**TOWARDS AN INTEGRATED MULTI-SCALE ZERO ENERGY BUILDING FRAMEWORK FOR RESIDENTIAL
BUILDINGS**

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TOWARDS AN INTEGRATED MULTI-SCALE ZERO ENERGY BUILDING FRAMEWORK FOR RESIDENTIAL BUILDINGS

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A thesis

Submitted to the Victoria University of Wellington

In total fulfilment of the requirements of the degree of
Doctor of Philosophy

March 2017

Wellington, New Zealand

Key words: Zero Energy Buildings- Residential Buildings- Building Embodied Energy- Building Operation Energy- Transport Embodied Energy- Transport Operation Energy

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Printed by Victoria University School of Architecture and Design Press

PhD Thesis

Towards an integrated multi-scale zero energy building framework for residential buildings

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Abstract

In most developed economies, buildings are directly and indirectly accountable for at least 40% of the final energy use. Consequently, most world cities are increasingly surpassing sensitive environmental boundaries and continue to reach critical biophysical thresholds. Climate change is one of the biggest threats humanity faces today and there is an urgent need to reduce energy use and CO₂ emissions globally to zero or to less than zero, to address climate change. This often leads to the assumption that buildings must reduce energy demand and emit radically less CO₂ during construction and occupation periods. Certainly, this is often implemented through delivering ‘zero energy buildings’. The deployment of residential buildings which meet the zero energy criteria thereby allowing neighbourhoods and cities to convert to semi-autonomous energy systems is seen to have a promising potential for reducing and even eliminating energy demand and the associated greenhouse gas emissions. However, most current zero energy building approaches focus solely on operational energy overlooking other energy uses such as embodied energy and user transport energy. Embodied energy constitutes all energy requirements for manufacturing building materials, construction and replacement. Transport energy comprises the amount of energy required to provide mobility services to building users.

Zero energy building design decisions based on partial evaluation and quantification approaches might result in an increased energy demand at different or multiple scales of the built environment. Indeed, recent studies have demonstrated that embodied and transport energy demands account for more than half of the total annual energy demand of residential buildings built based on zero energy criteria. Current zero energy building frameworks, tools and policies therefore may overlook more than ~80% of the total net energy balance annually.

The original contribution of this thesis is an integrated multi-scale zero energy building framework which has the capacity to gauge the relative effectiveness towards

the deployment of zero energy residential buildings and neighbourhoods. This framework takes into account energy requirements and CO₂ emissions at the building scale, i.e. the embodied energy and operation energy demands, and at the city scale, i.e. the embodied energy of related transport modes including infrastructure and the transport operational energy demand of its users. This framework is implemented through the development of a quantification methodology which allows the analysis and evaluation of energy demand and CO₂ emissions pertaining to the deployment of zero energy residential buildings and districts. A case study, located in Auckland, New Zealand is used to verify, validate and investigate the potential of the developed framework.

Results confirm that each of the building (embodied and operational) and transport (embodied and operational) energy requirements represent a very significant share of the annual overall energy demand and associated CO₂ emissions of zero energy buildings. Consequently, rather than the respect of achieving a net zero energy building balance at the building scale, the research has revealed that it is more important, above all, to minimise building user-related and transportation energy demand at the city scale and maximise renewable energy production coupled with efficiency improvements at grid level. The application of the developed evaluation framework will enable building designers, urban planners, researchers and policy makers to deliver effective multi-scale zero energy building strategies which will ultimately contribute to reducing the overall environmental impact of the built environment today.

Declaration

I Dekhani Nsaliwa, certify that this thesis embodied the results of my own work and to the best of my knowledge it comprises no materials previously published or which have been accepted for award of any other degree at Victoria University of Wellington or any institution of higher learning, except where due acknowledgement or references to the works of other persons is appropriately made in the thesis.

In addition, I certify that the thesis is fewer than 100,000 words in length, exclusive of bibliographies, tables and appendices.

Signature of student:..... Date:...23/09/2016.....

Acknowledgements

First and foremost, I would like to praise God and his almighty ways for the abundant showers of blessings he bestowed upon me. At the end of this energetic adventure, I would like to particularly thank Victoria University of Wellington through Victoria Research Trust for awarding me the Victoria Doctoral Scholarship.

This thesis embodies the fruits of my research under the tutelage of my supervisors and mentors, Professor Robert Vale and Dr Nigel Isaacs, who trained me to be precise and concise, and aptly imparted the art of Architectural Science research with a professional accent. You have both been there like two giant pillars of knowledge in what at times seemed like an expansive sea of confusion and never-ending process. While only I could have completed this journey, your overwhelming support helped me in reaching my final destination. I further owe you a debt of gratitude for the original idea of this thesis, your help, careful follow-up, valuable comments on my work and your precious time, which I will forever cherish. In addition, I would also like to particularly thank Associate Professor Leon Gurevitch, Emeritus Professor Roger Fay and Professor Hugh Byrd for carefully reading my work, providing critical feedback and making recommendations for publications.

The data requirements for this research were very substantial. A number of organizations and individuals gave willingly of their time to assist me with data and information requests. Essentially, I have been enlightened by the generosity of Mr. Shay Brazier from Solar City New Zealand and Ms. Jo Woods of e-Cubed Building Workshop Ltd. who provided data on the Auckland Zero Energy House. I am also indebted to Dr Andre Stephan and his work on Life Cycle Assessment. His PhD thesis provided the necessary foundations to create a logical flow of Chapters in this work. In particular; chapter structuring, reinforcing arguments and emphasis of integrating building and transport energy demand and the generation of relevant equation variables including equations 4.1 to 4.30., Dr Robert Crawford, Dr Igor Sartori, Dr Anna Joanna Marszal and Dr Andrew Alcorn for providing relevant data

and inspiring my research. I also register my gratitude to Professor Susan Roaf, Dr Doug Harris and Dr Laurent Galbrun from Heriot-Watt University in Edinburgh for their career guidance which initiated me into a journey that has taken me across the world.

To other doctoral researchers at the School of Architecture, I really cherished your companionship, wisdom and support network we founded. I also enjoyed sharing with you numerous lunches and chai latte over the past years – *You know who you are!* My appreciation also goes to my colleagues in Scotland and Malawi. Alfred Kaliwo, in particular for always being there for me. Serdar Aydın and Iman Khajehzadeh proffered myriad support throughout my candidature.

To my family, near and far, I say thank you for your incredible support you have rendered whilst I focused on my scholarly pursuits. I am sincerely grateful to my father Charles and my mother Martha for their words of encouragement throughout my candidature and for casting their editorial eye over various chapters of my thesis towards the end of this PhD – *doumo arigatou gozaimashita!*

Dedication

To my father Charles and my mother Martha, *who dream great dreams and who first taught me the beauty, greatness and integrity of our world. Without their sacrifices my goals and dreams would not have been possible.*

To my siblings; Larry, Ruth, Peter Jr and Tadala; *who bring a lot of joy in my life.*

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List of acronyms

AASHTO	American Association of State Highway and Transportation Officials
ASB	Australian Bureau of Statistics
ASHRAE	American Society of Heating Refrigerating and Air Conditioning Engineers
BDSL	Building Design Life
BOQ	Bills Of Quantities
BPEV	Battery Powered Electric Vehicle
BRANZ	Building Research Association of New Zealand
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Built Environment
CBD	Central Business District
CC	Cylinder Capacity
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient Of Performance
DEWHA	Department Of the Environment ,Water, Heritage and the Arts
CHP	Combined Heat and Power
DHW	Domestic Hot Water
ECUK	Energy Consumption in the United Kingdom
EE	Embodied Energy
EIA	Energy Information Administration
EPBD	Energy Performance of Building Directive
EPBT	Energy Payback Time
EU	European Union
EV	Electric Vehicle

GFA	Gross Floor Area
GHG	Greenhouse Gas Emissions
HEEP	Household Energy End use Project
HVAC	Heating Ventilation and Air Conditioning
ICEDD	Institute of Consulting and Studies on Sustainable Development
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organisation
LCA	Life Cycle Analysis
LCE	Life Cycle Energy
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
NIWA	National Institute for Water and Atmospheric Research
NZ	New Zealand
OECD	Organisation for Economic Collaboration and Development
PAUP	Proposed Auckland Unitary Plan
PET	Polyester Insulation
PV	Photovoltaic
RES	Renewable Energy Systems
RE	Renewable Energy
SHC	Solar Heating and Cooling
ST	Solar Thermal Collectors
TAS	Thermal Analysis Simulation
TRNSYS	Transient System Simulation Tool
UK	United Kingdom
UFA	Usable Floor Area

UN	United Nations
USA	United States of America
V2G	Vehicle-to-Grid
V2B	Vehicle-to-Building
WW II	World War Two
ZEB	Zero Energy Building
ZEH	Zero Energy House

Case study

BASE_C	Base case
BC_NBH	Base case neighbourhood with BASE_CNBH and BASE_CNBH3
BASE_CNBH	200m ² ZEH occupied by 2 users
BASE_CNBH3	200m ² ZEH occupied by 3 users
BEST_C	Best case scenario
BEST_C3	Best case scenario for 3 users
DBOE	Scenario where building operational energy demand for the base case is reduced by 20%
HS-3	Household size is modified from 2 users to 3 users.
HS-5	Household size is modified from 3 users to 5 users.
IBOE	Scenario where building operational energy demand for the base case is increased by 20%
PRM_EFeI+GHGF	Evolution of the primary energy and greenhouse gas conversion factors for electricity
STD_H	Standard house
STD_H2010PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2010 for STD_H
STD_H2015PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2015 for STD_H

STD_H2020PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2020 for STD_H
STD_H2025PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2025 for STD_H
STD_H2030PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2030 for STD_H
STD_H2035PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2035 for STD_H
STD_RH+STD_TRCH	Alternative neighbourhood scenario with STD_RH and STD_TRCH
STD_RH	Scenario where 50% of alternative neighbourhood is replaced by a group of row houses
STD_TRCH	Scenario where 50% of alternative neighbourhood is replaced by a group of double storey houses
STD_RHSV+STD_TRCHSV	Scenario where alternative neighbourhood house are shrunk (34.2%)
STD_RHSV5+STD_TRCHSV5	Scenario where shrunk alternative neighbourhood household sizes are increased to 5 users
STD_RHSV_EV-I+TRCHSV_EV-I	Scenario where shrunk alternative neighbourhood users switch to 100% electric vehicles
STD_RHSV_PT-Tr+TRCHSV_PT-Tr	Scenario where shrunk alternative neighbourhood users switch to public electric transport
STD_RHSV2010PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2010 for STD_RHSV

STD_RHSV2015PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2015 for STD_RHSV
STD_RHSV2020PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2020 for STD_RHSV
STD_RHSV2025PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2025 for STD_RHSV
STD_RHSV2030PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2030 for STD_RHSV
STD_RHSV2035PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2035 for STD_RHSV
STD_TRCHSV2010PRM_EF+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2010 for STD_TRCHSV
STD_TRCHSV2015PRM_EF+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2015 for STD_TRCHSV
STD_TRCHSV2020PRM_EF+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2020 for STD_TRCHSV
STD_TRCHSV2025PRM_EF+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2025 for STD_TRCHSV
STD_TRCHSV2030PRM_EF+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2030 for STD_TRCHSV

STD_TRCHSV2035PRM_EF+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2035 for STD_TRCHSV
ZEH_2010PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2010 for BASE_C
ZEH_2015PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2015 for BASE_C
ZEH_2020PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2020 for BASE_C
ZEH_2025PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2025 for BASE_C
ZEH_2030PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2030 for BASE_C
ZEH_2035PRM_EFeI+GHGF	Evolution of primary energy and greenhouse gas emission conversion factors for electricity in 2035for BASE_C

Equation variables

Equation variables are not included in this section. They are defined after each equation in the thesis. Note that such equations are generic in nature, but the building life cycle energy equations derived for this thesis are based on the original equations developed in Stephan (2013).

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Chapter 1 | Introduction

1.1 Problem statement

Scouring human prehistory for evidence of sudden earth and sea changes, climate researchers have frequently suggested that human activities have the potential to destabilize the planet's environmental balance. Indeed, modern day increasing global temperatures, wildfires, famine and mega-droughts are no longer anomalies. They are likely visible products of climate change and more can be anticipated. Emitting greenhouse gases into the atmosphere is often identified to be one of the major impelling causes of climate change (IPCC 2014). More significantly, carbon dioxide (CO₂) is an important heat-trapping greenhouse gas, which is released through human activities including energy generation. Currently, ~80% of global energy production is generated from fossil fuels; this comprises oil (31.1%), coal (28.9%) and natural gas (21.4%) (IEA 2015). Nuclear contributes (4.8%), hydro (2.4%), biofuels and waste (10.2%), while other renewables such as geothermal, solar and wind amongst others, contribute 1.2% of the total generation (IEA 2015).

Given that global energy demand is projected to increase 56% by 2040 (International Energy Outlook 2016), the significant challenges ahead in transitioning to a low carbon energy future cannot be ignored. Generally, in most developed countries, energy consumed in the building sector accounts for 40% of the final energy use and approximately one third of greenhouse gas emissions (IEA 2010). Consequently, over recent decades, many countries and regions have adopted minimum building energy performance standards to address energy use and greenhouse gas emissions. To date, these approaches have primarily focused on improving building energy efficiency, typically targeting heating and cooling energy requirements during building operation (Lee and Yik 2004; Míguez et al., 2006).

Falling broadly under the banner of energy efficiency, the International Energy Agency's (IEA) joint Solar Heating and Cooling (SHC) Task 40 and Energy in

Buildings and Communities Programme (ECBCS) Annex 52: “Towards Net Zero Solar Buildings” has set the pace for being in the vanguard of CO₂ emission legislation in the building sector through standardisation of zero energy building frameworks globally (IEA-SHC programme 2011). Zero energy buildings strive to minimize net CO₂ emissions by substantially reducing energy demand through efficiency gains and promoting local energy production from renewable energy (RE) systems (Marszal and Heiselberg 2011; Sartori et al., 2012; Cole and Fedoruk 2014). An example of a prevailing construction practice conforming to such norms is the recast of the Energy Performance of Buildings Directive (EPBD), which requires all new buildings in EU member states to be at a nearly zero energy level by the year 2020 (European Commission 2009). This trend towards adopting zero energy building practices and policies is also manifest across many regions in the world today, for example; North America, Australia and Asia Pacific (Kapsalaki and Leal 2011; Panagiotidou and Fuller 2013; Moore et al., 2014). The term "zero energy building" (ZEB) is used in this thesis to cover a wide range of definitions of possible approaches in practice, as set out by Torcellini et al. (2006). These detailed definitions are discussed in Chapter 3.

However, such zero energy building practices, which fundamentally focus on building energy efficiency and local energy generation pay less attention to demand issues and often fail to take a holistic approach. In a way, limiting the focus towards building operational energy, the so-called “embodied energy”: the total energy required for the extraction, processing manufacture and maintenance of building materials and components is often overlooked. Ideally, the closer energy efficient buildings come to achieving zero energy during the operation phase, the more important the proportion of embodied energy associated with building materials and RE systems becomes. In addition, some of the materials used are themselves highly energy intensive to produce and often have short replacement cycles during the building operation phase. This likely results in higher overall energy demand such that the zero energy level might be difficult to achieve, contrary to the main goal of promoting zero energy building notions or policies (Hernandez and Kenny

2010; Leckner and Zmeureanu 2011; Rovers 2015; Balouktsi and Lützkendorf 2016).

With that in mind, the zero energy building concept itself is arguably an oxymoron of sorts since it focuses on energy requirements at the building scale whilst overlooking other demands associated with the building users' mobility at the city scale, i.e. transport energy (Bourrelle et al., 2013; Marique and Reiter 2014; Rovers 2015; Pan and Ning 2014; Kylili and Fokaids 2015; Hui 2015). In fact, multiple studies from different cities around the world have frequently demonstrated that user transport energy can be higher than both building operational and embodied energy combined (see for example Norman et al., 2006; Ramaswami et al., 2008; Heinonen and Junnila (2011a, 2011b); Fuller and Crawford 2011; Stephan et al., 2011; Marique and Reiter 2012; Stephan 2013; Stephan et al., 2012, Stephan et al., (2013a, 2013b); Marique and Reiter 2014). A zero energy house located in the suburban neighbourhoods might use more energy and subsequently emit much more CO₂ because the zero operational energy achieved could be offset by higher user transport energy requirements. The absence of an inter-scale level (considering aspects of both the building and its location) zero energy building approach calls into question the ability to achieve environmental objectives.

With prevailing zero energy building policies and an increasing interest in zero energy neighbourhoods (Wheeler and Segar 2013; Glaiser and Stroeve 2014; Marique and Reiter 2014), it is very likely that the focus at the building scale alone fails to capture necessary energy requirements associated with zero energy buildings and their users. Consequently, it is urgent and crucial to design and evaluate zero energy residential buildings based on different scales of the built environment.

1.2 Research aim

The aim of this research is to develop and establish the feasibility of an integrated design and evaluation framework for zero energy residential buildings and their users encompassing both the building and city scales.

1.3 Scope of research

The residential building sector is the largest contributor of environmental impact in the built environment due to its energy intensive nature arising from multiple dimensions including building operation, traveling activities of residents, manufacture and supply of building materials, construction of buildings and other related infrastructure. (United Nations Human Settlement Programme 2009).

For instance, in the U.S.A, 22% of energy consumed and 21% of greenhouse gas emissions produced in 2013 came from the residential sector (U.S Energy Information Administration 2013). Similarly, in 2014, the residential sector in the United Kingdom consumed 38.2 million tonnes of oil equivalent (Mtoe), representing 15% of the total greenhouse gas emissions (ECUK 2015). In New Zealand, electricity consumption in the residential sector was ~33% higher than the commercial sector in 2013 (Batstone and Reeve 2014). These figures show that in many countries the residential sector is one of the major energy intensive sectors (Perez-Lombard et al., 2008). Consequently, this research focuses on zero energy residential buildings, their users and related greenhouse gas emissions.

Historically, the notions of zero energy have been applied to the building's operational energy budget. However, the priority of achieving zero energy compliance can be further expanded to other related environmental dimensions such as food, waste generation, water and so on (Vale and Vale 1975; Bazilian et al., 2011; Scott et al., 2011; Joustra and Yeh 2014). In a pragmatic sense, the greatest environmental impact resulting from buildings is closely linked to energy use nonetheless (Junnila 2004).

To demonstrate the potential of the developed integrated multi-scale zero energy building framework, this research uses a case study located in Auckland, New Zealand. New Zealand is an island country in the Southern western Pacific under a temperate climate with a relatively small population residing in major cities. While other independent energy efficiency rating tools such as Homestar™ exist, building energy efficiency schemes for new residential buildings in New Zealand are

regulated by Clause H1 of the Building Code (Department of Building and Housing 2006).

In parallel, successive governments in New Zealand have to some extent taken a *laissez-faire* position towards questioning urban form development within the country's major cities (Harris 2007; Clover 2013). Consequently, the declining role of public transportation has become apparent. The city of Auckland is one of the most private vehicle dependent cities in the world (Mees and Dodson 2007; Howden-Chapman et al., 2010). While Wellington city enjoys a higher use of public transportation, the city itself is still very dependent on private vehicles and is at par internationally with cities that have high private vehicle transport energy demand and low density (Newman and Kenworthy 2006).

In this research, New Zealand is selected as a representative of a developed economy with unique climate, transportation systems, construction paradigms, life styles and so on.

1.4 Significance

This thesis draws together research, practice and policy oriented issues of contemporary importance. Climate change, buildings, and energy policies are being developed at a rapid rate globally, yet there appears to be little understanding of the implications of multiple aspects indirectly linked to the users in the built environment, on the efficacy of such policies. This thesis, which tackles zero energy building notions at different scales of complexity will impart valuable insights and significantly improve the current understanding and offer policy makers, researchers, architects, engineers and urban planners timely inputs that will assist in the development of more integrated policies, design strategies and approaches. In particular:

- This research is amongst the first known to the author that comprehensively tests the wider societal implications surrounding the current deployment of zero energy buildings. It therefore represents significant advancement of knowledge in terms of the approach adopted

to clarify and explore the links between zero energy buildings and their users, the integrated framework, building design and policy implications that may lay the necessary foundations upon which to build future research in this field.

- The multi-scale zero energy building framework proposed in this research significantly contributes to the existing literature on zero energy building practices by integrating methods from various academic disciplines, in order to capture various dimensions of the complexity. In contrast, existing literature in this field is narrowly defined and focused at the building scale. The multi-scale framework may be very useful for evaluating the implications of zero energy building deployment in different regions that are similarly reforming their buildings and energy policies. The framework may also be significant for capturing the important links between other infrastructure industries within the built environment such as food, water and others.
- Testing zero energy building practices at different scales of complexity through the framework enables the quantification of not only the direct energy related to the buildings and their users but also the indirect energy aspects at the city scale: user transportation energy. The inclusion of these indirect energy flows is very critical since most understood zero energy building applications recently comprise single-family detached houses which are often located in the suburbs, where the occupants have a huge reliance on private vehicles. Consequently, by testing this situation in the manner proposed in this research proffers novel insights into the interconnectedness of this relationship. In contrast, the existing quantification approaches tend to focus at the building scale and therefore are not suitable for identifying the potential trade-offs between the building and city scales in order to realistically move towards a low energy society.
- The research puts forward recommendations that may benefit researchers, policy makers, architects, engineers, urban planners, international

organizations such as the International Energy Agency and government institutions involved with the development and implementation of zero energy-emission building practices and policies.

1.5 Structure

This thesis comprises eight chapters, which are structured in the manner presented below:

Chapter 1: Introduction: begins by stating the problem, states the major aim of the thesis as well as the scope of research, its significance and finally provides the structure of how the thesis is organised.

Chapter 2: Interconnections between energy, buildings and users: reviews the concepts of energy and buildings with explicit specific links to building users underpinning their intersection. Through historical background, the purpose of the review is to explore how the nature of this relationship led to the current quest for low and zero energy building concepts. The interplay between energy and users in the context of zero energy building notions is emphasized. With this background, the chapter also highlights the current state of play for zero energy building practices and policies in order to determine the reasons for doing them and how they are currently being designed and evaluated.

Chapter 3: Current application of zero energy building concepts: reviews the current mainstream approaches for designing and evaluating zero energy buildings. The recently developed existing zero energy building design and evaluation framework is thus presented. Aspects of the framework are given with particular focus on the zero energy building balancing techniques. Main energy demands including building operation and embodied as well as user transport energy (operation and embodied) are presented and their quantification methods are briefly discussed. Examples of existing research addressing zero energy buildings at multiple system boundaries are presented and the limitations of the

current approaches are identified. The lack of a more holistic zero energy building framework which integrates energy use at multiple scales of complexity in the built environment in the context of residential buildings is observed. The research questions are presented at the end of the chapter.

Chapter 4: An integrated multi-scale zero energy building framework for residential buildings:

introduces the proposed framework and describes the relevant procedure involved in the development. It begins by setting the boundaries within the context of the research and the reasons for selection. At inter-scale level, main energy demands considered are described and various quantification techniques for energy and greenhouses gas emissions are also reviewed. In addition, the most appropriate approaches are adopted in the thesis. Thereafter, relevant computer programs and related equations used for its application are also described and generated respectively. Additional quantification aspects of different steps involved in integrating the disparate energy use parts are further provided. The underlying assumptions and necessary simplification approaches undertaken are also identified. Finally, the limitations of the approach are highlighted as well as the verification of the integration approach.

Chapter 5: Elaboration of case study testing the capacity of the framework: describes the case study used to illustrate the potential of the developed methodological framework. The relevance of choice for the case study is also given in this chapter.

Chapter 6: Case study results: presents the case study findings and provides the foundations necessary for discussions in Chapter 7.

Chapter 7: Discussion: presents the interpretation of the application of the framework. The limitations of the framework are provided and

potential development of the framework is further suggested and implications discussed.

Chapter 8: Conclusion: draws the main conclusions from this research. The purpose of this chapter is to synthesise the findings from the previous chapters, in order to suggest inputs for development of more integrated zero energy building policies. Finally, areas of future research are proposed.

Chapter 2 | Interconnections between energy, buildings and users

Around the cradles of civilization, the transition of *Homo sapiens* from hunter-gatherers to urbanites initiated the advent of modern cities which adopted interconnected energy systems (Rutter and Keirstead 2012). Buildings, as components of cities, depend on a wide spectrum of energy systems to deliver services such as heating, cooling, lighting, communication, mobility of the users and so on. In 2009, looking at the city scale, built environment-related energy demand for buildings and mobility accounted for 62% of global final energy consumption (Anderson et al., 2015). In this sense, the summation of all human-made structures, infrastructure as well as mobility systems, implies vast amounts of direct and indirect energy demand at the city scale (Perez-Lombard et al., 2008; Howard et al., 2012 ; Stephan 2013; Stephan et al., 2013b). With this in mind, various concepts interconnecting energy, buildings and their users at multiple scales of the built environment exist today.

The purpose of this chapter is to elaborate and define the principles and terminology used in this thesis. The concepts of energy, buildings, and users are first defined followed by a brief historical background of the advent of zero energy building approaches. Finally, a description of some of the interconnections and interplay between energy and users in the context of zero energy building concepts is provided.

2.1 Definitions and concepts

2.1.1 Energy

Today, the term energy is used to describe fundamental phenomena beyond discipline-specific boundaries including physics, chemistry, biology, engineering, and so on. Nonetheless, the critical question still remains: what is energy?

Tracing back the etymological series of events from which the term energy evolved paints rather a perplexing picture. Originally, the term did not refer to any issues

relating to physical theories but rather to qualities of persons, languages, expressions etc. (Boyle et al., 2003). For instance, Aristotle used the term '*energia*' to denote a species of metaphor which evoked an imaginary picture of something acting or moving. Following in the footsteps of Aristotle, Roman writers took up the term in a more loose sense to refer to the force or vigour of verbal expression. Eventually, an English physicist, Thomas Young further adopted the term 'energy' into physical theory by 1807, borrowing from ancient Greek, 'energy' combined '*en*', meaning 'in', with '*ergon*', meaning, '*work*'. Literally translated from Greek, energy means '*in work*'. Consequently, the simplest 21st century definition of energy is considered as: "*the ability of matter or radiation to do work because of its motion, its mass, or its electric charge, etc...*" (Hornby et al., 2011). Although this is hardly a profound definition, it could therefore be taken as the potential of doing work that involves the movement of a body possessing a certain mass or charge.

Drafted from the board of theoretical physics, the laws of thermodynamics became the essence of modern science. The first law of thermodynamics (a version of conservation of energy) states that the total energy of an isolated system is constant, hence, energy cannot be created or destroyed but can only be transformed from one form to another. In addition, the second law of thermodynamics governs the conditions under which energy can alter its form. Ultimately, the rate at which energy is altered from one form to another such as motion or heat can be referred to as power. Power is therefore crucial for a certain quantity of energy to be dispatched and is generally expressed in Watts (W). The interplay between energy and power in mathematical terms is formally expressed as Kilo-Watt-hours (kWh) or Joules (J). Energy can therefore be considered as a crucial quantity integral to power derived from the utilization of physical or chemical resources to provide services such as lighting, heating or to move machines. Consequently, while in reality it can be argued that energy transforms from one form to another, in this thesis, however, it is judged suitable to assume that energy can actually be used to produce a certain service attributed to different scales of the built environment. For example, material manufacturing, space heating and cooling, operating

appliances or private vehicle-related propulsion for mobility purposes (Stephan 2013).

2.1.1.1 Energy use as a proxy for environmental impacts

Environmental concerns related to high energy use across urbanising cities form a classic global agenda (Jenks et al., 2000). Consequently, amongst other spheres of measureable quantities present today, such as toxicity, water consumption, waste generation, food production amongst others, energy is chosen as a de-facto measure of environmental impact in this work. In a practical sense, somewhere along all energy chains, beginning from resource extraction to the provision of energy services at whatever scale of the built environment, pollutants are produced or emitted, often with severe health and adverse environmental impacts (IEA 2011). In other terms, there is no energy production or conversion technology without risk or without waste. In fact, the majority of energy supply and use, based, as it is, on limited fossil fuels, is responsible for the release of vast amounts of greenhouse gas emissions in the atmosphere which are subsequently linked to the global climate change phenomena as discussed in Section 1.1 (IPCC 2014).

In addition, globally, in 2009, 55% of greenhouse gas emissions were attributed to the conversion and use of energy in the built environment especially in the buildings and transportation sectors (IEA 2011). This is projected to increase by between 20% to 44% from 2009 to 2035 for climate mitigation and business-as-usual scenarios respectively (IEA 2011). Certainly, it can be argued that high energy use in the built environment implies depletion of fossil fuels which are chiefly responsible for urban air pollution, regional acidification and most importantly the risk of human-induced global climate change. Additionally, it can further be argued that energy is a universal fundamental quantity which is directly linked to greenhouse gas emissions and other environmental impacts and therefore qualifies as a good metric. See for example; Junnila (2004).

For all the reasons given above, energy is judged suitable in this thesis to be considered as a good measure of environmental impact associated with buildings. Other related metrics such as toxicity, water, waste, food etc. can also be used to

comprehensively inform environmentally conscious built environment processes. However since these aspects fall beyond the scope of this thesis, their exclusion is judged appropriate and does not dilute the quality of this work. Consideration of these aspects within the context of this work is detailed in Section 7.3.2.

2.1.1.2 *Energy definitions*

Multiple terminologies are used when describing energy use. Therefore, it is a key requirement to address the various definitions relevant to this thesis. In particular:

- *Primary energy*: the amount of energy put into a supply system, as opposed to the ‘useful energy’ that the supply system outputs to consumers including building users. For instance, the coal fed to a coal power plant is considered primary energy, while the electricity that exits the power plant is considered as secondary energy.
- *Secondary energy (also called delivered energy)*: the amount of energy delivered to the building (electricity), without taking into account the efficiency of the end use system being serviced.
- *Final energy (also called useful energy)*: the amount of energy which achieves the functions required in a building for lighting, heating etc. in the form of fuel or electricity. In other terms, losses during production (at primary energy level) and distribution (at secondary energy level) are included, as is the efficiency of the systems that convert the delivered energy into the required services for the building users.
- *Passive and Active energy*: in the context of buildings, *passive energy* is considered as the final energy present naturally without intervention of any related mechanical systems such as natural ventilation and so on. On the other hand, *active energy* is the amount of final energy used through technical systems, such as mechanically driven space heating.

Generally, conceptual attributes affecting energy use in the context of the built environment can be distinguished as ‘embodied’ or ‘operational’ (Howard et al., 2012).

- *Operational energy*: the amount of energy consumed for sustaining the process itself. For example, running operational energy systems for space heating, lighting, burning fuel or consuming electricity for private vehicle propulsion.
- *Embodied energy*: the amount of energy consumed by all processes in the production and subsequent maintenance of components. For example, extraction and manufacturing of materials related to buildings and associated infrastructure as well as the production of transportation modes.

One aspect which has to be borne in mind is that all these energy types are different by definition. Therefore in order to specifically classify the various building energy demands used per service, a clear qualification ought to be adopted. With this regard, it is increasingly acknowledged in the literature that the *primary energy* metric is arguably the best indicator since it comprises an energy form found in nature and that which has not been subjected to any conversion or transformation process (Sartori and Hestnes 2007 ; Gustavsson and Joelsson 2010 ; Dadoo et al., 2011 ; Santos et al., 2013). Clearly, it is due to such unanimous agreements in the literature that *primary energy* is chosen as the metric used in this thesis.

On the other hand, the conversion of final-delivered to primary energy implies a panoply of factors associated with the primary energy multiplication coefficients. For instance, the conversion of energy into delivered from primary energy takes into account all losses apparent within the grid infrastructure itself (distribution losses mainly due to resistance in electrical cables) as well as the power plant, where “Carnot’s Efficiency Law” comes into play and so on (Stephan 2013):. Consequently, primary energy coefficients for the electricity supply in the majority of countries are generally high. For example, UK uses 2.9, while France and Germany use 2.5 and 2.6 respectively (Molenbroek et al., 2011). In addition, regions in Australia such as Victoria use a value as high as 3.4 due to the almost total reliance on brown coal for electricity (Stephan 2013; Stephan et al., 2013b). However, regions with a high share of renewables in the electricity grid such as New Zealand use a lower figure of 1.5 (Alcorn 2010).

2.1.2 Buildings

As evidenced from the above, evaluation of energy types and systems linked to the built environment is a complex task, so it is equally crucial to define the energy boundaries.

A building can be defined as an enclosed structure intended for human occupancy which constitutes the structure itself and non-structural components such as roofing, cladding, interior walls, ceilings, HVAC and electrical systems etc. Likewise, this definition has a concrete focus pertinent to the actual form of the building as a collection of structures and elements encapsulating a wide range of human activities. In a pragmatic sense, however, the definition of a building can actually go beyond structural compositions and elements (de Botton 2006). For instance, an architectural sociologist can define a building based on a repertoire of abstract narratives and symbolic bonds between the built structure itself and the user. This could be in the form of aesthetic fondness, a sense of accomplishment and the feeling of ‘the good life’ (de Botton, 2006). At the same time, urban designers could define a building as a mere aspect of land-use characteristics associated with the wider urban fabric (Rickwood et al., 2008).

Essentially, buildings are introduced in the built environment for numerous reasons. For instance, to provide shelter, places of celebrations, work, worshipping, amongst others. Consequently, the process of ascribing the purpose of buildings has a strong lineage related to the way in which the design of the building is informed by its function and the demands of climate relative to the requirements for thermal comfort, ventilation, materials, systems and other factors (Coch 1998; Szokolay 2008; Amusaed 2011; Olgyay et al., 2015). As such, given this reflectivity surrounding how buildings can be described, it is apparent that buildings undergo certain stages during their service lifespan (Crawford 2011). Figure 2.1 below presents various life cycle stages commonly associated with buildings: design/construction/build stage, use stage, refurbish and the demolition stages.

Figure 2.1: Stages of a building's life cycle

As a general rule, the use stage usually lasts longer than other stages and is often associated with the largest portion of lifetime energy demand (Junnila et al., 2006, Ramesh et al., 2010; Sharma et al., 2011; Crawford 2011).

With this pinpointed, a building in this thesis is therefore considered as a composition of structure and components characterized by various materials, relying on dedicated systems which provide energy services to the user, e.g. heating, lighting and others. In addition, at the wider scale of the built environment (suburban or city context), a building in this thesis is also regarded as part of a function that regulates fundamental services linking the building and the city such as communication and provision of mobility to its users.

As one of the mainstays of defining buildings, it is also crucial to distinguish building types per specified function. Buildings can be characterised based on two categories: residential buildings and non-residential buildings. The former category comprises separate houses, flats/apartments, other mobile dwellings etc. The latter, on the other hand, comprises buildings such as offices, motor vehicle sales, retail, theatres, health centres, liquor outlets/taverns, service stations, tourist-type attraction buildings and so on. It is worth recalling that this thesis focuses on the category of residential buildings as was previously declared (see Section 1.3). For

this reason, Table 2.1 below presents numbers and proportions of occupied residential buildings by unit types in the United States of America, Australia and New Zealand. Comparison of these countries is actually valid since they all have one city feature in common: low density urban configurations.

Table 2.1: Numbers and proportions of occupied residential building types in the U.S.A, Australia and New Zealand

Location	Dwelling type	Number of units	Percentage of total (%)
United States of America*	Separate house	79,700,000	71.7%
	Apartments	24,500,000	22.1%
	Other dwellings [†]	6,800,000	6.2%
	Total	111,100,000	100%
Australia**	Separate house	6131376	85.8%
	Apartments	932869	13.1%
	Other dwellings [†]	79851	1.1%
	Total	7144096	100%
New Zealand***	Separate house	1,193,358	76%
	Apartments	266,748	17%
	Other dwellings [†]	11,058,9	7%
	Total	1,570695	100%

[†]Consists of mobile and improvised dwellings, roofless or rough sleepers, and dwellings in a motor camp, batches, cribs, other holiday homes, adjoined to or part of a business or shop.

Source: *EIA (2009), **ABS (2006) as cited in Stephan (2013) and ***Statistics New Zealand (2013)

As can be observed in Table 2.1 above, separate houses are the dominant form in many countries, accounting for 71.7% of total residential buildings in U.S.A, 85.8% in Australia and 76% in New Zealand compared to apartments, which only account for 22.1%, 13.1% and 17% respectively. However, different housing types have different environmental consequences (Fuller and Crawford 2011). Usually, the overriding message from this assertion is that residential buildings located in denser urban configurations such as apartments are commonly thought to be associated with lower greenhouse gas emissions (a proxy for energy use) than separate houses in peripheral suburban neighbourhoods (Glaeser and Kahn 2010 ; Minx et al., 2013; Weidenhofer et al., 2013). Nevertheless, recent studies have also

demonstrated that massive suburbanization in a large metropolis can cancel out any reductions in emissions achieved in the urban core (Jones and Kammen 2013). Consequently, the complex interconnections of energy systems in urban environments do not only depend on the typology of residential buildings, but also on the socio-demographic characteristics of building users (Stead et al., 2000; van de Coevering and Schwanen 2006; Minx et al., 2013). This entails that, amidst the interplay between energy and buildings, it is therefore crucial to also take into account other important key players: the users.

2.1.3 Users

Users can be defined as people/persons who reside in or are present in a building at a given time. In this way, different buildings tend to have occupancy patterns that vary widely (Steemers and Yun 2009). This wide variation in building occupancy coupled with the users' social-economic aspects and behaviour are chiefly responsible for the way energy is consumed in relation to the building (Gram-Hanssen 2010; Zheng et al., 2014). For instance, Chen et al. (2013) found that socio-economic and lifestyles aspects attributed to users can account for nearly 30% variation of heating and cooling demand of buildings.

It can be argued therefore that energy demand associated with buildings is strongly connected with the users' socio-economic aspects and dimensions of behaviour, i.e. their mind, feelings, needs, desires of comfort etc. Furthermore, energy related to the building is consumed in order to cater for the users' needs such as visual comfort, thermal comfort, operating appliances and so on (Yun and Steemers 2011; Chen et al., 2013). Consequently, the building mirrors the people who live in it on many levels, including physiological, material, cultural and so on. Beyond the building scale, users also tend to exploit the benefits of energy by acquiring mobility services at the urban/city scale (Rickwood et al., 2008; Marique and Reiter 2012; Stephan 2013; Stephan et al., 2013b; Anderson et al., 2015). Certainly, building-related energy consumption at different scales of the built environment is directly connected to the users' consciousness to satisfy their desire for emotionally and physically rewarding activities.

Frequently, building energy reduction policies tend to focus solely on some aspects of operational energy whilst overlooking user related energy demand such as appliances (Lee and Yik 2004; Míguez et al., 2006; Perez-Lombard et al., 2008; Stephan 2013; Stephan et al., 2012). As was pinpointed above, it can therefore be argued that more meaningful reductions can be achieved if boundaries encompass other user related energy demands such as appliances and transportation (Howard et al., 2012; Stephan 2013; Stephan et al., 2012; Anderson et al., 2015). Given this backdrop, the range of direct and indirect pressures that buildings and their users exert on the environment makes it easy to overlook the full impacts of buildings as components of the wider built environment. Arguably, such problems come into the limelight due to the methods by which environmental consequences of energy use in buildings have historically been addressed (see for example Meggers et al., 2012). It is to such discursive constructions that the following section now turns to enunciate a number of prominent historical elements of this discourse.

2.2 Historical overview

“If you would understand anything, observe its beginning and its development”-

Aristotle¹

Contemporary building principles have inherited the pragmatic models of ‘Modernism’ and methods of thinking which were developed based upon social and cultural conditions in the past century, especially between the 1940s-1960s (Meggers et al., 2012). At best, these inherited construction norms cater to a fundamental need for shelter at different scales of the built environment and the provision of certain basic services ranging from space heating/cooling, cooking, hot water, lighting, appliances and transportation. Today, such construction paradigms have extended in functionality and grown in complexity in order to meet the desires of modern day comforts (Rutter and Keirstead 2012). Ultimately, they are now considered to be the single largest contributor to global CO₂ emissions.

¹ Adapted from Abeles and Fuller (2016, p.35)

With that in mind, the Intergovernmental Panel on Climate Change (IPCC), in the Fifth Assessment Report identifies the reduction in energy consumed or embodied in buildings as one of the three measures to cost-effectively reduce building sector greenhouse gas emissions to nearly zero (IPCC 2014). Consequently, the reduction of energy use and greenhouse gas emissions to nearly zero in the building sector entails the implementation of ‘zero energy building’ practices (i.e. building methods which strive to minimize net emissions from the building stock by substantially reducing energy demand and promoting local energy production from renewables). Historically, the development of buildings which conform to such norms is closely linked to technology, e.g. high performance materials, efficient building systems etc. (Vale and Vale 2000; Marszal and Heiselberg 2011; Bourelle et al., 2010; Rovers et al., 2010). Yet the performance of technology and systems which regulate energy use in the buildings is chiefly dependent upon the users’ needs and desires for comfort (see Section 2.1.3). Certainly, energy use in buildings and the users’ characteristics are therefore inextricably connected. However, this fact is often overlooked and not always integrated into zero energy building concepts. Ideally, these challenges, although of great magnitude, ought to be unraveled, but firstly, root causes of such problems need to be identified. With this regard, a brief historical overview pertaining to the advent of zero energy building concepts is presented in the following section.

2.2.1 Designing buildings in sympathy with climate

The ultimate shift from hunter-gathering to a more settled human lifestyle resulted in the emergence of local building paradigms. At that juncture, the main ingredients interconnecting building traditions were local climate and availability of materials. In that typical fashion, vernacular architecture flourished and indigenous building techniques were adapted to local climates, hence, bioclimatism came into play. Consequently, construction paradigms capitalizing on local characteristics of sites, including passive energy designs, were in full effect. Multiple examples of these construction norms exist, from the tents of the Qashqai to the inner courtyards of the Mediterranean (Tzikopoulos et al., 2005) as cited in Stephan (2013)) and these ideas were in use in the distant past. From more than six thousand years ago,

archeological discoveries have revealed methods which permitted Chinese buildings to exploit energy from the sun on an annual basis (Perlin 2013). Later, in the book *Xianqing ou ji*², an ancient Chinese philosopher of the 17th century, Yu Li, equated a correctly built house to a person who dresses appropriately in accordance to the fluctuation of weather. He brought forth an argument contesting that: “*As it is true that clothing should be cool in summer and warm in winter, the same holds true for a house. A house must have the correct orientation. It has to face south to catch the heat and light of the winter's sun [...]*” (Perlin 2013 p.3).

In this context, the synthesis of human physiological elements, climate and how to position a building, embodies the first principles of energy performance in buildings which are applied in many construction paradigms seen today (Coch 1998; Szokolay 2008; Amusaed 2011). In fact, this notion of designing buildings in sympathy with climatic conditions still stands out as the premier research puzzle of the energy and buildings’ discourse (Olgyay et al., 2015). However, at the early stage of development, the marriage between buildings and technological systems, in the modern sense of the word, was not yet exploited. The energy use for basic services in such buildings including cooking, lighting, warmth amongst others, was mainly provided by fire, while the surplus energy required to cover for desired thermal comfort was drawn from the cohesion between design and natural elements, mainly from solar energy, wind and vegetation. Nonetheless, gradual advancement of technology around the past centuries begun to shift traditional urban built environment trends.

2.2.2 Technological fix approach

Around the 1820s, due to moral and economic grounds, the ‘abolitionist movement’ embarked on a campaign to abolish human slavery so as to trade manpower for machines. It was indeed an era of the *Industrial Revolution*. Ultimately, these social and economic transformations led to the restructuring of the built environment and the urgent need to provide urban energy services via networks of interconnected infrastructure (Malanima and Volckart 2007; Rutter and Keirstead

² Mandarin Chinese: “Xianqing ou ji”. English: “The enjoyment in leisure time”.

2012). Certainly, inventors were quick to understand the interplay between magnetism and electricity, Michael Faraday, Thomas Edison and Nikola Tesla, amongst others (Fouquet 2010), together galvanized social transitions leading to a massive surge in standards of living from squalor to splendour in buildings. Indeed, the *Industrial Revolution* led towards a new age of promise coupled with unprecedented increase in mankind's productivity, and with it, a substantial increase in income per capita. Building construction paradigms shifted and this resulted in improved qualities of built spaces. However, these novel habitats became energy intensive due to favoured increase in indoor visual and thermal comfort levels (Fouquet and Pearson 1998). This became apparent in the United Kingdom when the development of the first central heating systems using hot water and warm air penetrated the domestic market since the 1850s (Bruegmann 1978) as cited in Stephan (2013)) , Fouquet 2010).

After global peace agreements resulting from World War II, fossil fuels entered urban energy systems at high rates and energy consumption levels signaled resource depletion hazards. Consequently, warnings were given by some individuals such as M. King Hubbert (1949 p. 108) who made clear the possible effect of oil depletion on the world given its addiction to fossil fuels. The 20th century marked another massive shift in the transmission of energy and the ability to supply vast amounts of grid electric power to remote built locations (Fouquet 2010). This penetration of the electricity grid provided a consistent supply of energy to allow every household in developed economies to consume. At household level, this proffered convenience and cleanliness, user-related versatility features which enabled electricity to become a major urban energy source.

At the same time, former U.S.A. president Dwight D. Eisenhower introduced the world's largest public works project in the 1950s: *The National Systems of Interstate and Defense Highways* (Tillemann 2015). This development connected the entire U.S.A. into a massive system of highways which allowed the emergence of suburbs. Such phenomenon is believed to have had an influence to other western countries

towards unleashing a societal twist that drove many people into suburban settlements (Rutter and Keirstead 2012).

2.2.3 The warnings begin

As a major warning to the wider society, the quadrupling of oil prices in the 1970s halted the delusion of unlimited earth resources and marked a turning point in the history of energy policy globally (Stephan 2013). One result was that countries in western society gathered a scientific community to explore energy efficiency. Energy efficiency in buildings spans a long history although the topic gained much momentum when several downsides of the dominant lifestyles in developed countries became apparent. Eventually, a series of alarming reports infiltrated global environmental debates. See for example, Club of Rome's *The Limits to Growth*, Paul Ehrlich's *The Population Bomb*, etc. (Meadows 1972; Ehrlich 1971; Turner 2008). During this period of gloomy ecological predictions of Earth, former United States President John F. Kennedys' space programme came to represent a beacon of hope in that it showed how apparently impossible problems could be solved while technological solutions derived from life support systems (LSSs) and the thermal balance of spacecraft became useful applications for the design of efficient buildings and self-sufficient habitats. See, for instance, the New Alchemists, Alexander Pike etc. (Vale and Vale 1975; Vale and Vale 2000; Bourelle et al., 2010).

The desire to secure biological survival of the human species and the energy crisis led to the incorporation of ecological approaches and energy efficiency improvements in buildings thereafter. Particularly, the resurgence of bioclimaticism in combination with renewable energy applications resulted in building construction paradigms with highly insulated envelopes that had close to zero heating energy on an annual basis, e.g. the Vagn Korsgaard Zero Energy House in Denmark, the Lo-Cal House in U.S.A, the Saskatchewan Conservation House and the R-2000 program in Canada and later on project MONITOR/BUILDING 2000 in Europe (Esbensen and Korsgaard 1977; Butti and Perlin 1980; Nisson and Dutt 1985; Lewis 1996).

With these achievements in mind, reduction of energy consumption in buildings proceeded in parallel with the quest for other new methods of reducing their environmental impact. Hence, the “life cycle assessment” (originally “energy analysis” in the building context), was developed around the early 1970s (Udo de Haes and Heijungs 2007).

2.2.4 *The need of means to reduce building environmental impact*

Historically, reducing environmental impact of buildings is closely linked to the genesis of sustainable development. This notion was coined in the 1987 report *Our Common Future*, i.e. the so-called “Brundtland Report” (World Commission on Environment and Development 1987). The first United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, 1992 which adopted the *Agenda 21* became the primal catalyst of the sustainable development notion (United Nations 1992).

Theoretically this discourse follows a fundamentally different approach compared to the energy driven agenda of the 1970s. *Agenda 21* embraced sustainability from three dimensions: environment, social and economic. Consequently, the problematic complexity relative to the theory of sustainable development lies in the versatility of its definition as it involves a wide array of factors related to social and environmental sciences and many other fields. It is therefore almost impossible to discuss this notion only from one angle. Research is still being conducted to establish the common principles which will govern its overall definition among multiple disciplines and spheres (Lindsey 2011) as cited in Stephan (2013)).

Likewise, to confine discussion to the three dimensions that characterize sustainable development as defined by the ‘Brundtland Report’, the environment must be considered as equal amongst the others. Internationally, it is believed that buildings have a huge environmental impact due to the associated greenhouse gases relative to their intensive energy requirements (IPCC 2014). Consequently, the environmental dimension of sustainability evoked a sense of urgency to promote energy efficiency in buildings during the early 1990s. Ultimately, construction paradigms shifted and resulted in the use of improved and fewer materials than the

previously more demanding active zero energy designs of the 1970s, and it is claimed this made passive house techniques more suitable for large scale applications (Feist 2007). In fact, building techniques that prefigure the modern passive house design such as air tightness (1.3 air changes at 50Pa) and air-to-air heat exchangers, were first applied in the Saskatchewan Conservation House some 40 years ago (see Section 2.2.3).

Practically, the passive house standard requires compliance with certain energy ceilings: a maximum final energy use for space heating of 15 kWh/m²/annum and overall operation primary energy of 120 kWh/m²/annum. However, in specific situations such impositions can arguably encourage more consumption. For instance, on average, a typical New Zealand household consumes roughly 95kWh/m²/annum of primary energy, including a high percentage of renewable electricity generation. It can be argued therefore that promoting the passive house standard in specific New Zealand regions entails the promotion of over-consumption. In addition, expressing building energy consumption on a per meter square basis tends to favour more efficient large buildings. Yet a smaller building which is less efficient on a per metre square basis can use much less energy overall than a large efficient one (Clune et al., 2012; Stephan and Crawford 2015). The relevance of passive houses in achieving lower energy use in particular regions is yet to be unraveled.

2.2.5 Current developments

As communities attempted to further reduce environmental impact of the built environment, numerous green building codes and certification systems proliferated between the late 20th and early 21st centuries. These certifications come sometimes in the form of voluntary assessment methods and some are developed by Green Building Councils within respective countries. For example, Homestar™ in New Zealand, Greenstar in Australia, LEED in U.S.A, BREEAM in the U.K, CASBEE in Japan, etc. All these certifications tackle a range of sustainability aspects related to buildings. Nonetheless, they tend to be limited to qualitative analyses and express results based on scores (Perez-Lombard et al., 2009; Stephan 2013). In

addition, it has also been frequently argued in the literature that some of these certifications are dubious and often do not guarantee energy savings. Especially LEED, which is often found to provide worryingly high variability in performance results (Nesham et al, 2009; Scofield, 2009; Suh et al., 2014). Mystery regarding the relevance of such tools still surrounds them and therefore their capacity remains to be tested (Lee 2012; 2013 ; Stephan 2013).

In parallel, the aftermath of *Hurricane Katrina* in 2005 further sensitized public opinion about the adverse effects of climate change and evoked the sense of urgency required to mobilize the international attention needed. This trend ran in harmony with the central theme of former United States vice president Al Gore's 2006 documentary film *An Inconvenient Truth* (Gore 2006), which reenergized the "environmental movement" and helped to raise global awareness about climate change. Within the realms of such developments, supplementary standards encompassing those stipulated in most national building regulations across North America and Europe flourished (Perez-Lombard et al., 2008). For instance, zero carbon homes in the United Kingdom and low energy houses in other parts of Europe (Germany, Sweden, and Netherlands) and North America (see Table 2.2 overleaf).

Table 2.2: Supplementary building energy standards in Europe and North America

Standard	Definition	Driver
Zero carbon homes	Will produce net zero emissions of CO ₂ from energy use during operations	Generate more or less energy, Reduce CO ₂ emissions
Low energy houses	Will consume less energy stipulated in the building code	Reduce energy, Reduce CO ₂ emissions, Generate energy

Source: Based on Williams (2012)

On the other hand, politicians and policy makers used climate concerns and policies promoting the diffusion of renewable energy technologies as means to promote their 'green' credentials, which were high in the public agenda after the

financial crisis of 2007-2008 (Orsato et al., 2012). Certainly, renewable energy applications and efficiency in buildings were widely advocated as the icon for leading towards zero energy buildings (Marszal et al., 2011). Zero energy buildings implies buildings with greatly reduced energy demand through efficiency measures, such that the residual energy demand can be covered by renewable energy on-site or off-site, (see discussion in Section 3.1.2). Hence, more stringent regulations that will accelerate the adoption of zero energy building concepts have emerged. For instance, the European Parliament voted on 23rd April 2009 that, for new residential buildings, all member states should require they achieve zero energy use by 31st December 2018 (European Commission 2009). Similar regulations have also come into effect in the U.S.A and also in Japan as shown in the timeline in Figure 2.2 below.

Figure 2.2: Countries planning to make zero energy building concepts mandatory-timeline

Source: Based on Pike Research (2012)

In 2012, a new wave of thinking and a method emerged for establishing zero energy building balance solutions. This method is known as the zero energy building (ZEB) framework and is described in Section 3.1.3. Although the work of the International Energy Agency has provided a certain degree of clarity (IEA-SHC programme 2011; Sartori et al., 2012) regarding the application of the ZEB concept, this promising method most often focuses solely at the building scale whilst incorporating operational energy aspects only.

2.3 The interplay between energy and users in the context of zero energy building concepts

The descriptions of energy, buildings and users have demonstrated the complexity associated with their interconnections in the built environment (see Section 2.1). It can be argued that users ought to be considered as a key component in the context of zero energy building concepts. Moreover, research following the evolution of buildings which conform to these concepts throughout the years has demonstrated that social expectations and consumption patterns of their users can distort the most clever innovations (Keesee 2005; Stevenson and Rijal 2010 ; Bourelle 2014 ; Berry et al., 2014).

It can be further argued that zero energy building principles can be applied at multiple scales of complexity. In particular, buildings in the built environment can be scrutinized on two different scales; building scale: materials and systems required for construction of architectural space for operation including building shape /compactness, envelope, shading, glazing, integration of renewable systems amongst others and city/urban scale: the interplay between urban form, transportation. These aspects include; the amount of energy which building users consume when traveling around the built environment and other infrastructure (Stephan et al., 2012; Stephan 2013; Howard et al., 2012; Anderson et al., 2015).

In order to comprehensively apply zero energy building concepts, building scale, city scale and user parameters need to be collectively considered. In that way, zero energy building practices can capture the energy service inflows and outflows

associated with the buildings in the context of the user demand of energy services at multiple scales of the built environment.

2.4 Conclusion

This chapter has enunciated particular conceptual dimensions regarding energy, buildings and users. Energy use in buildings is dependent upon a wide spectrum of factors at different scales of complexity. These factors involve interconnected multiple avenues ranging from architectural design, materials, operational systems, urban form, transportation, and user behavior and consumption patterns. In this sense, solving the riddle of how multiple energy domains are interconnected with buildings in the wider built environment could proffer a much bigger payoff. Ultimately, one fundamental question that can be posed relative to the current developments (see Section 2.2.5) is: how are these complex interconnections being addressed in the context of current application of zero energy building concepts today? In particular:

- What tools and methods are being used?
- What are their limits?
- Have previous studies attempted to apply zero energy building principles integrating both the building and city scales?

The work described in the following chapter answers these questions by providing a review of current theories and practices of zero energy building concepts. The limitations of current approaches are highlighted and research questions are posed at the end of the chapter.

Chapter 3 | Current application of zero energy building concepts

As previously discussed in Section 2.2.2, during the trend of massive suburbanization after World War II, consumers did not just acquire spacious single-family detached houses, furniture, kitchens equipped with machines and gardens with lawnmowers, they also acquired private vehicles to complement this lifestyle (Geels et al., 2012). In the suburbs, life is by necessity private-vehicle-centric owing to lack of public transport in these dispersed areas (Jenks et al., 2000; Newman and Kenworthy 2006). The climax of private vehicles as a societal icon is perhaps evidenced by the surge in popularity of ‘sports utility vehicles’ (SUVs), which have held a steady rise in record sales since the 1980s until recently (Wilkinson and Pickett 2009). In this fashion, the vehicle creates preconditions for its own inevitability since it is the only form of transport that permits to a large extent, numerous roles of family life, leisure and unlimited pleasure of movement (Sheller and Urry 2000; Urry 2007).

Pivotal along this thread is the convenience which the private vehicle provides as it intertwines with the users' deepest emotional resonances such as euphoria, envy, fear and frustration, up to the point that the vehicle itself becomes part and parcel of the ‘family members’ (Sheller 2003, p.17). The bondages of such comforts and vested interests acquired become significantly difficult to disintegrate in many life styles today (Geels et al., 2012). Therefore, it can be argued that user transport energy is strongly connected with building energy demand but at the wider scale of the built environment. It is very important to note, as was discussed in the previous chapter, that the success of zero energy building practices is not only a question of competent building designers and urban planners or indeed building energy modellers, but is also a question of understanding the life style of the user at multiple scales of complexity.

With this in mind, energy demand associated with buildings and their users can therefore be said to comprise the energy required to operate the building

(operational energy), the energy required for the extraction, manufacturing and supply of building materials as well as related infrastructure (embodied energy) and also the energy required to provide mobility services to building users (transport energy). All these energy demands require unique quantification methods if they are to be accounted for (Mithraratne et al., 2007; Alcorn 2010; Stephan 2013). Consequently, the purpose of this chapter is to review the current applications of zero energy building concepts with respect to these three types of energy demands.

The zero energy building concept is discussed first, followed by the zero energy building design applications and the fundamental energy demands of buildings. This is further followed by the analysis of existing studies which incorporate different energy flows within the zero energy balance achievement and finally, the limitations of the current application of the zero energy building concept are highlighted. The research questions are posed at the end of this chapter.

3.1 Zero energy building concept

3.1.1 What is the zero energy building concept?

The concept of a zero energy building (ZEB) entails one which produces as much energy as its users can consume within a given time period .i.e. monthly, annually etc. (Hernandez and Kenny 2010; Sartori et al., 2012; Marszal 2012; Athienitis and Brien 2015). A summary of the evolution of the ZEB definition can be found in Marszal et al. (2011). Throughout the past two decades, this approach has witnessed a dramatic evolution leading from research to reality (Panagiotidou and Fuller 2013). In addition, recent advances in construction technologies, renewable energy systems and rigorous academic research have also prompted the concept of a zero energy building to be increasingly feasible (Voss et al., 1996; Vale and Vale 2006; Noguchi et al., 2008; Parker 2009; Dobb 2009; Hawkes 2009; Attia 2010). Consequently, the number of buildings which meet this criterion of zero energy continues to increase (Mussal et al., 2010; Voss and Musall 2013; Grade et al., 2014). Governments and policy makers in Europe and in North America have championed the enquiry on how the development of buildings that meet this criterion could potentially benefit the entire society (Carlisle et al., 2009; IEA-SHC

programme 2011). The increasing awareness of their technical feasibility calls into question their applicability in the wider built environment today.

3.1.2 Application of the zero energy building concept

Zero energy building principles can be applied to a wide range of construction project types including residential and commercial buildings in both existing and new construction scenarios (Mussal et al., 2010). The application of zero energy building concepts to modern building practices has become possible not only through the progress made in new construction technologies and techniques, but it has also been significantly improved by academic research on conventional and experimental buildings which collected precise energy performance data across various market sectors and climate zones (Voss and Musall 2013; Grade et al., 2014).

An early application to the ZEB concept was proposed by Vale and Vale (1975) as an autonomous building with no connection to any offsite sources. However, the authors' conclusion when they built the Autonomous House in 1993 was that connecting domestic renewable systems to the electricity grid and achieving a “*net zero energy*” building can have the same or even much better life-cycle performance than a free-standing autonomous house (Vale and Vale 2000). This was due to the fact that the use of electricity storage systems was being avoided and that some flexibility in the use of appliances was being gained in the process. Ultimately, the title “*net zero energy*” makes the notion to specifically refer to the grid connected buildings only, by demonstrating that a form of energy balance is taking place with energy being both taken from and delivered to an existing energy grid. Nonetheless, stating the precise chronology of how the applications evolved from inception is difficult because such evolution probably happened in many forms. For instance, the Building Research Establishment (BRE) in 1997 published a guiding and pioneering document (written by Vale and Vale) entitled “*Building a sustainable future: homes for an autonomous community*” which reported on a design agenda for residential buildings in terms of three standards - autonomous, zero CO₂ : a building that creates no net CO₂ emission on an annual basis and obtains its heat and power

from renewable energy - and zero heating : a building which obtains all its space heating needs from its occupants and their activities (Building Research Establishment 1997). However, at the dawn of the 21st century, Torcellini et al. (2006) described such buildings with the following range of definitions:

- *Net zero site energy*: a building which produces as much energy as it uses in a year when accounted for at the site.
- *Net zero source energy*: a building which produces at least as much energy as it uses in a year, when accounted for at the source.
- *Net zero energy costs*: the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.
- *Net zero energy emissions*: a building which produces at least as much emissions-free renewable energy as it uses from emissions producing energy sources.

In 2008, the IEA established a joint ZEB research taskforce (IEA SHC Task 40/ECBCS Annex 52) “Towards Net Zero Energy Solar Buildings” that is made up of 70 participating building scientists and architects across 18 different countries. The main objective was to develop a common ZEB understanding across its member countries (IEA-SHC programme 2011). Much effort has fundamentally been exerted towards formulating clear definitions of buildings which embody the ZEB notion and this has so far provided a certain degree of clarity and theoretical framing (Marszal and Heiselberg 2011 ; Sartori et al., 2012 ; Cole and Fedoruk 2014).

With this highlighted, however, there is still no consensus regarding a common expression which can be satisfied by all participants in the research field due to the uniqueness of project goals and construction paradigms across different regions in the world (Panagiotidou and Fuller, 2013; Deng et al., 2014). Nevertheless, the work of Sartori et al. (2012) gives rather a more concrete definition framework

which contains different elements, such as boundary systems, balancing metrics etc. These aspects are discussed within the zero energy building framework in Section 3.1.3 of this thesis.

Ideally, energy use can be measured in a variety of ways: cost, energy or greenhouse gas emissions. Generally, when measuring the zero energy balance, both carbon and energy are used as units to determine the carbon dioxide emissions in relation to the energy consumption (Marszal and Heiselberg 2011; Sartori et al., 2012; Deng et al., 2014). Notwithstanding, as was evidenced previously in Section 2.2.4, the ascent of global climate change prompted policy makers globally to exploit the deployment of zero energy building principles with the aim of lowering greenhouse gas emissions and revitalizing energy generation (Williams 2012 ; La Roche 2012; Roaf et al., 2013). Consequently, it can be argued that the current trend of zero energy buildings is mainly driven by the environmental pillar of sustainability as defined by the World Commission on Environment and Development as was previously discussed in Section 2.2.4. Although other researchers such as Marszal (2012); Torcellini et al., (2014) and Pan and Ning (2014) tend to explore the ZEB notion in terms of economic and social dimensions respectively, in reality, the environmental sustainability agenda grounded in current ZEB practices is linked to the interplay between two crucial aspects: energy efficiency and renewable energy.

3.1.2.1 Energy efficiency

One major issue of concern associated with the application of ZEB principles which is often overlooked relates to the conflict of interest. Indeed, as with all scientific studies today, researchers' models, methods and assumptions as basis for their calculations vary widely because they sometimes tend to favour conservative beliefs or professional interests. For instance, the rule of energy efficiency first has become almost the standard in today's zero energy building concept ignoring the user behavioral aspects. There is a consensus especially amongst top researchers in Europe and North America that a building has first to reduce the energy demands using energy efficient technologies and thereafter off-set the remaining demand

with energy generated from renewable resources. See for example: Torcellini et al. (2006); Gupta and Chandiwalla (2009); Hernandez and Kenny (2010); Marszal et al. (2011), Marszal et al. (2012); McLeod et al. (2012); Sartori et al. (2012); Athienitis and Brien (2015).

However, this widely advocated building technique has not escaped criticism. For instance, Lausten (2008) opposed this view by highlighting that, in principle; a zero energy building can be a conventional building without extreme efficiency gains which is supplied with very large solar photovoltaic and solar thermal collectors. If these systems deliver more energy over the year than the use in the building then it is a net zero energy building. Similarly, in New Zealand, Vale and Vale (2006) demonstrated that there is no obvious technical barrier to zero energy building retrofit and they further suggested that the use of optimized solar photovoltaic systems combined with non-invasive energy improvements is an alternative to achieving the zero energy balance requirements. In this case, it can therefore be argued that zero energy building requirements can be achieved irrespective of stringent energy efficiency measures being advocated today. Consequently, one could question the imperative of advocating stringent energy efficiency rules when the zero energy requirements can actually be achieved without any technical barriers such as energy efficiency improvements.

According to a report from Navigant Research, worldwide revenue from zero energy buildings is expected to grow from US \$629 million annually to more than US \$1.4 trillion in 2035 (Navigant Research 2014). It is most important to note that the main drivers of the growth are related to the technological aspects associated with energy efficiency applications of zero energy buildings such as advanced wall insulation materials, advanced glazing and smart glass components, efficient HVAC systems, energy management systems and high efficient appliances amongst others. With regard to this and the financial forecasts of such magnitude, it can be argued that there is evidence which suggests that there is a possibility of vested interests associated with researchers advocating energy efficiency calculation rules in the face of zero energy buildings. In Norway, Sartori and his colleagues

could be argued to admit this by stating that: “*The aim of the Norwegian Research Centre on Zero Emission Buildings (ZEB) is to develop competitive products and solutions of buildings with zero emissions of greenhouse gases [...]*” (Sartori et al., 2013, p.188). The focus on "competitive products" could be seen as implying that the ZEB research is in order to create new technologies that could be sold.

This also echoes the issue discussed in Section 2.2.4 that the building industry has hardly yet deployed 45 year old energy efficiency technologies from the 1970s (see Section 2.2.3). Given this, the quest for more advanced building technologies before implementing existing knowledge becomes questionable. Notwithstanding, the danger is that the long term environmental implications of the large scale penetration of zero energy buildings into the built environment has not yet been comprehensively explored (Deng et al., 2014). This further leads to the suggestion that the dynamic attributes of the ZEB concept remain to be investigated.

3.1.2.2 *Grid connection and ZEBs*

As was previously discussed, central to the ZEB concept, is the availability of a two way grid operation mechanism. The majority of existing zero energy buildings today are connected to the electric grid, thereby allowing electricity generated from conventional sources such as coal, natural gas and others to be used when the renewable energy produced on-site cannot meet the building's energy demand. Conversely, when on-site generation surpasses the building's energy demand requirements, the excess amount of energy is exported into the utility grid, where permitted by law and/or the grid operator. Ideally, the surplus energy production cancels out the periods of excess demand resulting in a net zero energy consumption pattern. The interplay between zero energy buildings and the grid revolves around independent production of renewable energy.

3.1.2.2. a *Renewable energy*

For a typical zero energy building, once energy efficiency measures have been put in place, the remaining energy requirements can be met using renewable energy systems (RES). Common on-site energy generation from RES include: solar

photovoltaics, solar water heating, wind turbines and others such as biomass (Marszal et al., 2011; Sartori et al., 2012).

As noted, the Task 40/Annex 52 examined ZEBs (Kim et al., 2015). Subtask A of this programme developed international standard ZEB definitions and notions along with monitoring and guidelines for post-occupancy verification while subtask B developed ZEB design and energy simulation tools and rules of thumb for design. In addition, subtask C tested ‘advanced building design technologies’ with the aim to provide guidelines for construction of demonstration projects as well as international collaborative projects. This exercise resulted in the formulation of a ZEB database that includes, 30 case studies of zero energy buildings categorized by country, climate, building use and renewable energy applications (see Section 3.1.2). Analysis of these 30 case studies revealed that renewable energy systems were applied in virtually all cases. Solar photovoltaic systems were the most applied and they accounted for 97% (29 cases). The solar thermal systems accounted for 63% (19 cases) while the geothermal systems accounted for 33 % (10 cases). The wind and biomass were the least applied and they accounted for less than 20%.

The dominance of solar PV systems on zero energy buildings can also be observed in numerous housing projects that were not included in the case study database (see for example Vale and Vale 2006; Noguchi et al., 2008; Parker 2009; Doub 2009; Hawkes 2009; Attia 2010; Panagiotidou and Fuller 2013). It appears that solar PV systems are the most widely applied RES in zero energy buildings today.

Evidently, it can be argued therefore that the large scale adoption of zero energy buildings entails large scale penetration of solar PV systems. This further leads to a number of issues concerning the implications of increased solar penetration within existing grids today. One particular recent example stems from the U.S.A. In 2013, the California Systems Operator (CAISO) published a chart demonstrating the potential for electricity over-generation occurring at increased rates of solar photovoltaic penetration (Denholm et al., 2015). This phenomenon is illustrated by the “Duck Chart”, where the potential for PV to provide more energy than can be used, as in the case of net zero energy buildings, can have

technical constraints on grid operated systems. In their study, the CAISO conducted a detailed simulation for each day of the year from 2012 to 2020 in order to test out changing grid conditions due to large penetration of roof-mounted solar PVs in California State, U.S.A (Barranger and Cazalet 2014). Indeed, as shown in Figure 3.1 overleaf, the projected penetration for residential solar energy (at least in California) will have a limited impact on the system peak (duck's tail) in the morning around 4:00am as occupants get up and about to embark on their daily routine. A huge impact begins around 7:00am after the sun comes out and grid imported energy is replaced by supply from solar (producing the belly of the duck).

Figure 3.1: The "Duck Chart", showing demand on California grid 2012-2020

This introduces the risk of over generation during the afternoon and increased need for grid energy imports when solar finally drops off (the arch of the duck's neck). As projected by the year 2020, the increase in net load ramp as solar drops off in the late afternoon is shown to be more than ~13,000 MW in about 3 hours on most days. This is well beyond the limits of current grid system capabilities (Barranger and Cazalet 2014). Furthermore, Duck curves are not only apparent in California, but also in Hawaii, Germany and other countries with vast amounts of solar electricity generation (Carvallo and Cooper 2015). Ultimately, it can be argued that the balance between abundance of on-site energy generation and flexibility of demand remains to be worked out. In this way, one could further argue that the

interplay between abundant on-site generation, demand flexibility and massiveness of energy storage is a function of economic realities not yet comprehensible due to limitations of the grid technologies involved. Consequently, the large scale penetration of zero energy buildings will most likely not escape these obligations or uncertainties.

On the other hand, the domination of PVs as an application on zero energy buildings is very likely to continue reigning supreme due to their lower cost. Along this thread, a recent article by Bourrelle (2014) claims that the large scale adoption of zero energy buildings can be a potential weapon against the so-called “rebound effects” (Sorrell 2009), and also a potential tool to reduce global non-renewable energy demand. Bourrelle argues that by diverting cost savings from energy efficiency improvements into capital investment in RES, zero energy buildings could effectively help to dampen rebound effects where money saved from energy efficiency is spent on other energy consuming products or activities. However, the environmental impact associated with RES such as PV systems is often overlooked in most studies that evaluate zero energy buildings today (Cellura et al., 2014; Lützkendorf et al., 2014 ; Rovers 2015).

The manufacturing of current generation crystalline silicon-based PV systems (the dominant technology in most zero energy buildings’ installations globally) is energy and emission intensive (Yue et al., 2014). Generally, PV generated electricity ranges from 50-160 gCO₂-e/kWh or averages 99 gCO₂-e/kWh for ~1,700 kWh/m²/year solar irradiance, compared to electricity generated from other renewable sources such as hydro (10-18 gCO₂-e/kWh) (Laleman et al., 2013). In parallel, a number of prominent researchers attribute the plummeting cost of solar photovoltaics to advances in material science and more efficient manufacturing processes. See for example Candelise et al. (2013) and Tyagi et al. (2013). However, as can be seen in Figure 3.2 below, since 2006-2009, the average manufacturer-sale price of solar PV modules declined by over a factor of two, coinciding with a significant shift in scale of manufacturing from Western countries to Asia, especially China which produces ~67% of the global PV modules (Renewable Energy Policy Network 2014).

Figure 3.2: Price history of silicon PV cells in US dollar per watt

Source: Batra (2016) based on Bloomberg new energy finance and PV energy trend (2015)

With this fundamental shift in manufacturing location, the drop in PV prices has less to do with more efficient manufacturing but is more due to cheaper labour, larger-scale manufacturing and the resulting supply-chain benefits in Asia, particularly China (Goodrich et al., 2013). In addition, the Chinese electricity grid is approximately twice as carbon intensive and 50% less efficient compared to grids in Europe and North America (Yue et al., 2014; Itten et al., 2014). Since manufacturing of solar PV cells uses 95% electricity (Briner 2009) this implies that in spite of plummeting solar PV prices, the shift of production of solar cells to China rather than Europe or the USA is more emissions intensive. Consequently, it can be argued that the influence of energy and greenhouse gas emission intensities of RES PV applications on zero energy buildings need to be accounted for and cannot also be ignored.

At the same time, recent studies also seem to express a certain degree of scepticism regarding low-priced PV systems. A recent report by the Lawrence Berkeley National Laboratory has established that low-priced PV systems are generally 1.2 percentage points less efficient than high priced PV systems (efficiency <17%) (Nemet et al., 2016). Arguably, this entails that the reduction of PV prices has resulted in lower system efficiencies, contrary to what has been the school of thought so far.

Nevertheless, the aim of advancing the application of zero energy building concepts is to develop solutions leading towards zero energy and zero greenhouse gas emissions related to the production, operation and demolition of buildings. These ambitious performance targets have accelerated the advent of zero energy building practices based on basically zero external energy requirements resulting from the use of renewable energy sources covering to a great extent the building loads. Consequently, by developing a standard zero energy building framework, the IEA Task 40 / Annex 52 completed the objective which spearheads the promotion of zero energy buildings specifically through the harmonized definitions and the development of tools as well as the innovative solutions and guidelines. The zero energy building framework is briefly described hereunder.

3.1.3 Zero energy building framework

3.1.3.1 Ambition level

The application of zero energy building concepts sparks off from setting the level of ambition required in order to reach specific ZEB goals (IEA-SHC programme, 2011). As current zero energy buildings are grid-connected, this regard leads to the assertion that every country or region has different challenges associated with energy infrastructure amidst other factors, e.g. construction paradigms, climatic conditions etc. Therefore, it is a primary requirement to adopt a suitable definition of what constitutes a zero energy building for specific countries and regions (Marszal et al., 2011; Sartori et al., 2012). In this way, setting the country specific parameters will reflect the exact national political targets and other specific conditions towards the quest for zero energy buildings (e.g. reducing energy demand and eliminating greenhouse gas emissions etc.).

The significance of integrating the ZEB notion into National Building Codes and International Standards is widely recognized (Marszal et al., 2011; Weißenberger et al., 2014; IEA-SHC programme 2015). Consequently, the adoption of a zero energy buildings definition for country specific implementation is presented within the IEA SHC Task40/ESBCS Annex 52 which embodies criteria for design and energy balances based on Sartori et al. (2012). Different parameters recommended to be

addressed within the ZEB framework are presented in Figure 3.3 below together with the relevant terminology.

Figure 3.3: The zero energy building framework: sketch of connection between buildings and energy grids showing relevant stages

Source: Adapted from Sartori et al. (2012)

The process of adopting a suitable definition for local operation becomes an explicit building energy design and evaluation framework which begins by establishing the building system boundary.

3.1.3.1. a Building system boundary

As can be seen from Figure 3.3, the building system boundary identifies what energy flows across the boundary, i.e. is delivered and /or exported to or from the building or a cluster of buildings. The building systems boundary is characterized by two aspects: physical boundary and balance boundary.

PHYSICAL BOUNDARY

The physical boundary is the point where the comparisons/measurements or calculations of the energy inflows and outflows of the system are carried out in order to identify the energy from renewable sources on-site or offsite. This can comprise either a single building or a cluster of buildings. As opposed to a single building, a cluster of buildings implies a group of buildings operating in a synergistic set up. As was previously discussed, in principle, as far as ZEB practices are concerned, there exist two renewable supply options: on-site and off-site sources. Figure 3.4 below illustrates some possible options for the systems boundary associated with a building or a cluster of buildings.

Figure 3.4: Overview of possible renewable energy supply options

Source: Marszal et al. (2011)

For on-site sources, option one involves the use of renewable sources available within the building's footprint such as PV, solar hot water and wind integrated on the building. The second option involves the use of renewable sources available around the building site such as PV, solar hot water, low impact hydro and wind located on the site but not on the building. For off-site sources, option three

involves the use of renewable sources available off-site to generate energy on-site such as biomass, wood pellets, ethanol or biodiesel that can be imported from off-site, or waste streams from on-site processes that can be used to generate electricity and heat. Option four involves investment in dedicated renewable energy generating equipment offsite while option five involves the purchasing of energy from off-site renewable energy sources including utility based solar, wind, as well as emissions credits or other “green” purchasing options.

BALANCE BOUNDARY

The balancing boundary deals with the selection of parameters which define the types of energy uses to be included in the zero energy balance calculations. Typically, country specific operational energy end user breakdown characteristics are recommended. These include: appliances, cooking, requirements for hot water, lighting, heating, cooling and ventilation. This is similar to the breakdown found in national comprehensive domestic energy reports such as HEEP in New Zealand (Isaacs et al., 2010b) and the also in Australia: Energy Use in the Australian Residential Sector report (DEWHA 2008).

In order to broaden the scope of the balancing boundary, other energy uses which are not traditionally considered by national or regional building codes such as the embodied energy of building materials, treatment of rain water and also charging of electric vehicles can also be included. However, the current ZEB framework does not consider electric vehicle charging as a building related energy demand (Sartori et al., 2012). Yet it has been argued in Section 2.4.2 that this aspect of user transport energy requirements is related to the building energy demand through the user at the city scale. Therefore, it is crucial to account for such requirements.

This stage of establishing the balancing boundaries also enables the designer/evaluator to specify other aspects relating to energy performance of the building, e.g. type and use of building (i.e. either residential or commercial, climatic conditions, comfort requirements and user patterns).

3.1.3.2 Rules for calculation

It is of high importance to have clearly defined parameters for the calculations to be used in terms of both the crediting system and the zero energy balance.

3.1.3.2. a Crediting system

The crediting system, or weighting system, defines the conversion of physical energy units from different sources into quantifiable uniform metrics such as kWh, CO₂-e, etc. (see Figure 3.3). This takes into account properties of specific energy carriers with respect to energy transmission, distribution and related conversion coefficients. For instance, a building could be connected to grid infrastructure characterized by different energy carriers such as coal, natural gas or wind grids serving specific end uses. Consequently, the credit system allows an evaluation of the entire energy supply chain irrespective of multiple sources. This further allows a test of the “fuel switch” effect. The rule of calculation for this parameter involves making explicit choices regarding the desired metric.

METRIC

The choice of a given metric depends on the physical and balance boundaries (Sartori et al., 2012). Generally, four types of metrics are distinguished; site energy, source energy, energy cost and greenhouse gas emissions (see Section 3.1.2).

Bourrelle et al. (2013) and Cellura et al. (2014) argue for more environmentally oriented metrics, i.e. to account for the non-renewable part of primary energy and associated greenhouse gas emissions. Their choice of such metrics is arguably the most appropriate since it reflects the strategically motivated country specific targets associated with the choice of energy generation from various electricity carriers. However, calculation of primary energy and greenhouse gas emission conversion factors can be tedious due to the mix range of energy sources and their development over time (Sartori et al., 2012). Databases such as GEMIS® comprise various usable conversion factors for energy carriers for both fossils and renewable sources used from OECD countries (Fritsche 1999).

SYMMETRY

As the name indicates, the symmetric and asymmetric weighting regimes marshal the bi-directional flow qualities of the energy carrier (i.e. electricity). Symmetric weighting relies on the premise that the energy exported to the grid will avoid an equivalent generation somewhere in the grid thereby having the same average weighting factors as the grid involved. An example of this approach is the exclusion of embodied energy of PV on-site generation in the balance boundary as the off-site generation will also have a certain amount embodied energy. Ideally, embodied energy of on-site generation PV needs to be accounted for at the balance boundary, better to reflect the overall environmental impact of a zero energy building (Bourrelle et al., 2013; Cellura et al., 2014).

On the other hand, asymmetric weighing allows energy imports and exports to be weighted based on primary energy. Asymmetric weighting allows the accounting of the negative effects of on-site energy generation. In the above given example, in asymmetric weighting, the embodied energy of the PV is included in the balance. In general, for the asymmetric weighting regime, energy demand and supply do not have the same value and hence, they are weighted differently. However, a somewhat controversial situation arises when other metrics, such as energy cost, are used in the balance boundary. Due to political targets and economic policies, diffusion of on-site renewable capture devices (such as PV systems) can be accelerated by weighting exported energy higher. This situation is apparent in early PV feed-in-tariff adoption countries such as Germany, Italy and Spain (Sartori et al., 2012).

TIME DEPENDENT ACCOUNTING

Time dependent accounting is one of the hallmarks of addressing the complexity of the electric grid with respect to zero energy buildings. This involves the quasi-static and dynamic accounting of grid aspects pertaining to delivered primary energy and greenhouse gas emission conversion factors and also the cost of energy supply.

Quasi-static accounting is suitable for estimating long term grid development changes in terms of primary energy and greenhouse gas emissions coefficients i.e. the “temporal variability”. This stage is rarely taken into account in the current ZEB application (Noris et al., 2014). Dynamic accounting, on the other hand, is used to evaluate weighting factors on an hourly basis. This is applied to seasonal, monthly average values or daily bands for base/peak load. Consequently, energy demand can be tracked in real time of the power grid as well as the hourly fluctuation of emission factors from electricity generation.

3.1.3.2. b ZEB balance

The core of the ZEB concept is the balance between weighted energy demand and weighted energy supply (see Figure 3.3). At this balancing stage, delivered and exported energy quantities can be used to calculate the energy balance during post-occupancy building monitoring (i.e. import/export balance). Alternatively, at the design phase of the building, delivered and exported energy requirements can be estimated depending on the capability of generation and the expected building consumption patterns. However, most building regulations comprise quantification rules for building self-consumption and therefore are lacking proper stipulation for delivered and exported energy quantities (Marszal et al., 2011). In this case, only on-site generation and building load are considered. The so-called “load/generation balance” is then used. A digest of the ZEB balancing approaches is presented below.

SELECTION OF ZEB BALANCE BASED ON “IMPORT/EXPORT” QUANTITIES

In this approach, the selection of energy balance is based on the delivered and exported energy quantities. Consequently, the boundary is taken as the overall building as shown in Figure 3.3. The balance can be calculated as per Equation 3.1 given below.

$$\sum_i e_i \times w_{e,i} - \sum_i d_i \times w_{d,i} = E - D \geq 0 \quad \text{Equation 3.1}$$

Where:

- i = Energy carrier (e.g. electricity)
- e_i = Exported energy in kWh
- $w_{e,i}$ = Weighting factor for e_i
- d_i = Delivered energy in kWh
- $w_{d,i}$ = Weighting factor for d_i
- E = Weighted exported energy in kWh
- D = Weighted delivered energy in kWh

SELECTION OF ZEB BALANCE BASED ON “LOAD/GENERATION”

QUANTITIES

In this approach, all energy loads in the building including heating, cooling, DHW, ventilation, cooking, appliances and other auxiliary energy uses are typically considered in the balance. Consequently, the renewable energy generation is required to match the overall energy uses in the building usually on a yearly basis. The load/generation balance is obtained as per Equation 3.2 given below.

$$\sum_i g_i \times w_{e,i} - \sum_i l_i \times w_{d,i} = G - L \geq 0 \quad \text{Equation 3.2}$$

Where:

- i = Energy carrier (e.g. electricity)
- g_i = Energy generation in kWh
- $w_{e,i}$ = Weighting factor for g_i
- l_i = Building load in kWh
- $w_{d,i}$ = Weighting factor for l_i
- G = Weighted generation in kWh
- L = Weighted building load in kWh

$w_{e,i}$ is taken as the ratio of the embodied energy of the RES to its total energy generation over the useful life.

On the other hand, as previously discussed, energy efficiency measures (EEM) are considered as the path to achieving zero energy balance of buildings (Marszal et al., 2011; Sartori et al., 2012; Voss and Musall 2013). Consequently, after the suitable balancing technique has been chosen, the next step is to adopt measures for energy efficiency requirements. This can be undertaken through prescriptive or performance-based approaches. The former comprise of *U values* of floors, walls, windows and roofs, air-tightness of envelope, HVAC systems, COP of heat pumps and so on, while the latter comprise maximum energy use requirements for heating, cooling or lighting.

In addition, after establishing appropriate energy efficiency measures (EEM), to complement the balance, renewable energy supply choices have explicitly to be made. Hence, to select the required RE approaches, renewable energy supply options are usually prioritized based on three underlying principles:

- Renewable nature and reduced transportation, transmission and conversion losses.
- Availability over the life time of the building.
- Highly scalable, widely available and have potential replication on future zero energy buildings.

As pinpointed by Marszal et al. (2011), these principles formulate a hierarchy of RE supply options whereby on-site RE sources are given priority (Solar PV or CHP for instance), over off-site sources such as wind and so on (see Figure 3.4).

3.1.3.3 Temporal match of energy production and demand

At the threshold of achieving zero energy balance, zero energy buildings are required to operate in synergy with the supply grids and not cause any unnecessary pressures (Sartori et al., 2012). As previously discussed, ideally, buildings that rely on on-site energy generation systems have the ability to exploit local energy sources as well as the ability to exchange energy back and forth with local infrastructure (i.e. electricity grid and/or district heating/cooling grid).

This complex interweaving of energy flow aspects between the building and the grid exposes zero energy buildings' susceptibility to what is known as “temporal energy mismatch” (see “Time Varying Accounting” above). Consequently, to address the interplay associated with zero energy buildings and grids, two concepts representing mismatch factor groups have been developed: (1) load match (LM) and (2) grid interaction (GI) (Salom et al., 2014a; 2014b; Sartori et al., 2012). These indicators are useful to reveal the underlying differences between alternative design solutions.

3.1.3.3. a Load match index

The overlap between on-site energy generation and the building load is defined by the load match index in the form of Equation 3.3 given below.

$$f_{load,i} = \frac{1}{N} \times \sum_{year} \min \left[1, \frac{g_i(t)}{l_i(t)} \right] \quad \text{Equation 3.3}$$

Where:

- i = Energy carrier (e.g. electricity);
- $f_{load,i}$ = load match index;
- N = Number of data samples (i.e. 12 for monthly interval and 8760 for hourly interval);
- g_i = Energy generation in kW;
- l_i = Building load in kW;
- min = Minimum; and
- t = Time interval used (i.e. hour, day or month).

3.1.3.3. b Grid interaction index

The resulting import/export profile between the zero energy building and the grid is defined by the “grid interaction index” which represents the standard deviation of the net energy exports to the grid normalized on the highest absolute value on an annual basis. Hence, the net energy export to the grid is defined in terms of the difference between the exported and delivered energy with respect to the proposed time interval, such as a year. This is based on metering or simulation data of

delivered and exported energy quantities. The grid interaction index is obtained as per Equation 3.4 given below.

$$f_{grid,i} = STD \left[\frac{e_i(t) - d_i(t)}{[max[e_i(t) - d_i(t)]}] \right] \quad \text{Equation 3.4}$$

Where:

- i = Energy carrier (e.g. electricity);
- $f_{grid,i}$ = Grid interaction index;
- STD = Standard Deviation;
- e_i = Exported energy in kW;
- d_i = Delivered energy in kW;
- max = Maximum; and
- t = Time interval used (i.e. hour, day or month).

In summary, these two concepts or mismatch factor groups are evaluated for each energy carrier separately and at different time resolutions. For instance, monthly net metering is considered to be sufficient to describe and investigate seasonal performance. This is when a building uses the grid as an ideal storage mechanism for electricity from summer to winter, while hourly and sub-hourly simulation is required to describe daily and hourly fluctuations to define aspects concerning peak loads and so on. However, this stage of zero energy building design has not yet been standardized internationally although it has recently been encouraged that a detailed sub-hourly load management is required in order to design zero energy buildings with high grid interaction flexibility (Salom et al., 2014a).

3.1.3.4 Verification

Depending on the adopted ambition level, the implemented designed performance and calculations should be verified by monitoring and evaluation so as to transfer the knowledge acquired from one building to another (Sartori et al., 2012). When it comes to energy and greenhouse gas emissions, the most basic approach is to monitor the delivered and exported energy quantities for various RES in order to

verify if the design performance is indeed achieved. Consequently, monthly and annual performance of RE production, heating/cooling, DHW, lighting, appliances and other energy requirements should be monitored. Post-occupancy measurements of other aspects such as indoor climate should also be undertaken for shorter or longer periods. The proposed measurement and verification protocol for zero energy buildings is described in further detail in Noris et al. (2013).

3.2 Zero energy building concept at whole building level

Energy (i.e. the amount of kWh coming in the building system boundary and kWh going out of the system boundary) is the most studied metric with regards to the zero energy building notion. Zero energy building principles can be applied to virtually all types of buildings/clusters in different cities, countries and contexts. However, the resulting complexity of such tasks requires significantly large amounts of data and time to compile results. For this reason, the most common application of the zero energy building concept fundamentally deals with implementing buildings which produce as much energy as they consume in a year when accounted for at the site : “*net zero site energy*” (see Section 3.1.2). In addition, this is coupled with the fact that energy is responsible for most of the environmental impact associated with buildings (Junnla 2004).

The following section, therefore describes necessary simplifications and the inherent complexity associated with achieving a zero energy balance at whole building level.

3.2.1 Simplification of the zero energy building framework in the case of achieving the zero energy balance

Evaluating alternative strategies for designing zero energy buildings with net zero site energy performance results in a simplification of the four criteria of the ZEB framework. Indeed, the restriction of various metrics e.g. energy, cost, normalization etc. to a single metric, i.e. energy, narrows down the amount of variables to be taken into consideration in the zero energy balance. The level of ambition criteria remains crucial and unchanged as the main goals, targets/purpose

of the project and the system boundary for the zero energy balance achievement should be clearly selected at the beginning of the study.

The greatest simplification occurs in the second criterion of the ZEB framework under rules for calculation (see Section 3.1.3.2). Departing from the works by Marszal et al. (2011) and Sartori et al. (2012), the first sub-criterion under rules of calculation is the crediting systems. This brings forth the dilemma for weighting energy based on either primary energy or economically motivated weighting such as “feed-in-tariffs”. Economically motivated weighting paves the way to valuing exported energy higher so as to promote the diffusion of RES technologies. This norm is featured well in the packages for economic recovery policies and could accelerate the penetration of renewable energy at the building scale (Bourrelle et al., 2013).

Nevertheless, the long term benefits of such practice remain unclear and the outcomes may also not be environmentally conscious since the mechanism is primarily driven by providing long-term energy security to renewable energy producers purely based on the cost of each technology. At this turn of the century, economically driven weighting factors appear to contradict the purposes of perusing zero energy buildings which ultimately lie at the higher end of the environmental spectrum (Woods 2012; La Roche 2012). More importantly, as was argued in Section 3.1.2.2.a, the environmental sustainability of PV, versus zero energy buildings needs to be further investigated due to the high embodied and greenhouse gas emission intensity of the PV systems (Laleman et al., 2013; Cellura et al., 2014; Lützkendorf et al., 2014; Yue et al., 2014; Yao et al., 2014; Rovers 2015 ; Nemet et al., 2016). It can therefore be argued that the “*primary energy*” input is a suitable indicator within the crediting system which can be used for simplified calculation of the zero energy balance. In addition, it is however important to also note that the resulting greenhouse gas emissions are sometimes included in this evaluation, e.g. Bourrelle et al. (2013), Lützkendorf et al. (2014), Georges et al. (2014). Consequently, taking into account the associated greenhouse gas emissions

implies characterising the measurement based on global warming potential (GWP) in kilograms of carbon dioxide equivalent ($\text{kgCO}_2\text{-e}$).

Within the second criterion, the zero energy balance scope, the important aspect to consider is the simplification concerns as to whether the renewable energy is deemed to be produced on-site or off-site (Marszal et al., 2011; Heffernan et al., 2013). The production of renewable energy from off-site sources or out of the scope of the building footprint is presented as the least preferred option since it is viewed as potentially being of most environmental impact and offering least longevity over the life time of buildings (Marszal et al., 2011 ; Marszal 2012; Satori et al., 2012 ; Heffernan et al., 2013).

In addition, it can also be argued that in the interaction of the zero energy building concept and renewable energy supply options, local building users are likely to face a dilemma when it comes to deployment of RES around the neighbourhood or whole developments for off-site generation in the form of local opposition to the use of land for large-scale RES development at local level. This is often referred to as 'NIMBYism' ('not in my back yard') behaviours (Devine-Write 2010). However, NIMBYism has not yet been widely researched with regards to zero energy buildings and off-site renewable generation. Consequently, the calculation simplification of the zero energy balance based on on-site generation is reasonably justified.

For the third criterion, temporal energy match characteristics, evaluation or requirements of load matching and grid interaction can be set according to Equation 3.3 and Equation 3.4. However, the inclusion in calculations of this phase of design is not yet internationally standardized and has not been included (Berggren et al., 2012). The verification phase at the design stage is estimated based on the expected building energy consumption patterns and renewable energy production on an annual basis. However, during the use stage, relevant measurement and verification protocols can be implemented to monitor energy performance as well as indoor climatic conditions.

3.2.2 The inherent complexity related to the zero energy balance achievement of a whole building and its users

The determination of energy inputs to be included for the zero energy balance achievement of buildings requires the integration of industrial, construction and user related dimensions. This integration process is undertaken by considering a complex mix of aspects related to all building components and systems, operational energy requirements (i.e. energy carriers, heating/cooling and others), maintenance and replacement of various components, demolition and other related embodied energy intensities on an annual basis. This complexity could arguably explain the low number of zero energy buildings built in this regard. Indeed, in a recent literature review, Panagiotidou and Fuller (2013) identified only 70 built examples of zero energy building applications at whole building level located in 11 different countries. This number is rather small and limited to demonstration projects compared to thousands of other low energy building construction approaches seen today, e.g. passive houses (~25,000 globally).

The complexity of determining the zero energy balance at whole building level has generally driven the imposition of narrow balancing boundaries. In all cases reviewed by Panagiotidou and Fuller (2013), the evaluators/designers did not take into account building embodied energy and user transportation energy (both embodied and operational) requirements.

Buildings do not use energy but rather people do (Janda 2011). Consequently, if the building user is to be taken into account in determining the zero energy balance, ultimately, all related energy demands through the building should be considered (Stephan 2013). These demands include the energy required for building operation at both the building and the city scale. When the conventional zero energy building balancing boundary at whole building scale adopts a much wider scope to encompass the city scale energy parameters, the resulting overall energy requirements of a zero energy residential building will therefore also encompass energy demands associated with: the extraction of raw materials and manufacturing of building materials, the construction of the zero energy building itself, the operational and maintenance of the building, the embodied and operational energy

impacts directly related to the building users themselves as well as the energy demand required for demolition of the building.

The energy inputs related to a zero energy residential building and its users on an annual basis can therefore be categorized in two levels of demand: (1) building energy (i.e. operational and embodied energy) and (2) transport energy (i.e. operational and embodied energy). The description of these energy demands is given in the following section.

3.3 Energy demands associated with zero energy buildings and their users at both building and city scales

3.3.1 Building energy demand

Energy demand in the built environment at the building scale can be described as embodied energy and operational energy.

3.3.1.1 Operational energy

Building operational energy is the most considered energy demand taken into account in the current ZEB framework (Marszal et al., 2011; Sartori et al., 2012; Berggren et al., 2012 ; Panagiotidou and Fuller 2013; Lützkendorf et al., 2014). As previously mentioned in Section 3.1.3.1.a, operational energy breakdown factors typically included for the ZEB balance are: heating and cooling, cooking, domestic hot water, lighting and other appliances.

The annual operational energy demand is often given in terms of mega Joules or kiloWatt-hours per metre square of usable floor area of the building i.e. MJ/m² or kWh/m². Final or delivered units are generally used to further express operational energy values with respect to the energy service defined therein. For instance, delivered energy demand is used to express overall consumption of electricity while final energy is used to express the energy demand associated with typical breakdown of building end uses such as appliances, heating/cooling and so on. In the zero energy building framework, it has been argued that operational energy should be further converted into '*primary energy*' by using suitable final/delivered to

primary energy multiplication coefficients (Bourrelle et al., 2013; Cellura et al., 2014) (See section 3.2.1).

3.3.1.1. a *Operational energy types*

Residential building operational energy is further classified into two portions relative to the annual overall energy use: building-related and user-related operational energy. The former comprises space heating and cooling demands which are largely influenced by systems and climatic conditions (i.e. outdoor temperature, solar radiation, wind etc.). When it comes to the latter, lifestyle of the building users has a strong influence on energy end uses such as appliances and other non-thermal aspects within the building. Consequently, particular climates, countries/regions and building types manifest different operational energy patterns (Stephan 2013). In addition, identical buildings with the same number of users can have a variation of annual operational energy demand which might differ with a factor range of 2 to 4 (Steemers and Yun 2009; De Meyer and Feldheim 2011). It can therefore be argued that the main factors influencing operational energy breakdown of residential buildings are the design, user patterns, systems and climate.

On the international scale, these influences can be observed accordingly. For instance, on average, New Zealand households consume much less energy for space heating compared to European households: ~3,820 kWh/annum and ~12,700 kWh/annum respectively (Isaacs et al., 2010a; ICEDD 2010). This implies that in practice space heating energy demand increases when climate gets colder. On the user-related energy scope, New Zealand households consume ~7,482 kWh/annum for appliances and hot water whereas average European households consume ~5,600 kWh/annum for similar functions (Isaacs et al., 2010a; ICEDD 2010). With such comparable energy demands associated with appliances and hot water, user-related energy influences are confirmed since New Zealand and Europe are separated by large geographical distances.

Ideally, all these aspects need to be taken into account when determining the zero energy building balance. However, calculation of annual building operational

energy is a highly complex task since it requires the interrelated variables linking the building and the users to be accurately represented in order to obtain meaningful results. Fortunately, all this is made possible thanks to the various operational energy quantification techniques present today.

3.3.1.1. b *Operational energy quantification techniques*

Various quantification techniques for annual building operation energy requirements at the design stage are fully developed to date and have evolved from the usage of national empirical data, quasi-steady-state-methods to advanced dynamic building energy simulation software (Malkawi and Augenbroe 2004). Further details regarding these techniques are given in Section 4.2.1.1.

However, there exist a myriad of building performance simulation tools today, including TRNSYS®, Autodesk® Ecotect™ Analysis, EnergyPlus® and TAS® all which can simulate a wide range of operational energy types with a reasonable level of accuracy (Crawley et al., 2008). An almost complete list of current tools is published in the annual 'Building Energy Software Tools Directory' (BEST Directory 2015). Examples comparing the capabilities of major building energy performance simulation software are given by Crawley et al. (2008), Maile et al. (2007) and Zhu et al. (2012).

In addition, most of the above tools already provide simulation results in primary energy terms with respect to customizable primary energy multiplication factor functions.

3.3.1.2 *Embodied energy*

The topic of building embodied energy has long been a subject of study amongst architects/engineers and continues to be of interest (Treloar 2000; Crawford 2011, Dixit et al., 2015). Embodied energy represents the amount of energy required to construct and maintain built premises. For instance, with a brick wall, the embodied energy represents the amount of energy necessary to make the bricks, transport them to site, lay them and if necessary paint and plaster over the life time of the wall. In case of a full building, the initial embodied energy is the sum of all

total energy requirements of materials used together with the direct energy requirements for construction.

In particular, the more energy-efficient (towards zero energy) buildings become in the operation phase, the more important the proportion of energy requirements associated with raw material extraction, manufacturing, transporting to site, construction and maintenance of materials, becomes (i.e. embodied energy) (Hernandez and Kenny 2010; Leckner and Zmeureanu 2011; Rovers 2015). Consequently, it is very crucial to quantify and reduce the material and component energy requirements that arise starting from the product stage (embodied impacts resulting from manufacturing processes) through construction and maintenance and eventually demolition stages.

However, the choice of materials and components is primarily driven by their aesthetic function and cost while the embodied energy requirements are often overlooked (Tucker 2015). Consequently, at the design stage, building users do not possess the required information to judge building material requirements based on environmental factors such as the embodied energy intensity amidst other aspects pertaining to cost or aesthetics. However, this lack of interest over environmental concerns is likely to be remedied due to the rising awareness for the need of environmentally conscious choices for building materials. Indeed, this fundamental shift is becoming apparent in Europe particularly Germany and Scandinavia (Hegger et al., 2008; Bokalders and Block 2010; Stephan 2013; Weißenberger et al., 2014).

Nonetheless, a lot of confusion still exists today surrounding the need for an internationally agreed embodied energy measurement protocol for buildings (Dixit et al., 2012). To circumvent this issue, the IEA's Energy in Buildings and Communities Programme (EBC), established an international project with some 20 participating countries. Annex 57: Evaluation of Embodied Energy and Greenhouse Gas Emissions for Building supported development and improved understanding in this area so as to provide stakeholder-oriented guidelines and calculation methodologies for the design and construction of low embodied energy

and emission buildings (Balouktsi et al., 2014). With developments of such magnitude, the rising awareness of environmentally friendly building designs is very likely to progress especially within IEA member countries.

In its most conventional form, embodied energy of buildings is usually given in terms of primary energy and the figures are commonly expressed in terms of mega-Joules or kilo-Watt hours per meter square of the floor area (i.e. MJ/m² or kWh/m²), as for operational energy (see above). Additionally, embodied energy is quantified based on boundaries established in the various energy analysis methods, namely: process analysis, input-output analysis and hybrid analysis. These methods are used to calculate the material energy coefficients which are then multiplied by the relevant quantity of building materials to obtain their overall embodied energy. Further details regarding how each of the methods is conducted is given in Section 4.2.2.1

3.3.1.2. a *Initial embodied energy*

The initial building embodied energy is comprised of the energy use during raw material extraction, manufacturing, transportation, and construction life cycle phases up to building completion prior to occupation and any maintenance. Building designers have an important role to play in reducing initial embodied energy levels due to their significant involvement in preconstruction activities. Consequently, the initial embodied energy is based on factors associated with the choice of building materials relative to design and also manufacturing processes of individual materials including the energy source used, amount required, type of machinery involved and so on. All these aspects vary between countries or regions (Crawford 2011).

In reality, the assemblage of materials destined for specific functions at the building scale is subject to the durability of materials therein. Therefore, the initial building embodied energy should be taken into account in tandem with the recurrent embodied energy.

3.3.1.2. b *Recurrent embodied energy*

Recurrent embodied energy represents the amount of energy required to maintain, repair, restore, refurbish or replace materials, components or systems during the life of the building. During the service life of a building, materials and components with varying service lives need to be maintained or replaced depending on their durability. In general, some building aspects including lighting, carpentry, doors, ventilation systems and others tend to have shorter replacements cycles than their structural component counterparts (Mithraratne et al., 2007; Crawford 2011, Anderson et al., 2015). As such, the importance of low recurring building embodied energy is another reason why the choice of environmentally friendly materials and components is emphasized today.

While recurrent building embodied energy is believed to fall within the range of 20-30% of the initial embodied energy for a building service life of 50 years (Treloar 2000; Crawford 2010) as cited in Stephan (2013)), for a given building the actual recurrent embodied energy is quantified by multiplying the individual quantities of the initial embodied energy of materials by their number of replacement cycles throughout the life of the building.

Buildings eventually have to be demolished or recycled when they reach the end of their service lives. As such, the amount of energy consumed for the building demolition task is known as demolition energy demand.

3.3.1.2. c *Demolition energy*

Demolition and end-of-life energy represents the amount of energy depleted in the disposal and/or recycling of the building. Demolition energy demand of buildings can represent ~1% of the total life cycle energy demand (Crowther 1999) as cited in Stephan (2013)). Most recent studies consider demolition energy to be negligible compared to building operational energy (Mithraratne et al., 2007; Stephan 2013; Stephan et al., 2013b). However, assessing the destinies of building materials and components (in landfills), after demolition may reveal a number of environmental maladies associated with large amounts of waste generation.

On the other hand, incineration or recycling of building materials at their end of life has become a common trend these days (Stephan 2013). While in theory this practice is claimed to be advantageous, in reality, the assessment of energy quantities associated with recycling or incineration is still a subject under disagreement and remains controversial (Treloar 2000; Crawford 2011; Stephan 2013; Stephan et al., 2013b). Consequently, the allocation of recycling or incineration energy of building materials is an on-going argument which is interwoven between two perplexing intellectual views. The rationale behind the first point of view is that the energy quantity associated with either recycling or incineration should be deducted from the initial building embodied energy. In a pragmatic sense, the second point of view argues that when the material has a longer service life, its ultimate value remains unknown and therefore the advantages should be attributed to the recycled material in the future and not the present one (Treloar 2000; Stephan 2013; Stephan et al., 2013b). Clearly, the first point of view appears to hold a degree of bias towards the use of recyclable materials. Arguably, however, the second point of view is more realistic in practice and is therefore judged most suitable to be the governing school of thought in this work hereafter.

3.3.1.3 Relative importance of distinguishing the interplay between building operation and embodied energy in the case of the zero energy balance

The movement towards zero energy buildings has resulted in much greater emphasis on building embodied energy, for typically as operational energy is significantly reduced, embodied energy becomes more relevant (Hernandez and Kenny 2010; Leckner and Zmeureanu 2011; Rovers 2015; Balouktsi and Lützkendorf 2015). Consequently, understanding the relationship which exists between embodied and operational energy is critical to defining the zero energy balance which could effectively lead to the significant reduction of energy and greenhouse gas emissions at the building lifetime scale.

In the built environment, the relationship between building operational and embodied energy is expressed through the 'Energy Return Over Invested' (EROI),

or the ratio of the decrease in annual use to the annual increase in embodied energy (Hernandez and Kenny 2010; Läckner and Zmeureanu 2011). Hence, using this approach, the link between building operational and embodied energy can therefore be exploited to estimate the one as a fraction of the other during the early stages of design. The applications of EROI in the energy and building fields has been documented and intensively reviewed in Mulder and Hagens (2008) and Dutil and Rousse (2011).

However, in the context of zero energy buildings, a study in Switzerland conducted by Berggren et al. (2013), tests and provides valuable insights as regards this interconnectedness. The authors compared the operational and embodied energy demand of 11 Swiss '*Minergie-A*' building cases and hypothetically tested their transition from low energy status to two types of zero energy buildings statuses: the first zero energy building transition (ZEB_L) excluded energy requirements for lighting and other auxiliary services in the zero energy balance, while the second transition, (ZEB), included both thermal and non-thermal energy end uses in the zero energy balance. Figure 3.5, based on the study, presents the mean values of embodied energy, operation energy and the variation of the total energy use expressed in primary energy, comparing three different building standards: low energy '*Minergie-A*' buildings and zero energy buildings (i.e. ZEB_L and ZEB).

Figure 3.5: Mean values of embodied, operational energy and the variation of the total energy use expressed in primary energy (non-renewable), comparing three different building standards

Source: Adapted from Berggren et al. (2013)

The study claims that an increase in embodied energy does not negatively affect the transition from a low energy building towards a zero energy building. Consequently, when taking the step from a low energy building towards a zero energy building, the increase of embodied energy is $\sim 25\%$ with non-renewable building operational energy dropping by 100%, towards zero. In energy terms, the study further demonstrated that the annual overall energy demand associated with the zero energy houses represents $\sim 40\%$ of the total annual energy demand of the low energy houses. According to the authors, this implies that the annual total energy use of the zero energy houses is much lower than the annual total energy use of the low energy houses. Although ignored in the balance, the building embodied energy was found to be $\sim 60\%$ due to structural elements, $\sim 20\%$ due to HVAC systems, while RES e.g. PV and ST collectors also accounted for $\sim 20\%$.

In their concluding remarks, Berggren et al. (2013) further claim that RES such as PV systems, when applied on zero energy buildings, always reduce the operational energy demand more than the increase of the embodied energy incorporated in the technical system.

However, the ideas propagated by Berggren and his colleagues could be questionable and therefore need to be subjected to a certain degree of scrutiny here. First, as was pinpointed and argued in Section 3.1.2.2.a, evidence suggests that it is crucial to incorporate embodied energy associated with buildings and components within zero energy building design frameworks in order to achieve a meaningful reduction in energy use and greenhouse gas emissions (Cellura et al., 2014; Lützkendorf et al., 2014; Rovers 2015). Second, with respect to PV systems, the authors assume that PV generated electricity is emissions-free ('emissions' used here as a proxy for energy generation and use). See Figure 3.5 under ZEB. Yet it has been argued in Section 3.1.2.2.a that PV manufacturing is energy and emission intensive (Yue et al., 2014). Consequently PV generated electricity can have average emissions intensity of $99 \text{ gCO}_2\text{-e/kWh}$ for $\sim 1,700 \text{ kWh/m}^2/\text{year}$ solar irradiance

(Laleman et al., 2013) .This intensity could even be much higher for Switzerland which has an average solar irradiance of only $\sim \pm 1,200 \text{ kWh/m}^2/\text{year}$.

On the other hand, another aspect which the authors seem to overlook is that operational energy is very sensitive to building users' lifestyles (Steemers and Yun 2009; Gram-Hanssen 2010). This implies that the annual operational energy is very likely to fluctuate.

In cases where energy demand continues to increase, another aspect to consider is the 'technical potential' of renewable capture devices such as PV systems. The technical potential for solar energy capture devices is given as the gross output of the actual electricity possible . This implies the required inputs of energy in order to generate an energy output of the system (Mariaty and Honnery, 2010). Methodologically, energy researchers have approached this phenomenon differently. See for example, Lightfoot and Green (2002); Gross et al., (2003); Cho (2010) and Tomabeche (2010) rely on process analyses or purely input-output-based quantification techniques and provide higher figures for the technical potential of solar capture devices as argued by Mariaty and Honnery (2012). On the other hand, using hybrid analysis quantification techniques, Zhai and Williams (2009) demonstrated lower technical potential figures for PV systems than those previously calculated. Crawford (2009) also observed a similar trend for wind turbines. The argument that renewable energy from solar and wind will be able to cover societal needs in the near future with current technologies still remains unknown and a subject under debate (Mariaty and Honnery, 2010; Mariaty and Honnery 2012).

Undoubtedly, Berggren et al. (2013) appear to show somewhat less understanding regarding some crucial aspects influencing the interplay between embodied and operational energy requirements in the face of zero energy building practices. It can be argued that both embodied and operational energy should be considered collectively in the case of the zero energy building balance.

However, while the current zero energy building framework acknowledges energy demand at the building scale, another important energy demand associated with the building user at the city scale is generally omitted: user transport energy.

3.3.2 User transport energy

Mobility is one fundamental aspect of any city or country which has a cardinal social value. To a large extent, mobility in many developed countries is mainly provided by private vehicles (Geels et al., 2012; Givoni and Banister 2013). The increase in private vehicle ownership in the 1960s opened the gates to transport energy assessment when the underlying effects of road network expansion and traffic on urban environments become apparent in the developed world. See for example, the ‘Buchanan Report’: Traffic in Towns (Buchanan et al., 1963).

The wave of urban sprawl coupled with the increasing ownership of private vehicles have resulted in an exertion of massive mobility pressure across city hubs (Jenks et al., 2000; Melia et al., 2011). This has further resulted in large travel distances and consequently, high energy use for travel within urbanising centres. In this way, the high level of private vehicle dependence in cities has large implications for resource consumption especially energy use for transport and its subsequent greenhouse gas emissions (Newman and Kenworthy 1999). Ultimately, these vexing problems have prompted scholars to establish the interaction and interplay between urban form (land-use characteristics) and energy use for transport (Banister and Marshall 2000; Newman and Kenworthy 2006; van de Coevering and Schwanen 2006; Ewing and Cervero 2010; Jones and Kammen 2013).

Transportation energy demand in the city context generally encapsulates the interconnection between transport system operations and urban form (Ewing and Cervero 2010; Larson et al., 2012; Stephan 2013; Anderson et al., 2015). This comprises the embodied energy of supporting infrastructure, embodied energy of the transport mode itself plus related services and the operation energy of the transport mode with respect to its system efficiency (Chester and Hovarth 2009). User transport energy considered in this work can therefore be defined as the

embodied and operational energy requirements associated with the building users' mobility.

One main ingredient to consider when quantifying user transportation energy demand is the 'passenger travel distance'. Travel distance data associated with different transport modes is usually obtained through country-wide or regional/local surveys (Feng et al., 2013). This average data is arguably the best available source which can be used to evaluate transport energy associated with the mobility of building users since it already includes a swath of interwoven variables which influence user transport behaviour e.g. social, economic, demographic and land-use aspects, all of which would otherwise be very difficult to account for individually (Stephan et al., 2012; Stephan 2013; Stephan et al., 2013a).

To calculate the operational energy requirements, travel distances are multiplied by the energy intensity of a specific transport mode. Data comprising energy intensity of particular transport modes is generally available from manufacturers' data.

On the other hand, when it comes to transport embodied energy, most studies tend to overlook its influence (Stephan et al., 2012; Stephan 2013; Anderson et al., 2015). For instance, Lenzen (1999) established that embodied energy of transport can account for 43.1% to 82.3% of the total share of transport energy in Australia. In a similar fashion, Jonson (2007) as cited in Stephan (2013)) also found embodied energy of road transport to represent 46% of the total share in Sweden.

Although lower than the overseas studies, Mithraratne (2011) underscores the shares of operation and embodied energy requirements for New Zealand transport per specified modes including private and public. The results shown in Table 3.1 confirm the significance of considering embodied energy associated with user transportation. The share of embodied energy accounted for at most 23% and is over 12% in all cases studied. These ratios are based on figures expressed in mega-Joules per passenger-kilometre and therefore can be compared to other regions with similar transport systems and infrastructure construction paradigms when analysed using similar methodology.

Table 3.1: Share of operation and embodied energy requirements for transport modes in New Zealand

Mode	Operation energy	Embodied energy
<i>Private transportation</i>		
Vehicle, petrol	77%	23%
Motorcycle	88%	12%
<i>Public transportation</i>		
Bus, diesel	79%	21%
Train, diesel	88%	12%

Source: Adapted from Mithraratne (2011)

At the aggregate level, it can therefore be argued that incorporating embodied impacts associated with transport energy along with operational energy is crucial and cannot be ignored. In order to successfully do so, however, it is imperative to understand another major aspect concerning intra-urban user transport energy demand: urban structure. In user transport energetic terms, understanding urban structure implies encompassing the existence of linkages between patterns of urban mobility and land-use characteristics. Consequently, within the scope of this research, a number of prominent studies exploring this issue are analysed in the following section.

3.3.2.1 Connecting patterns of urban mobility and structure

A wide spectrum of research reveals a set of valuable insights which aims at addressing the cross-disciplinary boundaries that exist between urban form and energy use for travel. See for example Jenks et al. (2000) and Ng (2010) who offer a variety of highlights regarding this research field. However, in their study on New Zealand cities, Howden-Chapman et al. (2010) conclude that urban form has a significant influence on energy use for transport associated with building users. Additionally, they also acknowledge the significant influence of other user-related social aspects. At a higher spatial granularity, in the New Zealand context, Krumdieck (2010) and Donovan and Munro (2013) argue that urban form can significantly reduce energy demand and greenhouse gas emissions associated with travel by hindering sprawl and adopting higher density residential developments, mix-use urban configurations and implementing efficient public transport.

Underpinning this, researchers from other countries also seem to agree with this school of thought (see for example Newton 2000; Buxton 2000, Golob and Brownstone 2005; Karathodorou 2010; Glaeser and Kahn 2010; Fuller and Crawford 2011; Stephan 2013; Stephan et al., 2013; Minx et al., 2013; Weidenhofer et al., 2013). These studies have demonstrated that a strong correlation between urban density and energy use for transportation exists.

However, the ample evidence observed above, draws our attention back to the role of average urban density in transport-related energy consumption. Indeed, the legendary research conducted by Newman and Kenworthy in 1989, which they summarized in a later work, investigated the interplay between urban structure and energy use for travel (Newman and Kenworthy 1999).

In their attempt to help build agreement on matters concerning automobile dependence and sustainable urban development, Newman and Kenworthy highlighted that there is an interrelation between urban density and private vehicle transport energy. As shown in Figure 3.6, their famous hyperbola ‘urban density and transport-related energy consumption’ reveals a strong correlation ($R^2=0.86$) between average density and intra-urban private transport-related energy consumption per capita for cities in North America, Australia, Europe and Asia. These outcomes are due to density being highly correlated with transport modal distribution and the intensity of private vehicle usage (Newman and Kenworthy 1999; Newton 2000; Buxton 2000, Golob and Brownstone 2005; Lefevre 2009 ; Karathodorou 2010; Glaeser and Kahn 2010; Fuller and Crawford 2011; Stephan 2013; Stephan et al., 2013; Minx et al., 2013; Weidenhofer et al., 2013)..

Figure 3.6: Private transport-related energy consumption per capita in 1989, by city and urban density

Adapted from: Newman and Kenworthy, (1999)

As can be observed in Table 3.2, cities with lower density urban configurations exhibit an almost total predominance of private vehicle usage. In addition, overall transport energy demand is also of considerable amount (i.e. frequently more than 55,000 MJ/capita/annum). On the other hand, it can also be observed that cities with higher density urban configurations tend to manifest a more balanced nature of tri-modal distribution with stark emphasis on public transportation (i.e. ~40% to 60% of travel). The total private transport energy demand is therefore four to seven time lower than in cities with lower density configurations.

Table 3.2: City typology in terms of average density and transport

Representative regions	North America and Australian cities	European cities	Asian cities
Global urban density	Low <25hab/ha	Medium 50-100hab/ha	High >250hab+/ha
Modal distribution	MPT:80% PT:10% NMT:10%	MPT:50% PT:25% NMT:25%	MPT:25% PT:50% NMT:25%
Vehicle use(km/capita/annum)	>10 000		<5000
PT use(trips/capita/annum)	<50		>250
Energy use (MJ/capita/annum)	>55,000	35,000-20,000	<15,000

MPT: Motorised Private Transport, PT: Public Transport, MT: Non-Motorised Transport.

Adapted from: Newman and Kenworthy, (1999)

From Table 3.2 above, clearly, European cities occupy an intermediate position with regards to urban density (roughly between 50 and 100 inhabitants/hectare). Unsurprisingly, modal distribution is more balanced although private transport usage is still very dominant. The private vehicle aspects are apparent perhaps in peripheral low density suburban neighbourhoods. Consequently, the total transport energy demand is two to four times lower than in cities with low density urban configurations. In this regard, it can therefore be argued that density could be considered as an influencing factor of energy use for transport alongside mixed land use, and availability of public transport.

Nevertheless, while the general conclusion put forward by Newman and Kenworthy cannot be ignored, they have been criticised because their work overlooks the influence of user-related socio-economic aspects interconnected with spatial distribution activities. As such, multiple studies have expressed concern over this aspect, e.g. Stead et al. (2000), Dieleman et al (2002), Bertaud (2003). To circumvent this issue, Van de Coevering and Schwanen (2006) have added to

Newman and Kenworthy's 1989 pioneer work by intertwining socio-economic variables. Indeed, their findings demonstrated a stronger correlation between the users' socio-economic status and spatial distribution transport-related activities (travel distance, use of private vehicles, modal split amongst other factors) than with land-use characteristics (urban form). It can therefore be argued that in order to accurately represent intra-urban user transportation energy, traditional aspects of users' characteristics and land-use characteristics are required to be encompassed by integrating other parameters associated with spatial distribution of activities and households. In this way, user transport energy can be seen to be highly influenced by the link between buildings at the city scale as well as by user-related variables.

In parallel, Newman and Kenworthy's 1989 work is entirely focused on internal combustion engine vehicles (Newman and Kenworthy 1999). Recent work by Byrd et al, (2013) conducted similar research in the city of Auckland, New Zealand based on electric vehicles. In their conclusion, the authors suggest that low density urban configurations can be less energy intensive since the suburban built form has potential to produce more on-site electricity required to power electric vehicles used by the occupants than much denser configurations. However, although the work of Byrd et al., (2013) has significant observations, their findings could arguably be very conservative since the authors did not consider the embodied or indirect impacts resulting from on-site electricity production and electric vehicle batteries as was argued in Section 3.1.2.2.a and Section 4.2.1.1 respectively. Consequently, encompassing Newman and Kenworthy's work with electric vehicles is still a subject that warrants more research and this has been highlighted in Chapter 8 as an avenue of future research in relation to zero energy building developments.

3.4 Examples of studies applying the zero energy building concept to buildings and their users

A considerable number of published scholarly articles have reported on how different building projects have considered the zero energy building balance. The majority of the projects take into account just building operational energy within

the zero energy balance. Others have also taken into account building embodied energy and further included user behavioural schemes. Yet only a few have broadened the scope to include user transport energy. These studies are summarised in the following section as examples of the significance of integrating different methods and scales to enable a more meaningful move towards a zero energy built environment.

3.4.1 Studies incorporating building operational, embodied and transport energy

Outside the context of this work, multiple studies integrating building operation, embodied and transport energy requirements exist.

Ideally, addressing the impacts associated with residential buildings and their users in the built environment requires a high level of understanding spanning beyond the building scale. The importance of integrating building scale energy demand, (i.e. building operational and embodied energy) and user-related urban scale energy demand (i.e. transport operational and embodied requirements) is oftentimes highlighted in studies employing the life cycle assessment framework (LCA). See for example: Treloar et al. (2000), Fuller and Crawford (2011) and Stephan et al. (2013b) in Melbourne, Australia, Norman et al. (2006) in Toronto, Canada, Stephan et al. (2011); Stephan (2013) and Stephan et al. (2013a) in Brussels, Belgium., Anderson et al. (2015) in Munich, Germany.

These studies take into account a large spectrum of energy consuming activities encompassing both the building and the city scales, notably building operational energy (electricity etc.), embodied energy (initial and recurrent) and transport energy requirements (including operational and embodied energy of transport modes). Other studies such as Treloar et al. (2000) widen the scope further to include user-related aspects such as belongings and consumables (e.g. food). While these studies are undertaken in different locations and contexts, the significance of integrating building and user-related city scale energy requirements is, however, reinforced. Indeed, within these studies, the figures for user transport energy

requirements tend to fall in the range of $\sim 0.55 \text{ MWh} - 14 \text{ MWh}$ (representing $\sim 8 - 51\%$ share) of the total life cycle building energy demand per annum.

In parallel, other works which investigated the combination of building operational energy, transport energy and urban form of neighbourhoods also exist. Examples of such studies include: Ramaswami et al. (2008), Glaeser and Kahn (2010) in U.S.A, Heinonen and Junnila (2011a, 2011b) in Finland, Marique and Reiter (2012) in Belgium, Conte and Monno (2012) in Italy and Howard et al. (2012) in U.S.A. While these studies provide valuable insights regarding the measurement of operational and transport energy requirements whilst pinpointing guidelines for their reduction in the urban context, they tend to exclude embodied energy requirements, overlook user-related aspects and often remain at the urban scale.

More generally, despite offering first insights into multi-scale integrated energy analyses in the built environment, all these references aim towards reducing energy demand and therefore demonstrate limited underpinnings towards the ambitious goal of zero energy which, in its totality aims at completely eliminating non-renewable energy demand. Moreover, unlike building environmental impact measurement tools such as the LCA framework (highlighted in Section 2.2.3), the zero energy building framework provides technical clarity and interpretation techniques for application in practical building energy performance design processes (see Section 3.1.3).

Turning now to the main subject of interest, a significant number of projects have attempted to apply the zero energy building concept whilst taking into account building operational energy within the energy balance. Panagiotidou and Fuller (2013) have reviewed 70 built examples of zero energy building residential applications at whole building level. They found that, as a general conclusion, the zero energy balance can be achieved with a range of $\sim 70\% - 120\%$ of the operating energy balance. While these numbers suggest that the zero energy building balance can be achieved easily by taking into account operational energy only, it is very likely that they greatly underestimated the effect of the embodied energy component.

Indeed, the dominant majority of studies conducted tend to use the load/generation balance and often consider final energy as the chosen metric (see Section 3.1.3.2.b). For instance, in most cases and as found in other studies (Voss et al., 1996; Noguchi et al., 2008; Wang et al., 2009., Mohamed et al., 2014), the zero energy building balance is achieved 100% on an annual basis. In rare whole building case studies using the import/export zero energy building balance method with final energy as the metric (Bourelle et al., 2013), this ratio has dropped to 94.7% (Cellura et al., 2014). In other words, it can be argued that this systematically complete balancing method captures all the energy source related-aspects. Consequently, a zero energy building with 100% energy balance based on load/generation method, could have an energy balance much lower than 100% when expressed based on import/export balance method even with final energy metric as an indicator. All the studies achieving +100% zero energy balance based on load/generation balance method mentioned above focus only at the building scale and do not consider embodied and user transport energy.

3.4.2 Studies incorporating building operational, embodied and transport energy within the zero energy balance

Only two systematically completed studies integrating operational and embodied energy within the zero energy balance were found in the literature. In addition, one study integrating building operational and transport energy within the zero energy balance was also found. These are described hereafter, along with another study conducted by the author of this work, with results summarised in Table 3.3.

The significance of each of the operational and embodied requirements in the case of the zero energy building balance is highlighted in one of the most comprehensive studies investigating zero energy residential buildings by Dokka et al. (2013) in Oslo, Norway. In their modelling study of a typical single family (2 storey) Norwegian residential building, they took into account a wide spectrum of parameters necessary for components and solutions of a zero energy building in the Norwegian context. The first scenario modelled i.e. ZEB-O (operation), only included operational energy in the zero energy balance and achieved 100% annual energy balance. At the same time, as soon as they took into account building

embodied energy of materials and systems in the balance, i.e. scenario ZEB-OM (Operation & Materials), the energy balance reduces to 75%. The embodied energy therefore represented a significant share of the total annual energy demand.

Another study was completed by Cellura et al. (2014), looking at an apartment building comprising six flats located in Angeli di Rosara, Ancona, Italy. In this study, the authors' premise was to extend the zero energy building methodological framework (Sartori et al., 2012), through encompassing embodied energy of building materials and components along with operational energy in the energy balance. At final energy level, excluding embodied energy, the annual energy balance based on load/generation method was achieved at 94.7%. These outcomes highlight that the apartment complex could be considered as a 'nearly zero energy building' even when the encountered energy flows are measured at the final level. On the other hand, when the authors include the requirements of building embodied energy of materials and systems within the zero energy balance at primary energy level, the energy balance drops to 16.3%. Again, as in Dokka et al. (2013), each of the two energy flows, i.e. operational and embodied is found to represent a significant share and hence leads to the energy balance deficit.

To this extent, these two studies only deal with building embodied and operational energy. Another study completed by Marique and Reiter (2014), proposes a simplified 'zero energy neighbourhood framework' whilst taking into account building operational and transport energy only within the zero energy balance (excluding embodied). This study focuses on multiple dwellings in the city of Liège, Belgium and reveals that, on average, each dwelling can have a lower energy balance ranging from 27.8–45.7%. Arguably, the omission of building embodied energy in the balance entails that these ratios could even be much lower. In addition, this study also suffers from other major flaws. Firstly, the authors calculated annual transport energy demand based on the 'commute-energy performance index' developed for the Belgian Flanders region by Boussauw and Witlox (2009), which only takes into account user transportation energy for commuting. Yet transport energy for commuting tend to constitute 30% of the annual total transport energy,

as 70% is attributed to other purposes. This trend is apparent in the United States (AASHTO 2013), and also in New Zealand (Vale and Vale 2013). Another flaw is the omission of embodied energy of transport. For instance, they consider an energy requirement of 0.61 kWh/passenger-kilometre for a petrol vehicle, while Jonson (2007) has shown that embodied energy for Swedish road transport (i.e. European context) can be 45% of the total, meaning that their energy intensity figure for vehicles could almost double. The transport energy intensities used by Marique and Reiter can therefore be considered as very conservative. Incorporating embodied energy and accounting for other trips along with commuting in transport energy calculation is therefore likely to greatly increase its share in the total household energy demand and decrease the energy balance.

The studies by Dokka et al. (2013), Cellura et al. (2014) and Marique and Reiter (2014) deal with a European context which may not be transferrable to Southern Pacific conditions due to different climates, city layouts, construction paradigms and transport characteristics as well as variations in the electricity generation mix. In the face of the zero energy building concept, in order to verify that each of the three energy requirements constitutes a relevant portion in the total energy demand of households in this region as well, a preliminary study was undertaken by the author of this work for Auckland, New Zealand. The details of this study can be found in Nsaliwa et al. (2015). The work integrates building operational, embodied and transport energy requirements within the zero energy building balance for a household. While this study relies on average figures from the literature to calculate the building embodied energy aspects, the results demonstrate that each energy flow represents a significant share of the total annual energy demand and can therefore affect the energy balance (see Table 3.3) below.

Table 3.3: Annual energy demand and energy balances for studies incorporating operational, embodied or transport energy within the zero energy balance

Case	Location	BOE	BEE	TE	Energy balance	Balance method
Dokka et al. 2013	Oslo, Norway	6.2MWh	7.9MWh	N/A	75%	Load/generation

Cellura et al. 2014	Ancona, Italy	9.8 MWh	11 MWh	N/A	16.3%	Import/export
Marique and Reiter 2014	Liège, Belgium	8.8–9.5MWh	N/A	5.9–8MWh	27.8–45.7%	Load/generation
Nsaliwa et al. 2015	Auckland, New Zealand	2.3MWh	2.4MWh	22MWh	16.7%	Import/export

Table 3.3 shows that the two studies utilizing the import/export balance method provide much lower zero energy balances compared to studies utilizing load/generation balance. The absolute operational energy figures for European studies are higher due to the requirements for space heating in cold climates as compared to New Zealand (see Section 3.3.1.1.a). At the same time, building embodied energy figures are lower in the New Zealand study due to lower initial embodied energy residential building construction paradigms in New Zealand (Mithraratne et al., 2007).

Also, in general, embodied energy figures in different locations can vary widely due to methods of calculation. Ideally, studies relying on purely input-output methods provide lower figures than those relying on hybrid-based input-output based approaches (Crawford 2011). Further details regarding these techniques are elaborated in Section 4.2.1.2.a. For the Belgian study considering transport energy, the figures are much lower due to the sole inclusion of energy requirements for commuting only and the exclusion of transport embodied energy. With this highlighted, the only systematically complete study conducted in New Zealand reveals that current application of the zero energy building concept, which solely focuses on building operational energy, ignoring the embodied energy of buildings and transport energy of their users, might be overlooking ~83% of energy attributed to these two demands in the energy balance.

3.5 Limitations of current applications for a holistic zero energy building approach for buildings and their users

The built environment is increasingly seen as a setting where innovations that can trigger a social-technical transition toward more sustainable building trends is emerging and maturing. Consequently, highly ambitious goals such as zero energy building concepts abound in the academic literature. Nonetheless, even though there has been a certain degree of clarity and strong underpinnings regarding the current application of such notions, they still suffer from a variety of noticeable flaws. The complicated interplay between buildings and the variability of their users' behaviour makes it unclear whether the current zero energy building design approach captures all the necessary impacts in the built environment. The zero energy building framework attempts to provide an advanced technical guide towards practical design of building energy systems. However, there is still a great deal of uncertainty linked to the methods involved (Bourrelle et al., 2013). While there is a mutual agreement regarding the incorporation of building operational energy within the zero energy balance (Sartori et al., 2012), there exists *prima facie* evidence of ambivalence when it comes to building embodied energy. In addition, in the face of current zero energy building applications, the transport energy of users is generally overlooked with very minimal evidence towards its considerations.

Besides these limitations which are inherent to the integration of each building energy type at multiple scales of complexity, the three main problems which concern the current application of the zero energy building concept are detailed in this section. Firstly, the representation of buildings as 'stand-alone' objects in the current approach is described. Secondly, marginal representation of the user in the face of zero energy building concept application is presented. Finally, the third section exposes present fragmentation associated with the zero energy building concept and its 'scale-specific' nature with limited concern for uncertainty.

3.5.1 Representation of buildings as ‘stand-alone objects’ in current application of the zero energy building concept

Traditionally, energy at the city scope is considered in terms of building scale and urban scale (Anderson et al., 2015). While this demarcation is necessary for creating boundaries due to the complexity of the built environment in the city context, it brings forth a set of problems. In reality, not only are buildings interconnected to their surroundings through physical mechanisms such as infrastructure, but also through their users (e.g. residents, workers and so on). Consequently, the interconnectedness of buildings with their surrounding urban context needs to be quantitatively and collectively considered in designing for environmental implications.

For instance, the current zero energy building framework considers only building operational energy in the zero energy balance. Yet energy requirements resulting from the location of the building, i.e., user transportation and other infrastructure are omitted (Bourrelle et al., 2013; Marique and Reiter 2014; Hui 2015; Rovers 2015). Buildings and their users are responsible for these energy requirements at the city scale. Accounting for all these demands when implementing zero energy building principles would provide a much more comprehensive means of design approach and therefore more meaningful reduction of overall energy demand. Clearly, there are different environmental consequences between buildings located in dense urbanising centres and sprawling automobile-dependent low-density suburban areas (Glaeser and Kahn 2010; Jones and Kammen 2013; Minx et al., 2013; Wiedenhofer et al., 2013).

Today, the current zero energy building framework follows the traditional approach of most national energy efficiency programs by only taking into account building operational energy. While such building policies have praiseworthy ambitions at the building scale, they might fail to capture even greater energy requirements linked with the building at the urban scale. All these problems become apparent due to, in part, the marginal representation of the building user in the current zero energy building framework.

3.5.2 Marginal representation of the user in current application of the zero energy building concept

Energy performance associated with buildings has seldom been viewed as a technical exercise linked to the design stage (Stephan 2013). However, the rising awareness of building energy performance in operation has begun to shift this trend.

As such, another noticeable flaw arising from the current zero energy building concept application is the inability to join the technical aspects of the building with the user-related aspects (Pan and Ning 2014). For instance, the ambition of reaching zero energy at the building scale has resulted in the ambivalence towards the inclusion of other user related energy demands such as appliances. See for example, Sartori et al. (2012) and Berggren et al. (2013). Yet studies investigating the user-related operational energy in low energy buildings have underscored its significant contribution (Blom et al., 2011).

In addition, as was argued in the previous section, energy requirements linked to the building user at the urban scale such as transport energy and other infrastructure are typically not considered. Taking into account buildings and their users' energy requirements at different scales of complexity can encompass the current fragmentation towards the application of the zero energy building concept to buildings and their users.

3.5.3 Fragmenting the application of the zero energy building concept to buildings and their users

Current research in the built environment can be summarised based on ten categories: materials, architectural design, operational systems, structural systems, construction, urban form, density, transportation, infrastructure, consumption and analysis methods (Howard et al., 2012; Anderson et al., 2015). In simple terms, all these aspects can be further split into attributes affecting energy use at the building scale: operational and embodied energy and at the urban scale: transportation operational and embodied energy of other infrastructure.

Accurate representation of all the energy attributes further leads to the question of analysis methods. Indeed, energy analysis across different scales of the built environment is subjected to uncertainties related to the quantification of various parameters (Howard et al., 2012; Stephan et al., 2012; Stephan 2013; Anderson et al., 2015). When it comes to building operational energy, there could be errors related to the discretization of simulation models (De Wit 2004). These modelling uncertainties are typically reduced by subjecting the model to realistic building configurations. However, this good practice is not a general trend in the current zero energy building framework application. This often results in performance figures which diverge from design values during post-occupancy measurements. Also, other scenario-related uncertainties, e.g. influence of climate, user behaviour beyond the building scale (comfort choices, travel habits, mode choice etc.), are not taken into account.

Ideally, the absence of integrated impacts resulting from the interactions between buildings and their users in urban contexts further complicates the efforts being exerted towards reducing uncertainty accounting on energy analysis in the built environment. Essentially, all these vexing problems call into question the ability to achieve the desired environmental objectives, i.e. climate change mitigation within the built environment. Consequently, a new wave of thinking is urgently required to enable the current application of zero energy building practices to capture energy requirements from other sectors including manufacturing and transport.

3.6 Conclusion

This chapter has first reviewed the current methods and application of the zero energy building concept before comparing four studies integrating the combination of either building operational, embodied or transport energy of their users within the zero energy building balance.

Application of the zero energy building concept typically involves balancing the integration of building energy requirements for extraction and manufacturing of raw materials and systems, construction, operation, maintenance and demolition with energy production from on-site or off-site renewable sources. This framework

can offer a holistic building energy balancing technique at different resolutions, from individual materials to the city scale. However, the zero energy building framework is rarely utilized at whole building level and its full potential is currently under exploited due to the complexity of direct/indirect building-user energy requirements at different scales of the built environment.

Depending on the project goal or country specific building policy targets, designers and clients can generally agree on which particular energy demands are to be included within the zero energy balance boundary. Typically, these energy requirements are limited at the building scale: operational and embodied energy. When it comes to the balancing technique, the use of 'import/export' balance method typically generates more reliable energy balance figures compared to the load/generation since the approach takes into account energetic aspects attributed to the grid imported energy associated with carriers (i.e. electricity), e.g. grid losses and so on.

Amidst other metrics included in the zero energy balance such as cost amongst others, energy/emission is the most studied metric with regards to the zero energy building framework. Additionally, this is coupled with the fact that energy is responsible for much of the environmental impact associated with buildings. Ideally, zero energy building principles can be applied to all types of buildings, building clusters etc. However, due to the technical complexity of energy balance technique, this wide range of application is often limited to implementing buildings with extremely high efficiency gains and which produce as much energy as they consume in a year when accounted for at the site i.e. '*net zero site energy*'.

In parallel, most studies tackling mobility and user transport energy are undertaken at the city scale. Yet studies throughout the years have demonstrated a strong correlation between energy use for transport and urban form (land-use characteristics). At the same time, other studies have further shown that transport energy depends on the interplay between the building and the city scales based on the users' characteristics in the context of social and economic factors. In addition, studies employing LCA techniques also show that transport energy can account

for a very significant share of the total life cycle energy demand of buildings for over 50 years' service life.

The few zero energy building studies which have exploited the combination of either, building operational, embodied or transport energy requirements found that energy flows which are not currently universally integrated within the zero energy balance, i.e. building embodied and transport energy, can decrease the zero energy balance by approximately ~80% annually. This entails that if building embodied and user transport energy are not included in the zero energy balance, achieving zero energy balance through improving operational energy efficiency will most likely not meaningfully reduce energy use to zero and could even possibly increase it.

The zero energy building concept, as it is commonly applied today presents some noticeable flaws. First, treating buildings as 'stand-alone' objects and isolating them from their urban context results in impacts associated with location of the building not being captured in the energy balance. Second, limiting the zero energy building framework to 'technical' aspects of the building brings forth a segregation of its users such that user-related energy requirements at the building scale e.g. appliances demand and at the urban/city scale e.g. transport energy, are typically overlooked. Finally, the segregation of building scale from urban scale energy attributes in the current zero energy building approach results in further complexities towards addressing data uncertainty and parameter variability in energy quantification. As such, addressing these currently missing links is very crucial for a holistic zero energy policy in the built environment and in turn achieving environmental goals.

3.7 Research questions

In the face of current zero energy building practices, this fragmentation of scale is problematic as it ignores multi-scale levels of exploitation towards the ability to achieve environmental objectives. The absence of research regarding zero energy building notions at this inter-scale level calls for the development of a new zero energy building methodological framework to quantitatively capture, within the zero energy balance, all energy requirements resulting from the interplay of

individual buildings and the broader urban context, applicable for both new and retrofit scenarios.

Such a framework would help policy makers, researchers, architects, engineers and regional planners to test and determine the most appropriate means of implementing zero energy building principles across multiple scales of complexity. The establishment of a methodological framework aiming to determine the most appropriate means of implementing zero energy building principles across different scales in the built environment forms the main goal of this thesis. This will be informed by answering the following research questions.

- Is it possible to integrate transport energy (operation and embodied) together with building energy (operational and embodied) to form an integrated multi-scale zero energy building framework for residential buildings?
- What are the simplification aspects required in order to successfully integrate transport energy (operation and embodied) together with building energy (operational and embodied) to establish an integrated multi-scale zero energy building framework for residential buildings?
- How can an integrated multi-scale zero energy building framework for residential buildings inform design and urban/regional planning policy?

Chapter 4 | An integrated multi-scale zero energy framework for residential buildings

Although big strides have been made in the field of zero energy buildings in recent years, the current applications of zero energy building concepts discussed in Chapter 3 are narrow in focus and limited to the analysis of specific links. This fragmented approach mirrors exactly what is reflected in much of academic praxis today that is largely discipline-based. Put another way, the review from the previous chapter has revealed that this type of approach is unsuitable, particularly when testing highly complex, multi-dimensional issues such as the interdependence of buildings and their users at multiple scales.

In a pragmatic sense, the overall energy demand associated with zero energy buildings and their users is dependent on a panoply of factors at different scales of complexity. In Chapter 2, the interplay between energy and users in the context of zero energy building concepts has been pinpointed. The significance of considering energy as the environmental indicator has been justified and clearly emphasized. In addition, a brief historical overview pertaining to the advent of zero energy building concepts in chronological detail has been presented. Chapter 3 has reviewed and highlighted the current application of the zero energy building framework. This review has unravelled some major limitations surrounding the current methods of application associated with zero energy building concepts.

Studies which incorporate building embodied, operational and user transport energy within the zero energy balance, have also been presented and discussed. Specifically, these studies have highlighted that building embodied and user transport energy associated with zero energy buildings and their users, can account for a very high zero energy balance deficit on an annual basis.

Currently, building operational energy is generally the sole input incorporated within the zero energy building framework. There is ambivalence when it comes to the inclusion of building embodied energy. Furthermore, the exclusion of user

transport energy provides, rather, a more perplexing view of probing deeper into the problem. Certainly, the representation of buildings as “stand-alone” objects and the marginal representation of the user in most previous zero energy building studies have also been highlighted. Consequently, these observations regarding the absence of research on zero energy building concepts at this inter-scale level call for the development of a zero energy building methodological framework for residential buildings to encompass different scales of the built environment.

With this regard, the aim of this chapter is to define the research methodology used in order to answer the research questions presented at the end of Chapter 3 and develop a multi-scale zero energy building framework for residential buildings. Essentially, the methodological framework, ambition level and the various stages involved leading towards its development are first presented. Thereafter, the rules for calculation encompassing different quantification methods related to building embodied, operational and user transport energy are described, with reasons for selection clearly justified. The conversion of energy quantities into greenhouse gas emission metrics via the crediting system is then detailed and this is followed by an elaboration on uncertainty consideration. Finally, a brief description is then given of the case study used to verify the methodological framework and test its potential to explore how multi-scale zero energy approaches could inform building design and policy.

4.1 Ambition level

There are numerous other threats which have the potential to annihilate human existence, such as artificial intelligence (strong A.I.), pandemics, synthetic biology, nanotechnology and others (Bostrom 2014). However, as was presented in Section 2.2, the global climate crisis threat has become the defining moral issue of human present times (IPCC 2014). As such, the ambition level of the methodological framework is ultimately associated with the reduction of energy use and greenhouse gas emissions, which are closely linked to the phenomena of climate change in the built environment. The subsequent purpose of the framework is to impart the predominant pieces of information required to tackle energy demand and eliminate

greenhouse gas emissions in the residential sector in a potentially much broader perspective and at the same time provide much quicker alternatives. Significantly, the direct outcome of the developed framework is to implement a methodology which has the potential to inform on new design and living principles encompassing zero energy building practices today.

The developed framework will perform an ‘early stage’ integrated evaluation of design and living alternatives with the capacity to gauge the relative effectiveness towards the deployment of zero energy residential buildings at different scales of the built environment. Existing buildings which aim to conform to zero energy building concepts can then be audited with regard to building (embodied and operation energy) and user transport (embodied and operation energy) as well as the renewable energy supply options if available. The annual energy consumption of new buildings and their users, in terms of building embodied, operational and transport energy can be calculated along with their interplay with renewable energy supply options.

Building design parameters at early stages of design are often plagued with data limitations and constraints. Consequently, simple and yet realistic assumptions and approximations must be made to overcome the hurdles associated with inadequate information so as to provide meaningful results (Petersen and Svendsen 2010; Carlos and Nepomuceno 2012). On the other hand, however, the developed framework should also be flexible enough to allow for further development into a software tool for formalizing and automatic computation of variables in a quick and accurate manner.

The application of zero energy building concepts by integrating direct plus indirect energy demands originating from buildings and their users at different scales of the built environment is a daunting task, requiring skilled implementation of a medley of evaluation techniques. The building system boundary, data requirements and the different stages involved in the development are discussed hereafter.

4.1.1 Building system boundary

The framework considers all relevant aspects characterizing zero energy building concepts and allows for country specific solutions closely connected to the country's environmental targets and other local conditions (grid systems, renewable supply options and others). This methodological framework is based on the previous literature reviewed in Chapter 3 and builds upon the proposed concepts developed in the context of the IEA SHC Task 40 (Sartori et al., 2012). In order to help build bridges between the standard zero energy building framework and other common building environmental assessment tools such as LCA, the modified zero energy building methodological framework derived in this thesis contains other elements adopted from the comprehensive LCA framework developed by Stephan (2013).

Additionally, the framework developed should act as a basis for the evaluation of various design/retrofitting and living scenarios. Consequently, it is necessary to define the system boundary in order to establish which energy inflows and outflows are to be considered across the scope of the evaluation and investigation. At the building scale, the energy flows considered include; raw material extraction, material manufacture, construction and maintenance and building operation. While at the city scale, raw material extraction, material manufacture and maintenance of the transportation mode including infrastructure and operation are also considered. Thereafter, greenhouse gas emissions resulting from the energy use from all these conduits are taken into account.

Significantly, buildings that benefit from being connected to public infrastructure need be held accountable for their interconnected urban energy requirements (Carruthers and Ulfarsson 2003; Rickwood et al., 2008; Benito et al., 2010). Due to scarce data, the embodied energy requirements for other infrastructures supporting the building including sewage systems, water systems, electricity grid (low voltage), gas grid, plus demolition/disposal of building and transportation modes, cannot currently be considered in this framework. The exclusion of such aspects in this study is judged reasonable and does not affect the quality of the

results considering their lower energy intensity shares as reported in the literature. For instance, Norman et al. (2006) found that the existing infrastructure embodied energy of a suburban house near Toronto, Ontario, Canada represented ($\sim 7\%$) of the total life cycle energy demand over 50 years. More recently, Stephan (2013) and Stephan et al. (2013a) found similar figures ($\sim 7.4\%$) for a passive house located near Brussels, Belgium.

The methodological framework calculates energy demand in the context of a zero energy residential building and its user aspects on a year by year basis. From the designers'/evaluators', researchers' or policy makers' point of view, this is commonly known as the overall or total annual building energy demand. The total annual energy demand (as was stated previously) comprises energy demand at both the building and city scales. At the building scale, the energy inflows taken into account are: embodied and operational. Similarly, at the city scale, the energy inflows taken into account are: embodied energy of related transport infrastructure and operational energy of particular modes.

These energy *inflows* are oftentimes referred to as *life cycle energy stages* and the resulting energy *outflows* are commonly expressed in the form of environmental impact metrics such as CO₂-e and so on. (Finnveden et al., 2009; Crawford 2011). However, to maintain clarity and avoid confusion with other building measurement tools such as the “life cycle assessment” (see Section 2.2.3), the terms *inflows* and *outflows* are therefore frequently used in this work. Figure 4.1 overleaf, presents the energy *inflows* and *outflows* taken into account within the proposed framework. Embodied energy is normalised on an annual basis so as to be comparable with the annual operating energy demand.

Figure 4.1: Energy inflows and resulting outflows taken into account within the proposed methodological framework

Additionally, the framework will also allow the testing of urban neighbourhoods, composed of different buildings, i.e. building zones also known as districts. Throughout this thesis, a building zone or district is defined as a collection of multiple buildings of particular type. The reasons for extending the scope of investigation to encompass a whole suburban neighbourhood are explained hereafter.

The number of people living on earth has been projected to reach 11 billion by the year 2100 - a 50% increase from the current 7.13 billion (United Nations 2014). With developments of such magnitude, it is crucial to identify underlying concerns and potential pressures due to the expansion of the population. More importantly, this surge in population will be most prominent in ballooning mega-cities, whose

swelling occupancies will exacerbate social and environmental problems (United Nations 2014). Certainly, highly urbanizing centres and hubs which cater for people's needs will likely not escape these consequences (United Nations Human Settlement Programme 2009).

The increase in global population may trigger an overwhelming interest to develop new housing units in world cities. Multiple studies have concluded that increasing population in cities entails deployment of new buildings and expansion of road networks thereby paving the way for an increase in "low-density suburban neighbourhoods" (see e.g.; Angel et al., 2011; Yaping and Min 2009; Zhao 2010). This trend is already apparent in many countries, e.g. China, South America, North America, Australia, New Zealand etc. (Yaping and Min 2009; Howden-Chapman et al., 2010; Yew 2012; Stephan 2013; Rojas et al., 2013). Low-density suburban neighbourhoods are believed to be highly energy intensive since they often comprise large detached single family houses with high reliance on private vehicles for transport (Newman and Kenworthy 1999; Jenks et al., 2000; Van Coevaring and Schwanen 2006; Karathodorou et al., 2010 Glaeser and Kahn 2010 ; Stephan 2013; Stephan et al., 2013b; Minx et al., 2013; Weidenhofer et al., 2013).

As such, zero energy building concepts are increasingly becoming popular and are being adopted in many regions of the world as the basis for building energy regulations and policy (see Section 2.2.5 Figure 2.2 and Section 3.1.2). Thus, in addition to the fact that future cities will be characterized by low-density suburban neighbourhoods, it is imperative to stretch the building system boundaries and investigate the potential implications of zero energy residential buildings and their users at whole neighbourhood level across different scales of complexity.

4.1.2 Crediting system

A crediting system ensures a reflection of the desired regional/national environmental targets or preferences in the context of zero energy building practices and their wider societal implications. Consequently, the crediting system considered in this framework should allow the conversion of physical energy units associated with different energy carriers into uniform metrics, thereby facilitating

the consideration of an entire energy chain associated with energy carriers (i.e. distribution/transmission grids etc.). The conversion of physical energy units into other quantifiable metrics: kWh/MWh to CO₂-e, accounts for the energy use and the resulting environmental impact which is measured using various reference flows. Reference flows in accordance to each indicator (energy use or environmental impact) are chosen to calculate the annual energy demand *inflow* and greenhouse gas emissions *outflow* for residential buildings and building zones in the context of zero energy building concepts at different scales of the built environment. Table 4.1 provides the list of reference flows for each indicator used in the framework.

Table 4.1: Reference flows used for the methodological framework

Indicator unit		Evaluated building system boundary	
Energy use	Environmental impact	Building	Building zone/district
MWh	CO ₂ -e	✓	✓
MWh/annum	CO ₂ -e/annum	✓	✓
MWh/m ²	CO ₂ -e/m ²	✓	✓
MWh/capita	CO ₂ -e/capita	✓	✓
MWh/km ²	CO ₂ -e/km ²		✓
MWh/m ² /annum	CO ₂ -e/m ² /annum	✓	✓
MWh/capita/annum	CO ₂ -e/capita/annum	✓	✓
MWh/km ² /annum	CO ₂ -e/km ² /annum		✓

Analytically, the indicators account for the energy performance of the building system boundary: the *flows* controlled by the elements of the system and by the system itself in absolute terms (extensive) and in relation to the floor area under which it is performed (intensive). Accounting for or normalising energy use in terms of usable floor area as the indicator allows the comparison of buildings based on different sizes, types etc. This approach has also been widely used for similar scenarios globally (Stephan et al., 2012; Stephan 2013; Stephan et al., 2013a).

In addition, as was first argued in Section 2.1.3, expressing results using per capita reference flows paves the way for the consideration of user-related characteristics

for different households, e.g. lifestyle choices, number of users, consumption patterns and so on (García-Casals 2006; Chen et al., 2013; Stephan 2013; Stephan et al., 2013a). Furthermore, reporting results basing on per km² of building zone ensures a more transparent comparison of buildings based on larger built areas. More significantly, expressing the overall or total energy demand of households or building zones on an annual basis allows the comparison of different buildings or building zones with different household characteristics and consumption patterns for a given time period (Stephan 2013; Stephan et al., 2013a).

4.1.3 Data acquisition

One of the major tasks when executing calculations based on the framework is acquiring the relevant data to successfully quantify the requirements for building embodied and operational as well as transport energy (both embodied and operation). Consequently, datasets of each of the energy inflows stated above require to be sourced from the existing databases in order to execute the quantification processes effectively.

Essentially, the past 20 years has been an era under which multiple databases for embodied energy of different materials in the built environment have flourished (Alcorn 2010; Crawford 2011). Examples of some of the most prominent embodied energy databases and programs include: Ecoinvent®, GaBi®, SimaPro®, Athena® etc. In general, these databases are commonly used since they are believed to contain embodied energy data of reasonably high quality.

However, often this data is derived from either process-based or pure input-output based embodied energy calculation methods (Crawford 2011). As was discussed in Section 3.4.2, process or purely input-output-based embodied energy data tends to provide lower embodied energy figures than hybrid-based process/input-output data (Further details regarding these techniques is elaborated in Section 4.2.1.2.b). Ultimately, since no database which provides hybrid-based process/input-output data exists to date, the data provided by such databases might result in wrongly estimated figures as demonstrated and argued by Alcorn (2010), Crawford (2011) and also Stephan (2013). Nevertheless, in order to obtain an estimate of the

embodied energy requirements for building components, the data gathered from existing databases has to be used, with the proviso that more detailed hybrid data could be used in future research, should such data become available.

On the other hand, the quantification of operation energy is based on building energy simulation computer programs. In this regard, the framework relies on the collection of data for dynamic simulation obtained from preliminary building visualizations and documentations including photos of buildings, relevant measurements (building floor heights, type of façade, windows per façade, windows and roof materials, number of windows per façade and dedicated systems: solar photovoltaic array, DHW and others) and also actual technical documentation including energy audit reports and weather data from monitoring. In this way, the reliance on actual building performance data for setting simulation parameters enhances the accuracy of the modelling exercise and therefore solidifies the likely validity of operational energy figures.

The calculation of user transport energy is based on four key data ingredients: the travel distance data, modal split data, transport operational and embodied energy intensity coefficients. Generally, authorities from different countries/regions usually undertake nation-wide travel surveys and produce reliable average travel distance as well as modal split data for public consumption. In addition, travel distance data can be verified through personal occupant interviews for the studied dwellings (Perkins et al., 2009).

Data on operation energy intensities of transport is readily available in the public domain, especially through transport mode manufacturers' data. On the other hand, very little data exists when it comes to the embodied energy intensities of user transportation (Lenzen 1999; Mithraratne 2011; Stephan 2013). Consequently, it is judged suitable to implement reasonable assumptions based on studies of similar transportation contexts in the case where embodied energy data for transport is not locally available.

Finally, as was previously discussed, this work also takes into account the greenhouse gas emissions associated with energy use (see Section 2.1.1.1). Greenhouse gas emissions intensity coefficients for different materials and assemblies are usually incorporated in the same dataset as the embodied energy figures. In contrast, the greenhouse gas emissions closely linked to the building operation energy have to be calculated with respect to different types of energy sources, specified for each energy carrier (e.g. hydro power, wind, solar, coal, natural gas and so on).

In addition, the greenhouse gas emissions associated with transport operation requirements are generally available in the public domain, especially through the manufacturers, based on each specific vehicle or transport mode. On the other hand, transport embodied energy greenhouse gas emissions are usually incorporated in the same dataset together with the embodied energy intensity data. Furthermore, in case of electric transport, the greenhouse gas emissions for operational energy are calculated based on the type of energy sources used, specified per each energy carrier delivering energy to the transport mode, i.e. coal, hydro power, solar etc.

Essentially, it is imperative to acquire relevant data in order to test the potential applicability of this study. Consequently, in circumstances where significant data is not available, reasonable assumptions have to be made and documented to ensure that a degree of transparency and fairness of the research is clearly manifested. These assumptions will be explained as and when they occur.

4.1.4 Framework development procedure

There are three different stages required in order to establish the methodological framework used in this work. These stages include: framework development, integrating disparate energy use flows for complementing the multi-scale zero energy building framework and the verification of the framework calculations through case studies. Figure 4.2, presents the required stages involved in the development of the framework.

The first stage involves the development of quantification formulae used for calculating building embodied energy and user transportation energy. In addition, the quantification of building operation energy requirements using building energy simulation software is also presented. Further details regarding the parameters for choice of program are provided in section 4.2.1.1.a. Stage two involves the integration of disparate energy use flows resulting from different quantification techniques as developed in stage one. This stage elaborates how the resulting outputs from the different quantification techniques used are combined to effectively leverage the framework's applicability leading towards a multi-scale zero energy building approach. More details regarding this procedure are highlighted in Section 4.3. The third and final stage involves an elaboration on the verification of the methodological framework and testing out its potential through one case study. An overview of the case study is given in 5.2 in Chapter 5.

Figure 4.2: Stages involved in the development of the methodological framework

4.2 Rules of calculation

The quantification of disparate energy flows at both the building and city scales as pinpointed from the previous chapter can be very demanding and highly complex

because it involves multiple datasets from various sources. Despite the wide range of tools available for built environment analyses, it is still hard to find a program that can be used throughout the entire design process, where the requirements vary from the requisite speed to conduct rapid conceptual design iterations, to undertaking detailed building embodied energy, user transport operational and embodied energy analyses as well as exploring the dynamics of electricity grid development in the residential sector. Consequently, as declared in Section 4.1, the calculation process for interconnecting building and city scale energy use flow is undertaken separately and then outputs are integrated. Building operational energy is quantified through the computer program Energyplus®. Building embodied energy, transport operational and embodied energy are calculated manually through Microsoft Excel® spreadsheet using equations provided in Section 4.2.1.2.b to 4.2.1.2.d and Section 4.2.2.2 respectively.

In addition, by focusing on a fairly wide and oftentimes overlooked research arena, this thesis has opened itself to the potential pitfall of spreading itself too far. Consequently, crucial decisions had to be undertaken to facilitate the integration process and at the same time achieve timely and reliable results. The goal of the following sections, is therefore to elucidate the development and simplifications employed in order to achieve accurate and realistic integration of different energy use flows at both building and city scales.

Firstly, quantification features pertaining to building energy use (operation and embodied) and user transport energy use (operation and embodied) are presented. Various simplifications of the quantifications processes are established in Section 4.2.1 and 4.2.2 respectively. Finally, the integration of different quantification aspects is determined in Section 4.3.

4.2.1 Establishing building energy use

The following section gives information on the relevant calculation procedures with regards to building energy use (operational and embodied energy). Firstly, information regarding operational energy quantification aspects is discussed and relevant simplifications are established. Thereafter, details related to embodied

energy quantification aspects are also determined. As was previously mentioned, equation variables including 4.1 to 4.30 are based on the comprehensive LCA framework developed by Stephan (2013).

4.2.1.1 Building operational energy

As was previously discussed, building operation energy is the most considered energy demand within the current ZEB framework (Sartori et al., 2012). At the same time, embodied energy of building materials and components is also rarely considered (Hernandez and Kenny 2010; Rovers 2015) while the transport energy associated with the users is not taken into consideration. Furthermore, as was observed in Section 3.4, including building embodied and user transport energy can imply a very significant energy balance deficit for zero energy residential buildings. The operation energy breakdown considered in this work includes: heating, cooling, cooking, domestic hot water, lighting and appliances. This type of energy end use breakdown is typically used for most national statistics regarding building operation energy requirements. See for example; EIA (2009) in the U.S.A, DEHWA (2008) in Australia, ICEDD (2010) in Europe and the Household Energy End-use Project (HEEP) in New Zealand (Isaacs et al., 2010b).

In parallel, building systems that deliver energy services for end use operation such as HVACs or renewable energy generation systems (RES) are most likely to deteriorate across the buildings' service life. To a certain degree, the deterioration of building systems has implications on the performance of building operational energy in the course of the year. Ultimately, building systems may deteriorate in terms of their efficiencies and other technical constraints. Consequently, it is important to take into account the possibility of building system deterioration rates across their service lives in order to evaluate their implications on operational energy. However, due to the wide variation of building system types, building types and service lives, it is difficult to estimate their levels of deterioration although some studies have attempted to address this crucial aspect. For example, Jordan and Kurtz (2012) provide an in-depth view regarding the degradation rates of photovoltaic panels in the American context. At the same time, Griffith et al.

(2008) articulate and highlight the deterioration of HVAC systems. Nonetheless, details regarding these phenomena and how they affect building operational energy demand within such literature remain very sketchy and scarce and mostly unreliable. For these reasons, the degradation of building systems and their implications regarding operational energy are not considered within the calculations of this work. This aspect can however be considered for further research as pinpointed in the final Chapter.

Along these lines, in the face of zero energy building concepts, on-site energy storage systems have recently become a factor to consider thanks to the so-called “Tesla Powerwall” in particular (Rodrigues et al., 2016). Tesla Energy debuted the Powerwall at a launch at the end of April 2015 (Rodrigues et al., 2016). This product has proven popular in the U.S.A, Europe, Australia and New Zealand. Essentially, these home lithium-ion batteries are expected to proclaim victory over fossil fuels and eventually kill-off the centralised grids, for both residential and commercial building sectors (Bulman 2015). Residential buildings are expected to be powered entirely by roof-mounted PVs coupled with battery systems or connected to the grid (see Section 3.1.2). Vale and Vale (2000) noted that connecting residential on-site RE systems to the grid to achieve *net zero energy* can have the same or even much better performance than free-standing autonomous houses in a ‘life cycle’ perspective. This was due to the use of electric storage systems being avoided and some flexibility in the use of appliances being gained in the process. In addition, recent work in Australia by Khalilpour and Vassal (2015) has critically examined the idea behind completely ditching the grid in the context of residential buildings under various scenarios, e.g. PV-battery technologies, system sizes and building operation energy. Under the scenarios, staying connected to the grid resulted in lower operating costs, more reliability and much more convenience for the building occupants.

Lithium-ion batteries are more efficient and have higher performance than their counterpart lead-acid batteries. However, recent studies demonstrate that embodied energy for lithium ion batteries can actually be higher than for lead-acid

batteries: 1.4-1.87 MJ/Wh (United States Environmental Protection Agency 2013; Larcher and Tarascon 2014) and 0.87-1.19MJ/Wh (Rydh and Sanden 2005a, 2005b; Garcia et al., 2009), respectively. Surprisingly, Tesla Motors has been tight-lipped about the environmental implications of their storage batteries. It can be argued that the fate and implications of storage batteries such as Powerwalls are therefore far from being established and how the regulatory hurdles will be negotiated is still unclear. At this juncture, operational energy calculations within the proposed methodological framework therefore do not consider on-site energy storage. Likewise, this aspect might form a good basis for further research related to the findings of this study.

4.2.1.1. a Adopting suitable operation energy calculation method

There are three major approaches for quantifying annual building operation energy requirements namely; national empirical data, quasi-steady-state-methods and dynamic calculations. The following section elaborates on the available techniques for quantifying annual operation energy demand. In addition, the particular method for operation energy calculation selected for this study is highlighted.

NATIONAL EMPIRICAL DATA METHOD

National empirical data method is an approach that can be used to quantify building operational energy requirements. This approach provides a simple and a quick way to estimating annual operational energy demand compared to other available approaches such as quasi-steady-state-method and dynamic calculations.

Due to its simplistic nature, this method is very advantageous since the nation-wide data for building operational energy for most developed regions is readily available and easily accessible in the public domain, thereby making it easy to quantify operational energy requirements much faster within a reasonable timeframe. Examples of works relying on national average data to calculate building operational energy for residential buildings in the New Zealand contexts include; Mithraratne et al. (2007) and Alcorn (2010). The only principal requirement when using such technique is to ensure that the data is up-to-date.

However, as simple as this method appears to be, it may not be reliable. This is because the technique involves the estimation of numerous figures for complex building scenarios. This would most likely induce a medley of inaccuracies, errors and flaws in the calculations. Consequently, to avoid obtaining unreliable results, this method is not used in this work. Instead, the average national data will be used as a basis for comparison with the quantified figures and also for comparing variability of user-related building energy variables including domestic hot water, lighting, cooking and other appliances.

QUASI-STEADY-STATE METHOD

The second option for calculating building thermal energy demand is the use of quasi-steady-state heat transfer equations (also known as static heat transfer equations). These equations often rely on two key variables: (1) Building characteristics i.e. average heat transfer coefficients (*U values*), heat transfer surface areas, ventilation flow rates etc. (2) Climatic data : heating or cooling degree days or hours and other factors. In addition, solar heat gains and other heat resulting from electrical equipment are also generally accounted for.

This simplified method requires significant preliminary data such as building orientation, glazing surfaces, ventilation rates and heat transfer coefficients of the building envelope, most of which are not usually known at early stages of design. Some studies claiming to evaluate building thermal performance at early design stage based on these simple methods include the works by Neilsen (2005); Petersen and Svendsen (2010) and Carlos and Nepomuceno (2012).

Although these studies contain valuable insights regarding the quantification of thermal operation energy using steady-state methods, they often fail to indicate the level of approximation during the early design stages and are plagued with somewhat inconsistent data. Moreover, the steady-state methods also suffer from other flaws including the need for the designer or evaluator to accurately estimate building envelope areas, such that the designer or evaluator must compute and provide the properties of the envelope such as *U values*, thermal inertia of envelope, solar heat gain coefficients and reduction factors for shading devices. In addition,

these simple methods quantify building loads accounting for heating or cooling energy requirements, yet the remaining demands (non-thermal aspects) are usually determined from national average data. For the reasons mentioned above, quasi-steady-state- heat transfer methods will not be used for the methodological framework.

DYNAMIC CALCULATION METHOD

The most accurate method for quantifying annual building operation energy requirements is by using dynamic methods. This technique for energy quantification relies on building energy performance simulation programs, thereby enabling energy quantification on an hourly basis, through a series of iterations taking into account different heat transfer mechanisms and phenomena (Crawely et al., 2008).

Energy performance simulation programs are very powerful tools to evaluate energy performance and thermal comfort in buildings on an annual basis. Significantly, there are two types of building energy performance simulation programs being used today: design tools, which mainly focus on sizing HVAC equipment, and simulation tools, which predict the energy performance of the building annually. Design tools are based on worst case scenario calculation approaches to establish the selection of HVAC equipment size (based on summer and winter design days that characterize the extreme conditions for the building in question). These are based on steady state calculation equations. A critical summary of algorithms used in most popular building energy simulation programs such as EnergyPlus®, DeST® and DOE-2.1E® is provided in Zou et al. (2013).

Ideally, although building energy simulation programs require advanced expertise to operate, they should provide more accurate means of calculating annual building operational energy demand than relying on either national average data or steady-state-equations. For this reason, it is judged suitable to adopt dynamic calculation techniques to quantify annual building energy requirements in this work. Moreover, building energy simulation programs have been used to calculate operational energy within the current ZEB framework (see Section 3.1.3.1.a).

4.2.1.1. b *Calculating operational energy*

There are two major parameters that account for building operational energy requirements, notably: building-dependent parameters and user dependent-parameters (Erlandsson and Borg 2003). The latter category is characterized by the number of building occupants while the former consists of building-oriented aspects such as building size, thermal properties (material types, thermal conductivity, specific heat and so on) and building systems (HVAC, PV array, DHW). Calculation of operational energy in this work will be based on both building dependent-parameters and user-dependent parameters through calculations based on an energy simulation program.

Essentially, the whole building energy simulation method calculates heat or energy transfers between specific volumes of air, i.e. “thermal zones”, and also quantifies the energy consumption required before each thermal zone reaches the particular set points pertaining to temperature, humidity and/or ventilation. In that way, the process of creating a model for whole building simulation generally begins with defining thermal zones. A thermal zone can be a room or a group of rooms in a building which has similar internal conditions (e.g. number of people and their activities, lighting, electric equipment etc.). In this work, they are distinguished by three categories: living spaces which comprise living area, kitchen and bathrooms, bedroom spaces and others (e.g. laundry areas). Section 5.4.2 in Chapter 5 provides details of the data required for the whole building energy simulation used in this work.

BUILDING THERMAL AND SIMULATION PROGRAM

Energy simulation tools can estimate the annual energy performance of a given building and thermal comfort for its occupants. In general, they support the understanding of how a given building operates according to building or user-related variables and enable comparison of different design alternatives. Generally, there are numerous energy simulation programs available today. This work uses Version 8.1 of EnergyPlus®.

EnergyPlus® is a tool that can be used at multiple stages of the building's design life and that provides functionalities to exchange data with other related tools in question (Underwood and Yik 2004). For instance, it can couple to advanced HVAC analysing tools such as HEVACOMP®. Consequently, EnergyPlus® was selected for this work due to the following reasons:

- a) The significance of EnergyPlus® is underlined by its broad usage and wide recognition in the industry because it is well-tested and validated through Building Energy Simulation Test (BESTEST³) (Neymark et al., 2001 ; Witte et al., 2001; Henninger et al., 2003; Crawley et al., 2008) ; and
- b) EnergyPlus® has been used in multiple studies for simulating energy performance associated with zero energy residential buildings (Wang et al., 2009).

As was mentioned above, this work takes into account building related as well as user-related energy parameters associated with operational energy. EnergyPlus® is a thermal load and energy analysis calculation program which uses hourly or sub hourly time intervals to calculate building energy demand and advanced building physics aspects, e.g. air temperature stratification (Underwood and Yik 2004). This takes into account the interplay between building occupancy and aspects such as HVAC systems, cooking, lighting, hot water and other appliances. More details regarding the capabilities of EnergyPlus® are given in Crawley et al. (2001) and Crawley et al. (2008).

Nonetheless, although EnergyPlus® is suitable to be used in this work, the program itself suffers from flaws when it comes to simulation of one significant parameter used for modelling in this work: natural ventilation. To begin with, EnergyPlus® simulates the possible amount of outdoor fresh air to be vented in a particular building based on local outdoor conditions and openings or window characteristics through the “Airflow Network” algorithm (further details on this object can be found in EnergyPlus® Input/output reference Section 1.27).

³ BESTEST is a standard validation method of test for building energy simulation software.

Ideally, EnergyPlus® through the Airflow Network algorithm models one-way airflow, i.e. it does not model air leaving the building through the same opening/window supplying air to the building (Lixing 2007). This is likely to result in overestimated energy demand in the model. To overcome this limitation, other accurate Computational Fluid Dynamics (CFD) simulation programs can be used. However, the coupling of CFD programs with EnergyPlus® requires an additional set of programming skills and is data intensive, two conditions which have not been met in this thesis. However, there is evidence that using the simple natural ventilation option to model can provide a reasonably confident means of modelling natural ventilation since it uses weather files wind data to calculate specific ventilation rates based on specific wind speeds/direction and window characteristics per hour (or smaller) intervals on an annual basis (Deru et al., 2002). In other words, EnergyPlus® provided such data is available can still provide reasonably accurate results without the use of other external CFD programs. Further information regarding natural ventilation modelling in this work can be found in Section 5.4.2.2.f.

INPUT/OUTPUT PARAMETERS FOR BUILDING ENERGY SIMULATION

To integrate the operational energy results from the simulation exercise, modelling information and parameters have to carefully be gathered to ensure that successful energy simulations are achieved. Consequently, a systematic approach is observed for gathering building simulation information regarding geometrical approximations, materials, thermal zones, building systems and other energy use related parameters. Figure 4.3 below displays a summary of energy related information stages as used for modelling in this work.

Figure 4.3: A summary of building modelling stages as used for this work

Simulations can oftentimes be fallible due to the simplified modelling approach (Malkawi and Augenbroe 2004). However, the use of commonly available building energy performance data such as HEEP (Isaacs et al., 2010b) and the actual measured data for other residential buildings studied, enhances the model's realistic adaptability for simulation purposes.

Besides, as with any given building energy performance simulation exercise, the accuracy of the simulation is determined by the specifics of the input data. The input simulation data in this work consists of: building geometry, assigning thermal zones, internal loads, and HVAC and RE system components, weather data, operation strategies and occupancy schedules (discussed in Section 5.4.2.2). Essentially, once the modelling parameters have been assembled, the next step necessary is to introduce the required data in question to the simulation tool. Consequently, within the EnergyPlus® tool, the applied calculation process considered for this work is performed in the manner as shown in Figure 4.4 below.

Figure 4.4: Building operational energy calculation process using Energyplus® to obtain annual energy demand for particular building

CONVERTING FINAL ENERGY DEMAND TO DELIVERED AND PRIMARY ENERGY

As was argued earlier in Section 2.1.1.2, the *primary energy* metric is arguably the best indicator for measuring total energy demand since it comprises an energy form found in nature and that which has not been subjected to any conversion or transformation processes. Consequently, the final energy requirements are further converted to primary energy units based on the appropriate conversion factors (e.g. for hydro, wind, solar, coal and so on). The conversion from final energy (or useful energy) to primary terms firstly involves the conversion of the actual final energy to delivered energy taking into account the efficiencies of the systems of end-use aspects. Each of the delivered energy demands can be calculated based on the following Equation 4.1 presented overleaf.

$$DOPE = \frac{(1-SF_{end-use})}{\eta_{end-use}} \times FOPE_{end-use} \quad \text{Equation 4.1}$$

Where:

- $DOPE$ = Annual delivered operational energy demand for the end use in MWh;
 $SF_{end-use}$ = Share of energy provided by solar on-site generation system (*solar fraction*) or nullified if no RE system is installed;
 $FOPE_{end-use}$ = Annual final operation energy demand for end use in MWh; and
 η = Efficiency of the system used in end use terms.

When electricity is used to provide an operational energy service, the overall efficiency, $\eta_{end-use}$ for the systems in question is given as the ratio of useful output to the amount of energy input used. The required primary energy values are then obtained from multiplying the delivered energy figures by the primary energy coefficients based on the particular energy source. However, the primary energy value does not include extra embodied inputs such as the embodied energy of the electricity power plant itself. The primary energy is established based on Equation 4.2 given below.

$$POPE_{end-use} = DOPE_{end-use} \times PEC_{end-use} \quad \text{Equation 4.2}$$

Where:

- $POPE_{end-use}$ = Annual primary operational energy demand for end use in MWh;
 $DOPE_{end-use}$ = Annual delivered operational energy demand for end use in MWh;
 and
 $PEC_{end-use}$ = Primary energy coefficient for energy source used for the end use.

Furthermore, the total primary energy use of the building and its users can be calculated from summing up the primary energy demand of each service including heating, cooling, domestic hot water, cooking, lighting and other appliances. This is given by Equation 4.3. overleaf.

$$POPE_{total} = \sum_{end-use=1}^{end-use} POPE_{end-use} \quad \text{Equation 4.3}$$

Where:

$POPE_{total}$ = Total building operation energy demand in MWh; and

$POPE_{end-use}$ = Annual primary operation energy demand for the end use in MWh.

Finally, after operational energy requirements are determined, the next step is to quantify the embodied energy requirements in order to implement the first step of integration. This aspect is tackled in the following section.

4.2.1.2 Building embodied energy

At the building scale, embodied energy is characterized by the amount of energy embedded in the building constituent materials and components (including the energy generating ones). All direct construction energy requirements should also be accounted for. The total embodied energy of construction materials and components as well as the process energy used in construction of the whole building assembly is known as initial embodied energy (Mithraratne et al. 2007; Crawford 2011). After the building is occupied, it is maintained and some of its components and systems are replaced over its service life due to a wide range of factors, (e.g. functional defect, technology deterioration, aesthetic reasons etc.). Consequently, the total embodied energy of materials and processes used in maintenance and replacement activities is known as recurrent embodied energy (Mithraratne et al., 2007; Crawford 2011).

The crucial step in considering these aspects as per useful energy demand pertaining to materials and components, is to evaluate and estimate their service lives. For building components such as RE sources or HVAC systems, it is much easier to estimate their service life as it is often based on the period of manufacturers' guarantee, although it is highly recommended to estimate based on real life expectancy figures obtained from average national/regional data if accessible.

Besides, for particular building components, (e.g. envelope and structure), their service lives are much more difficult to predict considering that some components could last for over 100 years with little refurbishment, while others might undergo major refurbishments or even be demolished within or less than 50 years. Generally, due to such contradictions, recurrent embodied energy is usually taken as a percentage of the initial embodied energy (Treloar 2000; Crawford 2010; Fuller and Crawford 2011). The average value used is commonly taken in the range of 20%-30% for a 50 year service life (see Section 3.1.3.2. b).

Finally, there are different quantification techniques which are used to derive embodied energy coefficients of construction materials. These coefficients are multiplied by the material quantities of the building and summed up to eventually determine the total embodied energy of the building. The following section elaborates on the different methods available to derive embodied energy coefficients.

4.2.1.2. a Adopting suitable embodied energy calculation method

The procedure for determining embodied energy coefficients which are then used to quantify the total embodied energy of a built facility is generally undertaken according to three methods: process analysis, input-out analysis and hybrid analysis (Treloar, 1998; Alcorn 2010; Crawford 2011, Dixit 2015;). The following section discusses the three common methods mentioned previously above.

PROCESS ANALYSIS

Process analysis is regarded as the most accurate and reliable method commonly used to derive embodied energy coefficients in order to calculate embodied energy (Alcorn 2010; Mithraratne et al., 2007, Crawford 2011). For construction materials, the energy inputs are collected directly from the main manufacturing plant and are further traced upstream of the main manufacturing process.

The process of accounting for energy inputs going into the upstream part of building or construction becomes increasingly difficult to trace due to the large effort required to identify and account for each input of the complex upstream process (Alcorn and Baird 1996). Consequently, process analysis is subjected to the so-called “truncation errors” due to the exclusion of particular inputs (Crawford 2011). In this way, this method is biased to specialised studies but considered incomplete due to the boundary truncation (Dixit et al., 2010; Crawford 2011). For these reasons, process-analysis-based embodied energy coefficients are not used for this work.

Besides, another method known as statistical analysis also exists. This utilizes national statistics to derive embodied energy coefficients based on the total energy supplied to a particular industry sector and its total output (Treloar 1998; Mithraratne et al., 2007). However, this technique is similar to, and has got the same limitations as, process analysis (Langston and Langston 2008). Therefore, it is not discussed further in this work.

INPUT-OUTPUT ANALYSIS

This method uses the national input-output statistical information on the monetary transactions among various industry sectors of the economy (Mithraratne et al., 2007). Ideally, if inputs purchased by an industry sector from an energy providing sector are not known, the energy intensity of the industry sector is quantified using the energy prices. By utilizing these economic flows, it is possible to determine the energy tariffs in terms of MJ/\$ for each sector of the economy (Mithraratne et al., 2007).

The advantages of the approach to deriving embodied energy coefficients of construction materials is in its simplicity in nature and the wide availability of particular data involved. In addition, the approach is also capable of tracing minor tributary processes which the process-based approach fails to capture. However, this method of calculating embodied energy coefficients is also subject to some major flaws. In particular, different construction products with a wide range variation in terms of energy requirements tend to be considered as part of the same economy sector. For instance, glass products with higher energy intensity: 16-26 MJ/kg, are placed in the same statistical category as concrete products with lower energy intensity (0.9-2 MJ/kg) (Mithraratne et al., 2007).

For all the reasons mentioned above, purely input-output-based embodied energy coefficients are therefore not appropriate for this work.

HYBRID ANALYSIS

Hybrid analysis method exploits the advantages of both the process and input-output analysis methods to provide much more complete, accurate, robust and material specific results (Treloar 1998; Mithraratne et al., 2007; Alcorn 2010; Crawford 2011; Stephan 2013). The fundamental goal of uniting the two methods in hybrid analysis is to feature completeness and specificity within the process-based or input-output based frameworks (Treloar 1998).

There are two types of hybrid analyses: process-based and input-output-based hybrid analyses. The latter focuses on improving the reliability of embodied energy coefficient calculations by inserting the process-based energy data into the input-output framework, while the former focuses on the completeness of the system boundary of the process-based method by integrating input-output data within the process-based framework (Treloar 1998; Dixit et al., 2015).

Process-based hybrid embodied energy coefficients for New Zealand construction materials have been developed and updated by (Alcorn and Wood 1998; Alcorn 2003; Alcorn 2010). These have shown to be much more reliable than those derived from the pure input-output-based approach (Baird and Chan 1983), and

pure process-based approaches (Alcorn 1996). Moreover, the use of hybrid-based approaches to derive embodied energy coefficients has been widely advocated by a wide spectrum of scholars, e.g. Mithraratne et al. (2007), Dixit et al. (2010), Crawford (2011) Dixit et al. (2012), Dixit et al. (2015). For these reasons, process-based hybrid embodied energy coefficients developed for New Zealand are utilized for this work.

In summary, embodied energy coefficients calculated using different methods discussed vary considerably. Pure input-output-based or process-based derived coefficients tend to provide lower and unreliable embodied energy figures (Treloar 1998, Mithraratne et al., 2007; Crawford 2011; Stephan et al., 2012, Stephan 2013, 2013b). Besides, process-based hybrid coefficients suffer from flaws because non-material energy requirements such as insurance and advertising, (i.e. the input-output remainder) are generally excluded. However, since the coefficients used in this study are specifically developed for New Zealand building materials, it is judged appropriate to use the figures rather than relying on conservative input-output hybrid based coefficients from other countries such as Australia or Europe which have different residential building construction paradigms from New Zealand.

4.2.1.2. b Calculating Embodied energy

INITIAL EMBODIED ENERGY

Building embodied energy calculation in this work is undertaken at the building scale, i.e. the sum of the embodied energy of the building and its components, (including the energy generating components). Materials and components making up the building are further broken down into different elements: structure, finishing, systems, and envelope. Ideally, the breakdown of embodied energy in this manner provides a more simplified version of guidance to the designer/evaluator to establish the most energy demanding elements of the building's design composition.

Alcorn (2003, 2010) derived embodied energy coefficients for construction materials in New Zealand building materials using the process-based hybrid

method. These coefficients are then multiplied by the materials quantities of the building and summed up to determine its total initial embodied energy requirements.

In addition, it is arguably necessary to also account for the direct energy requirements linked to building construction and other associated services, e.g. insurance, marketing, administration and so on (Stephan 2013). However, calculation of energy requirements for these items is based on pure input-output methods as the process-based data does not usually exist (Finnveden et al., 2009). In this way, relying on pure input-output-based methods is subjected to numerous flaws and could therefore dilute the quality of the results (see section 4.2.1.2. a), so this is not included in this work.

The building initial embodied energy is calculated according to Equation 4.4 provided below (excluding the input-output remainder displayed in greyscale format in the equation below). In addition, Section 4.2.1.2. d provides further details describing how different material quantities of the buildings are determined.

$$IBEE_b = \sum_{m=1}^M (EC_m \times Q_m) + \left\{ TER_s - \sum_{m=1}^M TER_m \right\} \times C_b \quad \text{Equation 4.4}$$

Where:

- $IBEE_b$ = Total initial embodied energy demand of building b , in MWh;
- m = Material constituent;
- EC_m = Hybrid energy coefficient of material m , in MWh/unit of material;
- Q_m = Quantity of material m , in units of material;
- TER_s = Total energy demand of building construction-related input-output sector, MWh/currency unit;
- TER_m = Total energy demand of the input-output pathways accounting for the material production processes, in MWh/unit currency; and
- C_b = Cost of the building b , in unit currency (e.g. \$).

RECURRENT EMBODIED ENERGY

The recurrent embodied energy is taken as the sum of all the energy used during the maintenance and replacement activities. Practically, these activities involve energy intensive processes and they are expected to contribute to a significant share of the overall building embodied energy (see Section 4.2.1.2).

To formalise the calculation in this research, it is theoretically assumed that the recurrent embodied energy of the building materials and components is fully replaced when they reach the end of their useful life and that their embodied energy in the future is the same as today. In a pragmatic sense, however, this may not be the case since the embodied energy of replacement materials may be different with respect to the energy mix used during their production. However, this aspect of accounting for future energy mix and the evolution of embodied energy coefficients could also be considered for further development of this research. The recurrent embodied energy (excluding the input-output remainder as displayed in grey scale font in the equation below) is obtained through Equation 4.5 given below.

$$RBE_b = \sum_{m=1}^M \left[\left(\left[\frac{SL_b}{SL_m} \right] - 1 \right) \times [EC_m \times Q_m] + \{TER_s - TER_m - TER_{i \neq m}\} \right. \\ \left. \times C_m \right] \quad \text{Equation 4.5}$$

Where:

$REBE_b$ = Total recurrent embodied energy of building b , in MWh;

m = Material constituent;

SL_b = Building service life, in years;

SL_m = Average service life of Material in years;

EC_m = Hybrid energy coefficient of material m , in MWh/unit of material;

Q_m = Quantity of material m , in units of material;

TER_s = Total energy demand of building construction-related input-output sector s , MWh/unit currency;

TER_m = Total energy demand of the input-output pathways accounting for the material production processes, in MWh/unit currency;

$TER_{i \neq m}$ = Total energy demand of all input-output pathways not associated with the production process or installation of material m , in MWh/unit currency; and

C_m = Replacement cost of material, in unit currency (e.g. \$).

Ideally, a significant number of replacement cycles do occur during the building service life. The most commonly cited building service lives are 50, 75 and 100 (Cole and Kernan 1996; Sartori and Hestnes 2007; Gustavsson and Joelsson 2010; Ramesh et al., 2010; Stephan 2013). For this reason, the building service life considered for recurrent embodied energy calculations is taken at the maximum 100 years. The results are then further converted to reflect annual energy demand.

TOTAL EMBODIED ENERGY DEMAND

The total embodied energy for building, b is calculated using the Equation 4.6 below, which is then divided by the assumed life time years to give an annualised value.

$$EE_b = IBEE_b + REE_b \quad \text{Equation 4.6}$$

Where:

EE_b = Total building embodied energy demand for building b , in MWh;

$IBEE_b$ = Total initial embodied energy demand of building b , in MWh; and

REE_b = Total recurrent embodied energy of building b , in MWh.

4.2.1.2. c Additional embodied energy quantification simplification aspects

Since a building encompasses a wide variety of material assemblies, the embodied energy of individual materials is generally categorised per building component (envelope, structure, systems and others) to simplify the calculation procedure (Crawford 2011), energy of a group of materials or components can be calculated and expressed using either of the two approaches: standard weighted average approach and total value approach (Stephan 2013). In this thesis, a group of

materials or components can be defined as a combination of individual building materials or components.

STANDARD WEIGHTED AVERAGE APPROACH

The standard weighted average approach is a method of calculating average values of embodied energy of a group of building materials or components based on the contribution of each individual material towards the total embodied energy or emission of the whole group or components (Stephan 2013). These average variables are taken as the ratio of process data (See Section 4.2.1.2. a) for the embodied energy as well as for greenhouse gas emissions. The quantification is undertaken by Equation 4.7 given below.

$$FEE_g = \frac{1}{EE_g} \sum_{m=1}^M \{EE_m \times Q_{m \rightarrow g} \times W_m \times FEE_m\} \quad \text{Equation 4.7}$$

Where:

FEE_g = Fraction of process data for embodied energy of material group g ;

EE_g = Embodied energy per functional unit of material group g , in MWh/unit;

m = Material constituent;

EE_m = Embodied energy per functional unit of material m in MWh/unit;

$Q_{m \rightarrow g}$ = Quantity of material m in material group g ;

W_m = Wastage factor of material m ; and

FEE_m = Fraction of process data for embodied energy of material m .

As mentioned in Section 4.2.1.2. a, the initial embodied energies at whole building level are calculated using a material catalogue database which relies on process-based hybrid coefficients. The standard weighted average approach is appropriate if the “input-output” remainder is to be added to complement the process data. These inputs are non-material factors relative to the building such as insurance, advertising etc. all of which are not considered in embodied energy figures for this research as discussed previously in Section 4.2.1.2. b. Therefore, this approach to simplifying embodied energy quantification is not used for this work.

On the other hand, wastage factors (See Equation 4.7) mainly deal with a mixture of different materials generated during or after construction-related processes. This can be defined as waste which arises from construction-related activities including land excavation, building construction, site clearance, renovation, demolition and roadwork activities (Kofoworola and Gheewala 2009). Current research suggest that the construction industry generates a significant amount of waste equivalent to four times that produced within households and is responsible for more than 50% of the waste deposited in landfills (Hwang et al., 2011). However, due to the absence of data on material wastage, this aspect is not considered in this research. Moreover, with the varying construction paradigms around the world, different construction sites are also subject to varying material wastage which would be very difficult to compare. Consequently, it is not appropriate to make assumptions.

TOTAL QUANTITY APPROACH

Rather than relying on the standard weighted average approach to simplify embodied energy quantification, the total quantity approach is instead used to obtain absolute variables of embodied energy and greenhouse gas emission figures (Stephan 2013). These figures are calculated by summing up the products of embodied energy or greenhouse gas emission coefficients of each material, the quantity of material per functional unit of material as well as the wastage factors. This is given by Equation 4.8 below.

$$EE_g = \sum_{m=1}^M \{EE_m \times Q_{m \rightarrow g} \times W_m\} \quad \text{Equation 4.8}$$

Where:

EE_g = Embodied energy per functional unit of material group g in MWh/unit;

m = Material constituent;

EE_m = Embodied energy per functional unit of material m in MWh/unit;

$Q_{m \rightarrow g}$ = Quantity in units of material m in material group g ; and

W_m = Wastage fraction of material m .

4.2.1.2. d *Estimating material quantities of building*

It should be noted that estimation of material quantities for other buildings in this thesis is undertaken based on per-meter square of the original building quantities which are obtained from the main contractor. However, to demonstrate the practicality of the developed methodology, the evaluator/designer may estimate of material quantities where data is not available following the process outlined in the following section (Stephan 2013).

In order to estimate and establish relevant quantities in this work, a list of materials in the following building element categories need to be taken into account:

- Rough carpentry materials (Floor, exterior walls and roof systems)
- Foundations (Concrete and steel)
- Finish carpentry material (windows, doors and interior walls)
- RES systems (PV and solar hot water)
- Other miscellaneous material (wires and pipes Heating/cooling outlets)

ROUGH CARPENTRY MATERIAL QUANTITIES

FLOOR AREA

Central to determining rough carpentry materials is the gross floor area (GFA) and net internal area (NIA) or usable floor area (UFA). GFA is taken as the sum of the floor area of each floor of a building measured from internal face of walls separating the building from adjacent buildings. Net internal area is taken as the sum of all areas on the floors of a building either assigned to, or available for assignment to, a building user or specific use or necessary for the general operation of a building. GFA and NIA can be estimated using the Equation 4.9 and Equation 4.10 presented below respectively.

$$GFA = w \times d \times NL \quad \text{Equation 4.9}$$

Where:

GFA = Gross floor area of the building in m²;

w = Width of the building in m;

d = Depth of the building in m; and

NL = Number of levels of the building.

The net internal area (NIA) can be based on actual measurements from inside of external walls. However, for this thesis, the NIA is calculated as follows:

$$NIA = GFA \times \alpha_{GFA \rightarrow NIA} \quad \text{Equation 4.10}$$

Where:

NIA = Net internal area of the building in m^2

GFA = Gross floor area of the building in m^2 ;

$\alpha_{GFA \rightarrow NIA}$ = GFA to NIA conversion factor

However, since the quantification approaches presented are taken as methods of simplification, the calculations do not take into account the areas of common and shared amenities of row or terrace houses (further details regarding this aspect can be found in Section 5.4.5.2). Although this might affect the embodied figures to a certain extent, it is assumed that the effect is small and does not affect the quality of the overall results.

ROOF AREA

Estimation of the roof area is done using Equation 4.11 given below, in accordance with the roof slope and the type of the building. This implies that for terraced buildings, roof area for specific building types (i.e. districts) are divided equally in order to account for material quantities as well as the heat transfer surface.

$$A_{roof} = 2 \times \frac{W}{\cos(RF_{slope})} \times d \times \frac{1}{NDU} \quad \text{Equation 4.11}$$

Where:

A_{roof} = Area of roof in m^2 ;

W = Width of the building in m;

RF_{slope} = Roof slope in degrees;
 d = Depth of the building in m; and
 NDU = Number of dwelling units.

EXTERIOR WALL AREA

The area of exterior wall surfaces which takes into account the number of façades is calculated based on two particular stages: initial and final stages. The initial stage which includes the area covered by window surfaces is obtained through Equation 4.12 given below.

$$A_{Wall.Ext \rightarrow window} = \{2 \times W + (NF - 2) \times d \times h \times NDU\} \quad \text{Equation 4.12}$$

Where:

$A_{Wall.Ext \rightarrow window}$ = Area of exterior walls including windows in m²;
 W = Width of the building in m;
 NF = Number of façades of the building (i.e. 1, 2, 3 or 4);
 d = Depth of the building in m;
 h = Height between floors of the building in m; and
 NDU = Number of dwelling units.

The second stage of the calculation is undertaken by subtracting the window area associated with the exterior wall surface and adding the remainder to factor in the gable under the roof. This is obtained through the following Equation 4.13 presented below.

$$A_{Wall.Ext \rightarrow gable} = A_{Wall.Ext \rightarrow window} - A_{window} + \frac{\tan(RF_{slope}) \times w^2}{2} \quad \text{Equation 4.13}$$

Where:

$A_{Wall.Ext \rightarrow gable}$ = Area of exterior wall including gables in m²;
 $A_{Wall.Ext \rightarrow window}$ = Area of exterior walls including windows in m²;
 A_{window} = Area of window in m²;
 RF_{slope} = Roof slope in degrees; and
 W = Width of the building in m.

From above, the window area (A_{window}) is calculated by multiplying the initial exterior wall area ($A_{Wall.Ext \rightarrow window}$) by the window to façade ratio of the building in question.

FINISH CARPENTRY QUANTITIES

The finish carpentry material quantities are associated with the interior floor spaces and doors.

INTERIOR FLOOR AREA

The interior floor area is determined according to each space. The usable floor area for each is then used to calculate the embodied energy based on the associated material group or component. The spaces in this work are simplified into three categories: living spaces, bedroom spaces and others. The living spaces comprise the living areas, kitchen and bathrooms. The actual areas per space function are calculated by multiplying the usable floor area by building space function coefficients. These coefficients are based on Du Bellay et al. (2006) (0.4 for living spaces, and 0.45 for bedroom areas for both single houses and row or terrace houses).

NUMBER OF DOORS

Internal or external door quantities are estimated based on the number of doors defined by each space in the building. The number of doors is established by assuming that each space in the building requires a door.

FOUNDATION QUANTITIES

CONCRETE AND STEEL QUANTITIES

Estimation of concrete and steel quantities is done in accordance to the type of foundation in question .i.e. raft, strip or individual footing. Firstly, the volume of the concrete should be calculated from a range of estimated materials including sand, cement, coarse aggregate and others. In addition, the volume can also be determined based on average foundation sizes for typical residential buildings within specific regions. Estimation of the reinforcement steel depends on the components of the structure .i.e. slab, beams etc. When drawings are available as

is the case in this work, the amount of steel is determined by multiplying the volume of concrete by the concrete reinforcement coefficient (i.e. weight of reinforcement steel per cubic meter of concrete). Alternatively, the amount of steel can also be determined by assuming the percentage of reinforcement generally required for different concrete components. The values can be subject to wide variation from structure to structure and can also be assumed based on past experiences of similar structure (e.g. for slabs=1.0% and for beams=2.0%). Concrete quantities for raft foundations in this work are determined through Equations 4.14 and Equation 4.15 given below.

$$VC_{raft} = \frac{GFA_{floor} \times t_{average}}{NDU} \quad \text{Equation 4.14}$$

Where:

- VC_{raft} = Volume of concrete for raft foundation, m³;
- GFA_{floor} = Gross floor area per storey, m²;
- $t_{average}$ = Average thickness of raft, m (i.e. 0.25m); and
- NDU = Number of dwelling units.

After the volume of concrete is determined, the next step is to quantify the amount of steel in the foundation. This is given by the Equation 4.15 below.

$$WS_f = VC_{raft} \times \alpha_{steel \rightarrow concrete} \quad \text{Equation 4.15}$$

Where:

- WS_f = Weight of steel in foundation in kg;
- VC_{raft} = Volume of concrete in raft foundation in m³; and
- $\alpha_{steel \rightarrow concrete}$ = Concrete reinforcement coefficient in kg/m³ (130 for terraces and 100 for individual dwelling).

RES SYSTEMS

The number of renewable energy capture devices such as photovoltaic and solar hot water panels are taken as default figures based on the actual number of panels

installed on the roof. In addition, the solar fraction is also based on the actual measured performance values of the systems.

OTHER MISCELLANEOUS QUANTITIES

Determining the number of other systems such as heating/cooling devices, wire and pipes assemblies is based on the average values for each specific system. Base data can be based on Stephan (2013); Stephan et al. (2013a).

HEATING/COOLING OUTLETS

In cases where heating or cooling systems are installed, it is assumed that the living and bedroom spaces require an individual unit. Therefore, the number of units for the space is calculated by the usable floor area by the average space size. This obtained using the Equation 4.16 given below.

$$NSU = \frac{UFA}{SS_{average}} \quad \text{Equation 4.16}$$

Where:

NSU = Number of system units (i.e. heating or cooling delivery unit);

UFA = Usable floor area of the building in m^2 ;

$SS_{average}$ = Average space size in m^2 .

WIRES AND PIPES

The length of wires and pipes can be based on a rule of thumb of length of wires for typical residential buildings, which range from 0.55-0.6m/ m^2 (De Bellay et al., 2006) as cited in Stephan (2013)). The average length of wire or pipes in m/ m^2 is then multiplied by the usable floor area of the building to establish their actual length per space function.

After establishing relevant material quantities and quantifying all necessary aspects pertaining to building embodied energy as described in the section above, the next crucial step is to determine the user transport energy requirements.

4.2.2 Establishing user transport energy

One of the critical aspects for the developed methodological framework concerns the extent to which household energy use is related to user energy parameters at urban inter-scale level: user transport. On the city scope front, buildings are an integral component of the urban lay-out and are therefore responsible for land-use characteristics, e.g. population, density etc. (Stephan 2013) (see Section 3.3.2.1).

While the independent effect of zero energy residential buildings may be relatively significant in building scale energetic terms, more significant outcomes could be yielded by considering other energy demands associated with the building users at the city scale i.e. user transport energy. In addition, Rickwood et al. (2008), Stephan (2013); Stephan et al. (2013a, 2013b) and recently, Anderson et al. (2015), have demonstrated that it is crucial to explore the integration of building energy (embodied and operational) with user transport energy (embodied and operational) in order to realise meaningful energy savings with regards to buildings and their users. Along the same thread, in the context of zero energy building notions, Bourrelle et al. (2013) contend that studying buildings as isolated entities throughout their design life could be a myopic approach to solving the environmental challenges afflicting the built environment and hence the wider society today. A building may be zero energy when looked upon as an independent entity but, as was argued in Section 3.5, buildings are part of a larger system.

With this in mind, as argued in Section 3.3.2.1, land use configurations, among other social aspects, closely correlate with energy use for transportation (Newman and Kenworthy 1999). Consequently, it can further be argued that a building's location influences its users' transportation means, behaviour and the resulting energy use. For all the reasons mentioned above, more research is indeed required to link buildings and their broader environmental consequences.

Changes in user transportation energy parameters, e.g. energy efficiency, type of fuel, and mode of transportation are most likely to undergo multiple changes over time (Stephan et al., 2013a, 2013b). Therefore, in the face of transport energy calculations, it is also crucial to incorporate such developments with respect to a

given time period. This aspect concerning the evolution of user transport energy parameters overtime is tackled through a *scenario approach* (this is further discussed in Section 4.2.7.2. b later in this Chapter).

In reality, one fundamental activity which needs to be carried out with respect to transport energy is a test of the potential shift from oil-based to electric transport. Indeed, the idea of the transportation sector relying on electricity as its main fuel has since represented a game changing episode from its inception and scientific hype-disappointment cycle to a tangible reality (Geels et al., 2012). While the outlook for widespread electric vehicle adoption is somewhat unpredictable, the potential prospects have so far directed the eyes of policy makers to alternative fuels and new technologies. There are three types of alternative fuel vehicles currently available: Internal Combustion Engine Vehicles (ICEVs) that use petrol, diesel, biofuels or natural gas, Hydrogen Fuel Cell Vehicles (HFCVs) and Electric Vehicles (EVs) both of which use electro-chemical batteries to drive electric motors. EVs can further be broken down into: series or parallel Hybrid Electric Vehicles (HEVs), series or parallel Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Powered Electric Vehicles (BPEVs) (Geels et al., 2012).

More importantly, battery powered electric Vehicles (BPEVs) and plug-in hybrid electric vehicles (PHEVs) are technologies currently being promoted with the objective of decarbonizing the world's private vehicle fleets (Geels et al., 2012; Givoni and Banister 2013). This development suggests that a trajectory of electrification of vehicles is well underway. It remains to be seen however, which EV technology will reign supreme and eventually dominate the vehicle fleet scene (Banivadekar et al., 2008). As of June 2015, the global electric vehicle market share comprised 64% of Battery Powered Electric Vehicles (BPEVs) while 36% accounted for Plug-in Hybrid Electric Vehicles (PHEVs). Consequently, BPEVs are considered in this work due to their higher market penetration rate.

However, analysis of electric transport comes with its own limitations. In particular, previous studies have already explored the consequences of EV penetration into existing grids and they conclude that there will indeed be a

requirement to implement supplementary generation capacity (Jenkins et al., 2008; Putrus et al., 2009; Duncan et al., 2010; Kiviluoma and Meibom 2011). Essentially, within these studies, it is admitted that the expected increase in demand will be most likely to be manageable within the existing grid. Consequently, electric transport calculations in this study are undertaken based on this assumption.

In addition, one possible outcome of EVs in relation to zero energy building notions is the possibility of utilising vehicles to exchange energy with buildings in a bidirectional flow: the so-called “V2G (Vehicle-to-Grid), V2B (Vehicle-to-Building) or B2V (Building-to-Vehicle)” ancillary services (Kempton and Tomic 2005; Ancillotti et al., 2014; Liu et al., 2015). ZEBs are highly regarded as potential candidates to embrace this notion, thanks to their grid interaction capabilities and energy harvesting nature. EVs provide a significant opportunity for maximizing the potential of existing grids through the V2G and V2B technologies. While these EV charging regimes are praiseworthy, most of the EVs produced in the current market do not yet support V2G/V2B/B2V interface technology. In other words, they are not equipped with bidirectional energy converters and communication systems (Liu et al., 2015). Large scale demonstrations of this concept with potential for being linked to distributed generation systems are being investigated as part of the ‘smart grid scheme’ on the Danish island of Bornholm in the Baltic Sea (Jørgensen et al., 2011).

Nevertheless, the evolution of grids relies primarily on the premise of meeting the demands of their immediate beneficiaries’: building users. How EVs will ultimately interface with the grid via V2G/V2B/B2V technologies remains unresolved (Putrus et al., 2009; Duncan et al., 2010). It is therefore judged suitable not to test out this relationship within the proposed methodology. Further details surrounding this issue fall beyond the scope of this study but may form another basis for future research based on this work.

On the other hand, apart from building user transport energy requirements, there are other transport energy demands that also need to be considered as they support active operation of residential buildings. In particular, mail delivery, incoming

building maintenance services (includes electricians and internet/telephone installation/repair technicians), waste collection etc. However, little data has been found to quantify such demands. For this reason, these aspects have not been taken into account in this work but may however form another significant portion of future research.

Finally, in a similar fashion to the quantification of building operational and embodied energy demands, user transportation (embodied and operational) also relies on particular methods of calculation. The following section presents the quantification techniques available to calculate transport energy.

4.2.2.1 Adopting suitable user transport energy calculation method

As was discussed in Section 3.3.2, crucial aspects to consider in order to calculate transport energy requirements are: modal split relative to private vehicles, buses, trains, walking and others, characteristics of each mode and passenger or user travel distances. Essentially, there are two methods available for calculating transport energy requirements: dynamic calculations and the use of statistical data.

4.2.2.1. a Transport dynamic modelling method

Transport dynamic modelling is a method used to quantify transport energy associated with the mobility of users within a particular context (e.g. urban,/city etc.). Generally, this is conducted through mobility simulation models and computer programs. These predictive models essentially perform what is commonly known as “realistic simulation of urban/city networks”. Some works claiming to have successfully developed models through urban mobility simulations include; Bezzani et al. (2003); Kim et al. (2009) and Bezzani et al. (2010). These models and tools provide valuable insights regarding transport energy quantification (i.e. the location of buildings, mobility of vehicles and pedestrians) but they tend to focus on a wide spectrum of parameters which fall beyond the scope of this research (e.g. traffic congestion, rush hour nodes, pressure on public transport and pedestrian footpaths etc.).

In parallel, other state-of-the-art simulation packages of urban mobility exist, such as the Simulation of Urban Mobility (SUMO) (Behrisch et al., 2011). SUMO is an open source, urban mobility simulation program that was first developed by the German Aerospace Center (DLR) in 2001 and has since evolved into a full featured tool for modelling transport parameters including traffic utilities, road networks, transport demand, destination matrices and traffic counts. It is composed of highly detailed simulation features usable at whole city/urban scale coupled with remote control interface to adopt simulations directly online.

In transport energy terms, these programs derive travel distances which are then aggregated with modal split characteristics to calculate the transport energy requirements therein. Put another way, these tools rely on calibration techniques based on the real transport statistical data. Such data typically includes; passenger travel distances, vehicle ownership, and modal split and so on. This statistical data is found in national-wide or regional surveys. Examples of such surveys include; "Nanjing Resident Travel Survey" in China (Nanjing Statistics Bureau 2009) and "Comparing travel modes: New Zealand Household Travel Survey" in New Zealand (Ministry of Transport 2015).

The goal of this work is to calculate the annual user transport energy requirements for residential building occupants in the context of zero energy building concepts. Consequently, the multiple details provided by mobility simulation programs and models are judged not relevant nor necessary and therefore urban mobility simulation programs and models will not be used in this thesis. Thus, transport energy calculation in this work is based upon statistical data. This approach is explained hereafter.

4.2.2.1. b *Statistical data method*

Another approach to quantifying user transport energy requirements is the use of statistical data, which typically comprises passenger travel distances. Travel distance figures can then be multiplied by the operational and embodied energy intensity of transport modes to obtain the transport energy demand. In this way, this method is advantageous since it is easy and quick to implement.

However, passenger travel distances are very sensitive to multiple parameters that generally influence travel behaviour, e.g. urban lay out, lifestyle factors, income, age, gender, household composition, vehicle ownership etc.(Dieleman et al., 2002; Curtis and Perkins 2006; Van Loon and Frank 2011; Feng et al., 2013). Consequently, the reliance on statistical data to quantify transport energy can be subjected to numerous errors and flaws due to the wide spectrum of parameters involved regarding travel distances (Carlsson-kanyama and Linden 1999) as cited in Stephan (2013)). Indeed, this aspect has been considered in this work and it is tackled through “parameter variability” (see Section 4.2.7.2. a).

At the aggregate level, one would still argue that relying on statistical data to calculate transport energy demand requires a significant understanding (or expertise) in terms of multiple factors that influence travel behaviour and therefore is not reliable (McNally and Rindt 2008). Current research argues that travel behaviour of people in the urban/city context can in fact be predictable. See for example; Gonzalez et al. (2008) and Song et al. (2010) and Feng et al., (2013) suggesting that the statistical data containing passenger travel distances can be judged reasonably consistent and reliable. Relying on statistical data to obtain travel distances for quantifying user transport energy seems likely to provide an acceptable level of accuracy sufficient for this work.

Travel distances considered in this work are the total distances travelled annually associated with multiple travelling purposes, e.g. commuting, leisure, shopping etc. (excluding distances travelled through air transport). As was mentioned in the previous Section, the statistical data comprising passenger travel distances is generally found in national surveys (Ministry of Transport 2015). For all the reasons mentioned above, user transport energy calculations in this work will be based on statistical data.

4.2.2.2 Calculating user transport energy

User transport energy in this work is split between private and public transport .In addition, the calculations are undertaken based on two energy inflows: operational energy demand, which encompasses the burning of fuel or electricity consumption

required to meet the propulsion needs for the transport mode in operation. Secondly, the embodied energy demand for both the car and roads, which encompasses the raw material extraction, manufacturing and distribution of transport mode components, whole assembly, maintenance and other supporting infrastructure. The embodied energy figures are generally derived from hybrid or purely input-output or process based calculation methods.

PRIVATE TRANSPORT CALCULATION REQUIREMENTS

VEHICLE OPERATION ENERGY DEMAND

In order to calculate the private vehicle operation energy requirements for a household on an annual basis, the annual travel distance travelled by vehicle is multiplied by the household's size and the operational energy intensity of the vehicles. This is defined as per Equation 4.17 below.

$$TOPE_b = TD_v \times HS \times \sum_{vt=1}^{vt} (FE_{vt} \times ECF_{vt}) \quad \text{Equation 4.17}$$

Where:

$TOPE_b$ = Annual transport operational energy demand associated with building b , in MWh;

TD_v = Annual travel distance by vehicle per capita, in MWh;

HS = Household size as the number of occupants;

vt = Vehicle technology (i.e. petrol, diesel etc.);

FE_{vt} = Fuel efficiency of the vehicle for particular technology, vt , in L/km; and

ECF_{vt} = Energy content of the fuel for particular technology, vt , in MWh /L.

When vehicles with alternative technology are used (i.e. electric vehicles), the operational energy requirement calculation becomes Equation 4.18 as given below.

$$TOPE_{bev} = TD_{ev} \times HS \times EF_{ev} \times PEF_{ev} \quad \text{Equation 4.18}$$

Where:

$TOPE_{bev}$ = Annual transport operation energy demand of electric vehicle associated with building b , in MWh;

- TD_{ev} = Annual travel distance by electric vehicle per capita, in km;
 HS = Household size as the number of occupants;
 EF_{ev} = Energy efficiency of the electric vehicle in MWh/km; and
 PEF_{ev} = Primary energy factor for electricity.

VEHICLE EMBODIED ENERGY DEMAND

The annual vehicle embodied energy demand in this work is calculated by multiplying the annual travel distance of each vehicle by the household size and the embodied energy intensity (MWh/p-km) linked with the vehicle. The choice of transport embodied energy intensities based MWh/passenger-kilometre metric is given in Section 4.2.2.2. a. In addition, the embodied energy intensity figures used for this research rely on input-output quantification methods and are obtained from Mithraratne (2011). The inflows accounted for in the embodied energy intensity figures include: fuel production, supporting infrastructure construction and maintenance, vehicle manufacture, maintenance as well as other services (i.e. insurance and registration). Equation 4.19 below presents how the embodied energy values of vehicle user transportation are calculated.

$$TEE_b = TD_v \times HS \times EEI_v \quad \text{Equation 4.19}$$

Where:

- TEE_b = Annual transport embodied energy demand associated with vehicle for building b , in MWh;
 TD_v = Annual travel distance by vehicle per capita in km;
 HS = Household size as the number of occupants; and
 EEI_v = Embodied energy intensity of the vehicle in MWh/p-km.

In cases where an EV is used, the annual transport embodied energy requirements associated with the household are calculated through multiplying the annual travel distance of each vehicle by the household size and the embodied energy intensity of the vehicle. See Equation 4.20 below.

$$TEE_b = TD_{ev} \times HS \times EEI_{ev} \quad \text{Equation 4.20}$$

Where:

TEE_b = Annual transport embodied energy demand associated with electric vehicle for building b , in MWh;

TD_{ev} = Annual travel distance by electric vehicle per capita in km;

HS = Household size as the number of occupants; and

EEl_{ev} = Embodied energy intensity of electric vehicles in MWh/p-km.

TOTAL VEHICLE USER TRANSPORT ENERGY DEMAND

The overall annual vehicle transport energy requirements for vehicles are derived by summing up the operational energy requirements and the embodied energy requirements as given in the Equation 4.21 below.

$$TTE_b = TOPE_b + TEE_b \quad \text{Equation 4.21}$$

Where:

TTE_b = Annual total vehicle transport energy demand associated with building b , in MWh;

$TOPE_b$ = Annual vehicle operational energy associated with building b , in MWh;

TEE_b = Annual vehicle embodied energy transport energy demand associated with building b in MWh.

PUBLIC TRANSPORT CALCULATION REQUIREMENTS

PUBLIC TRANSPORT OPERATIONAL ENERGY DEMAND

The annual public transport energy demand linked to a household is calculated by multiplying the annual travel distance of each user, with respect to the particular transport mode undertaken, by its operational energy intensity and summing them up accordingly with regards to the household size. This is given by the Equation 4.22 below.

$$PTOE_b = \sum_{pt=1}^{pt} (TD_{pt} \times EF_{pt} \times ECF_{pt}) \times HS \quad \text{Equation 4.22}$$

Where:

$PTOE_b$ = Annual public transport operational energy demand of building b , in MWh;

pt = Public transport mode technology (i.e. diesel);

TD_{pt} = Annual travel distance per capita, specified as per transport mode pt , undertaken, in km;

EF_{ptt} = Efficiency of fuel consumed by public transport mode pt , in L/km;

ECF_{ptt} = Energy content of fuel consumed by public transport mode pt , in MWh/L; and

HS = Household size as the number of occupants.

In cases where electric public transport is used (i.e. electric train etc.), the operational energy requirements are obtained by summing the product of travel distance of each user and the energy efficiency of the transportation mode and the primary energy coefficients for electricity. This is defined by Equation 4.23 provided below.

$$PTOE_b = \sum_{pt=1}^{pt} (TD_{ept} \times EF_{ept} \times PEF_{ept}) \times HS \quad \text{Equation 4.23}$$

Where:

$PTOE_b$ = Annual public transport operational energy requirements for the household, in MWh;

TD_{ept} = Annual travel distance per capita, specified as per transport mode ept , in km;

EF_{ept} = Efficiency on the transport mode ept , in MWh/km; and

PEF_{ept} = Primary energy factor for electricity servicing transport mode ept ; and

HS = Household size as the number of occupants.

PUBLIC TRANSPORT EMBODIED ENERGY DEMAND

The public transport embodied energy is calculated through the summation of the travel distances associated with each user, specified per transport mode then multiplied by its embodied energy intensity. This is defined by Equation 4.24 below. The embodied energy intensity of public transportation take into account the requirements for fuel production, manufacture of public transportation mode, whole assembly and other related services.

$$PTEE_b = \sum_{pt=1}^{pt} (TD_{pt} \times EEI_{pt}) \times HS \quad \text{Equation 4.24}$$

Where:

$PTEE_b$ = Annual public transport embodied energy demand for building b , in MWh;

TD_{pt} = Annual public transport travel distance per capita, specified as per transport mode pt , undertaken, in km;

EEI_{pt} = Embodied energy intensity of public transport, specified as per mode pt , in MWh/km; and

HS = Household size as the number of occupants.

In cases whereby electric public transportation is tested, the annual public transport embodied energy requirements are obtained from adding the products of travel distances of each user, specified as per transport mode and its embodied energy intensity as given in the Equation 4.25 below.

$$PTEE_b = \sum_{pt=1}^{pt} (TD_{ept} \times EEI_{ept}) \times HS \quad \text{Equation 4.25}$$

Where:

$PTEE_b$ = Annual public transport embodied energy demand associated with building b , in MWh;

TD_{ept} = Annual travel distance per capita, specified as per public transport mode ept , undertaken in km;

EEI_{ept} = Embodied energy intensity, specified as per public transport mode, in MWh/p-km; and

HS = Household size.

TOTAL PUBLIC TRANSPORT ENERGY DEMAND

The total public user transport energy demand for a particular household (building b) with a given number of occupants is calculated by the summation of the operational energy and the embodied energy demand as given per Equation 4.26 below.

$$PTTE_b = PTOPE_b + PTEE_b \quad \text{Equation 4.26}$$

Where:

$PTTE_b$ = Annual total public transportation energy demand for building b , in MWh;

$PTOE_b$ = Annual public transportation operational energy demand for building b , in MWh; and

$PTEE_b$ = Annual public transportation embodied energy demand for building b , in MWh.

4.2.2.2. a Additional user transport energy quantification simplification aspects

As was highlighted in Section 4.2.2.1, instead of relying on highly complex transport energy simulation tools, the use of simplified approach such statistical data method has been selected as the best approach for this work. The, user transport energy is calculated using the equations provided in Section 4.2.2.2 above. In summary, transport operational energy is finally obtained by multiplying the passenger travel distance by the household size (i.e. number of occupants) and the operational energy intensity of the transport mode (vehicle, train etc.). The embodied energy requirements associated with the mode and other related transport infrastructure is obtained from the transport energy intensity database for New Zealand transport compiled by Mithraratne (2011). This database contains input-output based embodied energy intensities of various transportation modes in New Zealand.

The embodied energy intensities are given in MJ/passenger-kilometre as well as CO₂-e/passenger-kilometre and have been translated into kWh/passenger-kilometre to adopt the quantification metrics used in this work. While metrics such as kWh/vehicle-kilometre or CO₂-e/vehicle-kilometre are significant in terms of potential technological improvements of transport modes, the kWh/passenger-kilometre metric captures the energy and greenhouse gas emissions intensity of moving passengers as a result of transport mode ridership or occupancy rates. Low ridership results in the largest energy consumption and emissions intensity per passenger-kilometre, at the worst performing times, while high ridership captures the mode's best performance (Chester and Hovarth 2009). This aspect of sensitivity to passenger occupancy has prompted this thesis to rely upon transport embodied energy intensity figures which are based on kWh/passenger-kilometre and CO₂-e/passenger-kilometre. Consequently, this provides a simplified energy

quantification approach since the transport energy intensities based on such metric are available for New Zealand (See for example ; Mithraratne 2011, .p 82-99).

4.2.3 Establishing annual total building energy demand

The overall annual energy demand associated with a zero energy residential building is calculated by summing up the building total energy demand .i.e. embodied and operational energy together with the user private and public total transport energy demand (.i.e. both embodied and operational energy) as given by Equation 4.27 below.

$$TE_b = [OPE_b + EE_b] + [TOPE_b + TEE_b] \quad \text{Equation 4.27}$$

Where:

TE_b = Annual total energy demand of building b , in MWh;

OPE_b = Annual total building operational energy demand of building b , in MWh;

EE_b = Annual total building embodied energy demand of building b , in MWh
(i.e. including RES);

$TOPE_b$ = Annual total user public and private transport operational energy demand of building b , in MWh; and

TEE_b = Annual total user public and private transport embodied energy demand for building b , in MWh.

As discussed in Section 4.1.2, the results can also be expressed in terms of MWh/capita or MWh/m². These expressions are determined by dividing the annual established value by the household size or usable floor area, respectively.

4.2.4 Calculating greenhouse gas emissions

The crediting system converts the physical energy units into quantifiable metrics .i.e. greenhouse gas emissions (see Section 4.1.2). The following section elaborates on the different techniques used in the methodological framework to calculate greenhouse gas emission outflows related to each of the evaluated building systems boundaries of building and transport energy inflows.

4.2.4.1 Building energy greenhouse gas emissions

4.2.4.1. a Building operation energy greenhouse gas emissions

As was previously discussed, “the greenhouse gas emissions associated with operational energy of the building are directly linked to the type of energy source used” (Stephan 2013). For example coal, hydro, wind and so on. Typically, there are individual emission factors attributed to particular greenhouse gases (CO₂, CH₄, N₂O and others). Yet often they are aggregated and expressed as CO₂-equivalents (CO₂-e). Table 4.2 presents the common fuel greenhouse gas emissions factors used for stationary combustion in New Zealand.

Ideally, the greenhouse gas emissions related to operational energy requirements are calculated by multiplying the physical primary energy units by each specific corresponding factor depending on the energy mix.

Table 4.2: Common fuel emission factors used for stationary combustion in New Zealand (2013)

Emission source	Unit	Emissions factor (kgCO ₂ -e/Unit)			Total emissions factor(kgCO ₂ -e /unit)
		CO ₂	CH ₄	N ₂ O	
Distributed natural gas	kWh	0.19	0.0166	0.0000966	0.208
Coal -Bituminous	Kg	2.63	0.210	0.0117	2.85
Coal -Sub-bituminous	Kg	1.99	0.154	0.00858	2.15
Coal -Lignite	Kg	1.42	0.109	0.00606	1.54
Coal-Default	Kg	1.65	0.127	0.00705	1.78
Diesel	Litre	2.67	0.000183	0.00435	2.68
LPG*	Kg	3.02	0.00141	0.00917	3.03
Heavy fuel oil	Litre	3.01	0.00292	0.00348	3.02
Light Fuel oil	Litre	2.95	0.00290	0.00346	2.96
Wood	Kg	1.003	0.0686	0.0109	0.0795

*LPG use data in litres can be converted to kilograms by multiplying by the specific density of 0.536 Kg/L

Source: Ministry of Business, Innovation and Employment (2015)

4.2.4.1. b *Embodied energy greenhouse gas emissions*

Generally, the databases that contain building embodied energy coefficients also feature their respective greenhouse gas emission multiplication factors which have been determined at the same time. As a consequence, the database used in this work compiled by Alcorn (2003, 2010) which is comprises process-based hybrid embodied energy figures is judged suitable. The embodied energy greenhouse gas emissions are therefore calculated by multiplying the embodied energy figures by the greenhouse gas emissions factors for particular building materials.

4.2.4.2 *Transport energy greenhouse gas emissions*

4.2.4.2. a *Transport operation greenhouse gas emissions*

The greenhouse gas emissions closely linked to transport operation energy demand are dependent on the source of fuel used and the efficiency of the transportation mode. As such, the emissions resulting from transport operation in this work are calculated based on the average fuel emission factors for specific sources of fuel used (e.g. petrol etc.).

On the other hand, when it comes to transport modes relying on electricity, the greenhouse gas emissions are calculated by multiplying the energy demand for the transport mode, the primary energy requirement, by the specific emission factor for electricity used to deliver energy to the transport mode.

4.2.4.2. b *Transport embodied energy*

The greenhouse gas embodied energy emissions for transport are calculated through the database compiled by Mithraratne (2011). This transport embodied energy database was derived from the LCA method commonly known as “Wells-to-Wheels”. This is a type of quantification strategy generally used to analyse total energy consumption or energy conversion efficiency and emissions impacts of motor vehicles including the fuels used for particular modes and greenhouse gas emissions in primary energy terms i.e. from oil wells to vehicle wheels (Hawkins et al., 2012).

4.2.5 Multi-scale zero energy building balance

The multi-scale, zero energy building balance in this work is calculated by subtracting the annual amount of energy harvested from RES fed into the grid by a particular building from the summation of the total primary energy requirements from building embodied, operation and transport of their users (both embodied and operational energy). The design/evaluation is undertaken at primary energy level p , although it is asymmetric as no conversion factor is applied to the renewable energy exported. The exported energy is that part of the generation energy which is exported to the grid. This refers to the generation with self-consumption subtracted. Self-consumption in this work refers to the amount of energy harvested from RES and used directly to cover building operational energy demand. The multi-scale zero energy building balance per annum is then given per Equation 4.28 below.

$$ZEB_{m,b}^p : \langle E_{exp,b} | - | OPE_b^p + EE_b^p + TOPE_b^p + TEE_b^p \rangle = 0 \quad \text{Equation 4.28}$$

Where:

$ZEB_{m,b}^p$ = Multi-scale zero energy building balance;

$E_{exp,b}$ = Annual total amount energy harvested from RES for building b , in MWh and fed into the grid minus self-consumption. Self-consumption is the amount of energy harvested from renewables and used for building operation;

OPE_b^p = Annual total building operational energy demand of building b , in MWh;

EE_b^p = Annual total building embodied energy demand of building b , in MWh (i.e. including RES);

$TOPE_b^p$ = Annual total user transport operational energy demand of building b , in MWh; and

TEE_b^p = Annual total user transport embodied energy demand for building b , in MWh.

4.2.6 Building zone evaluation

As was previously discussed in Section 4.1.1, the absolute energy demand for a specific building zone or district is calculated by multiplying the energy demand,

specified as per building type by the number of buildings of that particular type present within the zone. This is undertaken by Equation 4.29 presented below.

$$E_z = \sum_{b=1}^z (E_b \times N_b) \quad \text{Equation 4.29}$$

Where:

E_z = Energy demand of zone z , in MWh;

E_b = Energy demand of building type b , in MWh; and

N_b = Number of buildings, specified as per type b , in the zone.

When other reference floor metrics are used to express the results (e.g. MWh/m²), the values are averaged based on the specified number of each building type in the zone as given in the Equation 4.30 overleaf.

$$E_z = \sum_{b=1}^b \left(\frac{E_b \times N_b \times GFA_b}{BA_{ovr}} \right) \quad \text{Equation 4.30}$$

Where:

E_z = Energy demand of zone z , in MWh/unit;

E_b = Energy demand of building b , in MWh/unit;

N_b = Number of building of type b , in the zone;

GFA_b = Gross floor area of building b , in m²; and

BA_{ovr} = Overall residential built area in the zone z , in m².

In addition, in order to allow for the comparison of different building zones based on larger spatial metrics, another reference flow (i.e. MWh/km²), is also possible based on the average number of houses per square kilometre.

4.2.7 Establishing uncertainty for the multi-scale zero energy building framework

Historically, engineers and scientists have developed evaluation models based on particular framework platforms to represent real world phenomena using a

combination of physical laws and empirical tools based on observing system attributes of interest (system outputs). The intent of these models is to relate output variables (dependent variables) for a system with a set of other input variables (independent variables) (Ayyub and Klir 2006). Modelling of complete systems is not precisely predictable because of the existence of uncertainty within the system and the interaction of multiple sets of variables characterizing the system (Ayyub and Klir 2006). Consequently, it is equally crucial to address uncertainty in the developed methodological framework.

Essentially, the model developed in this framework encompasses zero energy building concept theories (see e.g. Sartori et al., 2012) and a mixture of selected energy and greenhouse gas emission quantification techniques in the built environment (see e.g. Stephan 2013). Ultimately, this unique blend of concepts and methods is likely to result in the making of multiple assumptions and approximations throughout the calculation process as already declared at the beginning of Section 4.1. Clearly, this could imply a distortion of real world phenomena due to multiple errors and uncertainties. Errors are described as recognisable deficiencies of the model or the algorithms employed, while uncertainties are the potential deficiencies that arise due to lack of knowledge of various parameters (Chakraverty 2014).

With interdisciplinary studies of this nature, it is very likely that uncertainties will emerge from different sources due to the wide spectrum of data sources used at both the building and urban/city scales (see Section 4.1.3). As years go by, changes at different scales of the built environment may occur. In particular: what will the household size be in the coming 30 years? Are consumption patterns likely to increase? What will the energy mix be? Are primary energy/greenhouse gas emission coefficients likely to evolve? Are users likely going to switch from their default transport modes? The answers to these questions can reveal valuable insights regarding the application of zero energy building concepts at different scales of the built environment today.

Even by accounting for such parameters, a significant amount of uncertainty related to the randomness of input parameters is expected to persist in the model. This type of uncertainty is known as aleatory uncertainty or parameter variability (Ali 2014). Aleatory uncertainty, the physical variability present in the model system or its components attempts to tackle the possibility of obtaining results which might otherwise entail a complete divergence from the real-world expectations. Put another way, aleatory uncertainty (or parameter variability) addresses the possible deviations from the calculated values or average figures. In this work, parameter variability is used to account for the rarely integrated behavioural aspects and transport energy requirements of building users in the current zero energy building framework as was discussed in Section 3.5.

Finally, after identifying the sources and characteristics of uncertainty, the next crucial step is to adopt the most appropriate techniques of measuring the anticipated uncertainty. There exist a wide range of methods, both quantitative and qualitative, that attempt to measure uncertainty. Since this work considers aleatory uncertainty (parameter variability) and is quantitative in nature, adopting quantitative measurement techniques is therefore judged to be appropriate. As such, the following section discusses the various methods available for uncertainty quantification.

4.2.7.1 Uncertainty calculation methods

The complexity of the model associated with this work is due to its multi-disciplinary nature. Ideally, accounting for energy requirements and associated greenhouse gas emissions at inter-scale level (i.e. building and city scales) is very daunting. Consequently, the integration of multiple parameters characterizing the methodological framework being developed implies a certain level of uncertainty as discussed in the previous section. More importantly, the objective of this section is to present an audit of different methods available to tackle uncertainty. These include: analytic probabilistic methods, simulation methods and interval analysis through interval mathematics.

4.2.7.1. a Analytic probabilistic methods

Numerous problems in engineering and other sciences deal with dependent variables which are a function of one or more independent random variables as pinpointed earlier in section 4.2.7 (Ayyub and Klir 2006). In this way, analytical methods determine the probabilistic behaviour of dependent random variables based on a given set of probabilistic characteristics of independent random variables.

Ideally, this involves propagation of multiple random input variables in the model based on their probabilistic distribution. In order to sample the distribution, the output variables are commonly analysed through the Central Limit Theorem (CLT)⁴. The major flaw surrounding analytical probabilistic approaches in tackling uncertainty becomes apparent when establishing the precise distribution of the multiple input variables. This often results in making numerous assumptions and approximations of the distribution of each random variable. Inconsistencies arise due to the data intensive sampling nature of multiple distribution of input variables (Ayyub and Klir 2006). Consequently, multiple errors can be induced, which would otherwise render most calculations in the model useless. For these reasons, analytical probabilistic methods are judged not suitable for this work.

4.2.7.1. b *Simulation methods*

The quest to account for uncertainty in the science and engineering fields through simulation programs can be traced back as early as the 1940s (Ayyub and Klir, 2006). This approach was initiated in order to develop inexpensive techniques for testing robust engineering systems by imitating their real behaviour. The idea was first exploited by scientists working on the ‘Manhattan Project’ (1942-45) that produced the world’s first atomic bombs. The method is commonly known as *Monte Carlo simulation technique*, named after the famous Monte Carlo gambling resort, in Monaco. The Monte Carlo method is a computerized mathematical technique which is most widely used for measuring parameter variability across various fields of study (Del Moral 2013).

⁴ CLT states that the distribution of average multiple variables will be approximately normal irrespective of the underlying distribution.

Ideally, the Monte Carlo technique furnishes the evaluator with a wide spectrum of possible outcomes and possibilities they will occur for any given choice of action. During the simulation, multiple random values are sampled from input distributions. Each set of samples (i.e. iteration) and the resulting outcome from that particular sample is recorded. Monte Carlo repeats this process multiple (or thousand) times and the result is a probability distribution of possible outputs. Generally, these model outputs are analysed statistically with other approaches, notably through Bayesian Decision Theory⁵.

While the Monte Carlo technique provides a much more comprehensive view of any possible uncertainty, the process itself requires advanced expertise and is data intensive. Consequently, the accuracy of the results of the simulation is highly dependent on having strategic and accurate definition of the model system at the initial stage. Lack of knowledge on probabilistic behaviour of input parameters at the initial stage applies for numerous assumptions. Inconsistencies of such magnitude may induce errors and affect the quality of results (Alefeld and Mayer 2000). For these reasons, it is also judged suitable not to rely on the Monte Carlo simulation method in this work.

4.2.7.1. c Interval analysis through interval arithmetic

Unlike probabilistic methods discussed in the previous sections, the application of interval analysis serves as a good arsenal for tackling uncertainty (Dawood 2011; 2014). In particular, the approach involves propagating multiple input variables in the model without their related probabilistic distribution (Moore 1979; Moore et al., 2009; Dawood 2011; 2014).

In interval analysis, the behaviour of multiple input variables is defined by what is generally known as the “Gaussian distribution”, with each variable having the same probability of occurrence. Consequently, when multiple quantities involved in the calculation take values inside intervals (ranges) of variation, the set of output variables determines a manifold bounded by two envelopes, i.e. the possible

⁵ Bayesian Decision Theory is statistical technique that attempts to quantify the trade-off between different decisions and making use of a range of possibilities.

maximum and minimum deviation of the variable. Significantly, this range (or interval) of values can be computed through interval arithmetic or can be based on theoretical or experimental evidence (Moore 1979; Alefeld and Mayer 2000; Moore et al., 2009; Dawood 2011; 2014).

Possible variability ranges associated with building embodied and operational energy based on interval analysis are available in the literature (see, e.g.; Pettersen 1994; Joudis et al., 2009; Stephan et al., 2012; Stephan 2013; Stephan et al., 2013a, 2013b). Consequently, to reduce computational time and minimize errors, it is judged suitable for this work to rely on interval based variability ranges already present in the literature.

4.2.7.2 Other sources of uncertainty

Besides aleatory uncertainty, the evolution of parameters in time (e.g. house/household size, evolution of primary energy/greenhouse gas emission factors, transport modal split, etc.) is likely to result in “temporal variability” due to future possible changes. Consequently, it is imperative to allow the methodological framework to test out the future possible scenarios in the context of inter-scale level zero energy building concepts. As such, temporal variability in this work is tackled through a scenario approach. A scenario is defined in the International Energy Agency’s (IEA) training manual on integrated environmental assessment and reporting (Jager et al., 2008, p.5) as:

“Description of journeys to possible futures. They reflect different assumptions about how current trends will unfold, how critical uncertainties will play out and what new factors will come into play”.

With that in mind, this thesis therefore relies on this definition particularly in the context of zero energy/emission concepts at multiple different scales of the built environment. In addition, it is well argued in literature that using scenarios is appropriate for establishing temporal variability of multiple parameters in the built environment (see for example Huijbregts 1998; Stephan et al., 2012; Stephan 2013). More importantly, using scenarios to tackle temporal variability gives the

designer/evaluator the opportunity to test out different future possible outcomes. Arguably, this prospect can massively enrich the value and broaden the scope of investigation of the framework.

Finally, this work relies on interval analysis based variability ranges to tackle parameter uncertainty, while the scenario technique is used to address the temporal variability of other relevant parameters.

4.2.7.2. a *Parameter variability*

Parameter variability or uncertainty associated with building embodied, operation and user transport energy as well as greenhouse gas emissions in this work is derived from fixed average interval analysis based ranges from the literature. Additional mathematical details regarding the application of interval analysis through interval arithmetic for tackling uncertainty can be found in multiple publications (see e.g. Moore 1979; Alefeld and Mayer 2003; Moore et al., 2009; Dawood 2011; 2014).

However, parameter uncertainty related to building or transport embodied energy is dependent upon the methods typically used to derive embodied energy coefficients (see Section 4.2.1.2. a). For process-based embodied energy data, the uncertainty ranges can be taken as $\pm 10\%$, $\pm 20\%$, $\pm 30\%$. When it comes to input-output-based data, the ranges can rise to $\pm 30\%$, $\pm 50\%$, $\pm 70\%$ (Crawford 2011, Stephan et al., 2012; Stephan 2013; Stephan et al., 2013b). On the other hand, variability of building operational and user transport energy is dependent upon the households' useful energy and the mode of transport respectively, along with other factors, e.g. lifestyle patterns and building location (Carlsson-Kanyama and Linden 1999; Dieleman et al., 2002; Van Loon and Frank 2011; Feng et al., 2013; Chen et al., 2013; Zheng et al., 2014). Consequently, uncertainty ranges for operational energy in the literature are taken as $\pm 10\%$, $\pm 15\text{-}20\%$ $\pm 30\%$ (Pettersen 1994; Joudis et al., 2009; Chen et al. 2013; Stephan 2013; Stephan et al., 2012, 2013a, 2013b). For transport operation, the ranges are also the same: $\pm 10\%$, $\pm 15\text{-}20\%$ $\pm 30\%$ (Stephan 2013; Stephan et al., 2012, 2013a, 2013b).

Since data in this study is provided at a neighbourhood scale, to avoid underestimated or overestimated results, the possible deviation of all energy inflows is assumed at medium $\pm 20\%$. In addition, a similar situation is also assumed for the greenhouse gas emission outflows.

4.2.7.2. b Scenario integration

Essentially, this work relies on prospective scenarios in order to test possible evolution of parameters (i.e. temporal variability). Ideally, this technique allows forecasting of future possible outcomes regarding the influence of particular parameters within the methodological framework. In that way, attempting to account for individual parameters sensitive to temporal variability in this framework entails processing vast amounts of data which can further be an invitation to multiple sources of error. Consequently, there is only a limited number of parameters that can be accounted for at this stage of development of this work. In particular:

1. Building size and number of users
2. User transport modal shift
3. User transport fuel switch
4. Primary energy coefficients for electricity and greenhouse gas emissions.

By limiting the scope of this research to the parameters pinpointed above, the designer/evaluator can test out a combination of these parameters and investigate their influence in the context of zero energy building principles at inter scale level (i.e. building and city scales). These parameters are discussed below.

BUILDING SIZE AND NUMBER OF USERS

As was previously highlighted in Section 2.2.4, a highly energy efficient building with larger floor area can consume more energy than a smaller less efficient building (Clune et al., 2012; Stephan and Crawford 2015). In the context of residential buildings, Vale and Vale (2010a) argue that as houses in developed economies have become more energy efficient due to building regulation requirements, the reduction in resource consumption has been counter-balanced

by the desire for larger houses and amenity. In addition, the number of people living in the building can change due to particular factors (e.g. age, education, health and income etc.). For instance, in New Zealand, average household size is predicted to fall from 2.6 people in 2006 to 2.4 in 2031 (Statistics New Zealand 2013). Besides, average house floor area in New Zealand has increased from ~149m² in 1990 to over 200m² after 2010 (Statistics New Zealand 2013). Given these changes it is imperative to test the future possible evolution of such parameters in relation to zero energy building concepts at multiple scales of the built environment.

USER TRANSPORT MODAL SHIFT

Urban transport in most developed economies is hugely reliant upon private vehicles (Newman and Kenworthy 1999; Newman and Kenworthy 2006, Rickwood et al., 2008; Givoni and Banister 2013). Hence, the increase in focus on climate change places additional pressure on urban transport to reduce its energy demand and associated greenhouse gas emissions (Newman and Kenworthy 2006; Geels et al., 2012; Givoni and Banister 2013).

Energy use for transport is closely linked to the type of mode employed (Newman and Kenworthy 1999; Chester and Hovarth 2009). Consequently, throughout the years, it has been argued that the negative effects of private transport can be compensated by shifting to less energy intensive public transport modes (Newman and Kenworthy 1999; Newman and Kenworthy 2006; Geels et al., 2012; Harman et al., 2012; Givoni and Banister 2013). This theme has so far motivated authorities and policy makers globally to exploit the environmental benefits of public transportation (Geels et al., 2012; Givoni and Banister 2013). However, the wide promotion of public transport has not escaped scepticism. For example, in December 2009, the “New Transit” magazine issue 6 promoted public transportation but with caution (notice the question mark in the title) as; “*The Great Green Opportunity?*” (Harman et al., 2012). In pragmatic terms, it can be argued as to how far the public transport prospects have led to significant environmental benefits to date. In addition, one would also argue and question the relevance of

public transport modes. In particular, is public transport better than private transport? Which public transport modes are more appropriate? These answerable questions can reveal valuable insights regarding the interplay between buildings and their users at inter-scale level of the built environment in the context of zero energy buildings.

USER TRANSPORT FUEL SWITCH

Among the most fundamental changes in transport technology is the switching from oil-based transportation to electric (Geels et al., 2012; Givoni and Banister 2013). Electric vehicles generally have no tail-pipe emissions, although other related processes (e.g. manufacturing, maintenance of battery packs, the source of energy used to power them etc.) might emit them.

Aside from harnessing their technological prospects, EVs have undergone massive surge in popularity recently although they were already in operation since the late 1800s. They remained popular until the early 20th century when they faced a fierce competition against mass-produced ICEVs (Geels et al., 2012). Interest in EVs returned since the 1970s twin “energy crises”. More significantly, the advent of electric vehicles was further given a boost around the 1990s when the U.S state of California pioneered zero emission vehicle regulations and policies. See for example, the controversial General Motors EV 1.

At the end of the 20th century, electric vehicles still lagged behind in terms of energy efficiency development and never achieved mass production (Orsato et al., 2012). This prompted most people to believe that EVs would have no future. Ultimately, on June 12th 1997, the *Financial Times* published an article entitled “*EVs are a turn-off*” (Kemp and Simon 2001). At the beginning of the 21st century, EV technology had remained stagnated for approximately 100 years (Calwell 2010). In fact, this can be evidenced by some recent flagship EVs such as the 2010 Nissan Leaf and Mitsubishi i-MiEV, which have exactly the same range as the 1908 Fritchle Model-A Victoria (~160 km).

Nevertheless, as was previously discussed in Section 2.2.4, the vision of the future under the wide image of sustainability as defined in the “Brundtland Report” still persists. In that way, the forgotten dream of EVs as one potential solution still reappears today. Consequently, electric vehicles have been making a comeback since 2008 with much more promising energy efficient propulsion technologies (Bandivadekar et al., 2008). These technological breakthroughs can be forecasted in order to test out their influence over total energy demand and greenhouse gas emissions in the built environment.

PRIMARY ENERGY COEFFICIENTS FOR ELECTRICITY AND GREENHOUSE GAS EMISSIONS

Historically, electricity grids have been necessary enablers for societal progression (see Section 2.1.1.2). In most developed countries, electricity accounts for a large share of operational energy requirements (IEA 2010). For instance, in New Zealand 69% of total residential end use energy is derived from electricity (Isaacs et al., 2010a; 2010b). Chiefly, in most developed countries, delivery of electricity is characterized by higher primary energy coefficients as highlighted in Section 2.1.1.2 (Molenbroek et al., 2011, Stephan 2013; Stephan et al., 2013b). Likewise, to embrace the notion of sustainable development from the environmental perspective, policy makers globally are looking towards the adoption of renewable energy alternatives (IEA 2015). Consequently, countries are expected to drop their average electricity carbon intensities below 100 gCO₂-e/kWh by the year 2050 from the current global average of 460-550 gCO₂-e/kWh (IEA 2010).

This is likely to result in significant changes in primary energy coefficients for electricity and greenhouse gas emissions. Theoretically, the evolution of primary energy multiplication factors for electricity and greenhouse gas emissions can be forecasted and their possible implication can be ascertained.

4.3 Integrating energy use flows at both building and city scales

The individual integration aspects presented in the previous sections emphasize the complexity of the methodological framework developed. The previous sections have highlighted quantification aspects at the building scale and also at the city

scale in an attempt to clarify the integration process for executing the necessary calculations in this work.

However, linking all these aspects in the manner adopted in this thesis is very complex in nature considering that disparate energy use flows have to be quantified using different techniques. Figure 4.5 overleaf depicts a simplified version of the developed methodological framework based on Equation 4.28 in Section 4.2.5. Intentionally, only the aggregated features have been highlighted in order to be able to distinguish the interconnectedness of both building and city scale energy use aspects. If all sub-categories were to be displayed, the diagram itself could have warranted another separate Chapter, an exercise which could have further diverted from the central focus of this thesis. In addition, future development of the integration approach for automation developed in this study is briefly explained in Chapter 8.

Figure 4.5: Core integration process towards multi-scale zero energy building framework for residential buildings

4.3.1 Sensitivity analysis

The sensitivity analysis is performed by a series of parametric variations which rank all possible scenarios against evaluated energy requirements and associated greenhouse gas emissions such as annual overall energy use, evolution of parameters linked to operational energy, initial embodied energy of outer walls, technology of transport modes etc. All possible combinations of the evaluated variables are then calculated and the output variables are ranked and expressed accordingly.

4.3.2 Verification of methodological framework

The verification of this thesis' methodological framework is focused on comparing the results to other similar, but less comprehensive, studies, and not on testing whether the results accurately represent reality. Future development of this model into a software tool for automatic calculations should take into account validation of the framework using other case studies and different contexts.

The process of verification is implemented in terms of the initial calculations consisting of building scale quantification aspects (i.e. building operational and embodied energy), plus city scale quantification aspects (i.e. user transport operational and embodied energy) as well as the greenhouse gas emissions. This implies that if calculated figures are comparable and fall within acceptable ranges as those obtained from previous studies then the rest of the calculated and obtained figures may be considered as realistic. This simple approach greatly reduced the verification time. In addition, compound annual growth rate is used for parameter evolution of operational energy (see Appendix A for further details.). This technique is chosen because it is frequently used by the IEA to account for parameter evolution associated with energy generation across multiple sectors (IEA 2011).

In some cases, the initial calculations are also compared with the variation outputs using relative differences. The relative difference ΔR_d is calculated through the Equation 4.31 presented overleaf.

$$\Delta R_d = \frac{V_{output} - I_{output}}{I_{output}} \quad \text{Equation 4.31}$$

Where:

ΔR_d = Relative difference %;

V_{output} = Variation output; and

I_{output} = Initial output.

4.3.2.1 Greenhouse gas emissions

The greenhouse gas emissions are calculated by multiplying the relevant energy requirements associated with a certain specific demand at both the building and city scales by the corresponding emissions factors according to the energy sources. Ideally, the greenhouse gas emission factors used in this work are weighted since they are based on Table 4.2 (see Section 4.2.4.1).

4.3.2.2 Building zone calculations

As was discussed previously in Section 4.1.1, building zones or districts in this work comprise the sum of multiple buildings of certain types. Previous studies which attempt to test zero energy buildings at neighbourhood scales such as Koch et al., (2012); Contractor and Musau (2014) and Marique and Reiter (2014) often fail to account for significant indirect energy requirements including building embodied energy and also transport operational and embodied energy. Consequently, these studies have limited scope compared to the proposed methodological framework in this research such that it is almost impossible to compare their results which are judged to be conservative. Consequently, it is assumed that the initial verification of the building scale energy demand and greenhouse gas emission calculations also mirrors the verification of the building zone or district level calculations. In addition, this leads to the suggestion that more research associated with zero energy residential buildings at different scales is indeed urgently required.

4.4 Case study for verification of calculations in the methodological framework

Although relevant details regarding the case study are described in Chapter 5, it is imperative to briefly underpin its role in relation to the general framework developed under this Section. Put another way, the case study comes into play in order to verify the calculation process of the proposed methodological framework developed in this Chapter. Essentially, development of the multi-scale zero energy building framework implies taking into account different quantification parameters at multiple scales of the built environment. Consequently, to test out whether inter-scale zero energy building solutions have the potential to inform building energy policy, it is imperative to undertake a relevant auditing process of this study's applicability. Therefore, this work considers one case study which complements the verification process of the methodological framework.

The reasons behind the choice of the case study are briefly highlighted below (See Table 4.3) and the case study is detailed in Chapter 5. To verify the framework calculation process, a case study of an existing zero energy house in Auckland, New Zealand is used. The building energy (embodied and operational) and user transport energy (embodied and operational) are calculated and results are compared to some of the existing previous studies undertaken for residential buildings in similar context and location by Mithraratne et al. (2007), Alcorn (2010) and Mithraratne (2011).

The aim of this comparison is to verify the validity of calculated energy and greenhouse gas emission figures undertaken from the calculation process of the methodological framework. At a suburban scale, the zero energy house is also used to compare with other alternative housing typologies. In this way, the building system boundary is taken at both the building level and also at building zone or district level and in so doing, taking into account the whole neighbourhood.

In addition, different housing typologies are also explored and tested against zero energy residential building configurations with the aim of establishing their influence at multiple scales of the built environment.

Table 4.3: Summary of case study used to verify calculations of the proposed methodological framework

Case study	Location	Building system boundary		Aims	Targets
		Building	Building Zone/District		
Zero energy house	Auckland, New Zealand	✓	✓	<ul style="list-style-type: none"> Verify calculation strategy 	<ul style="list-style-type: none"> Compare results from framework with existing studies
				<ul style="list-style-type: none"> Verify applicability of framework at larger scale 	<ul style="list-style-type: none"> Test out framework calculations at urban scale.
					<ul style="list-style-type: none"> Test out and compare different housing typologies

4.5 Conclusion

To move towards comprehensive zero energy building practices, the interplay between buildings and their users' needs to be understood at different scales of complexity: both building and city scales. In this chapter, the ambition level and the rules of calculation of the methodological framework have been described. The equations used to calculate building embodied and user transport energy requirements plus associated greenhouse gas emissions have been provided. The selection of the EnergyPlus® program for building operational energy quantification has been explained and the role of the case study as means to verifying calculation entities been highlighted. In addition, the consideration of uncertainty and variability has been emphasized.

In summary, the Chapter has tackled quantification aspects related to energy at different scales of the built environment. In particular; building operational energy is quantified using the energy simulation program, EnergyPlus®. The operational energy is further broken down into useful energy aspects: heating, cooling, domestic hot water, lighting, cooking and other appliances. Building embodied

energy is established using process-based hybrid energy coefficients and material quantities. Both the initial and recurrent building embodied energy are taken into account. The embodied energy values associated with relevant infrastructure directly linked to the building are not taken into account and reasons behind their exclusion have been provided. User transport energy requirements are based on statistical data and calculations are undertaken according to the average passenger travel distances as well as the transport modal characteristics. Generally, these travel distances are then multiplied by the energy intensity specified per transport mode to establish the energy requirements. The greenhouse gas emissions closely linked with building operation energy and user transport are determined through the average emissions from different fuels and energy sources used. The emissions related to building embodied energy are obtained through multiplying the greenhouse gas emission coefficients with the corresponding embodied energy figures calculated for specific material quantities. In addition, building zones or districts in this work are described as a collection of different types of buildings for particular urban context.

The parameter uncertainty and variability related to embodied, operational and transport energy requirements is assumed to be within the ranges of: $\pm 10\%$, $\pm 15\text{--}20\%$, $\pm 30\%$. In this thesis the variability range of $\pm 20\%$ is selected and reasons behind the choice has been elaborated. Furthermore, a number of scenarios related to the temporal variability of building size and number of users, user transport modal shift, user transport fuel switch as well as primary energy coefficients for electricity and greenhouse gas emission are also explored.

The methodological framework calculations will be firstly verified using a building level-like systems boundary case study of a zero energy house located in Auckland, New Zealand. Furthermore, the scope of the study is extended to encompass a building zone/district to test out and verify the framework differences in an urban context.

This chapter has answered the first research question: *“Is it possible to integrate transport energy (operation and embodied) together with building energy (operational and*

embodied) to form an integrated multi-scale zero energy building framework for residential building?” The answer to this question is evidenced in Section 4.2.5, Equation 4.28. It is indeed possible to integrate transport energy together with building energy to form an integrated multi-scale zero energy building framework for residential buildings.

Amidst the limitations acknowledged, the calculation of building operational energy requirements through the computer program Energyplus® along with the procedure have been described whilst the simplifications of the modelling process have been established (See Section 4.2.1.1. a). When it comes to building embodied energy, the simplified approaches towards quantities for various building related materials ranging from foundations, structural and system requirements and choice of coefficients’ database have also been established. In addition, the reliance on a transport energy intensities database consisting of figures based on kWh/per passenger-kilometre basis and the use of simplified statistical data method have been justified. Consequently, this chapter has answered the second research question: *“What are the simplifications aspects required in order to successfully integrate transport energy (operation and embodied) together with building energy (operational and embodied) to establish an integrated multi-scale zero energy building framework for residential building?”*

The methodological framework can now be tested on a case study in order to establish the capacity of an inter-scale zero energy building perspective. In order to finally realize the research aim, the third research question: *“How can an integrated multi-scale zero energy building framework for residential buildings inform design and urban planning policy?”*, has to be firstly established through describing, testing and discussing the results of the case study for Auckland, New Zealand in Chapters 5, 6 and 7 respectively.

Chapter 5 | Elaboration of case study testing the capacity of the framework

In Chapter 4, an inter-scale, methodological framework for zero energy residential buildings and building zones or districts was established. Further details regarding the integration of disparate calculation parts have also been described in Section 4.3. The next goal is to verify the potential of the developed methodological framework and test its capacity to inform building design, patterns of living and building energy policies. More significantly, to test how a multi-scale zero energy building approach with stretched building system boundaries can inform design, consumption patterns and policy decisions, parametric studies and sensitivity analyses are required to be conducted at different levels of the building system boundary.

The main goal of this chapter is to elaborate on the case study used to test the potential of the developed methodological framework. Eventually, the proposed multi-scale zero energy building quantification approach used to evaluate the case study will impart a novel and comprehensive methodology for design and patterns of living in the context of zero energy residential building principles at different scales of the built environment today.

5.1 Evaluated elements of the building system boundary

The quantification technique executed for case study analysis alludes to an adequate coverage of all the required elements which are stipulated in the methodological framework. The significant elements applicable for case study investigation under each level of the building systems boundary are presented in Table 5.1 overleaf.

Table 5.1: Significant elements of the methodological framework applicable through the case study

Framework elements applicable for investigation through case study	Building system boundary
Building structure	Building or Building Zone
Building typology	Building or Building Zone
Energy efficiency measures	Building or Building Zone
Non-thermal efficiency measures	Building or Building Zone
Renewable energy supply options	Building or Building Zone
Urban context	Building Zone
Different regions or city context	Building or Building Zone
Parameter evolution	Building or Building Zone

The case study chosen for this work should together embody all the 8 elements as given in the table above if relevant data is available. Investigating the aspects in such manner will enable the robustness of the developed methodological framework to be rigorously tested and in so doing showcase a novel perspective towards the deployment of zero energy building practices at multiple scales of complexity. The chosen case study is described in the following section.

5.2 Case study selection

The selected case study is located in Auckland, New Zealand. Ideally, it could have also been beneficial to select another case study from a different country or city context. However, the methodological rigour (see Chapter 6) applied to the single case study in a multi-contextual perspective is judged appropriate at this stage of framework development. Attempts to adopt another case study from a different country or city were made but no detailed and reliable data on a specific house could be found.

The case study first stage verifies and tests the framework on a single recently built zero energy house. The second stage stretches the building systems boundary (as discussed in Section 4.1.1) to encompass the whole suburban neighbourhood. The framework leads to a methodology to calculate building embodied, operational, user transport and total annual energy demand as well as greenhouse gas emissions

in order to establish solutions of zero energy residential buildings at multiple scales of complexity. In addition, the evolution of parameters is also tested in order to investigate their influence in time.

5.2.1 A zero energy house located near Auckland, New Zealand

The first stage of the case study involves running a series of parametric variations related to a house located in Auckland, New Zealand built recently to the current zero energy building standard (Sartori et al., 2012). As was previously discussed in Section 3.1, internationally, zero energy buildings feature leading-edge efficient technologies (i.e. advanced insulation, glazing, appliances and so on) as well on-site/off-site renewable energy supply systems. In many cases, they have extremely low heating and cooling requirements.

Although the scene of the research scope has already been set in the context of current ZEB framework (see Section 3.1.2 and 3.1.3), it is still imperative to elaborate on the case study in the context of zero energy buildings for the purpose of the case study. Essentially, as was discussed in Sections 2.2.5 and 3.1.2, in Europe the Energy Performance of Building Directive (EPBD) set an implementation target for new residential building to conform to zero energy building notions by the year 2020. Subsequently, the deployment and popularity of zero energy buildings in other parts of the world (e.g. U.S.A, Japan, Canada, Australia, New Zealand, China, Singapore, Hong Kong, India, and South Africa etc.) has increased rapidly. Consequently, the application of zero energy building concepts are growing in importance and are very likely going to represent a pinnacle for regulating energy in both existing and new buildings.

However, the current ZEB framework (see Section 3.1.3) rarely addresses embodied and user transport energy requirements but instead focuses entirely on operation energy largely in terms of thermal aspects of the building. Frequently, other significant aspects such as indoor environmental quality are usually addressed. While such efforts deserve to be praised, focusing solely on building operational energy has been evidenced to be a significant flaw in the current ZEB framework as discussed in Section 3.5. It is important to test zero energy houses

both in order to determine the energy demand which most affects their energy balance as well as in comparison to other housing forms. The goal is to establish whether they do result in net zero energy or net zero greenhouse gas emissions.

5.2.1.1 Investigating extended building system boundary

The first stage of case study analysis is conducted at the building level. At the second stage, the building system boundaries encompass the whole suburban neighbourhood in order to compare other buildings with different forms other than the zero energy single-family detached house. This is elaborated further in Section 5.4.5.2. As was discussed in Section 4.1.1, the building system boundary can be extended to test the zero energy house in the suburban neighbourhood context in comparison with other forms of housing. Consequently, the breadth and scope of investigation can be enriched. Table 5.2 below provides the elements of the methodological framework analysed through the case study by the scope of each building systems boundary. These Elements are based on Sartori et al., (2012) and Stephan (2013).

Table 5.2: Elements of the methodological framework analysed through the case study by the scope of each building systems boundary

Framework elements analysed through case study	Building system boundary	
	Building	Building Zone
Building structure	✓	✓
Building typology	✓	✓
Energy efficiency measures	✓	✓
Non-thermal efficiency measures	✓	✓
Renewable energy supply options	✓	✓
Different country or city context	✓	✓
Urban context	✓	✓
Parameter evolution	✓	✓

5.3 Sources of data

As was mentioned in section 4.1.3, the scope of investigation associated with the developed methodological framework needs to be subjected to robust and detailed data inputs. The main sources of data collected to analyse the case study are elaborated in this section.

5.3.1 Bill of quantities

The itemized schedule of materials and parts used to construct, repair and maintain the building structure was sourced from the Bills of Quantities (BOQ) from the main contractor. Reasonable assumptions are made to estimate the quantity of building assemblies when information is not available in specific circumstances. The material bill of quantities of the modelled dwellings is presented in Appendix B. The population densities used in the evaluation are based on the figures from the city in which the case studies are located: Auckland, New Zealand.

The user transport calculations are based on relevant travel distances for particular modes of transport for Auckland, New Zealand. The average travel distance figures are sourced from the Ministry of Transport (2014). In addition, as was discussed in Chapter 4, calculations in this work are conducted at two levels: Building scale calculations (operational and embodied energy) and city scale calculations (transport operational and embodied energy). These aspects are explained hereunder.

5.3.2 Building scale calculations

5.3.2.1 Operational energy calculations

The operational energy calculations are performed using EnergyPlus®, a modelling and simulation software package presented in Section 4.2.1.1. a.

Besides the available measured data for the case study, other data for average regional operational energy non-thermal aspects used in the study is based on the Household Energy End-Use Project (HEEP) (Isaacs et al., 2010b). The primary energy conversion factors or coefficients for electricity and greenhouse gas emissions are obtained from Alcorn (2010). The variables for operational energy investigated in this study are given in Table 5.3 below.

Table 5.3: Investigated operational energy variables

Main variables	Building system boundary	
	Building	Building Zone
Heating energy intensity (MWh/annum)	✓	✓
Cooling energy intensity (MWh/annum)	✓	✓
Appliances energy intensity (MWh/annum)	✓	✓
Lighting energy intensity (MWh/annum)	✓	✓
Cooking energy intensity (MWh/annum)	✓	✓
Domestic hot water energy intensity (MWh/annum)	✓	✓
Solar energy intensity (MWh/annum)	✓	✓
Primary energy coefficient for electricity (MWh_{prim}/MWh_{ele})	✓	✓

5.3.2.2 Embodied energy calculations

Building embodied energy calculations are undertaken in accordance with the equations given in Section 4.2.1.2. b (from equation 4.4 to Equation 4.16) using the database of embodied energy and greenhouse gas emission coefficients compiled by Alcorn (2010). The bill of quantities for various materials used for the case study investigated is presented from Table B.1 to B.6, of Appendix B.

5.3.3 City scale calculations

5.3.3.1 User transport energy calculations

The user transport energy calculations are performed according to the equations provided in Section 4.2.2.2 (from Equation 4.17 to Equation 4.26) and the data used for analysis are obtained from Mithraratne (2011). Operational energy requirements for petrol vehicles are established by multiplying the average fuel economy of a particular mode by the energy content of the fuel from Ministry of Business, Innovation and Employment (2015). Thereafter, the product is divided by the average vehicle occupancy (1.6 passengers). The average fuel economy for New Zealand vehicles is 10.1L/100km according to the Ministry of Transport (2014).

The operational energy requirements of electric transport modes is determined by multiplying the energy efficiency of a particular mode by the primary energy coefficient. The transport data used was complemented to fill the missing gaps

since no input-output study for embodied energy of electric modes running in New Zealand yet exists. Consequently, the embodied energy requirement of electric vehicles is assumed to represent 45% of the total operational requirements based on Hawkins et al., (2012). The train operational energy efficiency requirements are derived from similar trains in Switzerland, Austria and Germany⁶. Embodied energy requirements for trains are assumed to represent 50% of the total operational energy requirements based on Lenzen (1999).

The embodied and operational energy intensity of diesel buses are obtained from Mithraratne (2011). In 2012, the light passenger fleet in New Zealand was made up of 79.5% petrol and 7.4% diesel vehicles, (Ministry of Transport 2014). The 13.1% represent the light commercial vehicle fleet, which are not the focus in this thesis. Owing to lack of data in the New Zealand context, it is judged suitable not to consider diesel powered private vehicles at this stage of research. The operation and embodied energy intensities for each mode of transport in the city are presented in Table 5.4 below.

Table 5.4: Energy intensities of transport modes used in the city

Mode of transport	Operational energy intensity ^a (kWh/p-km)	Embodied energy intensity (kWh /p-km)
Private transport		
Vehicle (Petrol)	0.7 [#]	0.21 [#]
Vehicle (Electric)	0.15 (0.1*)	0.07*
Public transport		
Bus (Diesel)	0.84 [#]	0.1 [#]
Train	0.19 (0.13 ^{\$})	0.09 ^{\$}

Note: ^a The values in brackets are final useful energy prior to multiplication by the primary energy coefficient.

*[#]Based on Mithraratne (2011), *Stephan 2013; Stephan et al., (2013b), ^BBradley and Associates (2008), ^{\$}Siemens Transportation Systems (2009).*

5.3.4 Uncertainty and variability

As was previously discussed in Section 4.2.7.2., the uncertainty of embodied energy data and variability related to the user behaviour need to be taken into

⁶ This assumption is based on the fact that most common and efficient intra-urban trains running in Switzerland, Austria and Germany are manufactured in Spain, France and Germany. Auckland intra-urban trains are manufactured in Spain.

consideration. The embodied (hybrid process-based data), operation and transport energy requirements are considered to have a variability range of $\pm 20\%$.

5.4 A zero energy house located near Auckland, New Zealand

5.4.1 Elaboration of the house as a base case

The studied zero energy house is a 200m² detached single family house for 2 persons located in Point Chevalier, a low density suburb located 6 kilometres west of Auckland city, New Zealand (Latitude S36° 51'54", Longitude E174°42'54"). Built in 2012, the home has two storeys of approximately 74m² upper floor, 73m² ground floor and 53m² garage connected to the house. The house is accessed at the street level on the ground floor. It has a roof-mounted 4.16kW_p grid connected solar photovoltaic array and a 5000L rain tank supplying toilets, washing machine and outdoor taps. Figure 5.1 and Figure 5.2 below presents the plan and the photographic view of the house.

Figure 5.1: Plan view of the Auckland zero energy house

Figure 5.2: Photographic view of the Auckland zero energy house

Further project information regarding the dwelling can be found online: <http://zeroenergyhouse.co.nz/zero-energy/>. The façade of the house is composed of a timber-frame wall of 90 mm framing with weatherboard cladding. This standard framing typical in New Zealand houses has $\sim 16\%$ of thermal bridging which allows increased heat loss from the envelope (Brazier and Woods 2012). This was reduced in the case study house by removing the horizontal nogs from between the studs and replacing them with supporting battens that run along the wall frame externally. This reduces the thermal bridging to the points where the battens cross the framing.

The house is super insulated with 135 mm of polyester (PET) insulation (thermal conductivity $\lambda = 0.0358$ (W/m·K)) in the walls, 190 mm peripheral insulation (polyester) in the ground floor ceiling and 190 mm of polyester in the roof directly under the roof sheeting. All windows are double glazed argon filled low emissivity (Low E) glass in aluminium frames with solid timber liners. The *U values* and *R values* of the envelope components are presented in Table 5.5 below.

Table 5.5: U values of the envelope components of the zero energy house case study

Construction	R-value ($(\text{m}^2\text{k})/\text{W}$)	U-value ($\text{W}/(\text{m}^2\text{k})$)
Main roof	4.21	0.24
Membrane roof	3.52	0.28
Garage roof	3.63	0.28
External wall	3.20	0.31
Ground Floor	2.13	0.47
Exposed Floor	2.25	0.44
Internal Floor	2.14	0.47
Internal Wall	1.3	0.77
Glazing	0.59	1.68
Window/Door Frames	0.56	1.79

The relatively higher insulation levels of the zero energy house enable the targeted indoor temperatures to be maintained primarily by the heat from the sun (solar energy) and also through day-to-day living (heat from occupants and electrical equipment such as lighting and cooking).

The house is serviced by domestic solar water collector plates that deliver hot water in the building at a temperature of 50°C . As pinpointed in Section 2.1.1.2, electricity generation servicing houses in New Zealand comprises a high share of renewable energy. In particular; hydropower (54.5%) and natural gas power plants (19.4%) including other shares from geothermal (14.5%), coal (5.3%) and wind (4.8%). The zero energy house total useful energy demand is 2,361 kWh/annum and it generates on-site 5,387 kWh/annum through the solar photovoltaic array mounted on the roof of the house at $\sim 1,400 \text{ kWh}/\text{m}^2/\text{annum}$ of solar irradiance. The total energy import from the electricity grid is 1,348 kWh/annum, while 4,341 kWh/annum accounts for the amount of energy exported to the grid.

Two adults live in the house with an infant. The house owners possess two motor vehicles and rarely use the train or bus. The nearest railway station is located 2.3 km south of the house in Point Chevalier, while the nearest bus stop is 0.4 km south of the house. This dwelling is a very representative of a typical zero energy

building based on current principles (as discussed in Section 3.1.3) in New Zealand. More importantly, it is the first in New Zealand to be awarded Net Zero Energy Certification under the Living Building Challenge™ (International Living Future Institute 2014).

5.4.2 Modelling parameters

5.4.2.1 Embodied energy

The bill of quantity figures used were the same as those provided by the main contractor. The list of all used materials and their quantities is given in Table B.1, Appendix B.

5.4.2.2 Operational energy

The operation energy calculations in EnergyPlus® are based on the real/monitored performance data inputs of the house. The following section presents the detailed inputs of the EnergyPlus® model aspects considered for the calculation.

5.4.2.2. a Weather

The weather file used to model the house in EnergyPlus® for simulation was a NIWA weather file for Auckland, New Zealand, *NZL_Auckland_NIWA.epw*. This weather file was produced from the actual average weather data and therefore does not account for any extreme or unusual weather conditions that may occur.

5.4.2.2. b Floor areas

Table 5.6 below presents the modelled and actual floor areas of the house. The discrepancies between these areas are inherent in the EnergyPlus® modelling process and are, as shown, insignificant.

Table 5.6: Actual and modelled floor areas of the case study zero energy house

Room	Actual Floor Area (m ²)	EnergyPlus® Modelled Floor Area (m ²)	Relative difference	Status
Living spaces	59.4	60.2	+1.3%	Acceptable
Bedroom spaces	62.5	61.6	-1.4%	Acceptable
Garage spaces	56.8	56.2	-1.1%	Acceptable

5.4.2.2. c Occupancy loads

Occupants' heat loads were based on CIBSE Guide A and are presented in Table 5.7 below. The house was modelled with two occupants and this was also the case during the actual monitoring period. Towards the end of October 2013, a baby was also present in the house. However, it is assumed that the baby would not have added to the internal gains of the two thermal zones being investigated and that there is no requirement of active heating to keep the baby warm. For these reasons, this change in occupancy was not considered in the model.

Table 5.7: Heat loads from occupants

Person	Typical number of occupants	Heat load per occupant (W) based on CIBSE Guide A(2006)
Man	1	130.0
Woman	1	110.5

The occupant loads (W/m^2) for each thermal zone were determined based on the occupant load presented in Table 5.8 below and the floor areas of each space. The occupant loads were applied to the open plan living space and master bedroom as occupancy was typically assumed to be transient in all other spaces. Occupancy schedules presented in Table 5.9 below are based on the real occupancies for the house which is typically unoccupied for most of the day, but occupied in the morning and evening in the living and master bedroom spaces.

Table 5.8: Occupant loads for each thermal zone

Thermal zone	Total Load (W/m^2)	Sensible Load (W/m^2)	Latent Load (W/m^2)
Living space	4.7	2.9	1.8
Bedroom space	11.7	7.1	4.6
Other spaces	0.0	0.0	0.0

Table 5.9: Occupancy schedules

Hours	0-7	7-8	8-18	18-23	23-24
Living space	0%	100%	05	100%	0%
Bedroom space	100%	0%	0%	0%	100%
Other spaces	0%	0%	0%	0%	0%

5.4.2.2. d Lighting and equipment

The lighting and equipment loads used for each thermal zone are presented in Table 5.10. Lighting loads are calculated from the actual wattage of lights in the space. Where a space had more than one light switching zone then the load was calculated from the lights most likely to be used at the time i.e. a proportion of the total lighting wattage in that space.

Table 5.10: Lighting and equipment loads from each thermal zone

Thermal zone	Lighting load (W/m ²)	Equipment load (w/m ²)
Living spaces	1.5	9.0
Bedroom spaces	1.0	0.0
Other spaces	2.0	0.0

Similarly, the equipment loads (Table 5.11 overleaf) were based on the equipment power and expected usage. The living area is assumed to have the equipment load as it contains cooking equipment, fridge and television. The equipment in all other spaces is intermittent and therefore excluded from the model. Table 5.11 and 5.12 below provide the lighting and equipment load schedules respectively. These are based on typical expected hourly loadings.

Table 5.11: Lighting schedules

Hours	0-7	7-8	8-18	18-23	23-24
Living spaces	0%	100%	0%	100%	0%
Bedroom spaces	0%	0%	0%	0%	50%
Other spaces	0%	0%	0%	0%	0%

Table 5.12: Equipment schedules

Hours	0-7	7-8	8-18	18-23	23-24
Living spaces	50%	50%	50%	100%	50%
All other spaces	0%	0%	0%	0%	0%

5.4.2.2. e Infiltration

The infiltration rates used in the modelling are based on Table 4.21 CIBSE Guide A and are presented in Table 5.13 below. They assume the house is airtight but allow for leakage through any extract vents, as the seals on these are not airtight and for the front door being opened occasionally in the main entrance. Owing to lack of sufficient data on the usage of extract systems, infiltration due to such uses was not accounted for as it is relatively low and only occurred for a short period. In addition, it is further assumed that the house is new and the building envelope is built to be well sealed.

Table 5.13: Infiltration rates used for modelling

Space	Infiltration (ACH)
Space comprising extract system	0.50
Main entrance	0.5
All other spaces	0.25

5.4.2.2. f Ventilation

The house is designed to be naturally ventilated by manually controlled windows and doors that can either be turned to open like normal side hinged doors or windows or tilted open. In the tilt function, the doors and windows are secure.

Consequently, they can be left open when the house is unoccupied. It is difficult to realistically attempt to model natural ventilation as it depends on the occupants' preferences, what they are wearing and their metabolic rates. For this study, the windows and doors are assumed to only be used in the tilt function, not the turn function. Discussion with the occupants showed that the tilt function was the most used while the turn function was used sporadically. In the tilt function, the effective opening area is about ~15% of the window/door area.

Ideally, in the EnergyPlus® tool, simple natural ventilation is employed under the object *ZoneVentilation:WindandStackOpenArea*, which, with simplified equations, calculates wind and buoyancy driven flows at the thermal zone level based on the user-input parameters, e.g. wind direction, indoor-outdoor temperature difference, effective opening area, height difference etc. Further details regarding this object can be found in the EnergyPlus® input/output reference manual Section 1.27. Mechanical ventilation in the house includes kitchen and bathroom extract fans. Although important for the management of moisture and odours, the usage of these is intermittent and therefore not included in the model.

5.4.2.2. g *Shading*

The house was not shaded by any of the surrounding houses or vegetation, therefore these are not included in the model. Shading from the house itself, i.e. where the first floor overhangs the ground floor on the elevation or the main house shades the eastern sun to the garage, was included in the model.

5.4.2.2. h *Systems*

The house is not actively heated or cooled and therefore it is modelled as unconditioned. Consequently, the temperatures analysed are free-running. PV and DHW generation are modelled using the simple model *PhotovoltaicPerformance:Simple* and *SolarCollector:FlatPlate:Water* objects respectively based on real-time performance data. Further details regarding this object can be found in the EnergyPlus® input/output reference manual Section 1.53 and Section 1.38 respectively. The 3-Dimensional image in EnergyPlus® is presented in Figure 5.3 below.

Figure 5.3.3-Dimensional image used for modelling the Auckland zero energy house

5.4.2.3 User transport energy

The assumption used in order to calculate the user transport energy is that the household owns two vehicles, both running on petrol. These assumptions are based on average New Zealand figures for transportation fuel usage given in Section 5.3.3. Each vehicle was assumed to be driven 12,000 km per annum based on the figures from the New Zealand average annual fleet statistics (Ministry of Transport 2014).

In addition, internal combustion vehicles (ICEVs) as described in Section 4.2.2, in this work are categorized according to small, medium and large based on engine size or “cylinder capacity” (CC). The vehicles sizes studied are:

- a) Small vehicles → < 1600 CC
- b) Medium vehicles → 1600 - <2500 CC
- c) Larger vehicles → > 2500 CC

When testing a switch to 100% electric vehicles, the same travel distance is also assumed. In addition, it is also assumed that the main income earner prefers to charge their EV at home since it can be done by simply plugging the EV on-board charger to the outlet that is presumably installed within the private garage,

commonly known as the “conductive charging” regime. The standard power level of conductive charging is further assumed to be in accordance with the SA J1772 standard, AC level 2 single-phase 240 V, 32 A, 7.4 kW with 91%- 94% charging efficiency. This charging regime is designed with a low charging rate and is dedicated to charge the battery for a longer period of ~5-8 hours for full charge.

Since average daily travel distance covered through vehicles in New Zealand is approximately 40 km per day, and many EVs have a battery capacity that can cover roughly 160km or more, drivers find that their daily travel distance barely depletes the battery charge and therefore only requires overnight charging. For instance, assuming that the main income earner drives a Nissan Leaf, which has approximately 160km marketed driving range, and drives about 40 km daily, the battery will only be depleted about 30% each day. Since this charging regime will recover about 7 km of range per hour, the Nissan Leaf will revert to full charge approximately after 7 hours which essentially translates to an overnight charge.

5.4.3 Variations of the base case zero energy house

Variations in regards to the building embodied, operational and user transport (embodied and operational) energy requirements of the studied zero energy house are used to identify opportunities for optimizing the energy demand at both the building and city scales in the context of zero energy buildings and their users.

Ideally, all the variations concern crucial parameters which have been identified to have significant influence on the total annual energy demand associated with zero energy houses and their users. The least energy intensive scenarios identified will be combined to provide the best case scenario with the lowest overall energy demand. This scenario will then be used to compare with alternative dwellings.

5.4.3.1 Embodied energy variations

New Zealand houses tend to have a low initial embodied energy intensity (see discussion under Table 3.3 in Section 3.4.2). Consequently, in this case study, three building envelope variation of the superstructure of the house are considered. Wall, ceiling and roof insulation modifications are thus performed. These envelope

elements are varied because they represents the highest shares of embodied energy intensity in a typical New Zealand house of light weight construction (Mithraratne et al., 2007 p.159) and can be modified without compromising the energy performance of the zero energy house being studied.

INSULATION MATERIAL VARIATIONS

According to the current ZEB framework, one of the most prominent characteristics of zero energy houses is that they are extremely well insulated and so is the case in the current case study house. For this reason, it is imperative to test the effect on embodied energy of various insulation materials other than the polyester (PET) used in the house as built. Glass wool insulation, which has an embodied energy intensity of 32 MJ/kg (67.8% less energy intensive compared to polyester with 53 MJ/kg) but has similar heat transfer coefficients, is used to replace polyester in the walls, ground floor ceiling and roof. There were no changes made to the ground floor slab since it is not typically insulated by soft materials such as glass wool. The selection of alternative insulation materials is limited to the availability of data with regards to embodied energy and greenhouse gas emission coefficients. The changes made therefore are as follows⁷:

- a) 135 mm of PET in walls → 180 mm of glass wool,
- b) 190 mm of PET in floor ceiling → 210 mm glass wool; and
- c) 235 mm of PET in roof → 275 mm of glass wool.

5.4.3.2 Operational energy variations

Operational energy variations take into account the influences resulting from the changes in building useful energy to the behavioural patterns of the occupants.

EFFECT OF USER BEHAVIOURAL PATTERNS ON NON-THERMAL ASPECTS

Historically, social-economic dimensions are significant influencers of the interconnection between energy and user consumption patterns (highlighted in

⁷ The changes in thickness of PET to glass wool are based on BRANZ (2014), i.e. increase in glass wool thickness maintains the same heat transfer coefficients as original PET to maintain the modelling parameters in EnergyPlus®.

Section 2.3). In addition, research following the evolution of zero energy buildings has demonstrated that social expectations and consumption behaviours of their users can distort the most clever innovations (see for example Keese 2005; Stevenson and Rijal 2010; Bourelle 2014; Berry et al., 2014). For these reasons plus it is likely that people living in zero energy houses use energy efficient appliances (see Section 3.1.2.1), it is imperative to investigate both less and more energy intensive user behavioural patterns although in reality, less energy intensive behavioural aspects are not often the case (Janda 2011).

The effect of user behavioural patterns on non-thermal energy end-use aspects is modelled based on two scenarios. The first scenario reduces the final energy demand for all non-thermal energy demand by 20% over the base case, while the second scenario increases the final energy demand by 20%. The reduction factors for each scenario are given Table 5.14 below.

Table 5.14: Reduction and increment factors for final operational energy end uses

Final operational energy end-uses	Scenario - 1 reduction factor	Scenario -2 increment factor
Heating energy	0%	0%
Cooling energy	0%	0%
Monitoring system energy	-20%	+20%
Rain and grey water pump energy	-20%	+20%
Cooking energy	-20%	+20%
Domestic hot water	-20%	+20%
Lighting energy	-20%	+20%
Appliances energy	-20%	+20%

COMBINING LOW ENERGY DEMAND MEASURES

The energy saving measures are finally considered together. Ideally, the combination of these measures is expected to reveal significant energy consumption patterns associated with the zero energy house and its users on an annual basis.

5.4.3.3 User transport energy variations

As discussed in Section 4.2.2.2, user transport energy is closely connected to the type of transport mode used. It is also crucial to test for the effects of both the potential shift to public transport modes and also a switch to electric vehicles.

For all the reasons discussed earlier, the variations considered for user transport energy assume that the household owns one vehicle instead of two and also uses public transportation to commute and also for other purposes (e.g. shopping, leisure etc.). The changes made in regard to user transport energy for the studied house are:

- a) Two vehicles → One petrol vehicle driven 12,000 km per annum;
- b) One petrol vehicle → One electric vehicle (EV) driven 12,000 km per annum;
- c) The users take the bus to commute to Auckland CBD and also for other purposes; and
- d) The users take the train to commute to Auckland CBD and also for other purposes.

These assumptions to the variations of transport energy are based on the availability of urban transport modes in the city (Ministry of Transport 2014).

In parallel, when it comes to transport energy, it solely depends on the users to decide on which particular vehicle to drive given a wide variety of models present on the market today (Geels et al., 2012, Folkson 2014). In addition, user transport energy and associated emissions are highly reliant on factors such as: vehicle type, users' travel distance and energy/emission coefficients of different fuels involved, amongst other social factors as discussed previously (Geels et al., 2012). Consequently, due to the dominance of private vehicles in the city as discussed earlier in Section 1.3, another variation is also undertaken for further sensitivity analysis. A range of ICEVs is selected for variation based on engine size as declared in Section 5.4.2.3. The vehicles are selected based on the bestselling vehicles on the

New Zealand market. Certainly, the same criterion of selection is also applied to the variation of electric vehicles (see Table B.7, Appendix B).

5.4.3.4 Variation of other parameters

Apart from the variations in building embodied, operational and user transport energy requirements, two other parameters were also varied in order to test their influence on the annual total energy use of the zero energy house best case and the standard house. These parameters are related to the “temporal variability” (as discussed in Section 4.2.7.2.). Consequently, this evolution of parameters in this variation is applied to two of the aspects: number of users and evolution of primary energy coefficients for electricity and greenhouse gas emissions.

5.4.3.4. a Number of users (household size)

Variation of the number of users is based on the usable floor area of the base case zero energy house. The usable floor area for 2 persons in the base case scenario is $\sim 74 \text{ m}^2$ per person. An increase in household size from 2 to 3 results in a decrease in the usable living floor area per person from $\sim 74 \text{ m}^2$ to $\sim 49.3 \text{ m}^2$. On a per inhabitant basis, this figure is still high given that even 5 users could live in the house with 29.6 m^2 per person. The changes in composition of the household are increased from 2 to 3 and 5 persons. This is based on the assumption that average room area per particular liveable space in NZ households is $\sim 23.7 \text{ m}^2$ for 2.6 persons (Khajehzadeh and Vale 2016). The influence of the number of users on the annual total energy demand is presented in Section 6.1.4.1.

5.4.3.4. b Primary energy coefficients for electricity and greenhouse gas emissions

The reduction over time of primary energy coefficients for electricity and greenhouse gas emissions represents the potential for installation of additional renewable energy sources (e.g. wind, hydro, solar, tidal or wave energy etc.). Such renewable energy sources imply a net reduction of primary energy requirements since burning processes and inefficiencies are subtracted in the energy supply chain when compared to fossil fuel power plants. Similarly, the greenhouse gas emissions closely linked with the combustion processes are also subtracted.

Table 5.15 presents the values of the evolution of primary energy conversion factors and greenhouse gas factors for electricity at key dates associated with the testing period. As described in Section 4.2.7.2 and Section 4.3.2, the evolution of parameters associated with primary energy coefficients for electricity and greenhouse gas emissions are modelled through compound annual growth rate of renewables specified at each year of investigation (See Equation A.1 Appendix A). The evolution of parameters at key dates are inspired from the 450 scenario of the International Energy Agency -IEA 450 Scenario ⁸(IEA 2011).

Table 5.15: Values of evolving electricity parameters at key dates during the period of evolution of the Auckland zero energy case study house

Stage of period of evaluation [#]	Primary energy conversion factor ^{§,§}	Greenhouse gas emissions factor for electricity(kgCO ₂ -e/ MWh) ^{§,§}
2010	1.5	214
2015	1.4	179
2020	1.1	143
2025	0.8	107
2030	0.5	71
2035	0.3	36

Note: [#]Inspired from the 450 scenario of the IEA (2011), [§]before 2010 factors based on Alcorn (2010), [§]after 2010 factors interpolated from this study.

5.4.4 Best case

A best case scenario encompasses the combination of the lowest energy requirements resulting from the variation calculations. Logically, however, the characteristics of the best case scenario can only be realised after establishing the individual variations separately. Consequently, the overall best case features in this study are presented later in Section 6.1.5.

⁸ IEA 450 Scenario sets out an energy pathway consistent with the goal of limiting global increase in temperature to 2°C by limiting the concentration of CO₂ emissions in the atmosphere to ~450 parts per million of CO₂. This is broadly consistent with the World Energy Outlook in the implementation of renewable energy technologies from 2010 through 2035.

5.4.5 Comparison of alternative dwellings

As mentioned in Section 5.2.1.1, the studied zero energy house is compared to other types of housing based on stretched building system boundaries. At the building level, the zero energy house is compared to the standard family detached house, while at the building zone or district level, the building system boundary is stretched to investigate multiple zero energy houses versus other multiple housing forms in the urban context in the city of Auckland.

The influence of multiple parameters on the annual energy demand is tested through the two comparisons mentioned above. In particular: at the building level, the comparison of the standard house at the building context sheds more light on the influence of the choice of building materials/components and overall energy performance. On the other hand, the comparison of the house with other dwelling forms at the neighbourhood context tests the influence of urban scale parameters such as location, housing typology, public transport etc.

5.4.5.1 The standard house

The alternative standard family detached house is modelled with similar geometry as the zero energy house but instead follows the usual norms for standard construction in terms of insulation, structure etc. The standard house in Chapter 6 is referred to as *STD_H*. The changes made to the base case zero energy house therefore, are as follows:

- a) Modified exterior walls to normal timber-framed with weatherboard cladding (90 mm framing with PET insulation $U\ value = 0.45\ W/m^2\cdot K$);
- b) Modified insulation in the ground floor ceiling (100 mm of PET $U\ value = 0.67\ W/m^2\cdot K$);
- c) Install ducted air source heat pump⁹ (COP 3.5)
- d) Removed building energy monitoring system;
- e) Removed solar photovoltaic array from the roof; and

⁹ This assumption is based on the fact that New Zealand has been experiencing a rapid growth in sales of heat pumps the past decade (French et al., 2008).

- f) Removed rain and grey water recycling system and pumps.

All other parameters are kept constant with regards to the base case zero energy house.

5.4.5.2 Other housing forms

At building zone or district level, the zero energy house (with stretched building systems boundary) is studied at the urban context in comparison to other housing forms. The low density suburban neighbourhood where the zero energy house is located is used to investigate this aspect at a larger urban scale. In this way, the investigated neighbourhood is a representation of what is commonly known as ‘inner-sector’ suburban areas in New Zealand and many other regions in the world (this aspects is discussed in Section 4.1.1). The neighbourhood is based in the area of Point Chevalier (Latitude S36°50'18', Longitude E174°42'18"), 6km west of Auckland central business district. The reasons for focusing on an inner sector suburban neighbourhood in this case study are explained hereafter.

Due to the increasing population, the trend which is currently occurring in most cities is the development of outer-sector suburban neighbourhoods (Yaping and Min 2009; Howden-Chapman et al., 2010; Yew 2012; Rojas et al., 2013; Stephan 2013; Stephan et al., 2013b; United Nations 2014). Therefore, it can be argued that it could have been more beneficial to study the “outer-sector” suburban areas. In a pragmatic sense, however, it has also been contested that it is crucial to conduct more research on the best methods of transforming the existing ‘inner-sector suburbs’ to more efficient ones as a way of controlling sprawling of urban suburbs into open lands (see e.g.; Rickwood et al., 2008).

Theoretically, urban form is often considered as one significant determinant factor for achieving a more sustainable city (Jenks et al., 2000). Yet it has also been argued that current sustainable urban development models are not yet comprehensive and do not have strong conceptual underpinnings (Guy and Marwin 2000; Ng 2010). However, compact city living with high density urban configurations is arguably sustainable as it is believed to have the potential to support closer amenities,

encourage reduced trip lengths, use of public transport and therefore resulting in less energy intensive urban areas (see e.g. Newman and Kenworthy 1999; Jenks et al., 2000; Van Coevaring and Schwanen 2006; Karathodorou et al., 2010; Glaeser and Kahn 2010; Stephan et al., 2013b; Minx et al., 2013; Weidenhofer et al., 2013). Consequently, the promotion of high density residential developments in many regions across the world has become an orthodox part of urban planning. In fact, this phenomenon to promote more dense urban forms within outer and inner-sector city developments mirrors what has currently been adopted in the Auckland region through the 'Proposed Auckland Unitary Plan' (PAUP) (Auckland Council 2014)¹⁰.

Ideally, urban sprawl in the city of Auckland is not desired. Consequently, population densities in the city's residential suburbs will have to increase markedly if the region is to encompass almost 2 million inhabitants (projected population of Auckland at June 30th 2031). In order for the Point Chevalier suburb to absorb the required people and housing, under PAUP zoning areas have been simplified across the suburb into three types of residential zones. These are: Terrace and apartment housing, mixed housing and single housing. This intensification of the 'inner or outer-sector' developments is a small scale representation of one scenario that is likely to happen in other cities across the world in order to control the sprawling of urban suburbs into open lands and improve the efficiency of urban infrastructure and services (Rickwood et al., 2008; Ng 2010; Karathodorou et al., 2010; Glaeser and Kahn 2010; Stephan et al., 2013b; Minx et al., 2013; Weidenhofer et al., 2013). For all the above stated reasons, comparison between a zero energy building zone or district with other building forms for higher density configurations in this case study will be tested through variations to the building typologies.

¹⁰ The PAUP is defined as a tool to deliver a 30-year long ambitious vision to transform Auckland into the world's most liveable city. It is therefore a rule book that shapes how Auckland should grow upwards and condense its growth into the existing city parameters.

5.4.5.2. a *Elaboration of the base case suburban neighbourhood*

The Point Chevalier suburban neighbourhood is categorized into three sections, namely; East, South and West sections which have an area of 1.46 km², 1.29 km² and 1.26 km² respectively. Amongst the three sectors, the key area to undergo major transformation is Point Chevalier West (see Figure 5.4 overleaf) (Auckland Council 2014). Therefore, this case study is based in this sector. Furthermore, the population of Point Chevalier West is the middle value between the value of the other two sectors, i.e. Point Chevalier East has 4,116 inhabitants, West has 3,047.6 inhabitants, while South has 1,491 inhabitants. For these reasons, a density of Point Chevalier West of 2,419 inhabitants/km² is chosen to reflect the average density of the inner sector.

Figure 5.4: Map of Auckland and urban lay out of Point Chevalier West, East and South

The aim of this study is to provide a detailed investigation of a zero energy suburban neighbourhood compared to an alternative suburban neighbourhood comprising different high density housing forms that comply with standard

building code and energy efficiency regulations. Therefore, this study does not consider zero energy high density configurations as the most understood zero energy building notions are applicable to the stand-alone house (see Section 3.1 to Section 3.2). Actually, lack of understanding of mixed-use zero energy buildings is perhaps evidenced by the failure of the Beddington Zero (fossil) Energy Development (BedZED) in the United Kingdom (Bioregional 2014, p.21-22). It can therefore be argued that investigating stand-alone zero energy buildings in comparison with standard alternative buildings at neighbourhood scale using the methodological framework established in this work is likely to increase the current understanding of the “zero energy communities”.

5.4.5.2. b Dwellings used for modelling the base case neighbourhood

With that in mind, the base case neighbourhood BC_NBH is modelled with a surface area of 1.26 km² of which ($\sim 185,000 \text{ m}^2$)¹¹ is ascribed to the floor area of the residential buildings (Statistics New Zealand 2013). The remainder of the surface area is undeveloped land, other infrastructure, roads, gardens, footpaths and so on. The base case neighbourhood BC_NBH further comprises two types of zero energy buildings, i.e. BASE_CNBH and BASE_CNBH3, with each representing 50% of the built building stock to model the neighbourhood. Ideally, splitting 50% each provides a variety of household characteristics which in turn allows for better comparison of living patterns and energy consumption. This assumption is based on the fact that user characteristics are less understood in the current ZEB framework, as discussed in Section 2.3 and Section 3.5.2. Ideally, confining the base case zero energy house neighbourhood with a variety of user characteristics should enhance the current understanding regarding the importance of different living patterns within a common urban setting. Nevertheless, after establishing a significant understanding of issues mentioned above, further development of this framework to automate the calculations should allow for comparison of 100% of BASE_CNBH and

¹¹ There are 1,323 residential buildings in Point Chevalier west with an average floor area of $\sim 140 \text{ m}^2$ each.

BASE_CNBH3, which in turn allows for direct comparison between the 2 neighbourhoods.

The first house BASE_CNBH is 200m² in area and is assumed to be occupied by 2 persons while the second house BASE_CNBH3 is also 200m² in area but is assumed to be occupied by 3 persons. Essentially, both building zones/districts are based on the base case zero energy house (see Section 5.4.1). The increase in household size to 3 for zero energy building district BASE_CNBH3 is based on the assumptions given in Section 5.4.3.4. a.

The base case neighbourhood BC_NBH is modelled with 618 buildings of each type and the obtained density for the group of buildings in the zone or district is 2,452 inhabitants/km². The modelling parameters for the zero energy building district BC_NBH are the same as those provided in Section 5.4.2.

5.4.5.2. c *Comparison of zero energy building neighbourhood with other building forms based on typology*

Comparing the zero energy building neighbourhood with another neighbourhood comprising multiple building forms based on typology brings forth a discussion on “urban form”. This aspect is discussed under this section because it is related directly to the case study rather than the general framework presented in Chapter 4.

As was discussed in Section 5.4.5.2, urban form is viewed as an anchorage for leading cities towards a more sustainable future (Jenks et al., 2000). Along this thread, more dense and compact residential urban form configurations are often associated with reduced environmental impact in many regions across the world (Newman and Kenworthy 1999; Glaeser and Kahn 2010). Ideally, encouraging and even requiring high density urban developments is a major and a central principle of growth management programmes used by urban planners globally (Newman and Kenworthy 1999; Jenks et al., 2000; Van Coevaring and Schwanen 2006; Karathodorou et al., 2010; Glaeser and Kahn 2010; Stephan et al., 2013b; Minx et al., 2013; Weidenhofer et al., 2013). However, optimal density practices come with

multiple challenges and problems as the advantages are not entirely clear-cut. There is still a debate over whether high density automatically curtails greenhouse house gas emissions and is generally more sustainable. Along these lines, multiple studies have actually argued that often the advantages of increased densities within urban areas are exaggerated (see for example Williams 2000; Shin 2010; Lawson 2010; Wong 2010). It is therefore crucial to test the complexity of this case in order to identify the most favourable means of lowering environmental impact in urban areas. For all these reasons and also the reasons given in Section 5.4.5.2, comparison of zero energy building zones/districts with other building forms at neighbourhood scale based on high density configurations are investigated through variation in building typologies.

At the urban scale, dwellings are affected by a number of underlying factors e.g. existing site configurations and the building regulations. High density housing therefore obeys the basic principles at a range of scales, i.e., from the consideration of the whole neighbourhood to the full details of the urban fabric (Rickwood et al., 2008). One important factor to consider when addressing decision in high density developments is housing typologies. Ideally, when urban dwellers move closer together, a new set of housing types is often necessary (Rickwood et al., 2008; Stephan et al., 2013b). By its very nature, high density housing relies on particular forms of housing units such as semi-detached, group of row or terrace housing units or low/high rise apartments rather than traditional detached houses. Apartment buildings often require a significant amount of extra material for fire safety, lifts, systems, structure and additional operational energy for common areas (Rickwood et al., 2008; Stephan et al., 2013b). For this reason, only less energy intensive group of row and terraced houses are used for this investigation.

The introduction of this housing typology compared to the zero energy building district at a neighbourhood scale is tested through two scenarios. Significantly, one half of the built area of the base case neighbourhood BC_NBH which is $\sim 92,700 \text{ m}^2$ is replaced by a district of single storey row houses (STD_RH) while the other half of the

built area is assigned to a district of two -storey terrace houses (STD_TRCH). The breakdown of this housing typology is presented in the following section.

5.4.5.2. d Building typology scenarios

The base case neighbourhood scenario BC_NBH comprising of a district of zero energy buildings BASE_CNBH+BASE_CNBH3 is replaced by a district of row and terrace houses STD_RH and STD_TRCH i.e. the STD_RH+STD_TRCH scenario ,with each representing half of the built surface area. The 50% split is selected in order to understand a variety of building types within an urban setting to reflect different building zones as defined in this thesis. This assumption is also based on the fact that Point Chevalier suburb has been allocated to encompass multiple housing types within the current Proposed Auckland Unitary Plan, i.e. low rise apartments, semi-terrace houses etc. (Auckland Council 2014).

Typically, row and terrace houses have common boundary walls where all floors within a vertical element are in the same unit. These are an archetypal European model for typical high density housing. Generally, terrace houses are smaller compared to traditional single detached houses. In addition, space heating requirements are minimised due to the reduced thermal heat transfer surfaces as a result of shared walls. The embodied energy with such developments is expected to be lower due to the shared common party-walls which reduce the need for thermal insulation and waterproof materials in the internal walls between the housing units.

Consequently, the first alternative typology scenario STD_RH, consists of a series of four identical or mirror image houses sharing side walls such that the two middle houses denominated as STD_RH-1 (with 150m²) have two independent façades and the other outer two houses denominated as STD_RH-2 (also with area 150m²) on the ends have three independent façades. The basic geometric representation of the row housing units is given in Figure 5.5 overleaf.

Figure 5.5: Basic geometric presentation of the group of row housing units

The second scenario STD_TRCH involves a modification of the previous scenario. Here, the groups of houses are modified to feature a double storey set of housing units. See Figure 5.6 below.

Figure 5.6: Basic geometric representation of the multi-storey terrace housing units

This arrangement results in the accommodation of more people per metre square. The basic structural properties of the modelled houses in the STD_TRCH-1 and STD_TRCH-2 scenarios are presented in Table 5.16 below.

Table 5.16: Main characteristics of the modelled group of row and terrace houses which are compared to the zero energy building neighbourhood

Building descriptor	Width(m)	Depth(m)	Number of Floors	Gross Floor Area(m ²)	Number of façades
STD_RH-1	12.5	12	1	150	2
STD_RH-2	12.5	12	1	150	3
STD_TRCH-1	12.5	12	2	300	2
STD_TRCH-2	12.5	12	2	300	3

A depth of 12m is chosen since such range (>10m) allows for natural day lighting to evenly reach inside a house which has fewer than four façades as in the case of the semi-detached houses being studied (Stephan 2013; Stephan et al., 2013b). Similar dimensions are adopted for the houses in order to simplify calculations at this stage of framework development¹². Future development of this work should take into account a variety of housing unit dimensions so as to improve the reflection to what is actually happening in reality.

Otherwise the houses have the similar characteristics as in the base case neighbourhood houses including the travel distances and the number of users. In addition, all dwellings also have similar floor heights (2.5m) and roof pitch of 30°. The window to wall ratio for both row and terrace is 30%. The material bill of quantities used in the alternative building typology STD_RH+STD_TRCH neighbourhood is presented in Appendix B. The *U values* of the envelope components are provided in Table 5.17 overleaf.

¹²This assumption is based on the answer to the second research question provided in Chapter 4.

Table 5.17: U values of the envelope components for the group of row and terrace houses which are compared to the zero energy building neighbourhood

Envelope components	U-value ($\text{W}/\text{m}^2\cdot\text{K}$)	R-value ($\text{m}^2\cdot\text{K}/\text{W}$)
Roof	0.31	3.2
floor	0.31	3.2
wall	0.45	2.2
window	3.85	0.26

In parallel, a combination of multiple scenarios is used to test the influence of different parameters on the annual energy requirements associated with a building zone comprising different building typologies compared to the zero energy house base case neighbourhood. Based on Section 4.2.7.2. b, these scenarios are further tested since the building system boundary is stretched to encompass the whole suburban neighbourhood so as to differentiate the levels of analysis between building scale and building zone. The scenarios selected for this analysis are divided into categories which are provided below:

- Building size and number of users;
- Transport mode shift and fuel switch; and
- Primary energy coefficients for electricity and greenhouse gas emissions

5.5 Conclusion

This chapter has elaborated on the case study used to verify and investigate the potential of the established methodological framework. The wide spectrum of interconnected parameters studied ensures a robust testing of the methodology and its potential to provide diverse insights.

This chapter (and Appendix B) has also focused on the relevant details used and assumptions made associated with data sources and calculations. The case study on the zero energy house in Auckland is used to verify the potential of the framework at both the building and urban level. The possibility of stretching the building system boundaries to encompass both building and city scale aspects

demonstrates the framework's versatility to design and evaluate zero energy buildings, building zones and their users at multiple scales of complexity.

Chapter 6 reports on the results from the case study which investigated the potential of the developed framework so as to provide a new perspective regarding the application of zero energy building concepts within neighbourhoods and cities.

Chapter 6 | Case study results

The developed integrated multi-scale zero energy building framework for residential buildings from Chapter 4 is applied to the case study as described previously in Chapter 5.

The main goal of this chapter is to present the case study results. Thereafter, the results are reflected upon and then used as a basis for discussion in the following Chapter. The findings test the applicability of the developed methodological framework at two different scales of the built environment and in different urban contexts as set out in Chapters 4 and 5 respectively. The results from the analysis of the zero energy house are first presented followed by analysis in comparison to the suburban neighbourhood with alternative housing typologies.

In order to enhance and maintain a degree of clarity in the presentation, the results are presented following a similar structure to Chapter 5.

6.1 A zero energy house located in near Auckland, New Zealand

Energy demand and greenhouse gas emissions associated with the base case scenario are tested based on three dimensions, i.e. building (embodied and operational requirements), transport (embodied and operational requirements) and total requirements. Thereafter, parametric variations are presented in similar manner accordingly. In addition, the best case reduction of overall energy and greenhouse gas emissions through a multi-scale zero energy building approach is further presented. The best case scenario is then compared to other dwelling types, i.e. a standard house at building level and other alternative dwelling forms (different typologies) at building zone level to investigate the potential of the framework based on different building system boundaries as was previously highlighted.

6.1.1 Base case

The energy profile associated with the base case scenario as described in Section 5.4.1 and Section 5.4.2 is presented hereunder. In the text, the base case is referred

to as BASE_C. In addition, it is appreciated that some of the information contained in the following sections represents processed data in summary format in order to improve clarity and for record purposes. The reader interested is advised to consult the additional information provided in Appendix section of the thesis and the *ms-excel* sheets from 1-C to 30-C on the accompanying CD¹³.

6.1.1.1 Building embodied energy

The annual total building embodied energy value is obtained as a result of the summation of initial and recurrent energy values based on Equation 4.6 as was previously discussed in Section 4.2.1.2. b. The annual embodied energy and greenhouse gas emissions of the building are 0.02 MWh/m² per annum and 4.1 kgCO₂-e/m² per annum respectively. The total embodied energy breakdown by building component is presented in the Figure 6.1 below.

Figure 6.1: Annual total building embodied energy and greenhouse gas emissions breakdown by component

The figures obtained from this study fall roughly within the same range of values from other previous studies undertaken in New Zealand for houses with similar characteristics to the zero energy house largely in terms of building envelope aspects. Table 6.1 below presents a formal comparison of the figures for

¹³ **Note to reader:** The reader without access to the CD can request for the additional quantification information and files by e-mailing to: dekhanijuenalis@gmail.com

verification of calculation of the case study. Mithraratne et al. (2007) found annual embodied energy and greenhouse house gas emissions of 0.01 MWh/m² per annum and 1.3 kgCO₂-e/m² per annum respectively. In addition, Alcorn (2010, p. 299) also found similar figures with embodied energy values ranging from 0.01 MWh/m² per annum to 0.02 MWh/m² per annum and greenhouse gas emissions ranging from 1.2 kgCO₂-e/m² per annum to 2.2 kgCO₂-e/m² per annum respectively.

It can be observed that the figures obtained from this research are somewhat higher than those from other previous studies. The differences are most likely due to the additional technology i.e. RE systems in the current house which is built to the zero energy criteria (see Section 3.1.3), compared to the standard houses in the earlier studies. In her study, Mithraratne et al. (2007) did not include the requirements of PV systems. Whilst Alcorn (2010) accounted for the requirements of PV systems, the annual intensity figure used was 0.002 kgCO₂-e/kWh/m² (1,700 kWh/m²/year solar irradiance) which is lower than the intensity in this study i.e. 0.085 kgCO₂-e/kWh/m² (1,400 kWh/m²/year solar irradiance). It is very likely that Alcorn's study greatly underestimated the impact of PV systems as was emphasized in Section 3.1.2.2. a. Consequently, the obtained figures in this study are judged realistic.

Table 6.1: Comparison of modelled annual embodied energy figures with actual values from previous studies in similar context and location

Use	Modelled value (MWh/m ²)	Mithraratne et al. (2007) (MWh/m ²)	Alcorn (2010) (MWh/m ²)	Status
Energy				
Embodied energy	0.02	0.01	0.01-0.02	Acceptable
Emissions				
Embodied emissions	4.1	1.3	1.2-2.2	Acceptable

A more detailed perspective of building embodied energy and greenhouse gas emissions of the base case zero energy house is presented through a systematic

breakdown by materials including the systems. Figure 6.2 shows the annual energy requirements and greenhouse gas emissions associated with materials and RE generating components, respectively. It can be observed that steel and concrete are the most important materials besides the RE generation components. A significant amount of steel is used in the building for structural components, hardware, roof, finishes and fixtures. In addition, Table C.1 Appendix C contains information regarding the shifts in material contribution between the initial and life cycle embodied energy requirements of the base case zero energy house.

Figure 6.2: Annual building embodied energy and greenhouse gas emissions breakdown by material

The embodied energy associated with RE capture technologies for the building represent the most significant share of the total (~ 40% of the total). The 4.1kW_p mono c-Si photovoltaic system installed on the roof of house has a high energy and emissions intensity due to the energy intensive process that is required to manufacture the modules (Alsema and Nieuwlaar 2000, Yue et al., 2014). The recent study by Yao et al (2014) suggests that the carbon dioxide emissions intensity for PVs manufactured in China could be as high as 207 gCO₂/kWh, but the value of 72 gCO₂/kWh calculated by Yue et al (2014), which is slightly higher than comparable studies from the U.S.A and Europe, is used in this study to ensure that the research presented in this thesis cannot be considered to have over-estimated

the emissions impact of PV manufacturing. Consequently, as was argued in Section 3.1.2.2. a, selection of PV systems based on the location of their manufacture is very crucial. The sensitivity of PV manufacturing location as a proxy for greenhouse gas emissions intensity for electricity can be clearly seen in Table C.2 Appendix C. PV systems manufactured in China tend to have much higher emissions intensity than those manufactured in Europe or U.S.A. (as shown in Table C.2). In addition, the life cycle environmental impact of PV systems depends on factors such as solar irradiance and their service life. As was previously argued in Section 3.3.1.3, efficient PV systems installed in regions with low solar irradiance ($< \sim 950 \text{ kWh/m}^2/\text{year}$) will generally have poorer environmental performance compared to systems installed in regions with higher solar irradiance ($> \sim 1900 \text{ kWh/m}^2/\text{year}$) (Laleman et al., 2013).

6.1.1.2 Building operation energy

Figure 6.3 presents the building operational energy demand for the base case zero energy house by end use. The end uses analysed in this study are all operated by electricity from either the PV system and the grid. Ideally, the PV intermittent generation requires the building to borrow energy from the grid at times hence, “*net zero energy*”. However, as was previously discussed, grid electricity is subjected to higher primary energy conversion factors, i.e. the primary energy conversion factor for grid electricity used for this study is 1.4 based on Table 5.15 (Chapter 5).

Figure 6.3: Annual building operational energy demand by end use

From Figure 6.3 above, appliance energy demand represents the largest share of building operational energy demand, followed by rain and grey water pump systems, monitoring equipment, cooking, hot water and lighting. As was discussed in Chapter 3, it is argued in the literature that a zero energy building requires to dramatically reduce the building operational energy through energy efficiency measures (Marszal et al., 2011; Sartori et al., 2012). Certainly, this has been achieved to the point that the building does not require any heating or cooling but instead relies on natural ventilation. However, when heating or cooling demand is significantly reduced, other end use aspects become increasingly important (Blengini and Di Carlo 2010). Indeed, this trend can also be observed in this study as appliance energy demand becomes dominant to represent 51% of the total overall operation energy demand. Although overall energy is still reduced and appliances are representing 51% of a smaller total, the dominance arguably still represent an opportunity to further reduce the energy demand in order to move towards zero energy.

In addition, zero energy buildings are sometimes marketed as “smart buildings” (Athienitis and O'Brien 2015) because they incorporate other extra features notably; monitoring systems, as is this situation in this case study. From the Figure 6.4 overleaf, the energy monitoring system represents 12.9% of the total annual demand and consumes more energy than hot water (due to the use of solar water heating) or lighting (due to the use of higher efficiency bulbs) .

Figure 6.4: Annual building operational energy and greenhouse gas emissions breakdown by end use

Similar to building embodied energy as described in Section 6.1.1.1, the accuracy of the annual operational energy and associated emissions can also be verified by comparing the energy and emission requirements associated with houses of similar sizes and similar locations/context from previous studies. Table 6.2 below presents the annual building operation energy demand and greenhouse gas emissions obtained in this study compared with Alcorn's previous studies. The annual operational primary energy demand for the base case house is 0.015 MWh/m^2 , with $3.3 \text{ kgCO}_2\text{-e/m}^2$ of associated emissions. In his study, Alcorn (2010) found annual primary operational energy demand ranging from $0.04 - 0.5 \text{ MWh/m}^2$ with $9.1\text{-}10.2 \text{ kgCO}_2\text{-e/m}^2$ of associated emissions respectively. Alcorn's (2010) figures appear to be higher due to the inclusion of heating requirements and other user differences with regards to the usage patterns of appliances, cooking and hot water as compared to the base case zero energy house.

The base house operational energy value excludes heating, as it is not required (highlighted in Section 5.4.2.2. f). Consequently, comparing 0.015 MWh/m^2 with Alcorn's minimum figure of 0.04 MWh/m^2 (Table 6.2), a relative difference of **greater than 50%** can be observed. When it comes to the greenhouse gas emissions, Alcorn's study used emissions intensity figures from 2010 grid which are higher

that the intensity figures used for the case study house for 2015 since the New Zealand grid has improved as presented in Table 5.15 in Section 5.4.3.4. b . It can be observed therefore, that the operational energy figures established in this work are comparable to other studied houses in similar contexts. Consequently, the approach adopted for testing the case study is judged suitable at this stage of the developed framework.

Table 6.2: Annual primary energy demand and greenhouse gas emissions obtained in the case study compared with previous studies

Use	Modelled value (MWh/m ²)	Alcorn (2010) (MWh/m ²)	Status
Energy			
Operational energy	0.015	0.04 – 0.05	Acceptable
Emissions			
Operational emissions	3.3	9.1–10.2	Acceptable

6.1.1.3 User transport energy

The user total transport energy demand associated with the zero energy base case household is 28.13 MWh per annum with corresponding emissions of 4992 kgCO₂-e per annum .This value is split between operation (23.2 MWh per annum, (representing 82% of the total), with emissions 3984 kgCO₂-e per annum, (representing 79.8% of the total) and embodied (4.93 MWh per annum, (representing 18%) with emissions 1008 kgCO₂-e per annum, (representing 20.2% of the total).

Table 6.3, below presents the annual user transport embodied and operational energy demands and associated greenhouse gas emissions for a private vehicle obtained in this study compared with previous studies (Mithraratne 2011), of similar contexts. While the travel distances are approximately the same, the transport operational energy figures obtained in this study appear to be higher than those calculated from previous studies due to in part to differences in household sizes which fundamentally affect the vehicle occupancy. Indeed, in this study, the

vehicle occupancy is 2 persons but for the previous study, the vehicle occupancy is 1.6 persons. In addition, slight differences in fuel economy of the vehicles used could have also played a role: 10.1L/100 km, 9.8L/100 km, respectively. However, the figures are comparable. In support of this observation, the role of the parameters discussed above has been demonstrated through a sensitivity analysis. Relevant calculation details of the sensitivity study are shown on *ms-excel* sheet 1-C to 9-C which can be found in the accompanying CD. Hence, the approach used for transport energy calculation adopted in this work is also judged suitable at this stage of framework development.

Table 6.3: Annual user transport operational and embodied energy demand and associated greenhouse gas emissions for private vehicle obtained in this study compared with previous studies

Use	Modelled value (MWh)	Mithraratne (2011) (MWh)	Status
Energy			
Embodied energy	4.9	3.9	Acceptable
Operational energy	23.2	13.5	
Emissions (kgCO ₂ -e)			
Embodied emissions	1008	806	Acceptable
Operational emissions	3984	3187	

Based on the total annual values of building operational and embodied energy of the base case derived from Table 6.1 and Table 6.2 respectively, the overall contribution of user transport energy is dominant in the energy chain. The overall user transport energy demand represents 78% of the total household energy demand (building and transport embodied and operation combined). This ratio between the overall user transport energy demand and building energy demand (embodied and operation) underscores the significance of a more holistic zero energy building approach for residential buildings.

Apart from considering user transport energy demand, it is also necessary to reduce building operation energy in tandem with embodied energy demand when optimizing buildings towards zero energy due to the wide range of variations in

climate and construction paradigms across various regions in the world. Certainly, this resonates perfectly with the proposal of a multi-scale zero energy building framework for residential buildings earlier in Chapter 4. It thus becomes significant to optimise user transport energy demand alongside building operation and embodied energy within a single set of energy design criteria.

6.1.1.4 Multi-scale zero energy building balance

As was discussed in Chapter 4, the multi-scale zero energy building framework is generated from integrating building scale energy demand (operational and embodied energy) and city scale energy demand (user transport operation and embodied energy). Firstly, the relevance of building embodied energy within the zero energy balance is tested at the building scale using the current zero energy building framework discussed in Section 3.1.3. The relevance of building embodied energy is established first due to the ambivalence of its inclusion within the current zero energy building framework as was highlighted in Section 3.5. Ideally, this is done through subtracting the total building operation and embodied energy (including the RE devices) in primary energy terms from the building energy exports, including resulting emissions. Based on Table C.3 Appendix C, the building operation energy demand is split into two aspects: imported primary energy, 1.96 MWh which covers 57% of the demand in the studied building and the Solar Fraction ($SF_{end-use}$) (See Equation 4.1), 1.19 MWh, which covers 43% of the demand through the PV system installed on the roof of the case study house.

The building scale zero energy balance is given in Figure 6.5. As was mentioned above, this involves subtracting the total building operation and embodied energy (including the RE devices) from the building energy exports, including resulting emissions. The total building operation primary energy demand is 3.15 MWh per annum with 651 kgCO₂-e per annum of corresponding emissions. Building embodied energy and emissions are 4.3 MWh and 666 kgCO₂-e per annum respectively.

Note: BO= Building operational energy, BE=Building embodied energy and RES= Renewable energy sources

Figure 6.5: Building scale zero energy building balance showing the significance of incorporating embodied energy demand

Figure 6.5 above provides the data necessary to make the zero energy balance and reveal the impact. Certainly, in order to achieve the zero energy balance at the building scale it is required to reimburse the energy depleted and carbon emitted through the building operation and embodied phases through the energy produced by the RE devices. This includes: the energy imported from the grid (i.e. 57% of operational energy) and the building embodied energy including the PV and solar hot water systems. The renewable energy exported to the grid in the studied house is given as 4.34 MWh per annum as indicated above (based on Table C.3 Appendix C). From the graph above, an interesting observation emerges. Indeed, by subtracting the total building energy demand including building operation, embodied and RES embodied, from the energy exports, the value equates to – 3.12 MWh, or 796 kgCO₂-e emissions. This means that the energy exports do not exceed the energy consumed from building operation and embodied phases. This

finding confirms the conclusions by Cellura et al. (2014), Lützkendorf et al. (2014) and Georges et al. (2015) on the significance of including embodied impacts within current zero energy frameworks.

However, as has been acknowledged in this thesis, the figures obtained are subject to variation due to the uncertainty in the embodied energy data in particular. Indeed, $\pm 10\%$, $\pm 20\%$ or $\pm 30\%$ variations are possible based on the observed uncertainty. Along these lines, as part of the sensitivity study, i.e. considering an unlikely scenario of the minimal value of embodied energy where all the embodied energy coefficients of all materials used in this work are overestimated by 30%, the total energy use is 5.22 MWh, 922 kgCO₂-e, which gives a deficit of 0.88 MWh, 401 kgCO₂-e. Hence, even by considering the extreme uncertainty and variability numbers, the embodied energy still contributes to the overall non-net zero total energy condition of the house even though the operational energy use is negative as energy is exported.

Clearly, this outcome highlights that the studied house cannot be considered as a *net zero energy* house. These observations are essentially due in part to differences in the conversion factors from PV based electricity and grid imported electricity. The performance of the building studied is subject to ‘temporal load mismatch’ (See Section 3.1.3.3). Ideally, in many cases during the day or the year, the energy generated through the PV system on-site and the building energy demand do not match, therefore affecting the energy consumption and export patterns. These conclusions are put forward based on the following observations:

- There is a significant performance gap in the building time of energy use and time of generation. This implies the time of the day when energy is being generated does not necessarily match when energy is actually required in the building. This pattern can be observed from the energy simulation results of the PV generation throughout the year in Figure 6.6¹⁴. Arguably,

¹⁴ **Note:** The EnergyPlus® object used to model PV generation in this study is the simple model. In this model, the user specifies the efficiency with which surfaces convert incident solar radiation to electricity on monthly or annual basis and lacks the capability to analyse end uses on hourly/sub-

a likely case is that there is more energy use in the morning and in the evening during the week, while the PV system is most likely to generate electricity during the middle of the day. In this case, energy generated on-site does not keep up with the building's consumption patterns as often predicted during the design stage consequently requiring the building at times to draw energy directly from the grid.

- Based on the previous point, the load mismatch further brings forth a paradoxical situation whereby more building demand is being covered by grid based electricity which has a higher primary energy coefficient compared to renewable energy generation as in this case.

Figure 6.6: Annual energy generation and consumption of the base case

To circumvent the problems associated with the temporal mismatch between on-site energy generation and the building, minor demand adjustments can be implemented so as better to suit the generation patterns. This is generally done through what is commonly known as “demand side management” (DSM) and the

hourly basis. Other functional objects such Equivalent One-Diode model coupled with TRNSYS analyse in more detail (see ;e.g. Voung et al., 2015).The simple model in this study was selected based on the answers to the second research question.

integration of an on-site battery storage unit (Voss et al., 2011; Sartori et al., 2012; Salom et al., 2014a; 2014b). In their study, Guarino et al. (2015) claim to lower the energy imports from the grid by approximately 40%-90%. However, as was previously argued in Section 4.2.1.1, introducing storage batteries to help balance the grid system by acting as peak-shaving and load-shifting devices would introduce additional embodied energy (García-Valverde et al., 2009), which will further impact on the zero energy balance being sought.

The multi-scale zero energy building balance as defined in this work is obtained from Equation 4.28 presented in Section 4.2.5 based on Figure 4.5 in Section 4.3.

Figure 6.7 overleaf shows both building and city scale energy demands, i.e. considering building operational and embodied energy (including RE devices) and also user transport operational and embodied energy. In addition, the Figure also shows the total annual energy demand associated with the users at different scales. The total is obtained from the summation of the overall building energy demand (operational and embodied including RE devices and transport operation and embodied energy demand). The Figure demonstrates that the share of transport energy of building users is significant as it exceeds both the total building energy demand (embodied and operational) and energy exports. User transport (both operation and embodied) represents 79% of the combined building and transport energy (operation and embodied). Consequently, when the possible minimal values for building operation, embodied energy (including RES) and transport energy are combined they give a total of 28.5 MWh, 5047 kgCO₂-e. This makes it even harder to offset the energy used and emissions emitted through the extra energy generated and exported to the grid, which is in this case 4.34 MWh. Consequently, these findings underscore and reinforce the significance of holistic building energy policy, encompassing both the building and city scales, in the light of the current zero energy building practices.

Note: BO; =Building operational energy, BE: =Building embodied energy and RES: =Renewable energy sources

Figure 6.7: Multi-scale zero energy building balance showing the significance of incorporating embodied and transport energy requirements

From the above, it can be argued that attempting to balance out the amount of renewable energy consumed and the emissions offset against carbon-intensive grid imports is complex. Such complexities come into play due to the ambivalence in considering the import/export balance to define zero energy residential buildings as was argued in Section 3.4.1. In addition, by considering the “indirect impacts” associated with the building user such as transport energy increases this complexity further. A lack of understanding of these complexities can be highly problematic for if maintained at a policy scale could lead to increase in cumulative energy use and emissions.

It can therefore be argued that in order to develop more effective assessment tools for zero energy buildings, key factors to be collectively considered might include: user behavioural aspects, building function, site conditions, energy and carbon emission intensities of building systems and user transportation strategies, amongst

others. These measures further reinforce the proposals by Pan and Ning (2014) who argue for integration of other social aspects beyond the building scale in the light of current zero energy building frameworks.

6.1.2 Building energy variations

6.1.2.1 Embodied energy variations

As mentioned previously, the embodied energy variations to be explored take into account the insulation modifications. Other aspects such as structural components and infrastructure supporting the operation of the house are not considered as previously discussed in Section 5.4.3.1. In addition, other structural elements such as timber are not considered for modifications because it is assumed that they are renewable in nature. This assumption is valid when timber is harvested in a sustainable manner and at the same time based on Stephan (2013). Furthermore, other elements in the structural system such as concrete are also not considered because it is assumed that the idea of changing the material will result in changing the whole structural system with an associated redesign. The infrastructure supporting the house is assumed to be existing as discussed previously in Section 4.1.1.

6.1.2.1. a Insulation variations

Figure 6.8 overleaf presents the energy demand and emissions considered for variation in terms of embodied energy. This includes the use of glass wool instead of polyester for insulation. Significant variations can be observed as the 0.33 MWh, 63 kgCO₂-e per annum of the base case insulation reduces to 0.22 MWh, 42 kgCO₂-e per annum. When it comes to the total building embodied energy, changing the insulation results in the share of embodied energy dropping to 5% from 8%, while the emissions drop to 6.5% from 9.5%. These ratios represent a noticeable reduction of embodied energy associated with insulation compared to the total building embodied energy.

However, due to the considerable uncertainty in the embodied energy data as discussed in Section 5.3.4, the possibility of obtaining the best outcome scenario

through this variation cannot be guaranteed. Nonetheless, the results are judged suitable at this stage of the framework developed considering the less energy intensive nature of glass wool as compared to polyester insulation. The glass wool insulation material is made from up to 85% recycled glass while the PET product is made from new polyester (Alcorn 2010). The energy required to manufacture glass wool is offset by its durability and low maintenance.

Figure 6.8: Embodied energy of the base case insulation (Polyester) compared to modified insulation (Glass wool)

6.1.2.2 Operation energy variations

User behaviour is one significant determinant of the environmental impact associated with building operation energy. While current zero energy building frameworks encourage energy efficiency measures as means of lowering demand, the users' decisions and habits ultimately have major effects on the operational energy, particularly for non-thermal end use aspects as discussed in Section 2.3 and Section 3.5. For such reasons, decreased and increased demands are investigated as previously mentioned in Section 5.4.3.2. The cases considered herein are characterized as follows:

- a) Base case → BASE_C
- b) Decrease building operation energy according to scenario 1 given in Table 5.14 → DBOE

- c) Increase building operation energy according to scenario 2 given in Table 5.14 → lBOE

As shown in Figure 6.9, the reduction of energy use and emissions in DBOE is noticeable compared to other cases. By changing behaviour in the home and relying on efficient appliances and fittings, occupants can save up to ~24% of the annual primary operation energy. Similarly, operational greenhouse gas emissions reductions up to ~20% can also be observed. It should however, be noted that more significant reductions could be achieved by using very efficient appliances and less energy intensive user behaviour. The figures calculated for this scenario are based on the variability range selected for this work as highlighted earlier in Section 4.2.7.2. a.

On the other hand, by increasing consumption behaviour in the home and relying on efficient appliances i.e. lBOE scenario, the annual operational energy demand increases by ~ 18.7% and the greenhouse gas emissions also increase by ~20%. This variation reinforces the significance of adjusting to less energy intensive user behaviour in the home.

Figure 6.9: Total annual energy demand of the base case compared to other variations, broken down by operational and embodied energy

In general, the reduction of final energy demand and emissions due to adjustments in user behaviour is the necessary enabler to attain a much high solar fraction ($SF_{end-use}$) which results in lower primary energy imports.

Besides, another important finding concerns the relative importance of operation energy types. Ideally, the building envelope of the studied building is thermally optimized to the point that the house does not require heating in winter or cooling in summer as mentioned previously in Section 5.4.2.2. f. This greatly reduces the operation energy demand related to the building as highlighted in Section 6.1.1.2. Besides, another aspect that requires to be taken into account concerns the significant energy reductions which can be exploited when all necessary measures including building related and user related, are combined. This reinforces the need to account for not only building related energy requirements but also user behavioural related aspects.

From Figure 6.9, it can also be observed that the BASE_C, DBOE, IBOE cases have a net energy balance deficit of 3.13 MWh, 2.5 MWh, and 3.76 MWh per annum respectively. DBOE has the lowest net energy balance deficit in terms of energy demand as well as emissions compared to the base case and worst case scenarios combined. The DBOE variation is therefore selected for best case because it results in the lowest overall annual energy demand and greenhouse gas emissions. Table 6.4 below presents a brief summary deriving energy and greenhouse gas emission net values.

Table 6.4: Summary for deriving annual energy and greenhouse gas emission net values

	BASE_C		DBOE		IBOE	
	Energy (MWh)	Greenhouse gas emissions (kgCO ₂ -e)	Energy (MWh)	Greenhouse gas emissions (kgCO ₂ -e)	Energy (MWh)	Greenhouse gas emissions (kgCO ₂ -e)
Energy Exports	4.341	521	4.341	521	4.341	521
Building Operation	3.158	651	2.53	521	3.79	781
Building Embodied	2.62	530	2.62	530	2.62	530
RES Embodied	1.693	136	1.693	136	1.693	136

6.1.3 User transport energy variations

The transport energy variations comprise 23 modified scenarios with ICEVs, EVs, public bus and commuting train. As highlighted in Section 5.4.3.3, the range of different transport modes studied for the scenarios are denoted by descriptors given in Table B.7, Appendix B. Essentially, it should be noted that the descriptors are derived from the actual model of the particular transport modes, e.g. T for Toyota models, HD for Holden, PT-B for public diesel bus, PT-Tr for public electric train and so on.

In Figure 6.10, the range chosen of ICEVs is represented by three scenarios which explore large T-l, medium HD-2 and minimum HD-3 energy demands. Similarly, EVs are represented by, EV-6, EV-4, EV-l, (large, medium and minimum energy demand respectively), and public transport is represented by PT-B, PT-Tr, while the base case transport is represented by, BE-T. Refer to the complete set of transport variation results are given in Table C.4, Appendix C and also in Figure C.3 Appendix C.

To maintain clarity, Figure 6.10 presents only the maximum and minimum energy demand and emissions for each transport technology mode representing the extremes across the 23 scenarios. For example, when the building users shift transport mode from BC-T to T-I ICEV, the energy demand increases by 17.33% and emissions increase by 58%, from 27 MWh, 4704 kgCO₂-e per annum to 31.7 MWh, 7416 kgCO₂-e per annum. Given the increase in energy demand and emissions due to changing from the base case to transport choice T-I which has fuel economy 11.5L/100 km, this finding confirms the environmental impact of choosing ICEVs of much higher fuel economy.

Figure 6.10: Variation of user transport energy and greenhouse gas emissions compared to the base case, by mode

On the other hand, when the building users shift from BC-T to a smaller vehicle, HD-3 with fuel economy 5.1L/100 km, the energy demand and emissions reduce by 44% (14.96 MWh) and 18.4% (3336 kgCO₂-e) per annum respectively. This dramatic reduction of energy demand and emissions further reinforces the

importance of choosing smaller vehicles over large vehicles if energy and emission reductions are to be achieved.

In addition, since electric vehicles are currently being advocated as “green” and that their wide adoption is expected to disrupt the automotive industry (Folkson 2014; Marcus 2015), it is imperative to test a switch from ICEVs to purely electric vehicles as discussed in Section 5.4.3.3. When the building users change transport mode to EV-B, the energy demand and emissions become 13.6 MWh and 2895 kgCO₂-e per annum - a reduction of 48% and 38% for energy demand and emissions respectively. If transport mode EV-B ($\eta = 0.27$ kWh/km) is compared to HD-3 ($\eta = 0.48$ kWh/km), there is a reduction of 24% and 32% for operational energy and greenhouse gas emissions respectively. When it comes to embodied energy requirements, there is an increase by 40% and 106% for energy demand and greenhouse gas emissions respectively. However, when it comes to the total, no significant total difference observed in terms of energy demand (only 4% reduction difference). In terms of emissions, more significant savings can be observed (20% reduction difference).

In parallel, for transport mode EV-I ($\eta = 0.14$ kWh/km), the energy demand and emissions fall to 6.9 MWh and 1494 kgCO₂-e per annum. This translates into a reduction of 74% and 68% for energy and emissions respectively. The dramatic reduction of mode EV-I compared to mode EV-B underscores the significance of selecting very efficient EVs. The superior performance of EVs is due to the EVs running on the New Zealand low carbon emission grid since it is dominated largely by renewable energy.

This finding is consistent with the findings of Hawkins et al. (2012), Holland et al. (2015) and Onat et al. (2015) in U.S.A; Faria et al. (2013) in Portugal; and Stephan et al. (2013b) in Melbourne, Australia, who conclude that EVs perform better in regions where the grid is predominantly low carbon but perform very poorly where the grid is largely dominated by fossil fuels.

Besides, as noted previously on the comparison between transport mode EV-B and HD-3 above, environmental damage of EVs is somewhat controversial and may vary since they have a higher embodied energy as compared to ICEVs, due to, in part, the manufacturing, supply and replacement of batteries and other components such as motors (see Table C.4 Appendix C under EV descriptors). This can become apparent in specific cases. For instance, small and very efficient ICEVs can perform better than their EV counterparts as demonstrated in Nsaliwa et al. (2015) who found that high efficiency vehicles such as SmartForTwo ICEV can emit lower carbon emissions compared to other flagship electric vehicles such as Tesla Model S P85D and Nissan Leaf, irrespective of electricity grid mix.

Nevertheless, it should be noted here that the adoption of EVs clearly would result in a substantial increase in an average household's electric consumption and therefore affect the load demand on the grid (Givoni and Banister 2013; Batstone and Reeve 2014). The analysis of EVs in this study was undertaken with the assumption that we are currently at a very early stage of EV uptake and that EVs are not a material driver of increased household consumption until large-scale adoption in the near future. Therefore, the effects of increased load on grid due to EV penetration is not investigated but may form a basis for future research.

Apart from private transport variations, public transport options are also tested. When the building users shift to public transport mode PT-B (bus), the energy demand decreases by ~15% (22.53 MWh per annum), while emissions increase by ~9% (5110 kgCO₂-e per annum). The differences in value observed are likely due to the usage of energy and emission intensity data for buses from U.S.A as there is no suitable New Zealand data available.

To elaborate on this aspect, as was given in Table 5.4, the energy and emission intensities used for this variation are obtained from a comprehensive study conducted in U.S.A. by Bradley and Associates (2008). The data in the study derived from figures for 42,546 transit buses gathered from across the U.S.A. The breadth, transparency and magnitude of the data given in the study is judged

suitable for this work. The average energy intensity for a transit bus was given as 0.84 kWh per passenger-km. Indeed, this matches closely to the findings of Chester and Horvath (2009) who provide an energy intensity range of 0.14 -1.11 kWh per passenger-km for peak and off-peak transit bus respectively. This in addition to the fact that buses rely on diesel fuel which has higher emission intensity per kWh compared to petrol, reinforces the selection of public transportation modes based on their lower energy intensiveness.

Notwithstanding, larger energy and emissions reductions can be observed when transport mode PT-Ir (Train) is used. Energy demand and emissions reduce by 96% and 97% respectively, from 27 MWh, 4704 kgCO₂-e per annum to 0.9 MWh, 136 kgCO₂-e per annum. It can be observed that very significant energy and emission savings can be achieved when public transport, particularly the electric train, is used.

Not all public transport modes show equal benefit. An important finding in case of public transportation is the importance of efficiency and the energy source used for propulsion of transport mode. Indeed, by maintaining the same travel distance and switching to electric train, the reduction in energy demand and emissions was much greater than adopting the most efficient electric vehicles in the study. This finding (PT-Ir variation) supports the commonly held belief of the significance of public transport being less energy intensive than private vehicle travel (see, e.g. Geels et al., 2012; Givoni and Banister 2013; Stephan et al., 2013a, 2013b). Additionally, this study has further demonstrated that the choice of mode is very significant. The PT-Ir variation is therefore selected for the best case scenario.

6.1.4 Variation of other parameters

Apart from the building variations (operation and embodied) and user transport variations (operation and embodied), the household size and the evolution of primary energy coefficients for electricity and greenhouse gas emissions are also investigated to test their influence in the model. The following section elaborates the results from the key variables described above, beginning with the effect of

household size on the overall energy demand and thereafter, the temporal variability whilst paying attention to both absolute and per capita-based results.

6.1.4.1 Number of users (household size)

With the underlying assumption that transport energy for the household does not change, the household size is modified from 2 persons i.e. BASE_2 to 3 persons i.e. HS-3. Ideally, this assumption is based on the fact that transport energy is already expected to decrease due to sharing of transport mode operational and embodied energy demands. Certainly, the assumption is judged suitable at this stage. Future development of the framework to automation should analyse this aspect simultaneously. In addition, this approach to analysing household size is based on the second research question answered in Chapter 4.

As shown in Figure 6.11, this results in 18.7% increase in total energy demand per annum while a decrease of 24.8% per annum can be observed when the results are expressed on a per capita basis¹⁵. Analogous to the energy demand cases, a similar trend can also be observed when the emissions are considered. There is a 15% increase in emissions and a 23.3% decrease when the results are expressed on a per capita basis for HS-3 (See Figure 6.11).

The number of people living in the house has a significant impact on the annual overall energy demand and environmental footprint. When the household size is increased, a slightly higher energy demand and emissions trend can be observed due to increased patterns of usage in cooking, hot water and appliances energy demand. On the other hand, this leads to a more efficient energy use and a reduction in emissions on a per capita basis. From the previous paragraph, it can therefore be concluded that the household size and area per person are critical indicators which cannot be ignored within the zero energy building frameworks.

¹⁵ This includes house and transport energy demand, so all the increase is in the house energy

Note: HS-3= 3 users, HS-5= 5 users, RES= Renewable energy source
 Figure 6.11: Total annual energy per capita for increased number of users compared to the base case

Note: HS-3= 3 users, HS-5= 5 users, RES= Renewable energy source
 Figure 6.12: Total annual greenhouse gas emissions per capita for increased number of users compared to the base case

Indeed, there is increase in sharing of resources such as building embodied energy and user transport energy requirements amongst the building occupants and this explains the observed energy efficiency and decrease in emissions on the per capita basis indicator. In addition, the operation energy requirements closely related to the building such as heating/cooling are also shared. On the other hand, the increase in household size from 2 in the BASE_C to 3 (HS-3) results in a decrease in the usable living floor area per person from 74 m² to 49.3 m². On a per inhabitant basis, this figure is still high such that even 5 users can live in the house to reach a further optimal density. The rationale behind the underlying assumption to further increase the household size to 5 is given in Section 5.4.3.4. a.

Therefore, by increasing the household size to 5 (HS-5) equally results in increase in energy demand and emissions per annum for cooking, hot water and appliances. Indeed, a 45.5% increase in household energy demand and 45.1% increase in emissions per annum can be observed. However, on a per capita basis, a decrease in energy of 44.6% and 42% in emissions is observed. In this world of dwindling space and resources, the results clearly demonstrate the significance of downsizing houses whenever possible or increasing the number of occupants to reduce energy demand and consequently environmental impact through sharing of resources. Unfortunately these significant parameters are overlooked within zero energy building framework today. The evidence is highlighted in Section 3.5.2. The current zero energy building framework (Sartori et al., 2012), does not stipulate the household size as part of the design parameters.

However, smaller housing units with increased occupant densities brings other health risks associated with indoor environmental quality as highlighted in Pekkonen et al. (2015). Although potentially significant, this aspect falls beyond the scope of this study but may be the subject of future research. Considering the significance of the household size, the best case scenario is also tested with both HS-3 and HS-5. While the best case scenario can only be one, the two household sizes are tested as part of the sensitivity study to further reinforce to significance of household size.

6.1.4.2 *Primary energy coefficients for electricity and greenhouse gas emissions*

The potential temporal variability associated with the primary energy and greenhouse gas conversion factors for electricity i.e. $PRM_EF_{el}+GHGF$ is also explored in order to test its influence. Operational energy is characterized by higher primary energy and greenhouse gas conversion factors in many developed countries (See Section 4.2.7.2. b). Given the need in many countries to decarbonise electricity grids and hence reduce primary energy and emissions requirements through the integration of renewables, the effect of increasing efficiency and renewable energy share in grids versus the deployment of zero energy housing should be investigated in order to determine the most appropriate ways of reducing energy demand and emissions in the residential sector. As indicated in Section 5.4.3.4. and Table 5.15, this parameter i.e. $PRM_EF_{el}+GHGF$ forms a basis for comparison of alternative housing, i.e. at the building level, zero energy house versus standard house and also at the neighbourhood level (building zone), zero energy houses versus alternative housing typologies.

The variability associated with primary energy and greenhouse gas emissions factors for electricity are modelled according to the scenarios given in Table 5.15. The combined influence of these evolutions on annual operational energy demand and emissions is presented in Table 6.5 below. The summary of results presented only takes into account the evolution parameters associated with operation energy while embodied energy figures are assumed to be the same, although they could also be subjected to changes as the evolution of electricity parameters also affects other related industrial sectors such as material manufacturing and also transport, electric in particular. However, the embodied energy database used in this study compiled by Alcorn (2010) does not yet provide the flexibility to model the figures under any of these scenarios.

Table 6.5: Effect of parameter evolution in time on annual operational energy demand and greenhouse gas emissions for the base case zero energy house

Case	Annual building operation and embodied energy demand (MWh)		Annual building operation and embodied energy emissions (kgCO ₂ -e)	
	Value	Change	Value	Change
BASE_C	3.13	N/A	796	N/A
ZEH_2010PRM_EFeI+GHGF	3.269	+ 4.4%	821	+ 3.1%
ZEH_2015PRM_EFeI+GHGF	2.989	- 4.5%	770	- 3.2%
ZEH_2020PRM_EFeI+GHGF	2.709	- 13.5%	720	- 9.5%
ZEH_2025PRM_EFeI+GHGF	2.288	- 26.9%	644	- 19.1%
ZEH_2030PRM_EFeI+GHGF	1.868	- 40.3%	569	- 28.5%
ZEH_2035PRM_EFeI+GHGF	1.587	- 49.3%	518	- 34.9%

From Table 6.5 above, it can firstly be observed that the PRM_EFeI+GHGF has noticeable influences on the annual operation energy use and emissions for specific scenarios studied. By considering a moderate downwards evolution of primary energy and greenhouse gas emission factors (represented by ZEH_2020PRM_EFeI+GHGF), it can be observed that there is a decrease in primary operation energy by 13.5% with a decrease in emissions by 9.5%. In addition, by considering a dramatic evolution of parameters (represented by ZEH_2035PRM_EFeI+GHGF), there is a reduction of 49.3% in primary operation energy and further 34.9% reduction in emissions per annum compared to the base case. Overall, the PRM_EFeI+GHGF scenarios show that significant amounts of energy and emission savings can be achieved by retrofitting the electricity grid with more renewable energy and efficiency improvements, thereby reducing primary energy and greenhouse gas emission conversion factors whilst maintaining net zero energy deficit houses such as the base case.

The Figure 6.13 overleaf presents the impacts of evolution of parameters in time from 2010 to 2035 under PRM_EFeI+GHGF scenarios on operation energy and greenhouse gas emissions per annum compared with the base case scenario.

Figure 6.13: Effect of the evolution of parameters in time from 2010 to 2035 under PRM_EFeI+GHGF

As was mentioned previously, the effect of the evolution of parameters in time on the embodied energy demand and emissions is not investigated in this study as the current embodied energy database does not yet provide the flexibility to model the figures under any of these scenarios. On the transport energy front, the base case solely relies on petrol vehicles. Consequently, the impact of the evolution of primary energy and greenhouse gas emission conversion factors for electricity is applied on the transport energy requirements for public train only, case PT-Tr (See Section 6.1.3) according to scenarios presented in Table 5.15., under moderate conditions, i.e. (ZEH_2020PRM_EFeI+GHGF) and dramatic conditions i.e. ZEH_2035PRM_EFeI+GHGF. The results show a decrease in the operation energy requirements of 97.8% and emissions reduction of 98% under the moderate scenario conditions. On the other hand, by 2035 the transport operation energy is reduced by 99.4% and emissions by 99.5% compared to the base case.

However, the embodied energy requirements of trains are not taken into account for this evolution. Nevertheless, the dramatic reductions observed in operational energy further confirm the previous observation concerning the influence of parameter evolution associated with primary energy and greenhouse gas

conversion factors for electricity on overall electric transport. Future research could be further developed to account for all impacts associated with operation, embodied and user transport (electric-based) energy requirements.

It is clear however that electric transportation coupled with grid improvements is most likely to be a viable option if meaningful transport impacts are to be achieved. This finding further supports the arguments raised by Gilbert and Perl (2010), who urge policy makers globally to embrace electric transportation propositions and strategies.

6.1.5 Determining the best case

The best case scenario i.e. BEST_C involves the combination of multiple measures undertaken to lower the overall annual energy demand of the studied base case (BASE_C) house thereby facilitating the zero energy balance. Considering all the evaluations undertaken to obtain the results for this exercise and assuming that the infrastructure supporting the building is already existing and that no new infrastructure is required (i.e. not considered from the changes in the list), the best case scenario is represented by the following aspects:

- a) Replace polyester insulation in walls, floors and roof with glass wool insulation to reduce embodied energy (See Section 6.1.2.1).
- b) Reduce operational energy demand with respect to the first scenario as indicated in Table 5.14 (See Section 6.1.2.2).
- c) Using the train for commuting and other purposes as described in Section 6.1.3.

The BEST_C is also further tested with the 3 users (BEST_C3), parameter evolution (BEST_SCPRM_EFeI+GHGF) and the combination of both scenarios (BEST_C3PRM_EFeI+GHGF), i.e. number of users and evolution of primary energy and greenhouse gas emission conversion factors for electricity, based on the results obtained from Section 6.1.4.1 and 6.1.4.2 respectively. In particular, the effect of temporal variability in this case is performed in accordance to the best case scenario which is denoted by

the acronym: (ZEH_2035PRM_EFeI+GHGF). All other parameters are kept consistent with the zero energy base case house.

Figure 6.14 below provides the annual total energy demand and emissions of the BASE_C; BEST_C; BEST_C3; BEST_CPRM_EFeI+GHGF and BEST_C3PRM_EFeI+GHGF. The breakdown is presented by: Building (operation and embodied energy and emissions combined) and Transport (operation and embodied energy and emissions combined).

Figure 6.14: Annual total energy and greenhouse gas emissions for the best case zero energy house variations, by use at different scales of the built environment

6.1.5.1 Building energy demand and greenhouse gas emissions

Building energy demand comprises operation and embodied energy and the resulting greenhouse gas emissions. The annual energy demand and greenhouse gas emissions shown in Figure 6.14 for BEST_C are lower by 23.6% and 18.8% respectively, than BASE_C. Irrespective of the usage of glass wool in this case, which is 67.8% less energy intensive instead of polyester, significant energy and emission reductions are as a result of significantly reduced operational energy demand by changing user behaviour and the usage of more efficient appliances and equipment

as established previously in Section 6.1.2.2. Ideally, the reduction factors in Table 5.14 represent the afore mentioned less energy intensive user behavioural aspects. This assumption is based on the variability ranges of building operational energy due to user behaviour as commonly found in the literature (see ,for example Pettersen 1994; Joudis et al., 2009; Chen et al. 2013; Stephan et al., 2012, 2013a, 2013b). This is highlighted in Section 4.2.7.2. a.

In addition, the embodied and operation energy and emissions of BEST_C3PRM_EFel reduce to 84% and 72.3% respectively. The dramatic drop of the combination of operation and embodied energy and emissions under this scenario is due to: the increase in number of users which allows the annual building embodied energy intensity to be shared; the number of users further divides heating/cooling, lighting, appliances and cooking energy demand by a larger number 3 instead of 2, thereby lowering the operation energy demand and associated emissions; retrofitting the electricity grid with higher renewable energy penetration share and efficiency improvements lowers primary energy coefficients of electricity serving the dwelling.

6.1.5.2 User transport energy demand and greenhouse gas emissions

Transport energy demand comprises both embodied and operation energy. Compared to the BASE_C, the BEST_C saves 96.7% and 97.1% of user transport energy demand and greenhouse gas emissions respectively. The dramatic reduction is due to the use of train public transport. Similarly to the building operation and embodied energy, the BEST_C3 also uses less energy and emits fewer emissions for transport compared to the BASE_C even though the overall travel distances per mode in both cases are maintained. However, the effect of primary energy conversion factors should also be considered for an analysis of potential energy and emission savings for transport modes relying on electricity as discussed in Section 6.1.4.2 previously.

6.1.5.3 Total annual energy demand and greenhouse gas emissions

As presented in Figure 6.15 below, the BEST_C has a total annual energy demand and emission 89.1% and 85.8% lower than the BASE_C respectively. While the

BEST_C3PRM_EFel+GHGF has a total annual energy demand and emissions 95.4% and 94.4% lower than the BASE_C respectively. These significant reductions in the total annual energy demand and emissions reveal that zero energy houses might not always guarantee the minimum expected performance required in terms of operational energy as often reported in most zero energy building projects published today. See for example in reports such as the “IEA SHC Task 40: Position paper (2015)”. In other words, by increasing the number of occupants from 2 to 3 in this study, noticeable differences can be observed. Ideally, this contributes to the current knowledge of what other parameters are important and need to be considered within the current zero energy building framework. Essentially, to yield much greater energy and emission savings in the built environment, these findings suggest that there is a need to change user behaviour, consider lower primary energy and renewable sources, and use of efficient electric-based public transport.

Figure 6.15: Total annual energy and greenhouse gas emissions, by scenario

Figure 6.15, shows the overall annual energy demand and emissions by scenario. In summary, by integrating building and user transport energy, the BASE_C has ~30 MWh of energy demand with 5500 kgCO₂-e of corresponding greenhouse gas emissions. On the other hand, the best case scenario with the number of users

increased to 3, an improved electricity grid by lowering primary energy and greenhouse gas factors and by using the electric train for commuting and other travel, reduces the energy demand to 1.43 MWh and greenhouse gas emissions reduce to 309 kgCO₂-e. This further reinforces the need to consider other significant parameters in the light of current zero energy building frameworks. Buildings are part of the wider built environment (see Section 3.5.1), so zero energy building frameworks should include more than just the building.

More significantly, to highlight what has been established, this variation reveals that: (1) since the current zero energy building framework only consider operation energy whilst overlooking other demands including building embodied and user transport energy-both operational and embodied, very significant differences can be observed between two buildings built to the current zero energy criteria. In this case, the base case and best case houses respectively. (2) The increase in number of building users within the same living area as found in this work is a critical aspect because it greatly increases the efficient use of resources and results in a significant reduction of per person energy and associated greenhouse gas emissions. In particular, as mentioned previously, there is a sharing of embodied energy, other aspects of operation energy and the user transport energy requirements in some cases.

In parallel, the development of the electricity grid is considered in this thesis as the evolution of primary energy and greenhouse gas emission conversion factors. The influence of this aspect has been found to be much more important at the operational energy level as seen in this Section and previously in Section 6.1.4.2. However, it could have also been beneficial to observe its influence with regards to initial and recurrent embodied energy and on electric-based user transportation modes. Due to the original analysis approach developed in this thesis, it is difficult to establish the implications of the exclusion of this aspect as no other study has been found to have tested the evolution of primary energy and greenhouse gas factors for electricity with regards to embodied energy intensity of building materials. Certainly, future development of this framework should take this aspect

into account. Nevertheless, it is assumed that improvement of the electricity grid which affects industrial and material manufacturing sectors should result in lower embodied energy intensities which would otherwise enrich the quality of the results.

6.1.6 Comparison of alternative dwellings

A series of parametric studies pertaining to the base case zero energy house have been performed in the previous section. The analysis investigated the multiple effects of building energy (embodied and operation) and user transport energy (embodied and operation) variations including other parameters particularly household size and temporal variability associated with primary energy coefficients for electricity and greenhouse gas emissions. The following section compares the case study zero energy house to other types of dwellings. This includes the standard house at the building level and other alternative housing typologies at neighbourhood level.

6.1.6.1 Zero energy house vs. standard house

As was mentioned previously in Section 5.4.5.1, the standard house is assumed to be located at the same location and is a modified version of the base case zero energy house. In addition, the user transport energy scenarios are assumed to be the same for both houses and this is taken into account in the investigation and results. The variations made to the standard house case, therefore, are as follows:

- a) STD_H: the standard house as described in Section 5.4.5.1;
- b) STD_HPRM_EFeI+GHGF: the evolution of primary energy and greenhouse gas emission conversion factors for electricity servicing the standard house is varied in the study to observe its influence compared to the zero energy base case house.
- c) PT-Tr: the user transport energy for STD_HPRM_EFeI+GHGF scenario is considered as the best case transport scenario.

The standard house (STD_H) variations are compared to the base case zero energy house, .i.e. BASE_C and an alternative scenario ZEH_2035PRM_EFeI+GHGF (See Table 6.5).

Table 6.6 and Figure 6.16 present the effect of temporal variability associated with the evolution of primary energy and greenhouse gas emission coefficients for the STD_H scenario.

Table 6.6: Effect of parameter evolution on the operational energy demand and greenhouse gas emissions of the standard house

Case	Annual building operation and embodied energy demand (MWh)		Annual building operation and embodied energy emissions (kgCO ₂ -e)	
	Value	Change	Value	Change
STD_H	6.1	N/A	940	N/A
STD_H2010PRM_EFel+GHGF	6.3	+ 4.2%	1122	+19.4%
STD_H2015PRM_EFel+GHGF	5.8	- 4.3%	894	-4.9%
STD_H2020PRM_EFel+GHGF	5.3	- 12.8%	698	-25.7 %
STD_H2025PRM_EFel+GHGF	4.5	- 25.6%	513	-45.4%
STD_H2030PRM_EFel+GHGF	3.8	-38.4 %	383	-59.3 %
STD_H2035PRM_EFel+GHGF	3.2	-46.9%	319	-66.1 %

Figure 6.16: Effect of the evolution of parameters in time from 2012 to 2035 under STD_HPRM_EFel+GHGF

Results from Table 6.6 show that the improvement of electricity generation is most likely to result in a moderate reduction of operation energy demand and emissions requirements for the standard house by 12.8% and 25.7% respectively. The

moderate reduction in this case corresponds to the 2020 electricity grid scenario. Furthermore, dramatic reduction can also be observed when the 2035 grid conditions are considered. The energy demand and emissions are lowered by 46.9% and 66.1% respectively compared to the base case STD_H.

If the best case scenario of the standard house under optimized temporal variability as determined from above, STD_H2035PRM_EFeI+GHGF is further compared with the base case, BASE_C, it can be observed that there is an increase in operation energy by 2.8% but a reduction in emissions by 59.9% as presented in Table 6.7 below.

Table 6.7: Effect of parameter evolution in time on the annual operational energy demand and greenhouse gas emissions of the standard house versus base case and best case zero energy house

Case	Annual building operation and embodied energy demand (MWh)		Annual building operation and embodied energy emissions (KgCO ₂ -e)	
	Value	Change	Value	Change
BASE_C	3.13	N/A	796	N/A
ZEH_2035PRM_EFeI+GHGF	1.56	- 49.3%	518	- 34.9%
STD_H2035PRM_EFeI+GHGF	3.2	+ 2.8 %	319	- 59.9%

The slight increase in energy (operation and embodied) use in the STD_H2035PRM_EFeI+GHGF scenario is due to the requirements of additional heating and ventilation for the standard house as compared to the zero energy house. Although it is highly dependent on local climatic conditions, this finding reinforces the significance of exploiting passive design techniques irrespective of housing standard.

The zero energy house best case scenario (under temporal variability) ZEH_2035PRM_EFeI+GHGF is compared to the BASE_C, in order to compare the results further with the STD_H2035PRM_EFeI+GHGF. In that way, by comparing the STD_H2035PRM_EFeI+GHGF scenario with the BASE_C, the results show that there is a decrease in operation energy and emissions by 49.3% and 34.9% respectively. The increase in operation energy under the STD_H2035PRM_EFeI+GHGF is due to the lower thermal performance of the house compared to the base case as previously highlighted above.

There is a significant reduction in greenhouse gas emissions compared to both the BASE_C, and the ZEH_2035PRM_EFeI+GHGF. This is due to the different energy sources servicing the base case and the standard house. The STD_H2035PRM_EFeI+GHGF is reliant solely on electricity supply from the grid with 79.8% renewable energy with the majority coming from hydropower. On the other hand, the base case house uses on electricity from both the roof-mounted PV system installed (with the associated embodied energy) and the grid.

As discussed in Section 3.1.2.2. a and Section 6.1.1.1 regarding the impact of PV generated electricity, the observed variations in emissions between the base case zero energy house and the standard house are therefore due to the differences in the greenhouse gas emission intensities of grid generated electricity in the STD_H2035PRM_EFeI+GHGF scenario, compared the proportion of PV generated electricity in the ZEH_2035PRM_EFeI+GHGF scenario. These results show that houses built to the current zero energy criteria do not always result in lower net emission savings compared to standard houses which are being serviced by a higher proportion of renewable grid electricity. Besides, as was discussed in Section 4.1.1, the embodied energy and emission from the grid are not considered in the calculation. Certainly, to justify this argument, the embodied energy emissions from the grid and on-site PV still have to be compared.

Based on a study in by Rule et al. (2009) on embodied energy and emissions of power generation in New Zealand, the embodied energy of hydropower plants which services majority of New Zealand houses is given as 0.0046 kgCO₂-e/kWh. This emissions intensity is used to derive the embodied energy emissions of the grid for this case : 14.72 kgCO₂-e. Consequently, if the embodied energy emissions of the grid are added to the standard house scenario based on Table 6.7: STD_H2035PRM_EFeI+GHGF , the greenhouse gas emissions rise from 319 kgCO₂-e to 333.72 kgCO₂-e ,which is still less than the zero energy house scenario : ZEH_2035PRM_EFeI+GHGF that has 518 kgCO₂-e. Moreover, net zero energy houses at times also use the grid, therefore it could also be appropriate to increase the emissions for the zero energy building scenario by the percentage factor when the houses draw energy from the

grid. Further development of the framework derived in this study should take into account a more critical analysis of embodied energy and emissions of zero energy buildings (both materials components and systems).

In parallel, the embodied energy emissions of renewable generating systems of net zero energy houses are largely overlooked in the literature. See for example; Cellura et al. (2014) in Italy and Lützkendorf et al. (2014) in Norway. Studies such as these often fail to stipulate the emissions intensity associated with renewable generation systems of net zero energy houses. The developed methodology in this work shows significantly clear and higher figures associated with renewable energy generation systems of net zero energy houses.

On the other hand, when user transport is included in the evaluation, the relative importance of building operation and embodied energy combined becomes less significant (See Figure 6.17) overleaf. Although when an efficient and low emission mode of transport such as electric train is used, building operation and embodied energy also become significant (See optimized scenarios overleaf). These findings further suggest that the current approach of focusing solely at the building scale is a significant shortcoming in the building industry with regards to the current deployment of net zero energy houses today.

Figure 6.17: Annual total energy demand and greenhouse gas emissions for the standard house variations compared to the base case zero energy house, by use at different scales of the built environment

Overall, the results in this section suggest that improving efficiency and accelerating penetration of renewables within existing grids, thereby lowering the primary energy and greenhouse gas emission coefficients for electricity whilst maintaining standard houses in which the householders rely on efficient and lower energy/emission transport modes has a higher potential to lower energy demand and emissions than current net zero energy houses. Since the data used in this work is based in New Zealand, this mainly applies in regions which have similar characteristics with New Zealand in terms of energy sources, building construction paradigms and city/urban layouts. In addition, it has also been shown that energy demand can be lower in net zero energy houses with less energy intensive behaviours of their users, but the greenhouse gas emissions can be higher due to the embodied energy in the PV. Thus on a country basis they can be better in terms of operational energy savings, but on a global basis they may not be better. If the PV panels are manufactured in countries with very high emissions intensity and less efficient electricity grids such as China India or Australia, this will also increase the embodied energy.

6.1.6.2 *Zero energy house vs. other housing forms*

As was previously discussed, comparison of the zero energy house and other alternative housing is performed at the whole suburban neighbourhood level (See Section 5.2.1.1). Ideally, the building system boundary within the developed methodological framework can be extended to test the zero energy house in a suburban neighbourhood context in comparison with other forms of housing. The reasons for extending the building system boundary to encompass a whole suburban neighbourhood are discussed and given in Section 4.1.1. In that way, the scope of the case study is therefore extended to cover the suburb where the studied zero energy house is located, near, Auckland, New Zealand. Certainly, investigating extended building system boundaries further demonstrates the flexibility of the developed multi-scale zero energy building framework. The base case neighbourhood is presented in the next section below.

6.1.6.3 *Base case neighbourhood*

The base case neighbourhood is referred to as BC_NBH, which comprises 50% of BASE_CNBH (2 occupant houses) and 50% of BASE_CNBH3 (3 occupant houses), as described previously in Section 5.4.5.2. a. The reasons to confine the neighbourhood with houses comprising two different household sizes is also given in Section 5.4.5.2. b. The energy requirements and greenhouse gas emissions of the base case suburban neighbourhood are presented in the following section. It should be noted that the results of each of the housing types in the base case neighbourhood are firstly reported separately to improve clarity. Thereafter, the total energy demand is presented.

6.1.6.3. a *Embodied energy demand and greenhouse gas emissions*

The embodied energy demand of the base case neighbourhood i.e. BC_NBH is presented in Figure 6.18 and Figure 6.19 overleaf, respectively.

Figure 6.18: Annual embodied energy demand and greenhouse gas emissions BASE_CNBH of the BC_NBH

Figure 6.19: Annual embodied energy demand and greenhouse gas emissions BASE_CNBH3 of the BC_NBH

The results are expressed per element as shown : renewable energy sources (RES), building envelope, finishes and fixtures, plumbing and drainage and electrical works. The largest contribution of an element in terms of energy demand is the RES (1046 MWh per annum and 697 MWh per annum respectively) for both building types, BASE_CNBH and BASE_CNBH3 in the neighbourhood: BC_NBH. As discussed earlier in Section 6.1.1.1, the greenhouse gas emissions for RES are calculated based

on initial figures provided by Yue et al. (2014) but could be significantly higher if values calculated by Yao et al. (2014) are used.

On the other hand, the largest contribution element in terms of emissions is the envelope (192 and 128 kg CO₂-e per annum respectively). As can be observed from the previous figures, the embodied energy and emissions cannot be significantly reduced if only the requirements of one element are lowered. Given the suburban scale nature under which these cases are studied, all elements should be considered collectively together through other reduction techniques such as smaller house size.

6.1.6.3. b Operational energy demand and greenhouse gas emissions

As was highlighted previously, the base case neighbourhood, BC_NBH is comprised of building types: BASE_CNBH and BASE_CNBH3. The total operational energy of the base case suburban neighbourhood is modelled as 4.5 GWh with 927 tCO₂-e of associated emissions per annum and the embodied energy is calculated as 4.78 GWh with 715 tCO₂-e of the associated emissions. As discussed earlier in Chapter 5, these quantified energy demand and greenhouse gas emissions figures are generated from each representative building type in the building zone respectively. Thereafter, the representative buildings are multiplied to represent the entire suburban neighbourhood based on Equation 4.29 in Section 4.2.6. Table 6.8 below presents a summary for deriving the energy and greenhouse gas emission net values.

Table 6.8: Summary for deriving energy and greenhouse gas emission net values

	BASE_CNBH		BASE_CNBH3		BC_NBH	
	Energy (GWh)	Greenhouse gas emissions (tCO ₂ -e)	Energy (GWh)	Greenhouse gas emissions (tCO ₂ -e)	Energy (GWh)	Greenhouse gas emissions (tCO ₂ -e)
Energy Exports	2.84	322	2.56	321	5.4	643
Building Operation	1.97	402	2.53	525	4.5	927
Building Embodied	1.62	327	1.08	218	2.7	545
RES Embodied	1.04	84	1.04	84	2.08	168

From Table 6.8 above, the amount of energy exported by the neighbourhood to the grid through the roof-mounted PV systems is 5.4 GWh per annum with

corresponding generation emissions of 643 tCO₂-e. Consequently, the net zero energy and emissions deficit of the base case neighbourhood (BC_NBH) is 3.9 GWh, 997 tCO₂-e per annum; (BASE_CNBH: 1.79 GWh, 491 tCO₂-e and BASE_CNBH3: 2.09 GWh, 506 tCO₂-e).

Figures 6.20 and 6.21 overleaf present the operational energy and greenhouse gas emissions breakdown of the two parts of the building zones or districts: BASE_CNBH and BASE_CNBH3 respectively. As can be seen from the Figures 6.20 and Figure 6.21, the operational energy demand and emissions for both building types are largely dominated by appliances. For BASE_CNBH, appliances represent 43.4% of the total annual energy demand while as for BASE_CNBH3, appliances represent 49.8% of the total annual energy demand. The houses in the neighbourhood do not require heating or cooling since they are built to the current zero energy building criteria. The annual energy demand is generally lower than average standard housing stock. Favourable local climatic conditions in combination with efficiency gains of the building envelope make it possible to dramatically lower and ultimately eliminate heating and cooling demands. This further reduces energy demand and greenhouse gas emissions in the base case neighbourhood.

Figure 6.20: Annual operational energy demand and greenhouse gas emissions BASE_CNBH of the BC_NBH

Figure 6.21: Annual operational energy demand and greenhouse gas emissions BASE_C NBH3 of the BC_NBH

Nevertheless, the source of electricity also plays a role especially in greenhouse gas emissions with regards to end uses. Since the electricity used is either provided by the PV systems with solar fraction $\sim 43\%$ and also by imports $\sim 57\%$, the greenhouse gas emission contribution attributed to each end use is dependent on the user behavioural aspects which influence consumption patterns (See temporal energy match of production/demand in Section 3.1.3.3 and the Duck Chart phenomena in Section 3.1.2.2. a).

6.1.6.3. c Transport energy demand and greenhouse gas emissions

The annual total transport energy for the neighbourhood is 33.4 GWh per annum and the associated greenhouse gas emissions are 5814 tCO₂-e. The neighbourhood is assumed to be reliant upon private vehicles as the mode of transport. As noted in Chapter 5, user transport energy figures are quantified based on the base case transport mode for users for each representative building type (BC-I given in Table C.4 Appendix C).

The base case transport energy requirements are derived from the calculations based on Equation 4.17, Equation 4.19 and Equation 4.21 in Section 4.2.2.2. The

representative transport energy and greenhouse gas emission requirements per household specified for each type of building are multiplied to represent the entire suburban neighbourhood based on Equation 4.29 in Section 4.2.6. Further quantification details on transport energy are detailed in *ms-excel* sheet 1-C to 9-C on accompanying CD.

As can be observed from Table 6.9 overleaf, the building energy demand and emissions (operation and embodied) only represent 10.5% and 14.6% of the total when combined with transport energy demand respectively, while transport energy requirements and emissions represent 89.5% and 85.4% respectively. These ratios underpin the significance of integrating user transport energy requirements within existing building and planning regulations.

Table 6.9: Annual total building energy demand and greenhouse gas emissions of the neighbourhood compared with transport

Use	Energy		Greenhouse gas	
	Consumption (GWh)	Share	Emissions (tCO ₂ -e)	Share
Building	3.9	10.4%	991	14.6%
Transport	33.4	89.5%	5814	85.4%
Total	37	100%	6805	100%

6.1.6.3. d Annual total energy demand and greenhouse gas emissions

The annual total energy requirements and greenhouse gas emissions breakdown of the neighbourhood BC_NBH and the implications are further presented in this section. Figure 6.22 overleaf shows the energy requirements breakdown and associated greenhouse gas emissions resulting from both the building and city scales .i.e. buildings (operational and embodied energy combined) and user transportation (operational and embodied energy).

Figure 6.22: Annual total energy demand and greenhouse gas emissions breakdown at different scales of the built environment: Buildings and user transport

As was pinpointed in the previous section, the annual total energy harvested in the neighbourhood is 6.8 GWh. Ideally, if the user transportation and building requirements are included, the annual total energy demand and greenhouse gas emissions for the neighbourhood are 37 GWh and 6805 tCO₂ respectively. This energy demand represents 14.3% of the total solar energy hitting the built surface of the suburb in one year. This energy equates to ~259.6 GWh (1,400 kWh/m²/year over 185,500 m² built surface area of the neighbourhood) and cannot still be covered by the amount solar energy harvested by the on-site PVs. Since solar harvesting devices are often used in zero energy buildings, it may be assumed that it is possible to supply almost all required energy demands in the suburb (and export the remainder to the grid) through solar PV systems coupled with optimized on-site storage devices (such as batteries as discussed in Section 4.2.1.1. a). Clearly, this further suggests that the technical potential of PV systems requires further development.

6.1.6.3. e Comparison of zero energy building neighbourhood with other building forms based on typology

As discussed in Section 5.4.5.2. d, in the previous chapter, two alternative dwelling scenarios are considered and results are presented here (Figure 6.23): STD_RH and STD_TRCH, with which each replaces half of the built area of the suburban neighbourhood, $\sim 92,500 \text{ m}^2$ of each building block type, representing 620 single-storey row houses and 624 double-storey terrace houses, respectively. The reasons for selecting a 50% split of each residential district has also been given and discussed in Section 5.4.5.2.d. Essentially, this alternative housing typology neighbourhood is represented by the acronym: STD_RH+STD_TRCH. The Figure 6.23 below shows the modelled building energy demand (operational and embodied combined), user transport (operational and embodied) and the total of the entire STD_RH+STD_TRCH neighbourhood.

Similar to the calculations in the base case neighbourhood, these modelled figures for both building (operational and embodied energy combined) are generated from each representative building type in the building zone respectively, i.e. STD_RH and STD_TRCH. Thereafter, the representative buildings for each household in each particular zone are multiplied to represent the entire suburban neighbourhood based on Equation 4.29 in Section 4.2.6.

Figure 6.23: Breakdown of total annual energy demand and greenhouse gas emissions for alternative housing typology, STD_RH and STD_TRCH in the suburban neighbourhood

In addition, the user transport energy figures are quantified based on the base case transport mode (BE-I given in Table C.4 Appendix C). The base case transport energy requirements are calculated based on Equation 4.17, Equation 4.19 and Equation 4.21 in Section 4.2.2.2 as discussed in the previous section. In that way, the representative transport energy requirements per household are then finally multiplied to represent the entire suburban neighbourhood based on Equation 4.29 in Section 4.2.6.

More importantly, when the total building and transport energy demands for the two neighbourhoods: STD_RH+STD_TRCH and BASE_CNBH+BASE_CNBH3 are compared, Figure 6.24 below further demonstrates that ultra-low energy buildings built to the current zero energy building criteria, within suburban neighbourhoods can consume lower embodied and operational energy and emit much less greenhouse gas emissions than standard dense housing configurations and more compact buildings. However, it should be noted that the total building energy demand for BASE_CNBH+BASE_CNBH3 is taken as the net zero energy deficit (energy exports minus total building energy demand) calculated from Table 6.9 as highlighted Section 6.1.6.3.

b. Additionally, Table C.5, Appendix C contains the main characteristics of the different neighbourhoods herein.

Figure 6.24: Annual total energy demand and greenhouse gas emissions comparison between base case neighbourhood and alternative dwellings

This finding contradicts the commonly held belief that dense and more compact housing developments within urban settings are associated with much lower energy use and greenhouse gas emissions. See for example (Newman and Kenworthy 1999; Glaeser and Kahn 2010; Minx et al., 2013; Weidenhofer et al., 2013) as highlighted earlier in Section 2.1.2 and discussed further in Section 5.4.5.2. Essentially, it can be observed that the STD_RH+STD_TRCH scenario has an annual total energy demand of 55 GWh and 9558 tCO₂-e of associated greenhouse gas emissions for both buildings and user transport combined. This represents an increase in energy demand and greenhouse gas emissions of 48.6% and 40.5% compared to the BASE_CNBH+BASE_CNBH3 (BC_NBH) scenario respectively.

There are a number of parameters which are responsible for these observed differences in the annual total energy demand and greenhouse gas emissions. These parameters are closely related to the building (both embodied and operational) as well as user transport (both embodied and operation) requirements. These aspects are therefore discussed hereunder.

The building embodied energy and associated greenhouse gas emissions of the base case neighbourhood, BASE_CNBH+BASE_CNBH3 are much higher than the denser row and terrace house neighbourhood STD_RH+STD_TRCH scenario: 4.54 GWh with 707 tCO₂-e and 2.279 GWh with 271 tCO₂-e respectively. This represents 99.2% and 160.8% increase of embodied energy demand and greenhouse gas emissions for the base case neighbourhood compared to the alternative dwelling typology neighbourhood respectively. Firstly, this decrease in embodied energy is due to sharing party walls among houses and the smaller living areas per capita, typical higher density configurations. Furthermore, the base case neighbourhood is characterised by zero energy houses, which have energy harvesting devices, PV systems in this case. These systems installed on houses across the base case neighbourhood generally have a much higher energy intensity (representing over 40% of annual total building embodied energy intensity of the neighbourhood) as discussed previously in Section 6.1.1.1. In addition, the inclusion of the embodied emissions from the grid compared

to the impact of the PV in the analysis has been established to have much less or no significant influence on the results obtained (see Section 6.1.6.1.).

On the other hand, operational energy demand and greenhouse gas emissions of the alternative dwelling typology neighbourhood: STD_RH+STD_TRCH scenario are much higher by +215.5% and +171.8% respectively, when compared to the base case scenario (See Figure C.1 and Figure C.2, Appendix C which contains annual energy demand and greenhouse gas emissions of end uses associated with buildings in the alternative dwelling typology neighbourhood). This large increase observed is due to a number of reasons. In particular, the base case neighbourhood comprises dwellings which are built under the current zero energy building criteria (see Section 3.1.3). This implies that the buildings possess very efficient envelopes which significantly reduce the requirements for heating as compared to other existing houses in the same location under similar climatic conditions presumably. In addition, the buildings are modelled based on actual monitored performance data which shows a decrease of ~25% and ~20% compared to standard houses located in the same location (Isaacs et al., 2010b), for hot water and appliance requirements respectively. The former is due to the usage of solar hot water heating, while the latter is due to highly energy efficient appliances and fittings (typical of current zero energy building practices). This decrease is also coupled with major adjustments in user behavioural aspects as was highlighted earlier.

Furthermore, when breakdown by end uses is compared with the STD_RH+STD_TRCH scenario, the base case neighbourhood has significantly lower energy demand by 96%, 48%, 94%, and 100%, for hot water (due to SWH), appliances and cooking, lighting (low due to more efficient equipment) and heating (nearly zero due to high thermal performance) respectively. Ideally, lower increase in heating energy demand is found to be less significant as compared to the larger increase in hot water usage, appliances and cooking in the STD_RH+STD_TRCH scenario. Heating energy demand is linked to the building construction, orientation etc. in terms of thermal aspects, while hot water use, appliances and cooking are associated with the building users (See Section 4.2.1.1). This finding suggests that thermal optimisation of building

envelopes with the aim of reducing overall building energy demand can also be defeated by the consumption patterns of the users as highlighted in Section 2.3 (Keesee 2005; Stevenson and Rijal 2010; Bourelle 2014; Berry et al., 2014) . This further underscores the significance of promoting change in user behaviour coupled with efficient appliances and fittings if meaningful reductions of energy demand and associated emissions are to be achieved within the built environment.

There are no significant differences in energy demand and greenhouse gas emission requirements for transport from the base case neighbourhood compared to the STD_RH+STD_TRCH scenario. This is because in both scenarios, the user transport is modelled with the assumption that the neighbourhood inhabitants rely solely on private vehicles as the mode of transport. However, it is beneficial to investigate the influence of modal shifting and fuel switching in order to test the influence of transport mode options in the neighbourhood. This aspect is reported further in the sub-section to follow. In parallel, building size and the number of users are also identified as important determinant factors influencing energy demand and associated greenhouse gas emissions for houses (See Section 4.2.7.2.b). This aspect is also investigated for the neighbourhood with alternative dwellings forms in comparison to the zero energy building zones. The results are reported hereunder.

BUILDING SIZE AND NUMBER OF USERS VARIATION

As was discussed in Section 4.2.7.2. b, in the developed framework, the designer/evaluator can test the influence of each or combination of parameters. The building size is reduced by 34.2% in the scenario STD_RH+STD_TRCH which becomes STD_RHSV+STD_TRCHSV. This percentage reduction is based on the dramatic increase of average floor areas of New Zealand houses from $\sim 149\text{m}^2$ in 1990 to over 200m^2 after 2010 as was highlighted in Section 4.2.7.2. b. The combination of building size and increase in number of users scenario for this study becomes STD_RHSV5+STD_TRCHSV5. Here the number of users is increased from 2 to 5 based on the assumptions provided in Section 5.4.3.4. a.

Figure 6.25 overleaf presents the annual energy demand and greenhouse gas emission breakdown for the STD_RH+STD_TRCH scenario with house size reduced by 34.2%

STD_RHSV+STD_TRCHSV as described previously above with each respective building zone. While transport energy demand is not affected by the house size variation, this scenario reduces the annual energy demand and greenhouse gas emissions by 10.5% and 5.9% compared to the STD_RH+STD_TRCH scenario but is still higher than the base case neighbourhood as presented in Table 6.10 below .

Figure 6.25: Annual energy demand and greenhouse gas emissions breakdown of alternative neighbourhood STD_RH+STD_TRCH with size variation STD_RHSV+STD_TRCHSV

Table 6.10: Effect of building size on the annual operational energy demand and greenhouse gas emissions of the alternative neighbourhood versus the base case zero energy building neighbourhood

Case	Annual total energy demand (GWh)		Annual total greenhouse gas emissions (tCO ₂ -e)	
	Value	Change	Value	Change
BASE_CNH+CNH3	37.0	N/A	6725	N/A
STD_RH+TRCH	55.1	+48.8 %	9558	+42.1 %
STD_RHSV+TRCHSV	40.9	+10.5 %	7119	+5.9 %

The reduction of house size has resulted in a reduction of embodied energy by - 65.8% compared to the base case neighbourhood. For operational energy, the reduction is only -7%. The higher reduction in embodied energy demand is due to the reduced house size with lower material usage and hence lower embodied energy

demand and greenhouse gas emission intensities. On the other hand, operational energy demand reduction is much less in this particular case because the energy end uses which are affected by house size (geometry) are heating, ventilation and lighting, all of which are found to be lower for this study. Non-thermal energy end uses are found to be responsible for a larger share of operational energy for the STD_RH+STD_TRCH scenario as was also established in Section 6.1.6.3.b.

Figure 6.26: Annual energy demand and greenhouse gas emissions of the alternative neighbourhood scenario compared with base case under size variation based on per reference m² flow

In parallel, based on calculations derived from Equation 4.30 in Section 4.2.6, another interesting observation emerges when a different reference flow is used to interpret the results as shown in Figure 6.26 above. When the energy demand and greenhouse gas emissions are expressed on a per m² basis of the built surface area of the neighbourhood, the more dense scenarios are still more energy intensive but the reduction in energy demand is 49.4% higher than previous reference flows. This finding further suggest that intensification is associated with higher energy demand per surface area but likely to result in more efficient energy use when expressed on a per capita basis as shown in the scenario STD_RHSV5+STD_TRCHSV5 overleaf (see Figure 6.27 overleaf). A similar trend in the influence of number of users can also be observed in Section 6.1.4.1.

Figure 6.27: Annual energy demand and greenhouse gas emissions of the alternative neighbourhood scenario compared with the base case under size variation on per capita basis

As was previously found in this section, building energy (both embodied and operational) is closely correlated with house size. Therefore, the use of reference flow MWh/m² appears to favour efficiency gains in larger housing units. This confirms the recent findings by Stephan and Crawford (2015) as highlighted earlier in Section 2.2.4. In addition, these findings further suggest that using total and per capita reference flow (along with per m²) to express efficiency gains provides a more realistic picture in terms of energy demand and reduction strategies. The use of total or per capita metrics is not usually considered within the current zero energy building frameworks today.

In reality, reducing house size does not affect the energy intensity and greenhouse gas emissions associated with mobility of the people living in the neighbourhood. This means that reducing energy demand and greenhouse gas emissions of dwellings through the effect of house size alone is not an option enough to yield very significant energy demand and greenhouse gas emission reductions. By considering other energy demands associated with the neighbourhood dwellers such as transport, dramatic reductions in energy consumptions can be achieved as

already emphasized in Section 6.1.3. This aspect is therefore also investigated in the alternative neighbourhood through modal shift (shifting from private to public transport) and fuel substitution (switching from petrol based vehicles to battery powered electric vehicles). The results are reported hereunder.

TRANSPORT MODE SHIFT AND FUEL SWITCH

As was previously discussed in Section 4.2.7.2.b, environmental and health concerns associated with heavy reliance on private vehicles have directed of policy makers to promote the shift towards less energy intensive public transportation modes (Harman et al., 2012; Geels et al., 2012; Givoni and Banister 2013). Therefore, the second scenario, denominated as STD_RHSV_EV-I+TRCHSV_EV-I tests a 100% switch to electric vehicles on the alternative building typology neighbourhood. In addition, the possibility of adopting less energy intensive public transportation modes is also investigated under modified scenario STD_RHSV_PT-Tr+TRCHSV_PT-Tr. The characteristics of electric modes and public transport modes tested for this variation are based on the calculated less energy intensive modes presented Figure 6.10 in Section 6.1.3.

Figure 6.28 shows that by switching from petrol-based vehicles to battery powered electric vehicles, the STD_RHSV_EV-I+TRCHSV_EV-I neighbourhood scenario reduces transport energy demand and greenhouse gas emissions by 85.1% and 56.1%, respectively. The reduction is associated with the low primary energy coefficient and lower carbon emission intensity nature of the New Zealand electricity grid ($\sim 179 \text{ kgCO}_2\text{-e/MWh}$).

Figure 6.28: Transport mode switch from ICEVs to electric vehicles under the STD_RHSV_EV-I+TRCHSV_EV-I neighbourhood scenario

Overall, the reduction of energy demand observed in the STD_RHSV_EV-I+TRCHSV_EV-I scenario is due to the higher efficiency powertrain technology of the electric vehicle compared to its internal combustion engine counterpart (60-70% for electric vehicle while 15-18% for internal combustion engine vehicles) (Richardson 2013). On the other hand, the reduction in greenhouse gas emissions is not as dramatic as the energy demand. This is partly due to higher embodied impacts of the electric vehicles since the manufacturing, supply, distribution and maintenance of the batteries is subjected to certain energy demands which are characterized by various greenhouse gas emission intensities. Indeed, in Europe, Hawkins et al. (2012) demonstrate that embodied emissions of lithium battery-based electric vehicles is about 45-48% of the operation emissions, while it is 18-25% for internal combustion engine vehicles.

Apart from electric vehicle adoption, another option is a switch to effective public transportation. This aspect is also investigated for the neighbourhood and the results are reported in the remainder of the section. Figure 6.29 below shows that a shift to electric train transport significantly reduces the energy demand and

greenhouse gas emission for transportation by 92% and 79.8% respectively. These reductions in energy and emissions intensities are due to the efficient nature of modern electric trains coupled with the lower emission electricity grid in New Zealand.

Figure 6.29: Transport mode shift from private ICEVs to public transport under the STD_RHSV_PT-Tr and STD_TRCHSV_PT-Tr neighbourhood scenarios

PRIMARY ENERGY COEFFICIENTS FOR ELECTRICITY AND GHG EMISSIONS

The evolutions of primary energy coefficients for electricity and greenhouse gas emissions overtime are also further tested in a similar manner as described in Section 5.4.3.4. b and Table 5.15 at the neighbourhood scale. In order to test its influence on the building zone, this parameter PRM_EFeI+GHGF reduces the primary energy and greenhouse gas coefficients for the scenarios, STD_RHSV and STD_TRCHSV respectively. Thus, the variability associated with primary energy and greenhouse gas emissions factors for electricity for the buildings zones becomes: STD_RHSVPRM_EFeI+GHGF and STD_TRCHSVPRM_EFeI+GHGF. Ideally, Since scenario STD_RHSV +STD_TRCHSV are characterized by different building typologies, the parameter evolution on the studied neighbourhood is firstly reported individually at individual building zone/district level i.e. STD_RHSV and STD_TRCHSV respectively to ensure a better degree of clarity and transparency of results. Note that the parameter change from the 2010

grid, for instance, STD_RHSV2010PRM_EF+GHGF is higher and followed by a decrease from 2015 grid, STD_RHSV2015PRM_EF+GHGF onwards. This is due to the fact that the 2010 grid has higher primary energy and greenhouse gas emission factors than the following years of interpolation.

The combined influence of these evolutions on annual operational energy demand and emissions is presented in Table 6.11 below. The summary of results presented only takes into account the evolution parameters associated with operation energy. The reasons for excluding parameter evolution associated with embodied energy are given in Section 6.1.4.2.

Table 6.11: The effect of parameter evolution on annual total operational energy demand and greenhouse gas emissions in the neighbourhood with alternative building typologies

Case	Annual building operation and embodied energy demand (GWh)		Annual building operation and embodied energy emissions (tCO ₂ -e)	
	Value	Change	Value	Change
Row House				
STD_RHSV	10.9	N/A	1882	N/A
STD_RHSV2010PRM_EF+GHGF	11.6	+6.4 %	2372	+26%
STD_RHSV2015PRM_EF+GHGF	10.2	-6.4 %	1756	-6.7%
STD_RHSV2020PRM_EF+GHGF	8.8	-19.2 %	1231	-34.6%
STD_RHSV2025PRM_EF+GHGF	6.7	-38.4 %	732	-61.1 %
STD_RHSV2030PRM_EF+GHGF	4.6	-57.6%	382	-79.7%
STD_RHSV2035PRM_EF+GHGF	3.2	-70.4%	210	-88.8%
Terrace House				
STD_TRCHSV	10.6	N/A	1825	N/A
STD_TRCHSV2010PRM_EF+GHGF	11.3	+6.3 %	2299	+25.9%
STD_TRCHSV2015PRM_EF+GHGF	9.9	-6.6%	1704	-6.6%
STD_TRCHSV2020PRM_EF+GHGF	8.6	-19.2%	1196	-34.5%
STD_TRCHSV2025PRM_EF+GHGF	6.5	-38.2%	713	-60.9%
STD_TRCHSV2030PRM_EF+GHGF	4.5	-57.5%	375	-79.5%
STD_TRCHSV2035PRM_EF+GHGF	3.2	-70%	209	-88.5%

Table 6.11 shows that moderate parameter evolution denoted by the acronym STD_RHSV2020PRM_EF+GHGF (2020 grid scenario), reduces energy demand and greenhouse gas emissions by 19.2% and 34.6% respectively when compared to the STD_RHSV scenario. However, when dramatic parameter evolution conditions are considered in the scenario STD_RHSV2035PRM_EF+GHGF (2035 grid scenario), further dramatic reductions in energy demand and greenhouse gas emissions by 70.4% and 88.8% respectively can be observed.

On the other hand, when scenario STD_TRCHSV is considered, the energy demand and greenhouse gas emissions are reduced by 19.2% and 34.5% for the moderate parameter evolution scenario STD_TRCHSV2020PRM_EF+GHGF (2020 grid scenario). Furthermore, when the dramatic parameter evolution scenario is considered: STD_TRCHSV2035PRM_EF+GHGF (2035 grid scenario), energy demand and greenhouse gas emissions reduce by 70% and 88.5% respectively.

This finding further suggests that efficiency improvements in the electric grid to lower the requirements for primary energy in combination with reduced house sizes are likely to result in even greater reductions in operational energy and greenhouse gas emissions at a suburban neighbourhood scale. On the other hand, a summary of comparison of the entire neighbourhood under optimized scenarios for both reduces house sizes and parameter evolution as established above: STD_RHSV+STD_TRCHSV, with the base case BC_NBH is presented in Table C.6 Appendix C, by energy use breakdown.

6.2 Conclusion

The findings have helped to derive an understanding of zero energy buildings at a much broader perspective. This chapter has presented the verification and application potential of the developed methodological framework and technique. In particular, the framework has investigated various ways in which multi-scale zero energy approaches may influence design. Using various scenarios, a typical zero energy house located in the inner sector suburban area in Auckland, New Zealand has been tested against standard housing on the building scale and also with other housing typologies, at the neighbourhood scale.

The results demonstrate that buildings which have been built based on the current zero energy building criteria have net energy deficits when the building embodied energy is not accounted for in the energy balance. Ignoring transport energy which is responsible for the mobility services of the users, increases the energy deficit further. Overall, the results confirm that both operational, embodied and user transport energy must be included within zero energy building frameworks. Furthermore, all these aspects are intertwined with the building user choices at different scales of the built environment. Consequently, ignoring the user aspects has got noticeable implications to the building and energy industry as emphasized in this study.

Other measures including: house size, household size, transport mode shift and fuel switching (including the use of lower emission transport modes and displacing liquid transport fuels with low carbon grid electricity), and retrofitting electricity grids have been found to be integral to reducing building and transport energy operational and embodied demands. In summary, the findings from this chapter are further interpreted in the following chapter in order to shed more light and provide valuable insights pertaining to building design options, urban planning, life styles choices, and building energy policy strategies to ensure a low energy and preferably a zero energy society.

Chapter 7 | Discussion

The verification and application of the methodological framework in chapter 6 has demonstrated that the thermal aspects and operational energy requirements associated with dwellings represent only one part of the total energy consumption for residential buildings that meet the current criteria of zero energy. Furthermore, the investigation has proven that embodied and user transport energy requirements can potentially nullify the perceived superiority of zero energy buildings. Consequently, a reduction of energy use and emissions to lead towards a low energy society can only be realized by implementing a systematic combination of measures across different scales of the built environment.

The aim of this chapter is to synthesise the salient findings from Chapter 6 which are based on the verification and application of the methodological framework developed in Chapter 4 and discuss their potential implications. The following elaboration is grounded on the evidence of the scientific literature and various definitions and concepts reviewed in chapters 2 and 3. In the light of zero energy building principles, based on the developed framework and its applications, this chapter provides relevant suggestions to reduce overall energy demand and emissions associated with residential buildings and neighbourhoods.

7.1 Towards an integrated multi-scale zero energy building approach to reducing energy demand and greenhouse gas emissions of residential buildings and neighbourhoods

It has been evidenced from the case study analysis and results that the total annual energy demand of a household is not only dominant at the building scale or related to the physical building only, but rather spreads across multiple levels at the built environment scale. The proportion contribution of energy demand associated with users varies at inter-scale level, (building scale: embodied and operational energy, and at the city scale: transport embodied and operational energy). All these individual energy demands are closely linked with both building design options, urban planning strategies and building occupants' life style choices. Consequently,

in the light of residential buildings, various stakeholders involved in the development of buildings and cities such as architects, engineers, urban designers and policy makers, must collectively share the responsibility to lead the mission towards a low or zero energy built environment.

The following section, which is based upon the results in Chapter 6 and the general methodological framework, presents the proposed appropriate approaches to significantly lower energy demand towards zero at both the building and urban scales. In doing so, the section addresses the third research question in Section 3.7, i.e. *how can an integrated multi-scale zero energy building framework for residential buildings inform design and urban/regional planning policy?*. The answers are presented in form of a discussion which involves insights in zero energy building design, user behaviour and urban planning recommendations. Finally, requirements for multi-scale building energy policies in the built environment are then discussed.

7.1.1 Zero energy housing design

Suitable techniques for designing zero energy houses are very critical since the performance of the buildings and the ability to reduce energy demand depends on the design itself and how its occupants behave relative to different scales in the built environment as demonstrated in chapter 6. The requirements for embodied, operational and additionally the transport energy of their users therefore have significant influences. Although many clients often do not require optimal measures to deliver low environmental impact buildings (Williams and Dair 2007; Lockton et al., 2008), it is still the responsibility of the architect and engineer to raise the awareness to their clients of the most favourable alternatives which promote lower environmental impact and less energy intensive opportunities within the residential building sector.

For instance, the most well understood zero energy building design principles for residential buildings are applicable to single family detached houses which are typically characterized by larger floor areas. As a consequence, promoting very large floor areas per capita only increases the total embodied energy of the building and also potentially the requirements for space heating and ventilation in locations

with extreme climates. This effect of building size can be observed in the base case (BASE_C) Auckland zero energy house since the contribution of embodied energy to the zero energy balance deficit is 35.1% (See Section 6.1.1.4.). Furthermore, similar observations are also seen in the neighbourhood case study: the STD_RHSV+STD_TRCHSV scenario with reduced size relatively reduces heating, lighting and ventilation energy demand by 7% (See Section 6.1.6.3. e). Based on these findings, building designers can strive to exploit the opportunities associated with smaller housing units which retain all the necessary advantages of larger units such as lighting and thermal comfort coupled with a good choice of durable and less energy intensive materials.

However, there is another major factor apart from house size in relation to zero energy housing design. Decarbonising energy sources in the built environment has become a major policy issue and potentially an important impetus for diversification into on-site (or within building footprint) renewable energy capture devices for residential buildings. The most common renewable energy capture devices used in zero energy houses are mono/multi-crystalline based solar PV systems (See Section 3.1.2.2. a).

PV generated electricity (50-160 gCO₂-e/kWh or average 99 gCO₂-e/kWh for ~1,700 kWh/m²/year solar irradiance) is indeed over 70% less carbon intensive than electricity generated from various common sources such as natural gas (~360-720 gCO₂-e/kWh) and coal plants(average $\pm$ ~1019 gCO₂-e/kWh) (Laleman et al., 2013). The most cited energy payback times for solar PV systems are 2.4 and 2.3 years respectively (Laleman et al., 2013). However, as was discussed in Section 3.1.2.2. a and Section 6.1.1.1, manufacturing of PV modules (over 67%) has shifted to China and hence, the energy payback times and the greenhouse gas intensity therefore significantly are doubled due to the higher carbon intensity of the Chinese electricity grid (Yue et al., 2014). The impact is clearly demonstrated with ~40% of the embodied energy of the base case zero energy house in New Zealand is attributed to the solar PV system (See Section 6.1.1.1).

On the other hand, this leads further to the question still under investigation as to whether renewable energy will be able to supply all increased energy demand by

2050 (IEA 2015). As was previously highlighted in Section 3.3.1.3, in the context of zero energy buildings, another question regarding the technical potential of renewable energy capture devices such as PV systems, possibly becomes another point of concern. Mariaty and Honnery (2012) argue that studies such as Lightfoot and Green (2002), Gross et al. (2003), Cho (2010) and Tomabechei (2010) tend to provide overestimated higher figures for technical potential of solar capture devices due to the use of purely input-output quantification techniques. Other studies using hybrid techniques, such as Zhai and Williams (2009) and Crawford (2009) demonstrated lower technical potential figures for PV systems and wind turbines than those previously calculated. Nevertheless, it cannot be ignored that solar cells are improving in terms of efficiency and so is the process for manufacturing them. For instance, consumption of the most energy intensive component in solar cells, polysilicon, has reduced to 5.5 grams per Watt peak (g/Wp) (Yue et al., 2014). Consequently, technological improvements of photovoltaic systems are expected to yield better results in the near future (Yang et al., 2015).

Considering the significance of energy sources, it can be seen from Section 6.1.6.1 that improvements to the grid combined with standard houses located in New Zealand have a higher potential to reduce greenhouse gas emissions (by 59.5%) than the base case zero energy house. Even the modelled best case zero energy house with improved grid still emits 25% more emissions than a standard house. This is due to the low-carbon electric grid feeding the standard house (primarily hydro: $\sim 10\text{--}18$ gCO₂-e/kWh and wind: $\sim 9\text{--}17$ gCO₂-e/kWh) compared to the zero energy house which relies on both higher carbon solar and the lower carbon grid. It can be observed that the environmental benefits of roof-top solar PV-based zero energy houses located in New Zealand are less satisfactory if the grid becomes more decarbonised. This is also likely to be valid in other regions similar to New Zealand in terms of construction paradigms and electricity generation.

Nevertheless, this does not imply that PV technology itself is of no use. As was mentioned previously PV generated electricity is $\sim 70\%$ less carbon intensive than natural gas or coal generated electricity in general. Therefore in regions where these

are dominant such as the U.K (energy mix: ~ 450 gCO₂-e/kWh) and the U.S.A (energy mix: ~ 670 gCO₂-e/kWh), PV system based zero energy houses could be a viable option but possibly only in the short term, since in the longer terms these grids will have to become efficient and rely predominantly on renewables. More research is required in this area to further investigate this argument. Since PV technology is currently still under development, at the moment architects and engineers should assist their clients to select carefully the location from where to obtain the PV and also advise on where to install and whether to or not to install depending on regional energy mixes. In addition, the solar PV industry practitioners should also be encouraged to ensure that manufacturing of PV modules is done in countries which have low carbon electricity such as New Zealand, Norway, Costa Rica etc. and that panels be installed in countries with high carbon intensity grids such as U.S.A, China, India or Australia.

In parallel, as far as building related operational energy is concerned, architects are recommended to exploit the use of passive design techniques. Indeed, it has been observed from this work that exploiting local climatic conditions has a certain degree of significance toward reducing operation energy. The base case zero energy house employed passive design techniques and this avoided the requirements for heating and ventilation (See Section 6.1.1.2). Besides, operational energy is also linked to the type of energy source as previously discussed. In the light of zero energy houses, the buildings rely on both energy produced on-site and also from the grid due to RE intermittency. There comes a day when the energy being generated does not necessarily match when energy is required in the building leading to a significant performance gap. Ultimately, how much actual energy is used in the building could be considerably more than what was predicted in the design. This leads the building to absorbing more energy with a higher primary energy coefficient from the grid as previously discussed (See Section 3.1.2.2. a on Duck Curves). This mirrors exactly what has been observed in the zero energy house case study. On an annual basis, only 43% of the energy used for building operation was associated with the PV system while 57% came from the grid.

To circumvent this issue, several researchers, notably; Salom et al. (2014a; 2014b) and Guarino et al. (2015) have proposed load match and grid interaction optimization approaches to couple with on-site battery storage systems as was pinpointed in Section 6.1.1.4. Indeed, the issue of energy storage is no longer an academic question because several prominent manufacturers, notably Tesla Motors, are pushing for lithium ion batteries to complement on-site solar as noted earlier in Section 4.2.1.1. In pragmatic sense however, the advent of on-site storage devices is subjected to a number of constraints which determine their efficacy. In particular, energy storage batteries need to have reasonable capacity to store enough energy harvested from the PV system in order for building occupants to be able to consume energy adequately. However, the first generation of current state-of-the art on-site energy storage devices, such as Tesla Powerwalls, are expected to store ~6.5 kWh when used as daily storage media (See Section 4.2.1.1). The PV systems installed on the modelled buildings used in the case study comprise 4.13 kW_p, assuming that storage batteries are used in the dwelling, this means that the storage batteries would be expected to fill up within an hour and a half during peak solar irradiation periods. The remaining harvested energy is still expected to be injected back into the grid, thereby maintaining current criteria of zero energy housing (net). It appears that, the environmental impact resulting from the PV systems and the additional batteries is likely to increase the net energy deficits.

In addition, another aspect to take into account when considering PV-battery-optimised-systems is the so-called 'C-rate', (charging rate of the battery). The C-rate is the measure of the rate at which the battery is discharged relative to its maximum capacity (Kang and Ceder 2009). A 1C-rate battery discharges its capacity entirely in an hour. This means that a 10 kWh battery pack with 1C-rate can therefore provide 10 kWh of electricity for one hour. A higher C-rate battery increases the level of power that a battery can produce relative to its size while a lower C-rate battery reduces it.

Assuming the modelled houses installed the first generation Tesla Powerwalls, the batteries' output and charge rate would be limited to less than half of their effective

capacity since Tesla Powerwalls have C-rates below 0.5. This further leads to the question whether the storage system would be capable of providing continuous electric power in the homes during peak demand periods. However, since the development of the first generation Powerwall batteries, Tesla Energy debuted Powerwall 2, which predominantly feature improved power capacities. Although this is expected to circumvent the issues surrounding the first generation Powerwall's, their embodied impacts and efficiency with respect to improved capacity remains to be investigated in the context of the built environment.

Currently, there are no reported studies investigating PV-based lithium ion battery home systems although installation trials are well underway in Europe, North American, Australia, New Zealand and other regions. This aspect could form another basis for further research. In addition, more research is also required to investigate whether potential or beneficial trade-off between PV systems and storages devices could be exploited. Another recommendation which could improve the environmental performance of storage batteries is to manufacture them using renewable energy. Recently Tesla Energy announced that its “Gigafactory” will only use renewable energy to produce lithium-ion batteries for electric vehicles and home storage batteries (Powerwalls).

Section 6.1.1.4 suggest that houses built to the current zero energy building criteria often fail to achieve the required zero energy balance at primary energy level. Building occupants have got a significant level of understanding with regards to energy use since they are able to visualise the results of the service .For instance, switching on/off a light bulb or television. Consequently, it is a concrete idea for building designers to encourage occupants to consume less energy at an earlier stage. The use of large-scale renewable energy sources and adjustments in user behaviour have been found to be crucial in the New Zealand case study analysed. Hence, the development of zero energy buildings and their related technology, including PV systems amongst others, must be considered in different time horizons so that the saying from the great Voltaire (1764) is avoided “*Le mieux est*

l'ennemi du bien"¹⁶. Indeed, the word "zero" sounds extremely good but the risk is aiming for too much, demanding that all problems associated with sustainable housing be solved by one particular technological development.

If focus is solely on what is believed to be the best solution, good, easy and much quicker solutions might erroneously be discarded as simply not good enough. Issues concerning zero energy buildings are very critical and measures for their legislation around the world are well underway (See Section 2.2.5 Figure 2.2). Going down the wrong path is most likely to result in very serious consequences globally. Care should therefore be taken because a situation may arise whereby everyone would wait for "someone else" to find the ultimate solution without acting on the problems that can actually be addressed by employing minor adjustments to societal lifestyles and choices today. Consequently, it makes more strategic sense to extend the current notion of zero energy buildings to broader energy and societal contexts and adopt terms such as: zero energy cities, zero energy countries or preferably zero energy societies.

Finally, energy demand and greenhouse gas emissions associated with the users' mobility are also found to have very significant influence on zero energy houses (See Section 6.1.3). However, building designers possess less power to influence this aspect since it is related to the building users but at the city scale and within the broader scope of urban planning.

7.1.2 Urban planning

Urban planning has a significant impact on energy demand and greenhouse gas emissions of residential buildings within urban settings. Urban form integrates the relationship between outdoor spaces and buildings in terms of building distribution and lay-out, building typology, plot size, infrastructure outline, landscape distribution, population density and so on.

It was established in the New Zealand case study that the neighbourhood which comprises zero energy houses consumes and emits 48.6% and 40% less energy and

¹⁶ French: "Le mieux est l'ennemi du bien." English: "The best is the enemy of the good"

greenhouse gas emissions than the alternative neighbourhood with more dense and compact standard housing units (See Section 6.1.6.2.). This is contrary to the usual belief that higher density urban housing configurations are much more likely to result in lower energy use and greenhouse gas emissions than low density suburban scenarios. However, the zero energy house neighbourhood showed much higher embodied energy and related greenhouse gas emissions than the neighbourhood with alternative high density dwellings. This is due to the higher embodied energy of harvesting devices (PV systems) installed on the housing roofs as already discussed in the previous section. Additionally, the low embodied energy for the alternative neighbourhood is due in part to the smaller units and shared walls and spaces.

When it comes to operational energy, the higher value in the neighbourhood with alternative dwellings is attributed to user related end uses. This implies that higher density configurations might not guarantee a reduction in operational energy and associated greenhouse gas emissions. These findings agree with the points highlighted in Shelton et al. (2010) who argue that Hong Kong uses much higher building operational energy irrespective of its compactness although energy use for mobility is relatively lower than most cities of similar magnitude. In a similar fashion, this also echoes the recent argument raised by Ye et al. (2015) who in their study found out that energy demand and greenhouse gas emissions increased due to less access to green space and water bodies in areas with more compact urban forms in China. On the other hand, the zero energy house neighbourhood case study uses lower operational energy due to adjustments in user behaviour, use of passive design techniques and efficient appliances and fittings. This further suggests that encouraging building occupants to use less energy, exploiting passive design techniques, use of efficient appliances and having smaller dwelling units has a higher potential to reduce energy demand and associated greenhouse gas emissions than merely promoting optimal densities.

Nevertheless, it is however acknowledged that intensifying neighbourhoods can reduce their environmental impact through shared infrastructure, smaller dwelling

units and shorter travel distances, although there is evidence which suggests that people living in intensified urban areas with limited need for regular transport tend to undertake longer travel for leisure purposes to compensate for their limited access to green outdoor spaces. See for example Muniz et al. (2013) and Strandell and Hall (2015) on “compensation hypothesis”. Yet low-density suburban neighbourhoods may also have more potential to be resource-use efficient than intensified urban configurations, since being closer to land offers potential for self-sufficiency such as growing food and so on (Vale and Vale 2010b). Indeed, in their analysis of urban energy and material use in cities, Weisz and Steinberger (2010) found that the amount of energy and land required to sustain suburban neighbourhoods in terms of food and water and other material flows increases with intensification. All these contradictory findings further suggest that more research is still required in order to investigate the many unanswered questions associated with high density urban configurations.

Concomitant to the discussion of urban form above, is the issue concerning energy use for travel. The results in chapter 6 (Section 6.1.3 and Section 6.1.6.2.) suggest that energy demand and greenhouse gas emissions reductions at the building scale may easily be overridden by higher energy intensive behaviour at the urban scale such as energy use for transport. Another finding is that there is no significant difference in user transport energy and greenhouse gas emissions between the zero energy base case neighbourhood and the alternative dwelling neighbourhood since it is assumed that the users solely rely on private vehicles for travel (both commuting and as well as other purposes thereby retaining similar annual travel distances). Often researchers associate intensification with reduced travel distances (See Section 3.3.2.1). However, most of these studies only take into account travel energy for commuting. As was discussed in Section 3.4.2, transport energy use for commuting in New Zealand accounts for only 30% while 70% is attributed to other purposes. Unless users in high density urban configurations switch to less energy intensive transportation modes, their overall transportation energy demand is likely to remain high. Hence, the phenomenon commonly known as ‘paradox of intensification’ comes into play (Melia et al., 2011).

However, by switching from oil-based private vehicles to small and efficient battery powered electric vehicles, significant reductions in energy demand and greenhouse house gas emissions by 74-85.1% and 56.1-68% respectively, can be yielded as demonstrated in Section 6.1.3 and 6.1.6.2. Indeed, this finding, resonates very perfectly with Gilbert and Perl's (2010) '*Transport Revolutions*' that specifically recommends grid-connected electric vehicles as the most promising future direction. This implies that the logic of shifting to electric vehicles is reasonable and their adoption might be a viable option in the near future.

It should however be cautioned that battery powered electric vehicles' environmental performance depends on where they are being driven (this aspect has been previously discussed in Section 6.1.3). Moreover, most regions in the world currently do not generate sufficient low carbon emission electricity to capture the required emission reduction potential of battery powered electric vehicles (IEA 2010). For instance, assuming that similar vehicles are running in a region in which electricity generation is characterized by higher primary energy coefficient and higher greenhouse gas emission intensity such as Victoria, Australia ($\sim 332.5 \text{ kgCO}_2\text{-e/MWh}$: brown coal), much lower energy and emission savings are most likely to be observed. In such cases, other efficient internal combustion engines vehicles might offer better results than sometimes less efficient electric vehicles (See also Section 6.1.3). In addition, the implications of electric vehicles beyond their technology also remains unknown. Ideally, private vehicle usage is linked to urban sprawl (Newman and Kenworthy 2006, Rickwood et al., 2008). This further leads to a situation where much of what building users want and need is difficult to obtain unless they have a private vehicle. It can therefore be argued that the wide adoption of electric vehicles as they are perceived to be "green" might allow current controversial transport policies and practices to remain unquestioned. Similarly, the implications and societal perceptions of electric vehicles also remains unknown.

In parallel, a shift of mode to public transport also yields dramatic reductions particularly electric-rail based public transport. In addition, intensified housing

scenarios may also make public transport provision economically viable (Ng 2010), although developing new intensified neighbourhoods is most likely to come at an expense of embodied energy due to the need for new infrastructure which often represents at least 12% of the total energy demand of the whole neighbourhood (Stephan 2013; Stephan et al., 2013b). Furthermore, this work contends that building users should be encouraged to use less energy intensive and low carbon public transport and that more research and investment should be made into establishing favourable relationships between buildings, users and economically viable public transport provisions.

As the pace of change in the field of low carbon transport appears to be breathtaking, attention should also be given to some of the major emerging trends. In particular, Tesla Energy CEO, Elon Musk proposed the Hyperloop Alpha™ for passenger transport by pneumatic tubes powered by solar energy (Zou et al., 2015). Crowd-sourced transportation services such as Uber and Lyft are increasingly gaining popularity as viable transportation options (Chan et al., 2012; Boeckel et al., 2012). Motor Vehicle Companies such as Lucid Air and Faraday Future (FF) amongst others, announced the deployment of their high-end autonomous user-centric electric vehicles as AutoVots and TaxiBots. Amazon Prime Air proposed a futuristic drone service for delivery of goods in homes (Pandit and Poojari 2014). With developments of such magnitude, the expected changes in transportation suggest a number of important implications related to urban layouts, and how society functions today. Consequently, having technology companies control personal transportation might be the dawn of controlling the home and other large portions of building users' lifestyles. Therefore, more research is required in order to establish the underlying implications of these developments.

Meanwhile, urban planners and relevant authorities have a great responsibility to ensure that energy demand and greenhouse gas emissions are reduced within cities and urban settings. This could be achieved through promoting passive design techniques, encouraging smaller dwelling units, increasing household sizes and providing efficient, safe, easy to access, economically viable public transportation.

In addition, as was established in chapter 6, all the above measures need to be undertaken whilst also promoting changes in user behaviour.

7.1.3 User behaviour: alternative to technological fix?

The residential building industry's reliance on "technological fix" has endured since the *Industrial Revolution* as discussed previously in Section 2.2.2. Consequently, the critical role of building users in the built environment is poorly understood and often overlooked today. Previous studies have for long established that user behaviour is at least as significant as the physical characteristics of the dwelling in influencing energy demand and associated greenhouse gas emissions. See for example Pettersen (1994), Gram-Hanssen (2010), Stephan (2013) and Stephan et al., (2013a).

In the case of zero energy buildings, by understanding the relationship between human behaviour and physical variables of the buildings that people occupy, insightful facets concerning the complex relationship affecting energy use could be unravelled. Hence, a much clearer picture of where energy savings and emissions reductions can be made could emerge. This work has demonstrated that significant energy reduction by over ~20% can be achieved by changing user behaviour (See Section 6.1.2.2).

However, dwellings are heterogeneous. It is therefore significant to recognize that solutions employed for a particular dwelling may not necessarily work for another and cannot guarantee energy reductions. Predicting the effect of user behaviour on residential energy demand and associated greenhouse gas emissions is highly complex. This is because residential energy demand is uniquely intertwined together by factors such as income levels, age groups, lifestyles and behaviour of the occupants as discussed in Section 2.1.3 and 2.2.

Furthermore, the effects of user behaviour are not only restricted to the building scale, they also manifest at the urban or city scale and hence affect transport energy. Transportation habits may vary ranging from household to household and from one person to another and so on. Depending on location, building users may opt

for a particular transport mode based on economic viability over environmental issues and vice versa. In addition, urban layouts and availability of spaces in the city affect transport infrastructure provision. Consequently, building designers, urban planners and public authorities share a great responsibility by ensuring a greater focus on spatial planning strategies and public transport such as local and light rail in city areas. Also, by promoting walking and cycling wherever possible, public authorities can play a crucial role in encouraging innovations by public transport operators, including service development as well as new efficient technologies. All these measures should be accompanied by major shifts in transport user behaviour. In summary, these recommendations further substantiate the importance of an integrated building energy policy development.

7.1.4 Towards an integrated multi-scale building energy policy

Significant reductions in energy demand and greenhouse gas emissions could be accomplished by integrating multiple scales of the built environment through holistic energy policies. Such development is essential for governments and international bodies such as the International Energy Agency to elaborate norms which should guide the industry and ultimately reduce the dependence on energy and eventually mitigate greenhouse gas emissions in the built environment.

Current frameworks for zero energy building design proposed and adopted by the “*TEA SHC Task 40 / ECBCS Annex 52: Toward Net Zero Energy Solar Buildings*,” only focus on building energy demand, particularly operational energy and sometimes embodied energy. The case study analysed in Chapter 6 has demonstrated that energy at the building scale is only a part of the overall energy demand associated with building users at different scales of complexity. A multi-scale zero energy building policy is therefore required in order to reduce and mitigate greenhouse gas emissions in the built environment in a holistic manner.

At the aggregate level, this further implies that efforts undertaken to improve operation energy at the building level often become less important when all energy requirements associated with the building user are accounted for. Since user transport energy is not currently considered within current zero energy building

framework, global policies promoting the deployment of zero energy houses might be aiming towards the wrong targets. In particular, current zero energy building frameworks which solely focus on operation energy might only represent a small proportion of annual energy demand and emissions. In that way, considering all 53 variations analysed in the case study, it can be observed that the nominal shares associated with building energy demand (both embodied and operational) and transport energy demand (both embodied and operational) fall within the following ranges:

- a) Building energy demand $\rightarrow 4.8\% - 63.9\%$
- b) Transport energy demand $\rightarrow 36.1\% - 95.2\%$

Similarly, corresponding to the energy demand, the greenhouse gas emission shares fall within the following ranges:

- a) Building greenhouse gas emissions $\rightarrow 6.5\% - 79.2\%$
- b) Transport greenhouse gas emissions $\rightarrow 20.8\% - 93.5\%$

Indeed, by observing the minimum shares, it can be established that building energy (embodied and operational) and the associated greenhouse gas emissions fall below 10%. The low values are associated with the zero energy balance deficits (near zero energy), as was determined in chapter 6. With shares of this nature, energy demand at the building scale can easily be disregarded. Surprisingly, transport energy associated with building users at the city scale which represents the majority of the overall energy demand and associated greenhouse gas emissions is overlooked and not considered in zero energy building frameworks today.

On the other hand, when the maximum shares are considered, it can be observed that each of the building and city scale energy demand and associated greenhouse gas emissions can represent significant shares of the total annual requirements. Building energy (embodied and operational) as well as associated emissions can represent up to 63.9% and 79.2% of the total annual energy demand and associated greenhouse gas emissions respectively, for a zero energy (deficit) household which

uses a less energy intensive and low carbon transport mode. This further emphasises the promotion of changes in user behaviour.

Notwithstanding, zero energy building proponents would argue that building energy and transport energy could simply be compared and have priorities set separately. Such myopic arguments will not only lead the industry backwards, but also promote further increase of energy demand and greenhouse gas emissions in the built environment because the separation of these two demands will allow energy and emissions to be passed on from one scale to another, thereby increasing instead of decreasing. This is a phenomenon often classified as “*problem-shifting*” (Finnveden et al., 2009). Therefore, arguments of such sorts need to be intercepted by law or policy instruments and should not be tolerated nor promoted at all. The case study findings clearly demonstrate the need for integrating building and user transport energy into a single framework if significant and meaningful reductions of energy and greenhouse gas emissions in the built environment are to be achieved. In addition, the facts established in Chapter 6 further support and reinforce the arguments raised by Marique and Reiter (2014), Rovers (2015), Kylili and Fokaids (2015), Hui (2015), who support and propose the integration of embodied impacts and user transportation within existing zero energy building frameworks.

In parallel, on the user transport energy front, high reliance on oil-based passenger vehicles is a global phenomenon. In the face of uncertainties surrounding the future of oil reserves around the world, most governments in oil importing nations frame this notion in terms of energy security. Electric vehicles have been proposed as an obvious means of displacing oil and reducing its imports (Marcus 2015). However, the current focus in most developed economies such as U.S.A, U.K, Australia and New Zealand is the development of their nations’ domestic energy resources so as to displace oil imports. For instance, in New Zealand, the number one priority listed in the government’s 2011 Energy Strategy is the development of petroleum and mineral resources such as coal (Ministry of Economic Development 2011).

Nevertheless, Fatih Birol, Executive Director of the International Energy Agency warned in 2010 warned about the instability of oil prices and that the best option is to implement policies which reduce its dependence, and more recently it was also cautioned that prospects of exploiting unconventional oil are also uncertain and unreliable (Kurczy 2010; IEA 2012). Currently, New Zealand imports ~57.1% of its oil to cater for part of the 2,482,513 vehicle fleet (1.46 per household) (Ministry of Business Innovation and Employment 2015). If the New Zealand government would adopt policies that promote the use of much smaller and more efficient vehicles which consume less than half ($<1/2$) of what the majority of the fleet vehicles consume today, the scale of oil imports would most likely significantly reduce. The financial savings from this result could be reinvested in the promotion of social equity within neighbourhoods and provision of efficient, low carbon and economically viable public transport such as rail. This could also be extended to the provision and rolling out of public interurban or intercity transport such as high-speed rail (bullet trains) thereby reducing the requirements for short-haul flights. Hence, by adopting holistic energy policy for both buildings and transport, cost optimal solutions for reduction of energy demand and emissions at both scales could be easily realised and eventually achieved.

In addition, apart from the energy metric, it is also important to acknowledge the variation in greenhouse gas emission factors for building energy (both embodied and operational) and also transport energy (both embodied and operational). In the built environment, emission factors measure the amount of greenhouse gases released into the atmosphere as a result of resource consumption processes such as energy usage (See Section 4.2.4). Typically, emission factors are crucial in determining the environmental impact in the built environment. Consequently, emission factors for different countries vary considerably. For instance, New Zealand predominantly relies on renewable electricity. Thus, emission factors for operational energy and embodied energy can be comparable to similar countries in the short term. This might be contrary in other countries and regions such as U.S.A, U.K or Australia. On the other hand, emission factors for transport energy may also vary but only slightly, since most regions in the world rely on oil-based

internal combustion engine passenger vehicles. Therefore, the use of location specific emission factors for specific cases is encouraged and databases for emission factors associated with different countries should be regulated and constantly updated to enable and facilitate transparent comparisons.

One major necessary enabler that is pivotal towards leading significant transformations in energy policy is the adoption of renewable energy sources. Renewable energy sources: hydroelectric power, wind, geothermal, solar and biomass, provide substantial benefits in the society by contributing towards climate balance amongst other factors such as health and economy. Practices that promote electricity generation through non-renewable resources such as coal should be discouraged and stopped. As demonstrated in the Chapter 6 case study, the adoption of renewable energy promotes lower primary operational energy as well as transport energy.

Lastly, it is further recommended that energy use associated with households at the building and city scales, including relevant efficiencies, should be regulated on a per capita basis. When energy performance is expressed on a per capita basis, factors such as social aspects and living floor area per capita are transparently represented. This enables a good basis for comparing different buildings, different locations and variation of users' lifestyles (Gracia-Casals, 2006; Vale and Vale 2009; 2010b ; 2013 ; 2013; Stephan 2013; Stephan et al., 2013b; Stephan and Crawford 2015). In summary, zero energy building frameworks should integrate building energy (embodied and operational) as well as user transport energy (embodied and operational) in order to realise the dramatic potential of reducing energy demand and associated greenhouse gas emissions in cities. Building designers have restricted powers to influence transport energy strategies. Therefore, policy makers should collaborate with both urban/town planners as well as building designers to facilitate the integration of user transport energy into current existing building regulations. A holistic building energy policy entails an increase in the understanding of user behavioural aspects in the built environment (Rickwood et al., 2008; Perkins et al., 2009; Stephan and Crawford 2015). Consequently, it also

makes more strategic sense to promote notions such as “zero energy lifestyles” through integrated building energy policies, instead of merely “zero energy buildings”.

7.2 Limitations of the research and potential improvements to the developed methodological framework

Although this work established a multi-scale zero energy building framework for residential buildings, the results of the case study and the framework itself are not immune to other limitations and constraints. These aspects related to energy demand at the building scale, including embodied and operational as well as urban scale, including user transport embodied and operational energy, are discussed in the following section along with the implications of the case study chosen in this work.

7.2.1 Building energy demand

All due care was taken to maintain a rigorous yet valid approach to the building scale energy calculations. This encompasses embodied energy for building materials, components including systems and operational energy. Observed limitations of these aspects are discussed in the following section.

7.2.1.1 Embodied energy

The embodied energy as quantified and applied to the case study in this work suffers from a number of limitations. These include: source of data, age and type of data, building material life expectancy and data integration processes for calculation.

Since this work predominantly deals with zero energy buildings, the first avenue to account for in embodied energy limitations is associated with the renewable energy capture devices including PV and solar hot water systems. For PV systems, the dynamic comprehensive embodied and greenhouse gas emission intensity figures were firstly available for China based on initial studies by at an earlier stage of this research. Therefore, the embodied energy results of the New Zealand case study may show a significant variation when updated Chinese or Asian figures were used (This aspect is discussed previously in Section 6.1.1.1). When the utmost value is

considered, the embodied energy represents over 40% of the total annual embodied building energy. Indeed, if the work had relied upon updated Chinese or Asian figures, the emissions intensity could have been higher by over 50% (Yao et al., 2014). However, even in the case where the figures were underestimated, embodied energy and greenhouse gas emissions have been shown to be very significant. It is therefore crucial for future research and development of PV energy and emission intensity figures to take into account the location where the PV systems are manufactured and installed as advocated by Yao et al. (2014).

In addition, the solar hot water system figures are gathered from material inventory of similar systems in the literature (Marimuthu and Kirubakaran 2014). The material and carbon emission intensities were used although the emissions intensity calculated assumed that the plates are manufactured in New Zealand. The use of this simplified approach could have resulted in some inaccuracies. However, the study under which the material inventory is based upon is recent and therefore more reliable than most previous studies.

On the other hand, the embodied energy and greenhouse gas emission factors for building materials used for this work are gathered from Alcorn (2003; 2010). These coefficients were derived using process based-hybrid quantification methods (Treloar 1997), and therefore judged reliable. However, over time these data lose accuracy and eventually reliability. It could have been very beneficial to use up-to-date embodied energy and emission factors so as to reflect the seasonal changes in economy, energy use and emissions from the period when the figures were derived. It is therefore a prime requirement for built environment researchers not only in New Zealand but also in other regions to ensure that embodied energy databases are updated in a timely manner as urged by Berggren and Hall (2013). In parallel, reliance on process-based embodied energy coefficients in this work could have also been enhanced if input-output hybrid based coefficients were present and used instead, since process hybrid based derived figures can overlook ~21% of the initial embodied energy of residential building due to truncation errors (Crawford 2011).

Furthermore, from a built environment perspective, promoting recycling is generally accepted as reasonable since significant portions of energy for various materials can be retrieved at the end-of-life phase. However, this work did not account for recycling or potential reuse of materials. Accounting for this aspect in this work could have had a very positive impact for materials such as steel in terms of recurrent embodied energy and greenhouse gas emissions.

As discussed in Section 4.2.1.2. b., one major crucial aspect in embodied energy calculation is to estimate the building materials' life expectancy. This aspect has a very significant bearing on the annual or lifetime embodied energy and greenhouse gas emissions of buildings. Accurate life expectancy data of many materials is very difficult to obtain. For these reasons, assumptions have to be made in order to establish various materials' service lives. Consequently, this work relied upon the figures found in literature on similar materials and manufacturers' guarantees of durability for specific materials. The simple approach used in this work could have also been complemented by other comprehensive methods such as the International Standard, ISO 15686-1: Buildings and constructed assets which provides a general guidance for building materials' service life estimations (International Standard 15686-1 2011). This could have also enhanced the accuracy of embodied energy calculations.

While it is important to consider various facts associated with building embodied energy quantification as discussed above, it is equally important to address embodied energy in general at different scales of the built environment. This work did not include embodied and greenhouse gas emission requirements for other infrastructure related to residential buildings. It was assumed that infrastructure is already existing and this can represent ~7% of a residential neighbourhood (Norman et al., 2006). Moreover, infrastructure embodied energy for other aspects such as roads was counted within user transport embodied energy intensity figures (Mithraratne 2011).

In summary, it is acknowledged that indeed the embodied energy and greenhouse gas emissions of materials quantified in this work suffer from a number of errors

and flaws. However, the research attempted to utilize the best available and reasonably accurate data present such that all these limitations did not to some extent dilute its quality.

7.2.1.2 Operational energy

As far as building operational energy is concerned, one major limitation associated with the calculation is the modelling parameters such as geometrical approximations, occupant loads and so on. Although the computer program EnergyPlus®, maintains a certain level of accuracy as compared to relying on static heat transfer equations for thermal modelling, user related energy is modelled based on fixed occupancy schedules. This deterministic approach to modelling can produce figures which diverge from the real performance with regards to the non-thermal end uses of the building.

However, by modelling using the actual measured data for buildings in similar context and location, a reasonable level of accuracy can therefore be maintained. In addition, the measured energy demands in this work were found to be comparable to other previous studies undertaken for relatively similar building types and contexts (See Section 6.1.1). Further independent validation and Quality Assurance (QA) of energy models in this work should be considered in the future development of this methodological framework to minimise the risk of errors and ensure that simulation reflects the reality (Donn 1999; Malkawi and Augenbroe 2004; Ryan and Sanquist 2012). Guiding documents such as ASHRAE Guideline 14:2002 provide a glimpse of relevant approaches for calibrating simulated data with actual measured or monitored data (Haberl et al., 2005).

In addition, the buildings for alternative dwellings in the suburban neighbourhood are modelled with simplified geometry but in reality buildings are not merely rectangular boxes (Stephan (2013). However, due to the originality of this research approach, it was difficult to present the shapes as in reality since residential buildings in the suburb would have a variety of different types of dwellings with also varying characteristics. Consequently, for other building characteristics such as windows, door, and systems etc. rules of thumb were applied to determine their

quantity. Overall, average relative difference between a single dwelling unit in the alternative dwelling scenario compared to a standard house located in the same location (Isaacs et al., 2010b), was $\sim 13.1\%$ in primary energy terms. The simple modelling approach employed for this study is therefore judged suitable, although further robust validation is necessary and this should be taken into account in future development of the framework.

Another major weakness regarding operational energy in this work is that the buildings were modelled with the same orientation. This allowed the exploitation of local climatic conditions and optimal passive means such that the requirements for heating and cooling were significantly reduced. However, anomalies could be observed if the buildings changed orientation considering the approximated modelling parameters. A more adaptable and flexible modelling approach is therefore required so as to improve the quality of the results obtained in this work.

Finally, it could have also been beneficial to investigate variations of other aspects related to fuel switching, for instance, the usage of gas systems for end uses such as cooking and hot water. However, given that gas is more emission intensive ($360\text{--}720 \text{ kgCO}_2\text{-e/kWh}$) compared to hydro generated electricity ($10\text{--}18 \text{ kgCO}_2\text{-e/kWh}$) (Laleman et al., 2013), For this reason, it was therefore judged suitable not to consider this aspect at this stage of framework development.

7.2.2 Transport energy demand

Apart from building embodied and operational energy, user transport energy as calculated in this work also had some limitations. In particular, the local data containing energy and greenhouse gas emissions intensities of various transportation modes was limited to internal combustion engines (Mithraratne 2011), European figures were used for embodied energy and greenhouse gas emissions in the case of electric vehicles. Relying on overseas figures might imply some errors in estimations. However, Hawkins et al. (2012) produced one of the most comprehensive studies on environmental impact of vehicles in Europe and possibly globally. With data of such magnitude, the reliance on European figures

was judged suitable. In addition, with the growing interest in battery powered electric vehicles, a crucial step in improving databases containing energy and greenhouse gas intensities of transport modes is ensuring that they are up to date accordingly.

Overall, the presence of abundant transport energy data for New Zealand in terms of intensities of various modes as well as embodied energy figures of relevant transport infrastructure is judged sufficient for this work and therefore transport energy calculations do not require major developments. However, such data is hardly available for most countries since such studies are rarely undertaken. Other countries are therefore also encouraged to develop such databases. This would facilitate and promote the integration of building and transport energy policies globally.

7.2.3 *Uncertainty and variability*

The functional nature of the established multi-scale zero energy building framework, as was previously discussed, involves a wide array of multiple calculations and measurements of disparate energy parts at both building and city scales. Consequently, data has to be processed and analysed cautiously so as to maintain a certain level of confidence in the results. As a result, this work relied upon Interval Analysis and prospective scenarios as tools against uncertainty and variability within the calculation.

However, it is acknowledged that the simplified approach to Interval Analysis adopted in this work by merely providing parameter shifting towards maximum or minimum deviations of the central value based on the literature, might overlook other significant influencing aspects. For instance, if different uncertainty ranges were adopted for building energy demand (embodied and operational) or transport energy demand (embodied and operational) a situation could arise whereby the central values are different but at the same time register similar results when minimum and maximum fluctuations are observed. This could make the task of identifying the less energy and greenhouse gas emission intensive options very difficult to establish. Consequently, in order to improve the precision in uncertainty

and variability measurements, future development of this work needs to be coupled with more robust simulation techniques such as Monte-Carlo methods (See Section 4.2.7.1. b.), although this unique coupling would be very tedious and data intensive.

In addition, this work also relied on prospective scenarios to forecast the evolution of parameters relating to primary energy and greenhouse emissions conversion factors: $PRM_EF_{el}+GHGF$ (See Section 6.1.4.2 and 6.1.6.3). Undoubtedly, this novel approach in the light of current zero energy residential building notions has highlighted some significant issues regarding their implications to the society in the short and longer terms. However, this technique only considered building operational energy. Further development of this methodology should therefore also take into account parameter evolution with regards to embodied energy and user transport energy requirements.

Another major limitation associated with parameter evolution i.e. $PRM_EF_{el}+GHGF$ regarding operational energy greenhouse gas intensity, concerns the use of average grid energy figures. Indeed, there is growing awareness amongst researchers on the implications of using average versus marginal grid emission intensity figures (Chen et al., 2008; McCarthy and Yang 2010). In California, U.S.A, McCarthy and Yang, (2010) demonstrated that relying on marginal grid intensity figures is likely to show 14-79% higher than average grid emission intensity values. Nonetheless, as was mentioned in Section 7.1.4, there is an urgent need to shift to renewable energy electricity generation. Improvement of grids is therefore likely to reduce such effects. Hence, the use of average grid emission intensity figures in this work is judged suitable although more research in this area is required.

In summary, the simple techniques for addressing uncertainty and variability adopted in this work, particularly Interval Analysis and scenarios are judged appropriate and provided reasonably accurate results at this stage of framework level and development. Further development of this model will need to rely on more robust uncertainty measurement techniques in order to highly enrich confidence of results.

7.2.4 Case study

The case study used for this research critically tested the underlying implications towards the deployment of zero energy houses from a variety of related dimensions pertaining to user behavioural patterns at both building and urban scales, alternative housing typologies and different urban configurations. The International Energy Agency's "*IEA SHC Task 40 / ECBCS Annex 52: Toward Net Zero Energy Solar Buildings*," has so far provided a certain degree of clarity on conceptual underpinnings underlying the zero energy building notion. Consequently, policies accelerating the wide adoption of current zero energy practices today are well underway particularly in Europe and North America. Hence, the New Zealand case study represents this current trend of adopting zero energy building practices today.

In addition, by testing the case study from other perspectives such as urban contexts enhances the understanding of the performance of such buildings on a city scale front with respect to various urban forms. In particular, global urban forms have evolved as a result of modern planning practices. This regard is apparent in both developed and emerging world economies in "sprawl" as the prime urban form. Such is the case for developed countries like New Zealand, Australia and U.S.A as well as other emerging economies such as China and other cities in Latin America (Howden-Chapman et al., 2010; Yew 2012; Rojas et al., 2013). Consequently, the findings from this research can spread valuable insights across multiple contexts.

However, it could have also been beneficial to test the methodological framework in another region to establish adaptable parameters. Building construction paradigms, sources of energy and transport habits are different in most countries. For instance, in New Zealand ~78% of household trips are made by private vehicles, while in Sweden the share is ~53%. These differences imply that variations in user transport energy can be observed if this framework is applied in a different context. In addition, regional energy sources also play a crucial role in operational energy (See Section 7.1.1). Therefore, the approach used in this

research needs to also be tested in other countries and regions, although on an average level the results in this work are comparable to many avenues of the built environment.

Another major weakness of this work is the use of one case study as can be noted. This may entail a susceptibility to potential biases in the research outcomes. However, the selection of one case study used for this work was made due to data availability limitations and constraints. However, harnessing various methods from multiple scales of the built environment to inform a framework as developed in this work provides this study with a unique methodological rigour of analysis which can produce reliable results irrespective of case study numbers (See chapter 6).

7.3 Scaling up: Towards an integrated multi-scale zero energy building approach for the built environment

Zero energy housing is a precursor to the current movement of zero energy commercial buildings. Zero energy building policies are not only being developed for residential buildings but also for commercial buildings particularly in North America. On average, energy use in commercial office buildings can be 37.5-66.7% higher than residential buildings on a kWh per m² basis (Ramesh et al., 2010). Consequently, efforts seeking to reduce energy demand associated with commercial buildings also look towards exploiting zero energy building principles. Based on the findings in this work, these practices also have to be investigated in a holistic manner to determine whether zero energy commercial buildings indeed result in net zero energy savings.

In parallel, as was earlier discussed in Section 2.1.1.1, other aspects which are also crucial in the built environment relative to energy use such as water, food and land amongst others, need to be considered in the framework. The relevance and implications of these aspects are elucidated hereunder.

7.3.1 Zero energy commercial buildings

As was previously mentioned in Section 3.1.2, this growing trend of zero energy building practices is not only applied to residential buildings but also non-

residential project types including industrial and commercial buildings. This vision of zero energy commercial buildings is perhaps widely advocated in Griffith et al. (2007) who demonstrated that zero energy commercial buildings are achievable amidst other constraints.

However, while the operational energy of commercial buildings can be lowered through energy efficiency measures (Pérez-Lombard et al., 2008), the embodied energy intensity of the building becomes significant. For instance, in Melbourne, Australia, Treloar and colleagues demonstrated that embodied energy of high rise office buildings can be 60% higher than for low-rise office buildings (Treloar et al., 2001). In addition, comparing Treloar's figures to Crawford (2011), embodied energy of commercial buildings can be 39.2% higher than residential buildings on a per m² basis. The findings from this research suggest that embodied energy of the building and its systems at primary energy level can be crucial in the zero energy balance achievement. Indeed, the zero energy house base case scenario failed to achieve zero energy status due to in part the higher embodied energy of the building and its systems (See Section 6.1.1.4). Cellura et al. (2014), Lützkendorf et al. (2014) and Wiberg et al. (2014) also found similar findings in Italy and Norway respectively.

It can be argued therefore that, a zero energy commercial building built to the current zero energy building criteria is very likely to fail. It was noted in Section 7.1.1 that the current zero energy building concepts might not be viable options in specific regions in the shorter or longer term in other regions. Consequently, further development of the model also needs to address zero energy commercial buildings so as to determine if they indeed result in net zero energy savings when impacts from both the building and city scales are considered. These impacts include, building energy (embodied and operation) and transport energy (embodied and operational).

7.3.2 *Incorporating other metrics*

Having elucidated various crucial aspects to be considered with regards to zero energy commercial buildings in the previous section, the following section now turns to other crucial aspects related to the energy metric in the built environment.

While the energy metric is the pivotal focus in this research, other metrics related to the users such as water, food and waste are crucial parameters that also need to be accounted for in the built environment as previously discussed in Section 2.1.1.1. The numerous interconnections between energy, water and food represent a complex set of interrelated problems ranging from resource scarcity, price volatility and environmental impact (Bazilian et al., 2011). Integrating these aspects in similar fashion as proposed in this work can ensure that valuable environmental trade-offs are exploited and at the same time, the incipient quest for multi-sector efficiencies can also be promoted. Consequently, much broader system boundaries are required for the developed framework in order to address this swath of interwoven topics.

However, the methodological framework developed in this research has limited applicability to aspects such as food. On the other hand, the mesh of techniques employed for embodied energy calculations can easily be adaptable to also quantify water related embodied energy impacts (See Section 4.2.). Further relationships between water and energy are explained hereunder.

7.3.2.1 *Water versus energy*

Among the most serious issues of concern apart from the insatiable global appetite for energy in the built environment is the scarcity of water. New Zealand has abundant fresh water compared to many countries in the world. However, water quality in several urban and rural areas has degraded and increasingly is being subjected to immense pressure as land uses are being intensified (Ministry for the Environment 2015).

Therefore, inputs for water requirements in the built environment also need to be considered (Joustra and Yeh 2014). Water and energy are fundamentally

intertwined. For instance, electricity generation such as hydroelectric power requires water and water treatment and transportation also uses electricity. Consequently, the role of water in energy is often referred to as the “water-energy nexus” (Scott et al., 2011). The potential exists for embracing holistic approaches such as these to the managing of limited resources. However, the integration of these two aspects requires high-level aggregation systems and the process is data intensive. Should they be integrated nonetheless? Perhaps more research would reveal how their interconnectedness can inform energy policies in the built environment.

7.3.2.2 *Environmental impact*

The ascent of the global climate change debate in the past decades has brought into sharper focus the implications surrounding the relationships between energy and the built environment (See Section 2.2.4). However, climate change oriented impacts are often one-dimensional and focus mainly on accounting for greenhouse house emissions as a result of energy depletion, ignoring other categories such as resource depletion, ozone layer depletion, human health and ecosystem quality among others.

As can be observed in Section 3.1.3, the current zero energy building framework only considers climate change, broadly under the banner “Global Warming Potential”(IPCC 2014), by accounting for greenhouse gas emissions equivalents (CO₂-e). In a pragmatic sense, all environmental impact categories need to be accounted for. Indeed, Laleman et al., (2013) demonstrated that resource depletion can be the most significant contributor to environmental impact for solar PVs compared to their Global Warming Potential. Consequently, the developed methodological framework needs to flex its muscles and broaden its capabilities to encompass other significant environmental impact categories.

On the other hand, it is abundantly clear that human activities in the built environment have exposed the fragility and vulnerability of world cities today. As previously discussed in Section 2.2.2, resources in the global landscape are rather limited (Hubbert 1949 p. 108). The framework established in this research and the

findings if taken into consideration can equip multidisciplinary players in the built environment with an important tool to take action. Consequently, building designers, urban planners, policy decision-makers and citizens need to collaborate responsibly in order to exploit the immense possibilities of cities so as to embrace the inevitable trajectories of social change.

7.3.3 Spreading the knowledge: Engaging building professions, educational institutions and social actors

This section aims at stimulating a dispersed awareness of other avenues upon which society can take action. In this regard, the move towards a zero energy society requires significant transformations not only at the building scale but also changes in building users' lifestyles at multiple scales. Consequently, to achieve this goal, efforts have to be exerted collectively across various domains in the energy community. In particular, this work demonstrates that design professionals and policy makers need to work closely with users to deliver comprehensive energy and greenhouse gas emissions reductions in the built environment.

In addition, this work has also demonstrated the need for holistic approaches in designing buildings and cities for energy reduction. Awareness of such knowledge needs to be spread to practitioners and other research experts in order to facilitate the necessary integrations required. This can be done by promoting frequent interaction between researchers and professionals. Furthermore, policy decision makers also need to support changes within architects', engineers' and urban planners' curricula to ensure that the knowledge acquired is indeed implemented into practise.

Another way to promote social change is supporting programs which aim at teaching people (users) how to inhabit the built environment in less consumptive ways. Also, introducing these facets to people in their younger ages could also be vital. For instance, sustainable architecture topics and other human aspects of the built environment could be featured in secondary school curricula as staple subjects. Promoting such long term high level built environment literacy reifies the lessons absorbed from this research and further provides a basis for understanding

the need for social change in the society today. Finally, as was pinpointed in Section 7.1.4, governments need to encourage architects, engineers and planners to embrace holistic approaches so as to bring about the necessary deep changes.

Chapter 8 | Conclusion

This thesis investigates the significance of utilizing holistic approaches in the context of zero energy building practices within the built environment today. To achieve the research aim presented in Chapter 1, a review of current knowledge and applications of zero energy buildings concepts was undertaken in Chapter 2 and 3 to highlight their limitations. A methodological framework was developed in Chapter 4, which was then tested on a case study in Chapter 5. Although some clear observations have been made in Chapter 6 and 7 as a result of this research, there remain research questions still to be explored. A brief summary of thesis results and discussion is presented below.

8.1 Synopsis of thesis findings

The increasing public and political awareness of global climate change and environmental degradation have been prime catalysts for the shift of environmental consciousness across all spheres of the society. In the built environment, this is manifest in the growing demand for higher environmental standards for buildings, including net zero energy buildings. Consequently, the net zero energy building standard has been translated into explicit performance requirements for the residential sector. It is noted that these ambitions are increasingly embedded into national energy building policies, with many countries in Europe, North America and Asia pledging that new residential buildings should conform to a zero energy standard by specific dates.

Positive changes that guarantee significant reductions and ultimately elimination of greenhouse gas emissions in the built environment require collective efforts to be exerted on multiple scales. Ultimately, greater interest in holistic approaches and acknowledging relationships between buildings and their users' engagement in local community initiatives offer powerful means of influencing social changes beyond the building scale. The current approach to zero energy building, which solely focuses on the building scale, is handicapped because the focus on one scale with

the aim of reducing overall residential energy use and eliminating greenhouse house gas emissions results in increasing the energy demand associated with the user on another scale as evidenced in Section 6.1.1.4 of Chapter 6.

Against this backdrop, the goal of this research was to increase the understanding with regards to the interconnection between zero energy buildings and user transportation, thereby harnessing associated synergies with the view to contributing to the development of more integrated zero energy building design approaches and policies encompassing both building and urban scales. Consequently, the research has generated a methodological framework for developing a comprehensive understanding of the underlying implications associated with zero energy buildings beyond the building scale.

Ideally, accounting for other indirect energy requirements associated with the user at the city scale, such as transport energy, ensures realistic net energy and emission savings for residential buildings unlike the current approach which overlooks transport energy and oftentimes embodied energy as well. The case study of a zero energy house located near Auckland, New Zealand was investigated to firstly verify the validity of the quantification techniques proposed in the framework regarding building energy demand (embodied and operational) and transport energy (embodied and operational) and to then further investigate the potential of its applicability at both building and neighbourhood scale.

The results show that using the methodological framework established in this research, aiming for current zero energy housing standard for buildings located in New Zealand and other similar countries (in terms of construction paradigms and energy sources), is significantly flawed. The current zero energy building framework often fails to incorporate embodied energy within the zero energy balance which in the end they do not achieve (See Figure 6.5 in Section 6.1.1.4). In addition, when transport energy is considered, zero energy housing becomes even increasingly difficult to achieve (See Figure 6.7 in Section 6.1.1.4). When the transport energy was investigated, electric vehicles were not found to be the panacea either. While they were found to be a viable technology for specific

regions, their wide adoption still requires additional infrastructure and generation capacity amidst their embodied impacts (See Section 6.1.3).

If "zeroing" at the building scale proves to be very difficult with the current approaches, then what chance is there of zeroing in together with user transport energy? This work has demonstrated that isolated human activities in the built environment do not have isolated consequences; so a more integrated and holistic approach has a higher potential to lead towards a low or preferably a zero energy society.

Furthermore, the parameter evolution scenario, which takes into account development of the grid by lowering primary energy and greenhouse gas emission coefficients coupled with standard housing was found to also have a higher potential for reducing overall greenhouse gas emissions than zero energy houses in general. In light of efficient grids with a high share of renewables, it appears paradoxical that zero energy houses get penalized with the "balances" which they often do not achieve at primary energy level. Ideally, if energy use associated with residential buildings is to be significantly lowered, environmentally focused energy measurement of houses ought to be done depending on how much energy is consumed by users at multiple scales of complexity not merely depending on how much energy buildings generate. It can therefore be argued that, if the reason for deploying and promoting zero energy houses is because currently energy is generated non-renewably from polluting sources, then resource depletion should be the number one concern. This implies that users within the built environment simply have to be encouraged to consume less to use less energy.

At this juncture, this research suggests that holistic approaches are inevitable in the face of zero energy building practices. Consequently, the main aim of this research which sought to establish an integrated design and evaluation framework for zero energy residential buildings and their users encompassing both the building and city scales has been justified.

Understanding the physical and social complexities at multiple scales of the built environment, starting from the users, buildings, plots, amongst others, in a holistic manner has the potential to yield better results and lead towards a positive change. Building designers, urban planners and policy decision-makers have a shared responsibility in promoting smaller, efficient and shared houses, use of durable and less energy intensive materials, low emission energy sources and provision of economically viable low carbon public transportation. These measures should be accompanied by promoting social equity and major changes in lifestyles, then optimal urban densities can follow. Nonetheless, implementing segregated measures of such magnitude can be a difficult task since the key actors involved traditionally operate at different scales of the built environment. Therefore, efforts should be exerted at national or regional level starting with a holistic energy policy.

In parallel, the research in general, including the methodological framework developed, faced a number of limitations. Particular limitations were the reliance on data from other regions for some crucial aspects of user transport and embodied energy, the use of simplified models to calculate operational energy for alternative housing typology neighbourhoods and finally the use of simplified approach to Interval Analysis and scenarios to combat uncertainty and variability. The quality of the results can significantly improve if more robust embodied energy databases for building and transport are developed across many regions in the world.

Coupling Interval Analysis with other probabilistic approaches such as Monte Carlo methods could enrich the measurement of uncertainty and therefore produce more confident results. Nevertheless, priority now should be focusing towards developing a more robust calculation platform for rapid evaluation based on the methodological framework developed in Chapter 4. Amongst other avenues of investigation, this aspect forms the basis for discussion for future research and is explained hereunder.

8.2 Recommendations for future research

The weaknesses and limitations of the quantification techniques employed in the established framework of the research have indicated the following dimensions as recommendations for future research:

- Development of a software analysis tool to aggregate building energy (embodied and operational), transport energy (embodied and operational) and energy source technologies and storage devices at both building and city scales.
- Further investigation of zero energy buildings in the context of urban density and transportation, whilst focusing on the comparison between internal combustion engine vehicles versus electric vehicles.
- Integration of other significant environmental impact metrics associated with users such as food, waste generation and water amongst others.
- Incorporating other sustainable dimensions such as economic factors as well as social aspects.

In addition, extending the framework to also encompass commercial buildings could widen the scope of investigation and provide direction for future planning of cities.

In parallel, disparate parts of the developed framework need to be integrated into a single platform in order to formalize the calculation processes and allow rapid evaluation. Consequently, the development of a complex evaluation tool would be a significant step for further research.

Amongst other methods, which attempt to solve modelling techniques in the built environment such as statistical methods and other simplified engineering methods, the use of artificial intelligence (AI) models has been attracting wide attention. Consequently, future research of this work could investigate and test the potential to develop a built environment software using artificial intelligence (data mining

and machine learning), drones or Unmanned Air vehicles (UAVs) mounted with LiDAR¹⁷ sensors to perform airborne energy simulations encompassing both building and city scales respective to the interaction of buildings, users and urban transportation systems. Additionally, the 'simulation manager'¹⁸ could complement the software tool using augmented virtual reality (VR) technology to monitor and solve the simulation problems from a distance and the AI would distribute the solutions into the simulation loop. Ultimately, this would potentially allow for live energy performance simulation and mapping for identifying opportunities for reduction and regulation of consumption in order to potentially move towards zero energy cities and countries. Furthermore, such modelling technique could be applicable and beneficial to both developed and developing countries, which are under the quest for a sustainable energy future.

In the essence, such a tool could allow policy makers, architects, engineers and urban planners to explore a wide variety of analyses, regulation, design and construction scenarios. Complementary mobile and web-based applications could also be developed in order to simplify the interface with building users. Ideally, the tool could allow detailed quantification of building operational and embodied energy, transport embodied and operational energy coupled with detailed modelling of electricity grid operation mechanism, integrated renewable energy parameters and the efficacy of energy storage.

The development of such a platform requires collective effort from architects, engineers, urban planners and computer programmers, leveraging expertise from all related spheres. The equations generated from the framework in this work could form a basis for developing complex algorithms for calculation. Coupling other probabilistic uncertainty and variability techniques could also facilitate capturing of user behavioural aspects. Integrating other factors such as food, water and waste generation can broaden the capability of the engine. By allowing it to also

¹⁷ Light Detection and Ranging

¹⁸ This can be defined as the person managing and running the built environment performance simulation process.

incorporate valuation of commercial buildings can also enrich and widen the scope of its investigation potential.

However, devising all these linkages at high-level aggregation of this magnitude requires high quality data. Consequently, another avenue for future research concerns the updates of embodied energy databases for building materials. In addition, transport embodied and operational energy intensity databases should also be frequently updated in order to yield more accurate results in the system. Furthermore, to ensure that long term sustainability goals are to be met, other dimensions associated with sustainability including economic and social factors need to be accounted for.

8.3 Concluding remarks

Finally, as the journey towards the quest for a zero energy built environment continues, the way building occupants use and value natural resources at multiple scales needs to change to ensure the long term “sustainability” of cities. More broadly, one could question the imperative of most governments around the globe to achieve economic growth and prosperity at the expense of the impact on the environment and society’s wellbeing, when adjusting lifestyles and downsizing resource consumption could have lower environmental impacts without compromising society’s quality of life. In addition, the arguments set forth in this research contribution indicate that, the promotion of current zero energy building practices which solely focus at the building scale has significant flaws. A more integrated and holistic built environment approach is vital to bring the inevitable changes. Consequently, the significant findings in this research reinforce and provide the foundations for a discussion platform that all key players in the academic research, practice and policy development process can partake from to lead towards a zero energy built environment.

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Appendix A: Improvement in primary energy intensity

This appendix relates to Section 4.3.2 . It provides the equation used to determine the development of the electricity grid through integration of renewable energy share and efficiency improvement.

A.1 Background

Decarbonisation of the power sector is very crucial to the global economy, given the potential for electricity to provide low carbon fuel to multiple sectors including built environment. Consequently, the IEA under the 450 scenario sets out a potential energy pathway which aims to facilitate efforts of limiting global increase in temperature to 2 °C by limiting the concentration of greenhouse gas emissions in the atmosphere to approximately 450 parts per million of CO₂ .

This ambition serves as the IEA base line scenario and takes into account a wide range of policy commitments and plans that have been announced by different countries. These policy commitments include promotion of high penetration of high renewable energy and technologies, pledges to significantly reduce greenhouse gas emissions and phase out fossil-fuel subsidies.

A.2 Scenario adoption

Along this thread, the Ministry of Business, Innovation and Employment (2013) in New Zealand modelled the long term future of electricity in New Zealand up to the year 2040 using scenario analysis. Between 1990 and 2004, electricity demand in New Zealand rapidly increased, growing by 2% per annum as a consequence of strong economy and population growth. Since the global economic crisis and the devastating Christchurch earthquake, electricity demand growth slowed to an average of 0.5% per annum.

However, over the next few years, the New Zealand economy is expected to grow as the global economy recovers and the rebuild of Christchurch concludes. Owing to these outcomes, it was assumed that economic and population growth will drive an increased demand for electricity. Consequently three scenarios were modelled

sensitive to the mixture of renewables; High growth what-if economic and population growth are higher than expected?, Low growth what-if economic and population growth are lower than expected, 'Tiwai'¹⁹ closure-what if 'Tiwai Point aluminium smelter (13% of 2012 energy demand) was to close with energy demand gradually declining over 2016-2018?, and Global Low Carbon scenario (See Figure A.1 below) which is an intermediate between the high and low growth (Ministry of Business, Innovation and Employment 2013).

Figure A.2: Grid level electricity demand by scenario and sensitivity in New Zealand under global low carbon scenario

A.3 Scenario interpolation

The Global Low Carbon scenario was selected in this work because it takes into account the growth in demand mixed with renewables and possibility of high penetration of electric vehicles to 2040. Electric vehicles are considered to be a subject of significant contemporary importance, as discussed in this thesis.

Under the IEA 450 scenario (IEA 2011), following the integration of additional renewable power sources including wind, tidal, geothermal amongst others at utility scale in New Zealand, the compound annual growth rate of renewables

¹⁹ Tiwai Point smelter produces the world's highest purity primary aluminium

which implies a reduction in primary energy intensity and efficiency improvements can be calculated using the Equation A.1 given below.

$$CAGR_r = \left(\frac{FV_d}{PV_d} \right)^{\left(\frac{1}{n} \right)} - 1 \quad \text{Equation A.1}$$

Where:

CAGR_r = Compound annual growth rate of renewables (%)

FV_d = Beginning value of demand at key date, in MWh;

PV_d = Ending value of demand at key date, in MWh; and

n = Number of years.

Appendix B: Case study data

Table B.1: Material bill of quantities of the 200 m² base case (BASE_C) zero energy house case study with similar characteristics to BASE_CNBH and BASE_CNBH3 scenarios

Building component	Material group	Material	Quantity	Unit	services life	Description
Foundations	Concrete slab & others	30 MPa concrete	31.5	m ³	100	Lifetime based on Alcorn(2010)
		polyester	0.81	m ³	50	Lifetime based on Alcorn(2010)
		Sand blinding	3.04	m ³	150	Lifetime based on NAHB (2007)
		acrylic gap grout	12	L	50	Assumed lifetime
		steel	4.92	t	150	Lifetime based on Alcorn(2010)
Envelope	Hardware	steel	0.18	m ³	80	Lifetime based on Alcorn(2010)
		tape	31.5	m ²	30	Assumed life time
		timber	0.39	m ³	90	Lifetime based on Alcorn(2010)
		Polypropylene(wrap)	354.83	m ²	60	Assumed life time
		plastic	19.2	m ²		Lifetime based on NAHB (2007)
	Carpentry	aluminium	0.013	m ³	35	Lifetime based on Alcorn(2010)
		paint	0.5	L	15	Lifetime based on Alcorn (2010)
		plasterboard	0.59	m ³	30	Lifetime based on Treloar et al. (2000)
		bronze	6.5	kg	30	Assumed life time
		steel	0.09	m ³	50	Lifetime based on Alcorn (2010)

		Tape	20.62	m ³	30	Lifetime based on Alcorn (2010)
		timber	17.52	m ³	150	Lifetime based on Alcorn (2010)
		polypropylene	50.69	m ²	60	Assumed lifetime
	Cladding	timber	9.76	m ³	150	Lifetime based on Alcorn (2010)
	Insulation	polyester	73.15	m ³	150	Lifetime based on Alcorn (2010)
	Windows & doors	aluminium	0.02	m ³	35	Lifetime based on Alcorn (2010)
		glass	54.42	m ²	100	Lifetime based on Alcorn (2010)
	Floor & stairs	timber	2.09	m ³	150	Lifetime based on Alcorn (2010)
	Roofing	steel	96	m ²	50	Lifetime based on Alcorn (2010)
Electrical works	Monitoring & others	Equipment	1	no.	30	Assumed lifetime
		ceiling mounted PIR detector 12-24V AC/DC	3	no.	30	Assumed lifetime
		copper	10.5	m	30	Lifetime based on NAHB (2007)
Finishes and fixtures	Sanitary & accessories	aluminium	0.02	m ³	35	Assumed lifetime
		brass	0.023	m ³		Lifetime based on
		paint	12.5	L	15	Lifetime based on Alcorn (2010)
		ceramics	0.05	m ³		Lifetime based on NAHB (2007)
		plasterboard	6.81	m ³	30	Lifetime based on Treloar et al. (2000)
		steel	0.16	m ³		Lifetime based on Alcorn(2010)
		timber	2.06	m ³	150	Lifetime based on Alcorn (2010)

Plumbing & drainage	Sewer drain, down pipe & others	pipe	42.45	kg	25	Lifetime based on NAHB (2007)
		steel	0.02	m ³	30	Lifetime based on Alcorn(2010)
		tape	1.44	m ²	30	Assumed lifetime
		concrete	1.12	m ³	80	Lifetime based on Alcorn(2010)
Energy generation	Photovoltaic array	88×C21 roof tiles	27.9	m ²	30	Lifetime based on Laleman et al(2013)
	Solar hot water	SHW units	8	no.	25	Lifetime based on (Marimuthu and Kirubakaran 2014)

Table B.2: Material bill of quantities for the 200 m² STD_H

Building component	Material group	Material	Quantity	Unit	services life	Description
Foundations	Concrete slab & others	30 MPa concrete	31.5	m ³	100	Lifetime based on Alcorn(2010)
		polyester	0.81	m ³	50	Lifetime based on Alcorn(2010)
		Sand blinding	3.04	m ³	150	Lifetime based on NAHB (2007)
		acrylic gap grout	12	L	50	Assumed lifetime
		steel	4.92	t	150	Lifetime based on Alcorn(2010)
Envelope	Hardware	steel	0.16	m ³	80	Lifetime based on Alcorn(2010)
		tape	28.4	m ²	30	Assumed life time
		timber	0.35	m ³	90	Lifetime based on Alcorn(2010)
		Polypropylene(wrap)	319.3	m ²	60	Assumed life time
		plastic	17.3	m ²		Lifetime based on NAHB (2007)
	Carpentry	aluminium	0.012	m ³	35	Lifetime based on Alcorn(2010)
		paint	0.45	L	15	Lifetime based on Alcorn (2010)

		plasterboard	0.53	m ³	30	Lifetime based on Treloar et al. (2000)
		bronze	5.8	kg	30	Assumed life time
		steel	0.08	m ³	50	Lifetime based on Alcorn (2010)
		Tape	18.5	m ³	30	Lifetime based on Alcorn (2010)
		timber	15.8	m ³	150	Lifetime based on Alcorn (2010)
		polypropylene	45.6	m ²	60	Assumed lifetime
	Cladding	timber	8.8	m ³	150	Lifetime based on Alcorn (2010)
	Insulation	polyester	18.6	m ³	150	Lifetime based on Alcorn (2010)
	Windows & doors	aluminium	0.02	m ³	35	Lifetime based on Alcorn (2010)
		glass	48.9	m ²	100	Lifetime based on Alcorn (2010)
	Floor & stairs	timber	1.88	m ³	150	Lifetime based on Alcorn (2010)
	Roofing	steel	96	m ²	50	Lifetime based on Alcorn (2010)
Electrical works	Others	Equipment	1	no.	30	Assumed lifetime
		copper	9.45	m	30	Lifetime based on NAHB (2007)
Finishes and fixtures	Sanitary & accessories	aluminium	0.02	m ³	35	Assumed lifetime
		brass	0.023	m ³		Lifetime based on
		paint	11.3	L	15	Lifetime based on Alcorn (2010)
		ceramics	0.05	m ³		Lifetime based on NAHB (2007)
		plasterboard	6.13	m ³	30	Lifetime based on Treloar et al. (2000)

Plumbing & drainage	Sewer drain, down pipe & others	steel	0.14	m ³		Lifetime based on Alcorn(2010)
		timber	1.85	m ³	150	Lifetime based on Alcorn (2010)
		pipe	38.21	kg	25	Lifetime based on NAHB (2007)
		steel	0.02	m ³	30	Lifetime based on Alcorn(2010)
		tape	1.44	m ²	30	Assumed lifetime
		concrete	1.12	m ³	80	Lifetime based on Alcorn(2010)
Other	Ventilation systems	Ducted generation	1.05	no.	30	Assumed lifetime
	Solar hot water	Ducted delivery	9.45	no.	30	Assumed lifetime

Table B.3: Material bill of quantities for the 150 m² STD_RH-2 in the in the alternative neighbourhood case study

Building component	Material group	Material	Quantity	Unit	services life	Description
Foundations	Concrete slab & others	30 MPa concrete	23.63	m ³	100	Lifetime based on Alcorn(2010)
		polyester	0.61	m ³	50	Lifetime based on Alcorn(2010)
		Sand blinding	2.28	m ³	150	Lifetime based on NAHB (2007)
		acrylic gap grout	9	L	50	Assumed lifetime
		steel	3.69	t	150	Lifetime based on Alcorn(2010)
Envelope	Hardware	steel	0.14	m ³	80	Lifetime based on Alcorn(2010)
		tape	23.63	m ²	30	Assumed life time
		timber	0.29	m ³	90	Lifetime based on Alcorn(2010)
		Polypropylene(wrap)	266.12	m ²	60	Assumed life time
		plastic	14.4	m ²		Lifetime based on NAHB (2007)

Carpentry	aluminium	0.001	m ³	35	Lifetime based on Alcorn(2010)	
	paint	0.38	L	15	Lifetime based on Alcorn (2010)	
	plasterboard	0.44	m ³	30	Lifetime based on Treloar et al. (2000)	
	bronze	4.9	kg	30	Assumed life time	
	steel	0.07	m ³	50	Lifetime based on Alcorn (2010)	
	Tape	15.47	m ³	30	Lifetime based on Alcorn (2010)	
	timber	13.14	m ³	150	Lifetime based on Alcorn (2010)	
	polypropylene	38.02	m ²	60	Assumed lifetime	
	Cladding	timber	7.32	m ³	150	Lifetime based on Alcorn (2010)
	Insulation	polyester	54.86	m ³	150	Lifetime based on Alcorn (2010)
	Windows & doors	aluminium	0.015	m ³	35	Lifetime based on Alcorn (2010)
		glass	40.82	m ²	100	Lifetime based on Alcorn (2010)
	Floors	timber	1.57	m ³	150	Lifetime based on Alcorn (2010)
	Roofing	steel	72	m ²	50	Lifetime based on Alcorn (2010)
Electrical works	Others	copper	7.88	m	Lifetime based on NAHB (2007)	
Finishes and fixtures	Sanitary & accessories	aluminium	0.02	m ³	35	Assumed lifetime
		brass	0.023	m ³		Lifetime based on
		paint	12.5	L	15	Lifetime based on Alcorn (2010)
		ceramics	0.05	m ³		Lifetime based on NAHB (2007)
		plasterboard	6.81	m ³	30	Lifetime based on Treloar et al. (2000)

Plumbing & drainage	Sewer drain, down pipe & others	steel	0.16	m ³		Lifetime based on Alcorn(2010)
		timber	2.06	m ³	150	Lifetime based on Alcorn (2010)
		pipe	42.45	kg	25	Lifetime based on NAHB (2007)
		steel	0.02	m ³	30	Lifetime based on Alcorn(2010)
		tape	1.44	m ²	30	Assumed lifetime
		concrete	1.12	m ³	80	Lifetime based on Alcorn(2010)
Other	Ventilation systems	Ducted generation	1.05	no.	30	Assumed lifetime
		Ducted delivery	9.45	no.	30	Assumed lifetime

Table B.4: Material bill of quantities for the 150 m² STD_RH-I in the alternative neighbourhood case study

Building component	Material group	Material	Quantity	Unit	services life	Description
Foundations	Concrete slab & others	30 MPa concrete	11.82	m ³	100	Lifetime based on Alcorn(2010)
		polyester	0.31	m ³	50	Lifetime based on Alcorn(2010)
		Sand blinding	1.14	m ³	150	Lifetime based on NAHB (2007)
		acrylic gap grout	4.5	L	50	Assumed lifetime
		steel	1.85	t	150	Lifetime based on Alcorn(2010)
Envelope	Hardware	steel	0.07	m ³	80	Lifetime based on Alcorn(2010)
		tape	11.82	m ²	30	Assumed life time
		timber	0.15	m ³	90	Lifetime based on Alcorn(2010)
		Polypropylene(wrap)	133.1	m ²	60	Assumed life time
		plastic	7.2	m ²		Lifetime based on NAHB (2007)
	Carpentry	aluminium	0.001	m ³	35	Lifetime based on Alcorn(2010)

		paint	0.19	L	15	Lifetime based on Alcorn (2010)
		plasterboard	0.22	m ³	30	Lifetime based on Treloar et al. (2000)
		bronze	2.45	kg	30	Assumed life time
		steel	0.04	m ³	50	Lifetime based on Alcorn (2010)
		Tape	7.74	m ³	30	Lifetime based on Alcorn (2010)
		timber	6.6	m ³	150	Lifetime based on Alcorn (2010)
		polypropylene	19.01	m ²	60	Assumed lifetime
	Cladding	timber	3.66	m ³	150	Lifetime based on Alcorn (2010)
	Insulation	polyester	27.43	m ³	150	Lifetime based on Alcorn (2010)
	Windows & doors	aluminium	0.01	m ³	35	Lifetime based on Alcorn (2010)
		glass	20.41	m ²	100	Lifetime based on Alcorn (2010)
	Floors	timber	0.79	m ³	150	Lifetime based on Alcorn (2010)
	Roofing	steel	72	m ²	50	Lifetime based on Alcorn (2010)
Electrical works	Others	copper	3.94	m		Lifetime based on NAHB (2007)
Finishes and fixtures	Sanitary & accessories	aluminium	0.01	m ³	35	Assumed lifetime
		brass	0.011	m ³		Lifetime based on
		paint	6.3	L	15	Lifetime based on Alcorn (2010)
		ceramics	0.03	m ³		Lifetime based on NAHB (2007)
		plasterboard	3.41	m ³	30	Lifetime based on Treloar et al. (2000)

		steel	0.08	m ³		Lifetime based on Alcorn(2010)
		timber	1.03	m ³	150	Lifetime based on Alcorn (2010)
Plumbing & drainage	Sewer drain, down pipe & others	pipe	42.45	kg	25	Lifetime based on NAHB (2007)
		steel	0.02	m ³	30	Lifetime based on Alcorn(2010)
		tape	1.44	m ²	30	Assumed lifetime
		concrete	1.12	m ³	80	Lifetime based on Alcorn(2010)
Other	Ventilation systems	Ducted generation	1.05	no.	30	Assumed lifetime
		Ducted delivery	9.45	no.	30	Assumed lifetime

Table B.5: Material bill of quantities for the 300m² STD_TRCH-2 in the alternative neighbourhood case study

Building component	Material group	Material	Quantity	Unit	services life	Description
Foundations	Concrete slab & others	30 MPa concrete	23.63	m ³	100	Lifetime based on Alcorn(2010)
		polyester	0.61	m ³	50	Lifetime based on Alcorn(2010)
		Sand blinding	2.28	m ³	150	Lifetime based on NAHB (2007)
		acrylic gap grout	9	L	50	Assumed lifetime
		steel	3.69	t	150	Lifetime based on Alcorn(2010)
Envelope	Hardware	steel	0.28	m ³	80	Lifetime based on Alcorn(2010)
		tape	47.3	m ²	30	Assumed life time
		timber	0.58	m ³	90	Lifetime based on Alcorn(2010)
		Polypropylene(wrap)	532.2	m ²	60	Assumed life time
		plastic	28.8	m ²		Lifetime based on NAHB (2007)
	Carpentry	aluminium	0.002	m ³	35	Lifetime based on Alcorn(2010)

		paint	0.76	L	15	Lifetime based on Alcorn (2010)
		plasterboard	0.88	m ³	30	Lifetime based on Treloar et al. (2000)
		bronze	9.8	kg	30	Assumed life time
		steel	0.14	m ³	50	Lifetime based on Alcorn (2010)
		Tape	30.9	m ³	30	Lifetime based on Alcorn (2010)
		timber	26.28	m ³	150	Lifetime based on Alcorn (2010)
		polypropylene	76.04	m ²	60	Assumed lifetime
	Cladding	timber	14.64	m ³	150	Lifetime based on Alcorn (2010)
	Insulation	polyester	109.7	m ³	150	Lifetime based on Alcorn (2010)
	Windows & doors	aluminium	0.03	m ³	35	Lifetime based on Alcorn (2010)
		glass	81.64	m ²	100	Lifetime based on Alcorn (2010)
	Floors	timber	3.14	m ³	150	Lifetime based on Alcorn (2010)
	Roofing	steel	72	m ²	50	Lifetime based on Alcorn (2010)
Electrical works	Others	copper	15.8	m		Lifetime based on NAHB (2007)
Finishes and fixtures	Sanitary & accessories	aluminium	0.04	m ³	35	Assumed lifetime
		brass	0.05	m ³		Lifetime based on
		paint	25	L	15	Lifetime based on Alcorn (2010)
		ceramics	0.1	m ³		Lifetime based on NAHB (2007)
		plasterboard	13.62	m ³	30	Lifetime based on Treloar et al. (2000)

Plumbing & drainage	Sewer drain, down pipe & others	steel	0.32	m ³		Lifetime based on Alcorn(2010)
		timber	4.12	m ³	150	Lifetime based on Alcorn (2010)
		pipe	84.9	kg	25	Lifetime based on NAHB (2007)
		steel	0.04	m ³	30	Lifetime based on Alcorn(2010)
		tape	2.88	m ²	30	Assumed lifetime
		concrete	2.24	m ³	80	Lifetime based on Alcorn(2010)
Other	Ventilation systems	Ducted generation	2.1	no.	30	Assumed lifetime
		Ducted delivery	18.9	no.	30	Assumed lifetime

Table B.6: Material bill of quantities for the 300m² STD_TRCH-I in the alternative neighbourhood

Building component	Material group	Material	Quantity	Unit	services life	Description
Foundations	Concrete slab & others	30 MPa concrete	23.63	m ³	100	Lifetime based on Alcorn(2010)
		polyester	0.61	m ³	50	Lifetime based on Alcorn(2010)
		Sand blinding	2.28	m ³	150	Lifetime based on NAHB (2007)
		acrylic gap grout	9	L	50	Assumed lifetime
		steel	3.69	t	150	Lifetime based on Alcorn(2010)
Envelope	Hardware	steel	0.18	m ³	80	Lifetime based on Alcorn(2010)
		tape	29.8	m ²	30	Assumed life time
		timber	0.33	m ³	90	Lifetime based on Alcorn(2010)
		Polypropylene(wrap)	335.2	m ²	60	Assumed life time
		plastic	18.14	m ²		Lifetime based on NAHB (2007)
	Carpentry	aluminium	0.0013	m ³	35	Lifetime based on Alcorn(2010)

		paint	0.48	L	15	Lifetime based on Alcorn (2010)
		plasterboard	0.55	m ³	30	Lifetime based on Treloar et al. (2000)
		bronze	6.2	kg	30	Assumed life time
		steel	0.08	m ³	50	Lifetime based on Alcorn (2010)
		Tape	19.47	m ³	30	Lifetime based on Alcorn (2010)
		timber	16.6	m ³	150	Lifetime based on Alcorn (2010)
		polypropylene	47.9	m ²	60	Assumed lifetime
	Cladding	timber	9.22	m ³	150	Lifetime based on Alcorn (2010)
	Insulation	polyester	69.11	m ³	150	Lifetime based on Alcorn (2010)
	Windows & doors	aluminium	0.02	m ³	35	Lifetime based on Alcorn (2010)
		glass	51.43	m ²	100	Lifetime based on Alcorn (2010)
	Floors	timber	1.98	m ³	150	Lifetime based on Alcorn (2010)
	Roofing	steel	72	m ²	50	Lifetime based on Alcorn (2010)
Electrical works	Others	copper	9.95	m		Lifetime based on NAHB (2007)
Finishes and fixtures	Sanitary & accessories	aluminium	0.03	m ³	35	Assumed lifetime
		brass	0.032	m ³		Lifetime based on
		paint	15.8	L	15	Lifetime based on Alcorn (2010)
		ceramics	0.063	m ³		Lifetime based on NAHB (2007)
		plasterboard	8.6	m ³	30	Lifetime based on Treloar et al. (2000)
		steel	0.02	m ³		Lifetime based on Alcorn(2010)

		timber	2.6	m ³	150	Lifetime based on Alcorn (2010)
Plumbing & drainage	Sewer drain, down pipe & others	pipe	53.49	kg	25	Lifetime based on NAHB (2007)
		steel	0.03	m ³	30	Lifetime based on Alcorn(2010)
		tape	1.81	m ²	30	Assumed lifetime
		concrete	1.41	m ³	80	Lifetime based on Alcorn(2010)
Other	Ventilation systems	Ducted generation	1.32	no.	30	Assumed lifetime
		Ducted delivery	11.91	no.	30	Assumed lifetime

Table B.7: Characteristics of vehicles used in the transport variation

Descriptor	Type	Model	Efficiency (kWh/km)
T-1	ICEV	Toyota Land Cruiser*	1.11
T-2	ICEV	Toyota Aurion*	0.9
T-3	ICEV	Toyota Yaris*	0.55
F-1	ICEV	Ford Territory Titanium**	1.01
F-2	ICEV	Ford Trend**	0.64
F-3	ICEV	Ford Fiesta ST**	0.58
H-1	ICEV	Holden Captiva***	0.91
H-2	ICEV	Holden Malibu***	0.77
H-3	ICEV	Holden Barina spark***	0.54
M-1	ICEV	Mazda CX-9 [#]	1.06
M-2	ICEV	Mazda A6 [#]	0.58
M-3	ICEV	Mazda A2 [#]	0.5
HD-1	ICEV	Honda Euro Accord ^{##}	0.84
HD-2	ICEV	Honda Civic ^{##}	0.65
HD-3	ICEV	Honda Jazz S CVT ^{##}	0.49
BC-T	ICEV	Base Case Transport (NZ standard) ^{\$}	0.2
EV-3	EV	Mitsubishi i-MiEV [%]	0.16
EV-4	EV	Nissan Leaf [@]	0.189
EV-2	EV	Smart ForTwo Electric Drive [^]	0.151
EV-6	EV	Toyota RAV 4 EV*	0.27
EV-5	EV	Tesla Model S P85D [?]	0.24
EV-1	EV	BMW Active E ^{>}	0.14

Source: * Toyota NZ(2014) ; ** Ford NZ(2014) ; *** Holden NZ(2014) ; [#] Mazda NZ(2014) ; ^{##} Honda NZ(2014) ; [%] Mitsubishi NZ(2014) ; [@] Nissan NZ (2014) ; [^] Smart USA(2014) ; [?] Tesla(2014) ; [>] BMW NZ(2014) ; ^{\$} Mithraratne (2011).

Appendix C: Case study results

Table C.1: Shifts in material item contribution ranking between initial and life cycle embodied energy requirements of the base case zero energy house

Item	IEE rank	LCEE rank	Change
RES	1	1	0
Steel	2	2	0
Concrete	6	6	0
Plasterboard	4	3	-1
Insulation	5	4	+1
Timber	3	7	-4
Aluminium	8	5	+3
Glass	7	8	-1
Brass	10	9	+1
Plastic	9	10	-1
Paint	11	11	0
Others	12	12	0

Note: IEE= initial embodied energy and LCEE=life cycle embodied energy (initial+reccurent)

Table C.2: Comparison of LCA results of PV manufacturing impact from multiple global locations

Study	Location	Methodology	EPBT	Greenhouse gas emissions (gCO ₂ -e/kWh)
Yao et al. (2014)	China	Hybrid	4.7	207
Yue et al. (2014)	China	Hybrid		69.2-72.2
	Europe			31.8-37.3
Hsu et al. (2012)	13 studies in the U.S.A ,Europe, Japan, Australia and Brazil	N/A		26-118
Zhai and William (2010)	U.S.A	Hybrid	2.1	30
Fthenakis and Alsema (2006)	European countries	Process-based	1.9	30
Pacca et al. (2006)	U.S.A	Process-based	2.6	67

Table C.3: Energy consumption, generation and grid connection summary expressed in final energy units

	MWh
Total generation on-site	5.39
Exported energy	4.34
Consumed energy	2.36
Imported energy	1.35

Table C.4: Annual operational and embodied energy and greenhouse gas emissions for user transport variations

	Energy (MWh)	Greenhouse gas emissions (kgCO ₂ -e)
Transport Operation (T-1)	26.68	6504
Transport Embodied (T-1)	5	912
Transport Operation (F-1)	24.36	5976
Transport Embodied (F-1)	5	912
Transport Operation (H-1)	22.04	5208
Transport Embodied (H-1)	5	912
Transport Operation (M-1)	25.52	6480
Transport Embodied (M-1)	5	912
Transport Operation (HD-1)	20.18	4848
Transport Embodied (HD-1)	5	912
Transport Operation (T-2)	21.5	5160
Transport Embodied (T-2)	3.8	720
Transport Operation (F-2)	15.31	3696
Transport Embodied (F-2)	3.8	720
Transport Operation (H-2)	18.56	4368
Transport Embodied (H-2)	3.8	720
Transport Operation (M-2)	13.92	3720
Transport Embodied (M-2)	3.8	720
Transport Operation (HD-2)	15.54	3600
Transport Embodied (HD-2)	3.8	720
Transport Operation (T-3)	13.22	3216
Transport Embodied (T-3)	3.133	456
Transport Operation (F-3)	13.69	3312
Transport Embodied (F-3)	3.13	456

Transport Operation (H-3)	12.99	3000
Transport Embodied (H-3)	3.133	456
Transport Operation (M-3)	12.06	2904
Transport Embodied (M-3)	3.13	456
Transport Operation (HD-3)	11.83	2880
Transport Embodied (HD-3)	3.13	456
Transport Operation (EV-4)	9.05	1956
Transport Embodied (EV-4)	4.35	939
Transport Operation (EV-5)	8.03	1734
Transport Embodied (EV-5)	3.85	832
Transport Operation (EV-2)	6.35	1371
Transport Embodied (EV-2)	3.05	658
Transport Operation (EV-1)	5.6	1209
Transport Embodied (EV-1)	2.69	581
Transport Operation (EV-3)	5.04	1089
Transport Embodied (EV-3)	2.42	523
Transport Operation (EV-6)	4.67	1008
Transport Embodied (EV-6)	2.24	484
Transport Operation (PT-B)	20.13	4632
Transport Embodied (PT-B)	2.4	480
Transport Operation (PT-Tr)	0.65	94.1
Transport Embodied (PT-Tr)	0.294	42.34
Transport Operation (BC-T)	23.2	3984
Transport Embodied (BC-T)	3.8	720

Table C.5: Characteristics of modelled alternative building typology neighbourhood variation compared to the base case zero energy building zone

Case acronym	Built area (m ²)	Average living area(m ² /capita)	Density (inhabitant/km ²)	Comprising building	Number of dwelling units
BC_NBH	185,000	66.6	2,452	BASE_CNBH	618
				BASE_CNBH3	618
STD_RH+STD_TRCH	185,000	50	2,470	STD_RH	620
				STD_TRCH	624

Figure C. 1: Annual energy demand and greenhouse gas emissions breakdown for scenario STD_RH, by end use

Figure C.2: Annual energy demand and greenhouse gas emissions breakdown for scenario *STD_TRCH*, by end use

Table C.6: Comparison of the entire neighbourhood under optimized scenario: *STD_RHSV+STD_TRCHSV*, with the base case *BC_NBH* under multiple variations considered

Use	SV		EV-I		PT-Tr		PRM_EFel	
	Value	Relative difference with BC_NBH	Value	Relative difference with BC_NBH	Value	Relative difference with BC_NBH	Value	Relative difference with BC_NBH
Energy (GWh)								
Building Operation	6.58	+228%	6.58	0.0%	6.58	0.0%	6.39	-83%
Building Embodied	0.81	-50%	0.81	0.0%	0.81	0.0%	0.81	0.0%
Transport Operation	5.81	0.0%	5.81	-77%	0.87	-97%	0.87	0.0%
Transport Embodied	2.79	0.0%	2.79	-67%	0.37	-96%	0.37	0.0%
Emissions (tCO ₂ -e)								
Building Operation	1173	+115%	1173	0.0%	1173	0.0%	419	-94%
Building Embodied	95	-78.7%	95	0.0%	95	0.0%	95	0.0%
Transport Operation	1254	0.0%	1254	-71%	117	-97%	127	0.0%
Transport Embodied	602	0.0%	602	-59%	52	-96%	42	0.0%

Note: *BC_NBH*: base case neighbourhood, *SV*: 34.2% size reduction, *EV-I*: replacing petrol vehicles with efficient battery powered electric vehicles, *PT-Tr*: modal shifting to public electric train transport, *PRM_EFel*: Improvement of electricity grid .i.e. reduction of primary energy and greenhouse gas emission conversion factors.

Figure C. 3: Transport energy variations