luminaires (nos.)		20	6	7	46	25	120	78	91	198	204	319	198	175	1139	672	204	436
Façade material		Brick	Brick	Brick	concrete block	concrete block	Fibre cement	Fibre cement	reinforced concrete	reinforced concrete	reinforced concrete	reinforced concrete	reinforced concrete	reinforced concrete	reinforced concrete	reinforced concrete	reinforced concrete	reinforced concrete
WWR	Auckland & Northland	0.28	0.53	0.15	0.23	0.26	0.88	0.39	0.29	0.58	0.63	0.42	0.45	0.26	0.33	0.74	0.74	0.42
	Waikato & Bay of Plenty	0.28	0.54	0.20	0.23	0.27	0.82	0.26	0.31	0.58	0.63	0.40	0.47	0.30	0.27	0.70	0.76	0.38
	East & West coast	0.28	0.37	0.10	0.18	0.25	0.79	0.38	0.33	0.57	0.63	0.40	0.56	0.28	0.27	0.70	0.70	0.37
	Taranaki &Manawatu	0.32	0.44	0.15	0.24	0.26	0.89	0.35	0.40	0.59	0.63	0.42	0.54	0.33	0.31	0.74	0.76	0.40
	Wellington& Wairarapa	0.29	0.41	0.13	0.24	0.26	0.88	0.35	0.28	0.59	0.56	0.42	0.54	0.36	0.27	0.74	0.70	0.48
	Christchurch& Canterbury	0.28	0.37	0.12	0.16	0.21	0.76	0.25	0.33	0.56	0.56	0.39	0.46	0.24	0.25	0.70	0.66	0.45
	Southland & Otago	0.28	0.37	0.21	0.22	0.20	0.82	0.34	0.27	0.59	0.52	0.42	0.53	0.27	0.27	0.69	0.66	0.50
R value (Wall) (m^2-K/W)	Auckland & Northland	3.95	3.2	4.45	4.45	3.2	2.2	4.45	4.2	2.95	4.45	0.20	2.2	4.2	0.2	3.2	0.7	0.45
	Waikato & Bay of Plenty	3.95	3.2	4.45	4.45	4.45	1.7	4.45	4.2	3.45	4.45	0.20	3.7	3.7	0.2	4.2	1.2	3.7
	East & West coast	4.45	4.2	4.45	4.45	4.45	4.2	4.2	4.45	2.7	4.45	0.20	4.45	4.45	0.2	3.7	0.7	3.2
	Taranaki &Manawatu	4.2	3.7	4.45	4.45	4.2	4.2	4.45	4.45	2.7	4.45	0.20	3.2	4.45	0.2	4.45	3.45	4.45
	Wellington& Wairarapa	4.45	4.2	4.45	4.45	4.45	3.45	4.45	4.45	2.7	3.7	0.20	3.45	4.2	0.2	3.95	3.2	0.7
	Christchurch& Canterbury	4.45	4.2	4.45	4.45	4.45	3.95	4.45	3.95	4.45	3.7	0.20	4.45	4.45	0.45	4.45	4.45	0.45
	Southland & Otago	4.45	4.2	4.45	4.45	4.45	4.2	4.45	4.45	3.45	4.2	0.20	4.45	4.45	0.45	4.45	4.45	4.2
R value (Roof) (m^2-K/W)	Auckland & Northland	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	0.15	3.65	4.65	0.65	3.9	4.65	4.4
	Waikato & Bay of Plenty	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	0.4	4.65	4.65	1.65	4.65	4.65	4.65
	East & West coast	4.65	4.4	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	0.15	4.65	4.65	1.4	4.4	4.65	4.65
	Taranaki &Manawatu	4.65	4.4	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	0.15	4.65	4.65	1.4	4.65	4.65	4.65
	Wellington& Wairarapa	4.65	4.4	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	0.15	3.9	4.65	1.4	4.4	4.65	4.4
	Christchurch& Canterbury	4.65	4.4	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	0.65	4.65	4.65	3.15	4.65	4.65	4.65
	Southland & Otago	4.65	4.4	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	0.65	4.65	4.65	3.15	4.65	4.65	4.65
Annual Energy consumption (without PV) (kWh)	Auckland & Northland	45026	9369	15497	1996	25878	6845	401800	341163	43821	327773	201691	463704	56998	12051	2601807	199251	340377
	Waikato & Bay of Plenty	45625	9961	16116	2136	28713	7117	406118	342479	44918	328742	203188	464968	62759	14390	2598572	203518	341876
	East & West coast	45928	10098	16029	2112	28230	7679	408763	344010	45191	331475	203868	466393	63607	13314	2603981	206163	344756
	Taranaki &Manawatu	46615	10378	15761	2116	29896	7109	408225	344850	44039	331690	207294	462666	62130	16191	2576698	228812	345287
	Wellington& Wairarapa	46304	10187	15677	2019	32333	7274	407305	343329	43984	329999	205489	460126	62848	12624	2574853	227647	345014
	Christchurch& Canterbury	49005	11352	17075	2360	36674	8299	416542	349164	46752	336846	211508	486519	66932	20180	2586209	236908	356836
	Southland & Otago	47850	11179	16556	2293	38814	7729	428169	349789	44894	334763	212016	464668	64158	21664	2566139	238328	353957
Annual Energy consumption (with PV) (kWh)	Auckland & Northland	-4945	-10403	-26937	-87370	-4390	217667	61792	-11202	246338	101519	318543	-44451	-167566	2368020	46051	130897	222658
	Waikato & Bay of Plenty	-3854	-8917	-25800	-83896	-2129	223172	64268	-7100	250078	106333	324668	-35244	-159114	2372706	55512	139496	233048
	East & West coast	-4176	-9805	-26729	-86267	-3258	220862	64237	-8729	250273	103973	321606	-37553	-165786	2370850	53395	135865	230125
	Taranaki &Manawatu	-2220	-7070	-23383	-76078	3192	235793	64023	-2785	259794	118728	334438	-27448	-142392	2370217	93515	160277	250012
	Wellington& Wairarapa	-3294	-8698	-25208	-81483	-29	226972	62963	-2574	253288	111438	323388	-32728	-156613	2354554	83294	147623	238504
	Christchurch& Canterbury	-1488	-6158	-23611	-76402	4969	238128	68552	3371	263638	121717	338657	-24274	-141241	2375995	99160	168481	255466
	Southland & Otago	295	-3216	-19793	-64442	10337	255165	67400	10478	272389	135363	353403	-13559	-115876	2386962	120930	193414	290883
Total transport (tkm)	Auckland & Northland	161143.4	49509	70869	254326	126189	117762	329373	274270	238340	202157	327999	408288	447445	1153875	553523	263141	596626
	Waikato & Bay of Plenty	161145.6	48733	68511	254216	132122	123626	353397	271294	254247	208298	354157	446992	443791	1317850	623788	265872	755489
	East & West coast	167633.2	59104	74991	300275	148801	144578	355645	294466	268747	235386	419319	494700	524699	1584644	692458	323937	869657
	Taranaki &Manawatu	141605.7	48319	63565	235114	123541	110861	311466	239566	226062	190976	324526	383028	407406	1179589	557873	257518	696523
	Wellington& Wairarapa	147311	50623	65225	239744	126256	112462	316390	265140	229719	224481	380702	428380	442907	1482407	557918	302033	691310
	Christchurch& Canterbury	160115.1	56510	70330	431717	219536	149718	380615	289710	311073	263415	458443	573905	569531	1797604	750843	384464	834715
	Southland & Otago	167782.8	59179	69595	416041	223676	143241	372237	312123	294277	282665	453100	543523	564478	1815824	768262	389305	904861

SI-3 b) Results of Dunn's test with Bonferroni correction for individual comparisons between the scenarios for each impact category selected for this study. *

	GWP				ODP				PCOP		
	Z test score	p value (adjusted)	Significance		Z test score	p value (adjusted)	Significance		Z test score	p value (adjusted)	Significance
BAU - BCP	3.73E+00	7.76E-04	***	**BAU - BCP**	1.38E+00	1.69E-01	ns	**BAU - BCP**	5.98E+00	1.14E-08	***
BAU - PV	4.51E+00	3.97E-05	***	**BAU - PV**	-2.73E+00	1.90E-02	*	**BAU - PV**	1.05E+01	8.56E-25	***
BCP - PV	7.79E-01	1.00E+00	ns	**BCP - PV**	-4.11E+00	2.00E-04	***	**BCP - PV**	4.48E+00	1.53E-05	***
BAU - RE	3.74E+00	9.19E-04	***	**BAU - RE**	3.39E+00	2.83E-03	**	**BAU - RE**	5.16E+00	7.58E-07	***
BCP - RE	1.37E-02	9.89E-01	ns	**BCP - RE**	2.01E+00	8.88E-02	ns	**BCP - RE**	-8.21E-01	4.11E-01	ns
PV - RE	-7.65E-01	8.88E-01	ns	**PV - RE**	6.12E+00	7.08E-04	***	**PV - RE**	-5.30E+00	4.72E-07	***

	AP				EP				AD_r		
	Z test score	p value (adjusted)	Significance		Z test score	p value (adjusted)	Significance		Z test score	p value (adjusted)	Significance
BAU - BCP	3.35E+00	1.63E-03	**	**BAU - BCP**	2.13E+00	1.00E-01	ns	**BAU - BCP**	2.27E+00	6.95E-02	ns
BAU - PV	9.99E+00	1.06E-22	***	**BAU - PV**	2.01E+00	8.98E-02	ns	**BAU - PV**	-1.18E+01	1.55E-31	***
BCP - PV	6.64E+00	1.59E-10	***	**BCP - PV**	-1.23E-01	9.02E-01	ns	**BCP - PV**	-1.41E+01	3.43E-44	***
BAU - RE	5.70E+00	4.90E-08	***	**BAU - RE**	6.54E+00	3.79E-10	***	**BAU - RE**	9.70E-01	3.32E-01	ns
BCP - RE	5.70E+00	1.88E-02	**	**BCP - RE**	4.41E+00	4.17E-05	***	**BCP - RE**	-1.30E+00	3.87E-01	ns
PV - RE	-4.29E+00	5.38E-05	***	**PV - RE**	4.53E+00	2.94E-05	***	**PV - RE**	1.28E+01	1.20E-36	***

	AD_{ff}				HT carc				HT non carc		
	Z test score	p value (adjusted)	Significance		Z test score	p value (adjusted)	Significance		Z test score	p value (adjusted)	Significance
BAU - BCP	4.51E+00	3.17E-05	***	**BAU - BCP**	2.54E+00	3.36E-02	*	**BAU - BCP**	1.63E+00	3.10E-01	ns
BAU - PV	3.96E+00	2.25E-04	***	**BAU - PV**	2.41E+00	3.19E-02	*	**BAU - PV**	1.13E+00	5.13E-01	ns
BCP - PV	-5.55E-01	5.79E-01	ns	**BCP - PV**	-1.26E-01	9.00E-01	ns	**BCP - PV**	-4.94E-01	6.21E-01	ns
BAU - RE	8.40E+00	2.61E-16	***	**BAU - RE**	6.11E+00	6.13E-09	***	**BAU - RE**	5.22E+00	1.09E-06	***
BCP - RE	3.89E+00	2.02E-04	***	**BCP - RE**	3.57E+00	1.43E-03	***	**BCP - RE**	3.59E+00	1.33E-03	**
PV - RE	4.44E+00	3.54E-05	***	**PV - RE**	3.70E+00	1.10E-03	***	**PV - RE**	4.08E+00	2.23E-04	***

	$ET_{freshwater}$				PMF				IR		
	Z test score	p value (adjusted)	Significance		Z test score	p value (adjusted)	Significance		Z test score	p value (adjusted)	Significance
BAU - BCP	8.34E-02	0.934	ns	**BAU - BCP**	7.62E+00	1.47E-13	***	**BAU - BCP**	-1.33E+01	0.000	***
BAU - PV	1.67E+00	0.377	ns	**BAU - PV**	4.76E+00	7.84E-06	***	**BAU - PV**	-9.65E+00	0.000	***
BCP - PV	1.59E+00	0.336	ns	**BCP - PV**	-2.87E+00	1.24E-02	**	**BCP - PV**	3.65E+00	0.001	**
BAU - RE	1.80E+00	0.428	*	**BAU - RE**	4.95E+00	3.77E-06	***	**BAU - RE**	2.04E-01	0.838	ns
BCP - RE	1.72E+00	0.427	*	**BCP - RE**	-2.68E+00	1.48E-02	**	**BCP - RE**	1.35E+01	0.000	***
PV - RE	1.31E-01	1.000	ns	**PV - RE**	1.89E-01	8.50E-01	ns	**PV - RE**	9.85E+00	0.000	***

Significance codes - '***' $p<0.001$, '**' $p<0.01$, '*' $p< 0.05$, 'ns' $p> 0.05$ (not significant). * The Z score indicates how many standard deviations an element is from the mean. The Bonferroni correction sets the significance cut-off or adjusted p-value at α/n. It is used to counteract the errors introduced from multiple comparisons (Holm, 1979).

Refer: Holm, S. (1979). A simple sequentially rejective multiple test procedure. Scandinavian Journal of Statistics, 6(2), 65-70.

SI-3 c) General Additive Model (GAM) results

Tables 1-12 show the results of the parsimonious GAM models for all impact categories.

Note: To calculate the impact for any building in a specific scenario, add the intercept with the predicted results of each variable in the specific scenario depending on the specific attributes of the building. For details (refer equation 4 in chapter 5)

Table 1 GAM Model results for Global Warming Potential (GWP)

		GWP			
		BAU	PV	RE	BCP
	Intercept	87.2(45)			
Façade material	• Brick	312(70.8)***	-289(70.8)***	214(70.8)**	252(70.8)***
	• Concrete Block	324(71.4)***	-301(71.4)***	238(71.4)***	240.8(71.4)***
	• Fibre Cement	70(101)	-408(101)***	38.2(101)	58.7(101)
	• Reinforced Concrete	-20.4(94)	-649(94)***	-7.86(94)	-42.3(94)
R value (Wall)	m^2-K/W	-24.7(10.8)*	-3.87(10.8)	-14.6(10.8)	-24.2(10.8)*
Storeys	Nos.	16(8.9)	66(8.9)***	10.4(8.9)	13.8(8.9)
Roof Area	m^2	-0.002(0.06)	0.45(0.06)***	0.009(0.06)	-0.02(0.06)
WWR		761(90.3)***	761(90.3)***	761(90.3)***	761(90.3)***
Aluminium framed Window type	• Clear double glazed	73.2(53.7)	33.3(53.7)	56.6(53.7)	54(53.7)
	• low-e double glazed	-55(39)	-97.5(39)*	-8.97(39)	-86.9(39)*
	• Tinted low-e double glazed	-98(64)	-257(64)***	-34.4(64)	-131.6(64)*
Heat pumps	Nos.	-5.4(1.45)***	-11.4(1.45)***	-3.5(1.45)*	-4.7(1.45)**
Annual energy consumption	• Space heating & Cooling	0.004(0.002)*	0.005(0.002)*	0.003(0.002)	0.004(0.002)*
	• Lighting & Equipment	0.0004(6.4e-5)***	0.0004(6.4e-5)***	0.0004(6.4e-5)***	.0004(6.4e-5)***
Location	• Hamilton & Waikato	31(37)	26(37)	19.2(37)	29.7(37)
	• East & West Coast	50.5(38)	36.2(38)	30(38)	49.4(38)
	• Manawatu & Taranaki	32(39)	32(39)	19.2(39)	31.7(39)
	• Wellington & Wairarapa	31(38)	38.3(38)	17.3(38)	32(38)
	• Christchurch & Canterbury	76.2(39)*	81.2(39)*	47.5(39)	83.1(39)*
	• Otago & Southland	83(40)	105.5(40)**	46(40)	73.5(40)
	Adj R^2	*0.74*			
Deviance explained		*76.9 %*			

Significance codes - ‘***’ p≤0.001,‘**’ p≤0.01, ‘*’p≤0.05 ; ‘ ’ p> 0.05 (not significant)

Table 2 GAM Model results for Ozone Depletion Potential (ODP)

		ODP			
		BAU	PV	RE	BCP
	Intercept	3.67e-04 (1.27e-06)			
Façade material	• Brick	2.9e-05(1.9e-06)***	3.1e-05(1.9e-06)***	2.9e-05(1.9e-06)***	2.9e-05(1.9e-06)***
	• Concrete Block	3.3e-05 (2.1e-06)***	2.3e-05 (2.1e-06)***	3.1e-05 (2.1e-06)***	3.2e-05 (2.1e-06)***
	• Fibre Cement	2e-05(3.1e-06)***	1.2e-05(3.1e-06)***	1.9e-05(3.1e-06)***	1.9e-05(3.1e-06)***
	• Reinforced Concrete	1.8e-05(2.9e-06)***	3.4e-05(2.9e-06)	1.86e-05(2.9e-06)***	1.82e-05(2.9e-06)***
R value (Wall)	m^2-K/W	(-)6.8e-07(3.0e-07)*	(-)9.6e-08(3.3e-07)	(-)3.9e-07(3.3e-07)	(-)7.5e-07(3.0e-07)*
Storeys	Nos.	4.6e-07(2.7e-07)	1.8e-06(2.7e-07) ***	3.7e-07 (2.7e-07)	4.105e-07(2.7e-07)
Roof Area	m^2	9.5e-10 (1.9e-09)	1.6e-08(1.9e-09) ***	1.4e-09(1.9e-09)	3.7e-10 (1.9e-09)
WWR		2.10e-05(2.5e-06)***	1.6e-05(2.5e-06)***	1.3e-05(2.5e-06) ***	2.1e-05 (2.5e-06)***
Heat pumps	Nos.	(-)1.6e-07 (4.4e-08)***	(-)3.5e-07 (4.4e-08)***	(-)1.1e-07(4.4e-08)*	(-)1.5e-07(4.4e-08)***
Annual energy consumption	• Space heating & Cooling	1.5e-10(6.3e-11)*	1.1e-10(6.3e-11)	1.1e-10(6.3e-11)	1.6e-10(6.3e-11)*
	• Lighting & Equipment	9.9e-12(1.6e-12)***	1.3e-11(1.6e-12)***	5.1e-12(1.6e-12)***	1.0e-11(1.6e-12)***
Location	• Hamilton & Waikato	7.8e-7(1.2e-6)	7.8e-7(1.2e-6)	6.0e-7(1.2e-6)	7.6e-7(1.2e-6)
	• East & West Coast	1.2e-6(1.2e-6)	7.9e-7(1.2e-6)	8.23e-7(1.2e-6)	1.2e-6(1.2e-6)
	• Manawatu & Taranaki	5.5e-7(1.2e-6)	8.8e-7(1.2e-6)	3.1e-7(1.2e-6)	7.3e-7(1.2e-6)
	• Wellington & Wairarapa	8.4e-7(1.2e-6)	8.7e-7(1.2e-6)	5.6e-7(1.2e-6)	9.2e-7(1.2e-6)
	• Christchurch & Canterbury	2.4e-6(1.2e-6)*	2.5e-6(1.2e-6)*	1.8e-6(1.2e-6)	2.4e-6(1.2e-6)*
	• Otago & Southland	2.6e-6(1.2e-6)*	3.5e-6(1.2e-6)**	1.9e-6(1.2e-6)	2.7e-6(1.2e-6)*
	Adj R^2	0.79			
Deviance explained		76.9 %			

Significance codes - '***' p≤0.001,'**' p≤0.01, '*'p≤0.05 ; ' ' p> 0.05 (not significant)

Table 3 Model results for Photochemical Potential (PCOP)

		PCOP			
		BAU	PV	RE	BCP
	Intercept	7.5e-3(8.2e-3)			
Façade material	• Brick	9.8e-2(1.4e-2)***	(-)1.2e-2(1.4e-2)***	7.8e-2(1.4e-2)***	6.4e-2(1.4e-2)***
	• Concrete Block	7.6e-02(1.3e-2)***	(-)7.5e-02(1.3e-2)***	5.9e-02(1.3e-2)***	4.9e-02(1.3e-2)***
	• Fibre Cement	1.5e-02(2.4e-2)	(-)9.1e-02(2.0e-2)***	1.5e-02(2.4e-2)	4.0e-03(2.4e-2)
	• Reinforced Concrete	(-)1.1e-02(1.2e-2)	(-)1.3e-02(1.2e-2)***	3.5e-02(1.2e-2)	(-)1.9e-02(1.2e-2)
Storeys	Nos.	5.7e-3(2.0e-3)**	1.5e-2(2.0e-3)***	3.4e-3(2.0e-3)	4.7e-3(2.0e-3)*
Roof Area	m^2	2.0e-5(1.5e-5)	8.7e-5(1.5e-5)***	2.1e-5(1.5e-5)	8.6e-6(1.5e-5)
WWR		1.6e-01(2.1e-2)***	1.5e-01(2.1e-2)***	7.3e-02(2.1e-2)***	1.5e-01(2.1e-2)***
Aluminium framed Window type	• Clear double glazed	2.1e-2(1.2e-2)	1.2e-2(1.2e-2)	2.0e-2(1.2e-2)	1.2e-2(1.2e-2)
	• low-e double glazed	(-)7.7e-4(8.8e-3)	(-)9.8e-3(8.8e-3)	1.4e-2(8.8e-3)	(-)1.4e-2(8.8e-3)
	• Tinted low-e double glazed	(-)1.6e-2(1.4e-2)	(-)5.8e-2(1.4e-2)***	7.9e-3(1.4e-2)	(-)3.1e-2(1.4e-2)*
Heat pumps	Nos.	(-)1.6e-3(3.2e-4)***	(-)2.5e-3(3.2e-4)***	(-)9.8e-4(3.2e-4)**	(-)1.4e-3(3.2e-4)***
Annual energy consumption	• Space heating & Cooling	1.2e-6(4.5e-7)**	1.3e-6(4.5e-7)**	5.8e-7(4.5e-7)	1.2e-7(4.5e-7)**
	• Lighting & Equipment	1.0e-7(1.4e-8)***	1.0e-7(1.4e-8)***	5.1e-8(1.4e-8)***	9.0e-8(1.4e-8)***
	Adj R^2	*0.8*			
Deviance explained		*81.9 %*			

Significance codes - ‘***’ p≤0.001,‘**’ p≤0.01, ‘*’p≤0.05 ; ‘ ’ p> 0.05 (not significant)

Table 4 Model results for Acidification Potential (AP)

		AP			
		BAU	PV	RE	BCP
	Intercept	-4.6e-01(2.6e-01)			
Façade material	• Brick	2.1 (4.3e-01)***	-4.8 (4.3e-01)***	1.2 (4.3e-01)***	2.02 (4.3e-01)***
	• Concrete Block	2.1 (4.4e-01)***	-2.7 (4.4e-01)***	1.3 (4.4e-01)**	1.9(4.4e-01)***
	• Fibre Cement	7.8e-1(6.2e-1)	-2.8e-1(6.2e-1)***	5.0e-1(6.2e-1)	9.03e-1(6.2e-1)
	• Reinforced Concrete	1.9e-1(5.8e-1)	-3.73e-1(5.8e-1)***	3.1e-1(5.8e-1)	2.7e-1(5.8e-1)
R value (Wall)	m^2-K/W	-1.5e-1(6.4e-2)*	-5.2e-2(6.4e-2)	-6.2e-2(6.4e-2)	-1.4e-1(6.4e-2)*
Storeys	Nos.	1.1e-1(5.6e-2)	2.1e-3(5.6e-2)***	5.8e-2(5.6e-2)	9.1e-2(5.6e-2)
Roof Area	m^2	1.2e-4(4.0e-4)	2.1e-3(4.0e-4)***	2.3e-4(4.0e-4)	-4.2e-4(4.0e-4)
WWR		4.8(5.6e-1)***	4.7(5.6e-1)***	2.25(5.6e-1)***	4.4(5.6e-1)***
Aluminium framed Window type	• Clear double glazed	4.8e-1(3.3e-1)	1.4e-1(3.3e-1)	3.4e-1(3.3e-1)	3.5e-1(3.3e-1)
	• low-e double glazed	-2.7e-1(2.5e-1)	-6.7e-1(2.5e-1)**	1.4e-1(2.5e-1)	-4.8e-1(2.5e-1)
	• Tinted low-e double glazed	-5.9e-1(4e-1)	-1.8(4e-1)***	-2.5e-2(4e-1)	-7.8e-14e-1)*
Heat pumps	Nos.	-3.4e-2(9e-3)***	-6.2e-2(9e-3)***	-1.8e-2(9e-3)*	-3.0e-2(9e-3)***
Annual energy consumption	• Space heating & Cooling	3.1e-5(1.3-5)*	4.1e-5(1.3-5)**	1.5e-5(1.3-5)	2.8e-5(1.3-5)*
	• Lighting & Equipment	2.31e-6(3.9e-7)***	2.4e-6(3.9e-7)***	1.0e-6(3.9e-7)*	2.2e-6(3.9e-7)***
Location	• Hamilton & Waikato	1.9e-1(2.3e-1)	1.7e-1(2.3e-1)	9.2e-2(2.3e-1)	1.8e-1(2.3e-1)
	• East & West Coast	3.0e-1(2.3e-1)	2.3e-1(2.3e-1)	1.2e-1(2.3e-1)	2.9e-1(2.3e-1)
	• Manawatu & Taranaki	2.0e-1(2.4e-1)	2.5e-1(2.4e-1)	8.7e-2(2.4e-1)	1.9e-1(2.4e-1)
	• Wellington & Wairarapa	1.8e-1(2.4e-1)	1.9e-1(2.4e-1)	6.3e-2(2.4e-1)	1.9e-1(2.4e-1)
	• Christchurch & Canterbury	4.8e-1(2.6e-1)*	4.9e-1(2.6e-1)*	1.6e-1(2.6e-1)	4.8e-1(2.6e-1)*
	• Otago & Southland	4.5e-1(2.4e-1)	6.8e-1(2.4e-1)**	1.8e-1(2.4e-1)	4.3e-1(2.4e-1)
	Adj R^2	*0.85*			
Deviance explained		*86.9 %*			

Significance codes - '***' $p \leq 0.001$, '**' $p \leq 0.01$, '*' $p \leq 0.05$; ' ' $p > 0.05$ (not significant)

Table 5 Model results for Eutrophication Potential (EP)

		EP			
		BAU	PV	RE	BCP
	Intercept	3.3e-01(2.3e-01)			
Façade material	• Brick	1.5(3.8e-01)***	-6.9e-1 (3.8e-01)	6.9e-1 (3.8e-01)	1.4 (3.8e-01)***
	• Concrete Block	1.3(3.8e-01)***	-1.8(3.8e-01)***	6.3e-1(3.8e-01)	1.2(3.8e-01)**
	• Fibre Cement	4.3e-1(5.4e-1)	-2(5.4e-1)***	1.6e-1(5.4e-1)	3.47e-1(5.4e-1)
	• Reinforced Concrete	1.7e-1(5.1e-1)	-3.3(5.1e-1)***	2.6e-1(5.1e-1)	2.2e-2(5.1e-1)
R value (Wall)	m^2-K/W	-1.3e-1(5.8e-2)*	-6.4e-3(5.8e-2)	-5.03e-2(5.8e-2)	-1.3e-1(5.8e-2)*
Storeys	Nos.	9.2e-2(4.8e-2)	3.8e-1(4.8e-2)***	4.7e-2(4.8e-2)	8.6e-2(4.8e-2)
Roof Area	m^2	-3.5e-5(3.5e-4)	2.8e-3(3.5e-4)***	6.7e-5(3.5e-4)	-7.4e-5(3.5e-4)
WWR		3.9(4.8e-1)***	3.1(4.8e-1)***	1.4(4.8e-1)***	3.8(4.8e-1)***
Aluminium framed Window type	• Clear double glazed	3.9e-1(2.9e-1)	2.1e-1(2.9e-1)	2.5e-1(2.9e-1)	3.5e-1(2.9e-1)
	• low-e double glazed	-3.8e-1(2.1e-1)	-5.7e-1(2.4e-1)**	-7.3e-3(2.1e-1)	-4.5e-1(2.1e-1)*
	• Tinted low-e double glazed	-6.4e-1(3.4e-1)	-1.4(3.4e-1)***	-1.1e-1(3.6e-1)	-7.1e-1(3.5e-1)*
Heat pumps	Nos.	-3.1e-2(7.8e-3)***	-6.8e-2(7.8e-3)***	-1.5e-2(7.8e-3)*	-2.9e-2(7.8e-3)***
Annual energy consumption	• Space heating & Cooling	2.7e-5(1.3-5)*	2.4e-5(1.1-5)*	1.3e-5(1.1-5)	2.7e-5(1.1-5)*
	• Lighting & Equipment	2.2e-6(3.9e-7)***	2.7e-6(3.4e-7)***	9.8e-6(3.4e-7)**	2.12e-6(3.4e-7)***
Location	• Hamilton & Waikato	1.5e-1(2.0e-1)	1.3e-1(2.0e-1)	5.4e-2(2.0e-1)	1.6e-1(2.0e-1)
	• East & West Coast	2.7e-1(2.1e-1)	1.8e-1(2.1e-1)	1.0e-2(2.1e-1)	2.7e-1(2.1e-1)
	• Manawatu & Taranaki	1.6e-1(1.8e-1)	1.9e-1(1.8e-1)	5.6e-2(1.8e-1)	1.6e-1(1.8e-1)
	• Wellington & Wairarapa	1.6e-1(1.8e-1)	1.4e-1(1.8e-1)	4.9e-2(1.8e-1)	1.7e-1(1.8e-1)
	• Christchurch & Canterbury	4.5e-1(2.1e-1)*	4.3e-1(2.1e-1)*	1.6e-1(2.1e-1)	4.5e-1(2.1e-1)*
	• Otago & Southland	3.9e-1(2.1e-1)	5.57e-1(2.1e-1)**	1.5e-1(2.1e-1)	3.9e-1(2.1e-1)
	Adj R^2	*0.73*			
	Deviance explained	*76.2 %*			

Significance codes - '***' p≤0.001,'**' p≤0.01, '*'p≤0.05 ; ' ' p> 0.05 (not significant)

Table 6 Model results for Abiotic Depletion-resources (AD_r)

		AD_r			
		BAU	PV	RE	BCP
Intercept		1.5e-03(1.1e-04)			
Façade material	• Brick	-6.5e-4 (1.5e-4)***	9.3e-3 (1.5e-4)***	-6.5e-4 (1.5e-4)***	-7.5e-4 (1.5e-4)***
	• Concrete Block	-4.2e-4(1.6e-4)**	2.3e-3(1.6e-4)***	-4.4e-4(1.6e-4)**	-5.5e-4(1.6e-4)***
	• Fibre Cement	-1.1e-3(2.8e-4)***	1.3e-3(2.8e-4)***	-1.0e-3(2.8e-4)***	-1.1e-3(2.8e-4)***
	• Reinforced Concrete	-1.1e-3(2.8e-4)***	-1.3e-3(2.8e-4)***	-1.1e-3(2.8e-4)***	-1.2e-3(2.8e-4)***
Storeys	Nos.	6.6e-5(2.9e-5)*	2.4e-4(2.9e-5)***	6.1e-5(2.9e-5)*	5.9e-5(2.9e-5)*
Roof Area	m^2	2.3e-7(2.2e-7)	3.7e-6(2.2e-7)***	2.4e-7(2.2e-7)	1.6e-7(2.2e-7)
WWR		2.3e-3(2.7e-4)***	-5.2e-5(2.7e-4)	1.9e-3(2.7e-4)***	2.2e-3(2.7e-4)***
Heat pumps	Nos.	-1.9e-5(4.6e-6)***	-5.1e-5(4.6e-6)***	-1.6e-5(4.6e-6)***	-1.7e-5(4.6e-6)***
Annual energy consumption	• Lighting & Equipment	1.1(1.6e-10)***	1.6e-9(1.6e-10)***	9.5e-10(1.5e-10)***	1.1e-9(1.6e-10)***
Adj R^2		*0.97*			
Deviance explained		*98 %*			

Significance codes - '***' $p \leq 0.001$, '**' $p \leq 0.01$, '*' $p \leq 0.05$; ' ' $p > 0.05$ (not significant)

Table 7 Model results for Abiotic Depletion-fossil fuels (AD_{ff})

		AD_{ff}			
		BAU	PV	RE	BCP
	Intercept	238(298)			
Façade material		2815(70.8)***	-1061(70.8)*	1642(506)**	1968(506)***
	• Brick	2484(71.4)***	-1854(71.4)***	1560(482)**	1635(482)***
	• Concrete Block	156.9(101)	-2809(101)***	182.3(743)	-7.23(743)
	• Fibre Cement	-587.5(94)	-5027(94)***	30.5(706)	-822(706)
	• Reinforced Concrete				
Storeys	Nos.	188.7(73.5)*	586(73.5)***	65.9(73.5)	166.7(73.5)*
Roof Area	m^2	0.30(0.533)	4.12(0.533)***	0.33(0.534)	0.11(0.533)
WWR		6405(762)***	5291(762)***	1692(762)*	6117(762)***
Aluminium framed Window type	• Clear double glazed	569(442)	384(442)	436.8(442)	343(442)
	• low-e double glazed	-390(321)	-529.3(321)	410.1(321)	-748.7(321)*
	• Tinted low-e double glazed	-959(522)	-2101(522)***	331.5(522)	-1361(522)**
Heat pumps	Nos.	-57.4(11.8)***	-103.4(11.8)***	-20.5(11.8)	-50.5(11.8)***
Annual energy consumption	• Space heating & Cooling	0.05(0.017)**	0.036(0.017)*	0.013(0.017)	0.046(0.017)**
	• Lighting & Equipment	0.004(0.0005)***	0.004(0.0005)***	0.001(0.0005)*	0.0035(0.0005)***
	Adj R^2	*0.73*			
	Deviance explained	*76.7 %*			

Significance codes - '***' $p \leq 0.001$, '**' $p \leq 0.01$, '*' $p \leq 0.05$; ' ' $p > 0.05$ (not significant)

Table 8 Model results for Human Toxicity (HT carc)

		HT cancer			
		BAU	PV	RE	BCP
	Intercept	-6.23e-6(4.22e-6)			
Façade material	• Brick	3.2e-5(7.1e-6)***	-9.9e-6(7.1e-6)	2.1e-5(7.2e-6)**	2.9e-5(7.1e-6)***
	• Concrete Block	2.3e-5(6.8e-6)***	-2.8e-5(6.8e-6)***	1.4e-5(6.8e-6)*	2.2e-5(6.8e-6)**
	• Fibre Cement	4.5e-8(1.05e-5)	-3.5e-5(1.05e-5)***	2.6e-7(1.05e-5)	1.02e-6(1.05e-5)
	• Reinforced Concrete	-7.2e-6(9.98e-6)	-6.11e-5(9.98e-6)***	-1.3e-6(9.98e-6)	-6.54e-6(9.98e-6)
Storeys	Nos.	2.61e-6(1.04e-6)*	7.5e-6(1.04e-6)***	1.4e-6(1.04e-6)	2.34e-6(1.04e-6)*
Roof Area	m^2	4.4e-9(7.5e-9)	5.2e-8(7.5e-9)***	4.6e-9(7.5e-9)	2.7e-9(7.5e-9)
WWR		9.7e-5(1.1e-5)***	8.3e-5(1.1e-5)***	5.2e-5(1.1e-5)***	9.15e-5(1.1e-5)***
Aluminium framed Window type	• Clear double glazed	9.4e-6(6.2e-6)	7.4e-6(6.2e-6)	8.2e-6(6.2e-6)	7.5e-6(6.2e-6)
	• low-e double glazed	-3.4e-6(4.5e-6)	-4.8e-6(4.5e-6)	4.3e-6(4.5e-6)	-6.1e-6(4.5e-6)
	• Tinted low-e double glazed	-1.3e-5(7.4e-5)	-2.6e-5(7.4e-5)***	-4.4e-5(7.4e-6)	-1.6e-5(7.4e-5)*
Heat pumps	Nos.	-7.7e-7(1.7e-7)***	-1.3e-6(1.7e-7)***	-4.2e-7(1.7e-7)*	-7.2e-7(1.7e-7)***
Annual energy consumption	• Space heating & Cooling	7.4e-10(2.3e-10)**	5.8e-10(2.3e-10)*	4.1e-10(2.3e-10)	7.2e-10(2.3e-10)**
	• Lighting & Equipment	4.8e-11(7.3e-11)***	5.4e-11(7.3e-11)***	2.3e-11(7.3e-11)**	4.6e-11(7.3e-11)***
	Adj R^2	*0.68*			
	Deviance explained	*72.1 %*			

Significance codes - '***' p≤0.001,'**' p≤0.01, '*'p≤0.05 ; ' ' p> 0.05 (not significant)

Table 9 Model results for Human Toxicity (HT non carc)

		HT non cancer			
		BAU	PV	RE	BCP
	Intercept	7.1e-5(3.2e-5)			
Façade material	• Brick	2.1e-4(5.3e-5)***	-1.9e-5(5.3e-5)	1.2e-4(5.3e-5)*	1.9e-4(5.3e-5)***
	• Concrete Block	1.8e-4(5.4e-5)***	-2.3e-4(5.4e-5)***	1.1e-4(5.4e-5)*	1.7e-4(5.4e-5)**
	• Fibre Cement	6.5e-5(7.6e-5)	-2.5e-4(7.6e-5)***	3.4e-5(7.6e-5)	5.1e-5(7.6e-5)
	• Reinforced Concrete	-1.8e-5(7.2e-5)	-5.0e-4(7.2e-5)***	-6.7e-6(7.2e-5)	-2.9e-5(7.2e-5)
R value (Wall)	m^2-K/W	-1.9e-5(8.2e-6)*	-8.4e-7(8.2e-6)	-9.6e-6(8.2e-6)	-1.9e-5(8.2e-6)*
Storeys	Nos.	1.1e-5(6.8e-6)	5.3e-5(6.8e-6)***	5.7e-6(6.8e-6)	1.1e-5(6.7e-6)
Roof Area	m^2	-1.6e-8(4.8e-8)	4.1e-7(4.8e-8)***	-4.5e-9(4.8e-8)	-1.8e-8(4.8e-8)
WWR		5.7e-4(6.8e-5)***	4.5e-4(6.8e-5)***	2.8e-4(6.8e-5)***	5.6e-4(6.8e-5)***
Aluminium framed Window type	• Clear double glazed	4.1e-5(4.1e-5)	1.7e-5(4.1e-5)	2.5e-5(4.1e-5)	3.9e-5(4.1e-5)
	• low-e double glazed	-7.3e-5(2.9e-5)*	-9.6e-5(2.9e-5)**	-2.9e-5(2.9e-5)	-7.6e-5(2.9e-5)*
	• Tinted low-e double glazed	-1.1e-4(4.8e-5)*	-2.1e-4(4.8e-5)***	-4.5e-5(4.8e-5)	-1.1e-4(4.8e-5)*
Heat pumps	Nos.	-3.7e-6(1.1e-6)***	-9.1e-6(1.1e-6)***	-1.9e-6(1.1e-6)	-3.7e-6(1.1e-6)***
Annual energy consumption	• Space heating & Cooling	3.4e-9(1.5e-9)*	2.7e-9(1.5e-9)	1.7e-9(1.5e-9)	3.5e-9(1.5e-9)*
	• Lighting & Equipment	2.8e-10(4.8e-11)***	3.6e-10(4.8e-11)***	1.4e-10(4.8e-10)**	2.8e-10(4.8e-10)***
Location	• Hamilton & Waikato	2.4e-5(2.8e-5)	2.0e-5(2.8e-5)	1.3e-5(2.8e-5)	2.3e-5(2.8e-5)
	• East & West Coast	4.0e-5(2.8e-5)	2.7e-5(2.8e-5)	2.0e-5(2.8e-5)	3.9e-5(2.8e-5)
	• Manawatu & Taranaki	2.6e-5(2.9e-5)	2.9e-5(2.9e-5)	1.3e-5(2.9e-5)	2.5e-5(2.9e-5)
	• Wellington & Wairarapa	2.6e-5(2.9e-5)	2.2e-5(2.9e-5)	1.3e-5(2.9e-5)	2.6e-5(2.9e-5)
	• Christchurch & Canterbury	6.7e-5(2.9e-5)*	6.4e-5(2.9e-5)*	3.3e-5(2.9e-5)	6.7e-5(2.9e-5)*
	• Otago & Southland	5.9e-5(2.9e-5)	8.1e-5(2.9e-5)**	3.0e-5(2.9e-5)	5.8e-5(2.9e-5)
	Adj R^2	*0.74*			
	Deviance explained	*77.1 %*			

Significance codes - '***' p≤0.001,'**' p≤0.01, '*'p≤0.05 ; ' ' p> 0.05 (not significant)

Table 10 Model results for Freshwater Eco- Toxicity ($ET_{freshwater}$)

		$ET_{freshwater}$			
		BAU	PV	RE	BCP
	Intercept	-627(1379)			
Façade material	• Brick	9513(2336)***	-3060(2336)	8413(2336)***	9263(2336)***
	• Concrete Block	7678(2251)***	-11750(2251)***	6873(2251)**	7549(2251)***
	• Fibre Cement	1717(3366)	-11810(3366)***	1988(3366)	1939(3366)
	• Reinforced Concrete	-2019(3225)	-24090(3225)***	-1070(3225)	-1763(3225)
Storeys	Nos.	867.2(324.3)**	2881(324.3)***	735.1(324.3)*	865.6(324.3)**
Roof Area	m^2	8.1e-1(2.35)	21.3(2.35)***	8.0e-1e-1(2.35)	6.67e-1(2.35)
WWR		31130(3364)***	25880(24810)***	25880(3364)***	30840(3364)***
Aluminium framed Window type	• Clear double glazed	2782(1987)	1931(1987)	2587(1987)	2724(1987)
	• low-e double glazed	-2854(1443)*	-3541(1443)*	-1908(1443)	-2678(1443)
	• Tinted low-e double glazed	-4028(2326)	-8560(2326)***	-2662(2326)	-3774(2326)
Heat pumps	Nos.	-236.8(52.2)***	-480.4(52.2)***	-197.4(52.2)***	-234.2(52.2)***
Annual energy consumption	• Space heating & Cooling	0.169(0.074)*	0.11(0.074)	0.13(0.074)	0.159(0.074)*
	• Lighting & Equipment	0.017(0.002)***	0.019(0.002)***	0.014(0.002)***	0.0171(0.002)***
Location	• Hamilton & Waikato	879(1399)	1077(1399)	742(1399)	810.8(1399)
	• East & West Coast	1474(1402)	1417(1402)	1223(1402)	1400(1402)
	• Manawatu & Taranaki	598(1425)	1476(1425)	494(1425)	518(1425)
	• Wellington & Wairarapa	982(1429)	1132(1429)	805(1429)	914(1429)
	• Christchurch & Canterbury	2842(1440)*	3406(1440)*	2348(1440)	2780(1440)*
	• Otago & Southland	2171(1432)	4240(1432)**	1801(1432)	2026(1432)
	Adj R^2	*0.77*			
	Deviance explained	*78.3 %*			

Significance codes - '***' p≤0.001, '**' p≤0.01, '*' p≤0.05 ; ' ' p> 0.05 (not significant)

Table 11 Model results for Particulate Matter Formation (PMF)

		PMF			
		BAU	PV	RE	BCP
	Intercept	-2.5e-2(1.9e-2)			
Façade material	• Brick	1.6e-1(3.2e-2)***	-1.0e-1(3.2e-2)**	1.2e-1(3.2e-2)***	1.1e-1(3.2e-2)***
	• Concrete Block	1.3e-2(3.1e-2)***	-1.1e-1(3.1e-2)***	9.9e-2(3.1e-2)**	9.5e-2(3.1e-2)**
	• Fibre Cement	-9.3e-3(4.7e-2)	-1.7e-1(4.7e-2)***	-8.4e-2(4.7e-2)	1.5e-2(4.7e-2)
	• Reinforced Concrete	-4.1e-2(4.5e-2)	-2.7e-2(4.5e-2)***	-1.8e-2(4.5e-2)	-2.0e-2(4.5e-2)
Storeys	Nos.	1.3e-2(4.7e-3)**	3.3e-2(4.7e-3)***	8.6e-3(4.7e-3)	9.0e-3(4.7e-3)
Roof Area	m^2	3.8e-5(3.4e-5)	2.2e-4(3.4e-5)***	3.8e-5(3.4e-5)	6.9e-6(3.4e-5)
WWR		4.5e-1(4.85e-2)***	4.0e-1(4.85e-2)***	2.8e-1(4.85e-2)***	3.3e-1(4.85e-2)***
Aluminium framed Window type	• Clear double glazed	5.9e-2(2.8e-2)*	4.7e-2(2.8e-2)	5.4e-2(2.8e-2)	1.95e-2(2.8e-2)
	• low-e double glazed	1.4e-2(2.0e-2)	3.7e-2(2.0e-2)	-4.2e-2(2.0e-2)*	-3.7e-2(2.0e-2)
	• Tinted low-e double glazed	-2.6e-2(3.3e-2)	-9.2e-2(3.3e-2)**	-1.9e-2(3.3e-2)	-7.3e-2(3.3e-2)*
Heat pumps	Nos.	-3.8e-3(7.5e-4)***	-6.0e-3(7.5e-4)***	-2.5e-3(7.5e-4)***	-2.68e-3(7.5e-4)***
Annual energy consumption	• Space heating & Cooling	3.5e-6(1.1e-6)**	3.1e-6(1.1e-6)**	2.4e-6(1.1e-6)*	2.4e-6(1.1e-6)*
	• Lighting & Equipment	2.2e-7(3.3e-8)***	2.4e-7(3.3e-8)***	1.3e-7(3.3e-8)***	1.8e-7(3.3e-8)***
	Adj R^2	*0.67*			
	Deviance explained	*72 %*			

Significance codes - '***' p≤0.001,'**' p≤0.01, '*'p≤0.05 ; ' ' p> 0.05 (not significant)

Table 12 Model results for Ionizing Radiation (IR)

		IR			
		BAU	PV	RE	BCP
	Intercept	7.8(3.4e-1)			
Façade material	• Brick	-2.3(0.64)***	14.9(0.64)***	-2.4(0.64)***	12.1(0.64)***
	• Concrete Block	-1.5(0.68)*	2.2(0.68)**	-1.5(0.68)*	18.1(0.68)***
	• Fibre Cement	-4.5(0.84)***	-3.1(0.84)***	-4.6(0.84)***	-0.41(0.84)
	• Reinforced Concrete	-5.1(0.89)***	-8.2(0.89)***	-5.2(0.89)***	-0.39(0.89)
Storeys	Nos.	7.8e-1(1.2e-1)	4.7e-1(1.2e-1)***	7.6e-02(1.2e-1)	1.1e-1(1.2e-1)
Roof Area	m^2	3.1e-5(8.6e-4)	7.2e-3(8.6e-4)***	8.0e-1e-1(8.6e-4)	2.4e-3(8.6e-4)**
Aluminium framed Window type	• Clear double glazed	7.75e-2(7.4e-1)	1.02(7.4e-1)	8.9e-2(7.4e-1)	1.6(7.4e-1)*
	• low-e double glazed	-1.89e-1(4.92e-1)	1.19(4.92e-1)*	-1.4e-1(4.92e-1)	2.83(4.92e-1)***
	• Tinted low-e double glazed	-3.02e-1(8.48e-1)	2.21(8.48e-1)**	-2.4e-1(8.48e-1)	2.7(8.48e-1)**
Heat pumps	Nos.	-2.3e-2(1.7e-2)	-1.2e-1(1.7e-2)***	-2.26e-2(1.7e-2)	-8.3e-2(1.7e-2)***
Annual energy consumption	• Lighting & Equipment	1.7e-6(8.1e-7)*	3.9e-6(8.1e-7)***	1.7e-6(8.1e-7)*	5.5e-6(8.1e-7)***
	Adj R^2	*0.96*			
Deviance explained		*96.6 %*			

Significance codes - '***' $p \leq 0.001$, '**' $p \leq 0.01$, '*' $p \leq 0.05$; ' ' $p > 0.05$ (not significant)

Supporting Information - 4

d) Age of existing commercial building stock

e) Stock aggregated impact assessment results in 2050 based on building location

f) Stock aggregated impact assessment results in 2050 based on building groups (based on floor area)

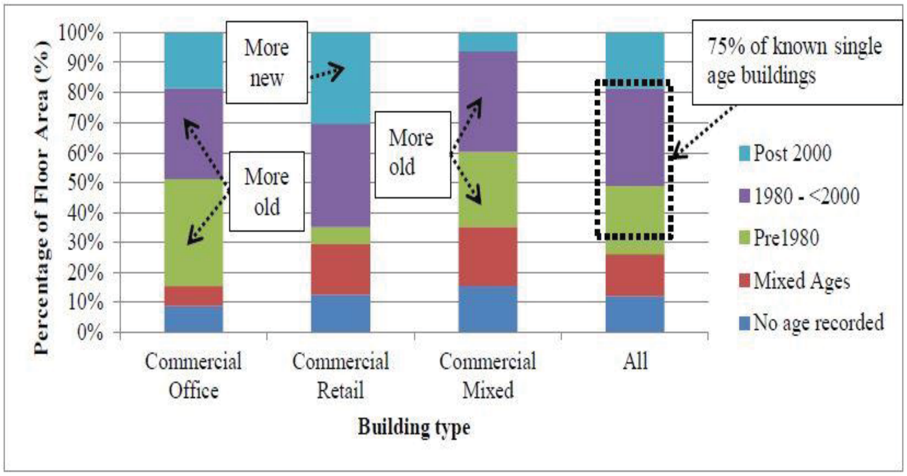

Figure SI 4 a Percentage of commercial office, retail and mixed floor area in different aged buildings. Figure adopted from Cory, (2016), *An Exploration of the Feasibility of Converting the New Zealand Commercial Building Stock to be Net Zero Energy*. (Doctor of Philosophy in Architecture monograph), Victoria University, Wellington

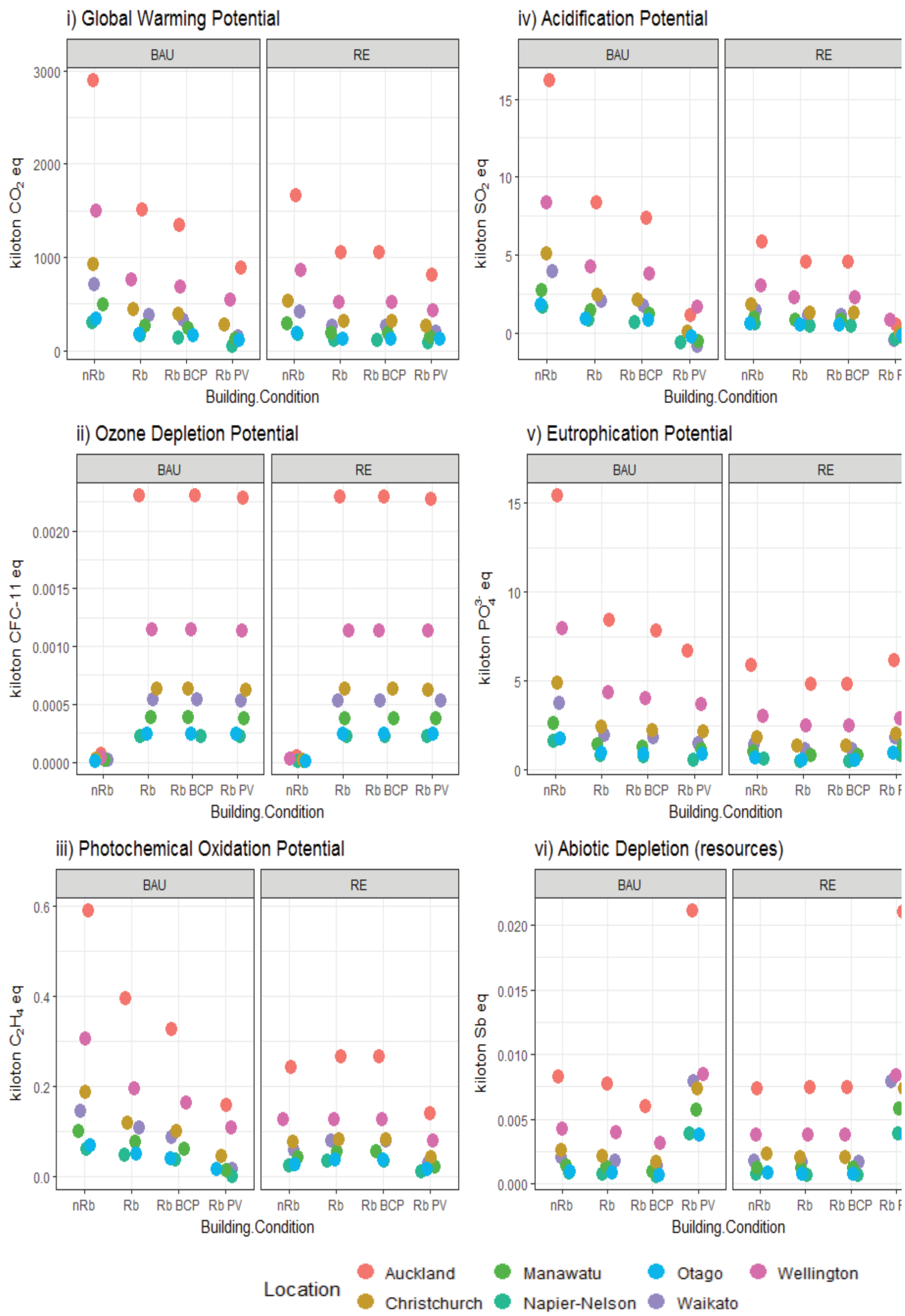

Figure SI 4(b-i) The stock aggregated impact assessment results in 2050 for buildings located in seven different locations, in three different conditions (nRb, Rb, Rb BCP, Rb PV) and two scenarios (BAU & RE) are shown for : i) Global warming potential, ii) Ozone depletion potential, iii) Photochemical oxidation potential, iv) Acidification potential, v) Eutrophication potential, vi) Abiotic depletion (resources) .

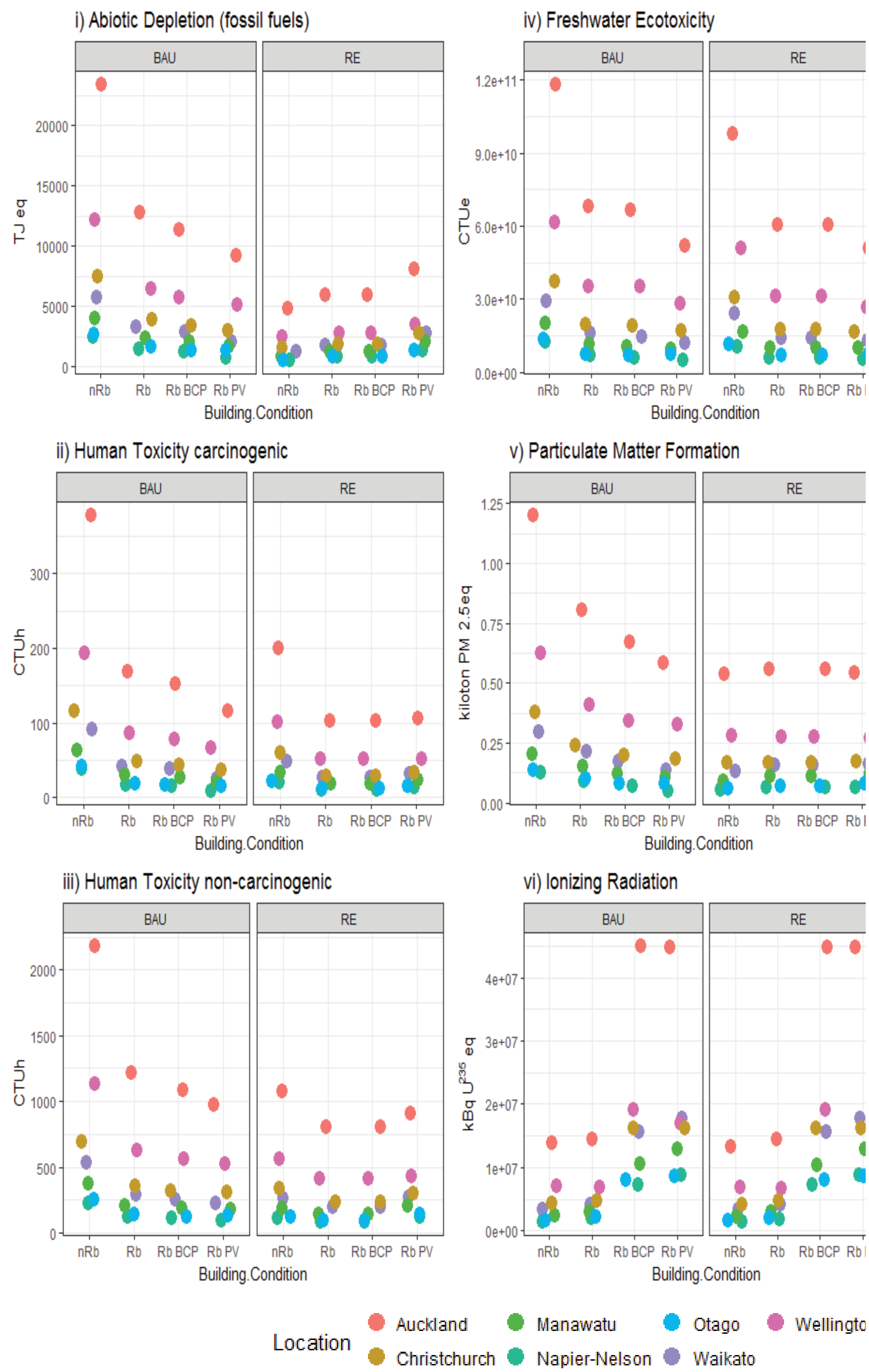

Figure SI 4(b-ii) The stock aggregated impact assessment results in 2050 for buildings located in seven different locations, in three different conditions (nRb, Rb, Rb BCP, Rb PV) and two scenarios (BAU & RE) are shown for : i) Abiotic depletion (fossil fuels) ii) Human toxicity (carcinogenic) iii) Human toxicity (non-carcinogenic) iv) Ecotoxicity (freshwater) v) Particulate matter formation and vi) Ionizing radiation.

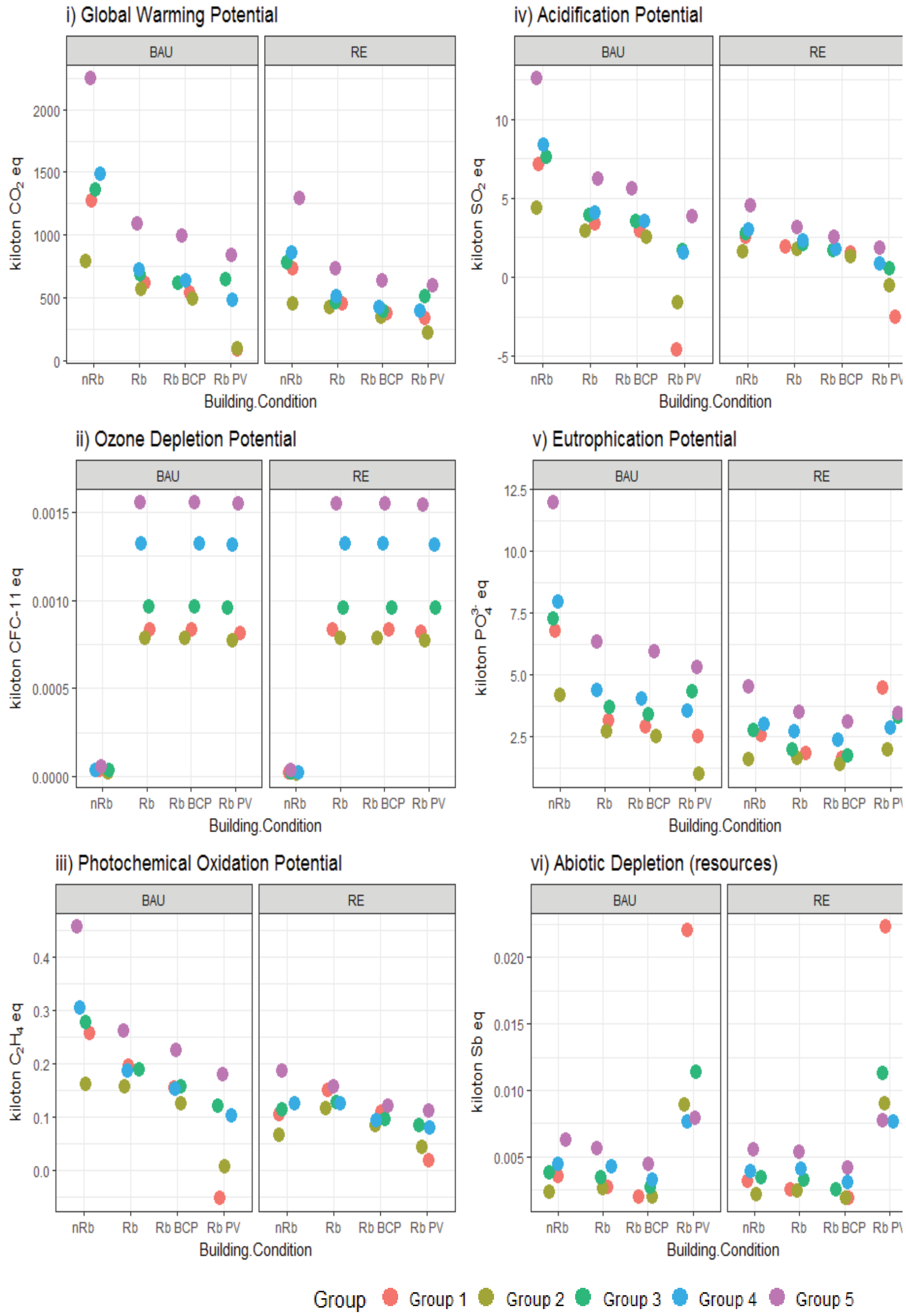

Figure SI 4(c-i) The stock aggregated impact assessment results in 2050 for building groups based on their floor area (see table 3 in the manuscript), in three different conditions (nRb, Rb, Rb BCP, Rb PV) and two scenarios (BAU & RE) are shown for : i) Global warming potential, ii) Ozone depletion potential, iii) Photochemical oxidation potential, iv) Acidification potential, v) Eutrophication potential, vi) Abiotic depletion (resources) .

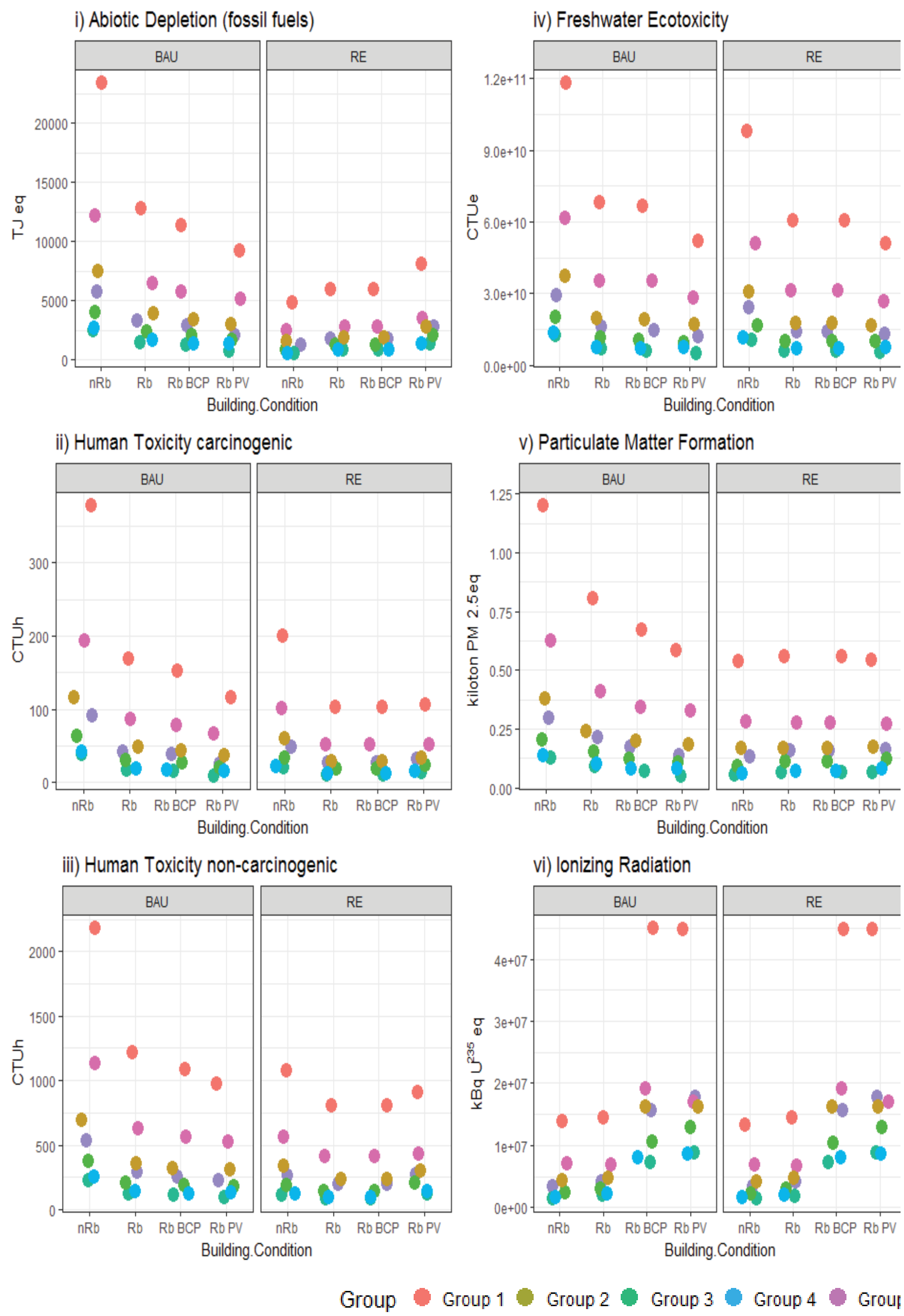

Figure SI 4(c-ii) The stock aggregated impact assessment results in 2050 for building groups based on their floor area (see table 3 in the manuscript), in three different conditions (nRb, Rb, Rb BCP, Rb PV) and two scenarios (BAU & RE) are shown for : i) Abiotic depletion (fossil fuels) ii) Human toxicity (carcinogenic) iii) Human toxicity (non-carcinogenic) iv) Ecotoxicity (freshwater) v) Particulate matter formation and vi) Ionizing radiation.

Appendix

The statement of contribution to manuscripts arising from this research is attached in the following pages.

DRC 16

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STATEMENT OF CONTRIBUTION TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Agneta Ghose

Name/Title of Principal Supervisor: Sarah J. McLaren

Name of Published Research Output and full reference:

Ghose, A., McLaren, J. S., Dowdell, D., and Phipps, R. (2017). Environmental assessment of deep energy refurbishment for energy efficiency- case study of an office building in New Zealand, Building and Environment, doi: 10.1016/j.buildenv.2017.03.012

In which Chapter is the Published Work: Chapter 3

Please indicate either:

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  and / or

- Describe the contribution that the candidate has made to the Published Work:

  TThe candidate was responsible for research conceptualization, data collection, performing the LCA, interpreting the results and writing the majority of the manuscript. The co-authors were involved in research conceptualization, guidance on data collection including connections to unreported industry data, interpreting the results, editing the manuscript, and supervising the overall research.

Agneta Ghose Digitally signed by Agneta Ghose DN: cn=Agneta Ghose, o, ou, email=agneta.20@gmail.com, c=IN Date: 2017.09.26 16:01:58 +13'00'

Candidate's Signature

25 September 2017

Date

Sarah McLaren Digitally signed by Sarah McLaren Date: 2017.09.25 09:37:32 +13'00'

Principal Supervisor's signature

25 September 2017

Date

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Name of Candidate: Agneta Ghose

Name/Title of Principal Supervisor: Sarah J. McLaren

Name of Published Research Output and full reference:

Ghose, A., Pizzol, M., and McLaren, J. S. 2017. Consequential LCA modelling of office building refurbishment in New Zealand: an evaluation of resource and waste management scenarios. Journal of Cleaner Production, doi:10.1016/j.jclepro.2017.07.099

In which Chapter is the Published Work: Chapter 4

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  and / or

- Describe the contribution that the candidate has made to the Published Work:

  The candidate was responsible for research collaboration, research conceptualization, data collection, performing the LCA, interpreting the results and writing majority of the manuscript. The co-authors were involved in research conceptualization, interpreting the results, editing the manuscript, and supervising the overall research.

Agneta Ghose Digitally signed by Agneta Ghose DN: cn=Agneta Ghose, o, ou, email=agneta.20@gmail.com, c=IN Date: 2017.10.05 13:18:59 +13'00' — 25 September 2017

Candidate's Signature — Date

Sarah McLaren Digitally signed by Sarah McLaren Date: 2017.09.22 10:39:25 +12'00' — 22 September 2017

Principal Supervisor's signature — Date

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Name of Candidate: Agneta Ghose

Name/Title of Principal Supervisor: Sarah J. McLaren

Name of Published Research Output and full reference:

Ghose, A., Pizzol, M., McLaren, J. S., Vignes, M., and Dowdell, D. Refurbishment of office buildings in New Zealand: identifying priorities for reducing environmental impacts. Submitted to Environmental Science and Technology

In which Chapter is the Published Work: Chapter 5

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Agneta Ghose Digitally signed by Agneta Ghose DN: cn=Agneta Ghose, o, ou, email=agneta.20@gmail.com, c=IN Date: 2017.10.05 13:17:25 +13'00'

Candidate's Signature

25 September 2017

Date

Sarah McLaren Digitally signed by Sarah McLaren Date: 2017.09.22 10:34:17 +12'00'

Principal Supervisor's signature

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Name of Candidate: Agneta Ghose

Name/Title of Principal Supervisor: Sarah J. McLaren

Name of Published Research Output and full reference:

Ghose, A., McLaren, J. S., and Dowdell, D. Comprehensive environmental impact assessment of New Zealand's office building stock. . Submitted to Journal of Industrial Ecology

In which Chapter is the Published Work: Chapter 6

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- Describe the contribution that the candidate has made to the Published Work:

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Agneta Ghose Digitally signed by Agneta Ghose DN: cn=Agneta Ghose, o, ou, email=agneta.20@gmail.com, c=IN Date: 2017.10.05 13:17:53 +13'00'
Candidate's Signature

25 September 2017
Date

Sarah McLaren Digitally signed by Sarah McLaren Date: 2017.09.22 10:35:41 +12'00'
Principal Supervisor's signature

22 September 2017
Date

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