

Curtin University Sustainability Policy (CUSP) Institute

Disruptive innovation and mainstreaming low-cost and low-carbon housing

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requirement for the Degree of
Doctor of Philosophy
of
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DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material, which has been accepted for the award of any other degree or diploma in any university.

The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number # RDHU-20-15.

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ABSTRACT

Applying theories of disruption and transition from Schumpeter, Kondratieff and Christensen to the rapidly emerging niche technologies of solar-storage and modular construction, this thesis examines the extent to which they are delivering low-cost and low-carbon housing. Electricity case studies in Perth are opportune as they demonstrate a city undergoing dramatic growth in solar, and now storage, and hence the first signs of disruption can be seen. The thesis analyses the technologies through disruptive innovation theory using three lenses: disruptive technologies, disruptive business models, and disruptive culture and behaviour change, assessing the impact that deployment could have on incumbent market alternatives in fossil fuel-based power systems and traditional home construction markets. Key findings for solar-storage include the following:

- Cities such as Perth are likely to continue to rapidly grow in solar and battery storage, meaning it is more possible for global electricity supply to become entirely decarbonised by 2048 than the usual forecasting models predict, as they do not consider disruption;
- There can be far greater uptake of rooftop solar by deploying micro-grids within attached housing using strata title, which represents a third of Australia's housing stock and demonstrates how shared community-based power can work anywhere; and
- Battery storage will have a profound impact on Australia's electricity system, but will not cause the so called 'death spiral' of the electricity grid; instead, as citizens are able to trade their surplus electricity with each other, the distribution role of the grid will become more valuable. The transmission network may have asset writedowns.

In relation to modular construction, a case study in Perth is evaluated to determine the potential of modular construction to deliver low-cost and low carbon housing. Key findings include the following:

- Modular construction can deliver lower cost and lower carbon outcomes when compared with traditional building approaches and could play a critical role in compacting cities, such as the sprawling cities of Australia, without impacting housing affordability.
- Market and policy reforms, particularly around financing, are necessary to realise the potential of modular construction in the Australian market, as has occurred in other countries.

- In the Australian context, modular construction cannot presently be considered to be a disruptive innovation although it has the potential to be.

The thesis suggests that within cities such as Perth, business, government and communities can do one or a combination of *'fight, flight or innovate'* in response to disruptions and that these choices will define the extent to which these innovations can thrive in the transition.

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Journal Paper 3

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Journal Paper 4

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Journal Paper 5

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Jemma Marie Green, PhD Candidate

STATEMENT OF CONTRIBUTION OF OTHERS

All of the written materials submitted as part of this PhD by Publication were conceived and coordinated by Jemma Marie Green. The majority of the calculations and writings for each publication were undertaken by Jemma Marie Green.

Signed detailed statements from each co-author relating to each publication are provided as appendices at the back of this volume (Appendix 1).

Signed:



Jemma Marie Green, PhD Candidate



Professor Peter Newman, Supervisor

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1. INTRODUCTION

The world is now committed to reaching 100 per cent less greenhouse gas emissions by 2100 and hopefully 80 per cent less greenhouse gas emissions by 2050 (COP 21 2015). Most greenhouse gas emissions are produced in cities and towns across the world (IPCC 2014a; World Bank 2011). The shift from a fossil-fuel based global economy to a low-carbon economy requires significant technological and behavioural shifts (UNEP 2013, IDDR 2014 and Climate Works 2014). Electricity and heat production represents approximately one quarter of greenhouse gas emissions when broken down by sector (IPCC 2014a). In using electricity for construction and operation, buildings contribute approximately 20 per cent of total human emissions (IPCC 2014a). To successfully decrease the carbon intensity of electricity used in the residential built environment significant technological shifts are required by traditional electricity utilities, traditional building designs and construction approaches and materials. As the urban system is predominantly fossil-fuel dependent it will require disruptive innovations in the form of technologies, business models and governance frameworks, to enable the kind of rapid transition that is necessary to keep climates within safe limits (IPCC 2013).

Innovations in technology, governance structures, business models, culture, and lifestyle change, also termed as ‘catalysts’, will have a profound impact on the world’s trajectory towards this future. In the residential built environment, the main carbon emission sources stem from fossil fuel-based electricity usage in the built form (DIIS 2013 and UNEP 2009). This mostly means the fuel source used for power in building materials construction and transport of goods¹ but also includes the electricity that is used in the buildings throughout their useful life (Cabeza 2014 and Ramesh 2010). Inevitably, the carbon efficiency of buildings is a function of building design, materials, the amount and source of electricity consumed, and how householders behave (Shrestha and Kulkarni 2010; Diakaki 2010).

This doctoral research examines the way that the built environment can begin to be rapidly modified by what is now called ‘disruptive innovation’ and whether this is likely to create new low-cost and low-carbon housing. Bower and Christensen (1995) explain disruptive

¹ This thesis does not focus on transport fuel except when discussing electric vehicles and their links to solar and batteries. This is an important part of the transition to low carbon cities but the main focus of this thesis is on the residential built environment, i.e. housing.

innovation as the phenomenon of new and innovative products entering a market. Related to, and as a part of disruptive innovation theory, transition theory is a framework that can be used to evaluate major transitions in electricity and housing systems (Geels, 2010; Geels, 2013; Rip and Kemp, 1998).

Building upon this literature, further outlined below, the overarching question to be addressed by this doctoral research is: “How can disruptive innovation contribute towards *mainstreaming* low-cost and low-carbon housing?”²

The research also focuses on the business models and behavioural choices that impact electricity demand. Through five journal papers, this research examines key leverage points for understanding how disruptive innovations associated with solar-storage and modular construction could deliver low-cost and low-carbon housing, with a focus on underpinning rapid mainstreaming globally.

The thesis examines two disruptive technologies, new business models, culture and behaviour change. These are likely to significantly shift in their combinations and implications as we move towards a low-carbon future. The two disruptive technologies that are examined in this thesis are modular construction and rooftop photovoltaic cells (PV) combined with lithium-ion-phosphate batteries (which have been labelled ‘solar-storage’). Modular construction is evaluated for its potential to deliver low-cost and low-carbon housing, and the extent to which it is a disruptive innovation to the traditional building industry. Solar-storage is evaluated in terms of its ability to contribute to low-cost and low-carbon housing and how it disrupts traditional utility business models and ways of managing housing supply, especially multi-unit housing.

In relation to the **first disruptive technology**, solar-storage, the **first paper** in this thesis examines the global electricity context and forecasts the impact this technology would have on global electricity markets under a range of scenarios. An assessment of global electricity markets against the risks posed by solar-storage technology, as a potential disruptive innovation, finds that the traditional electricity systems are undergoing significant structural shifts.

² The term mainstream is a noun but in this thesis the term *mainstreaming* is used as short hand for ‘to bring into the mainstream’ i.e. as a verb.

For the **second paper**, solar-storage technology is examined in terms of the extent to which it will be disruptive to traditional electricity systems in the Perth market.

There are three potential responses that incumbent industries can have in reacting to disruption: *Fight, flight or innovate*. These responses are outlined separately below, but may be displayed concurrently, i.e. a company could simultaneously lobby against an innovation and simultaneously employ innovative strategies to adapt their business model. In this paper, the question of disruptive governance is addressed through understanding three potential responses by incumbent utilities to solar-storage through '*fight, flight or innovate*' approaches. These are analysed to examine how changes can be more effectively addressed.

The **second disruptive technology**, modular construction, is evaluated in the **third paper**. The method of modular construction is an alternative to the traditional construction industry and is analysed in this thesis as a growing market threat to these methods. While modular construction presently only accounts for around 3 per cent of construction in Australia (Green and Newman 2014), international growth and acceptance suggests that this could increase significantly in the future. Modular construction's disruptive influence is also analysed in terms of the same '*fight, flight or innovate*' responses.

An example of a business model, which can be implemented to address disruptive market circumstances, is created in the **fourth paper**. In evaluating the disruptive business model, this paper develops an innovative governance framework that facilitates the deployment of renewable energy in multi-unit residential dwellings in Australia. Up until now, solar PV systems in Australia have not experienced the same penetration rates on medium or high-density housing when compared with dwellings on freehold land and this is found to be a global issue. This is in large part because there has been little financial incentive for developers and owners to incorporate systems that solely benefits occupants.

The **fifth paper** examines the willingness for people to prioritise sustainability features in their decision-making when selecting a place to live. This is done through analysing actual, rather than stated, consumer preferences when choosing a medium-density home to live in and the relative importance of sustainability features, against other dwelling and location features. The relative importance of sustainability features in actual housing preferences is evaluated to

better understand and facilitate the selection or incorporation of low-carbon features by renters, homebuyers, and developers.

Combined, the research undertaken in this thesis evaluates not just how these disruptions may contribute to a low-carbon future, but also how they contribute to affordable living, and thus, greater social equity. Furthermore, the thesis suggests that disruptive innovations like solar-storage and modular construction will have a profound impact in mainstreaming low-cost and low-carbon housing through the catalysts of technology, governance models and behaviour change. The major drivers will be market-based led by consumer demand, as with other disruptive innovations, though policies and institutional barriers can certainly slow or enable this change.

1.2 Research Aim

In this section, the main theoretical concept of disruptive innovation will be outlined first. The literature review will then cover the main application areas of solar-storage and modular construction to show why these two innovations were chosen to illustrate the potential for rapid disruption.

The overarching question this research seeks to answer is:

How can disruptive innovation contribute towards mainstreaming low-cost and low-carbon housing?

This question will be addressed through an analysis of literature about disruptive innovation, the assessment of two new niche technologies for low-cost and low-carbon housing (modular construction and solar-storage), and an examination of the policy and governance barriers to low-cost, low-carbon housing and solutions to overcome them. An evaluation about whether these technologies are disruptive is also provided. Impacts these technologies may have on incumbent sectors will also be examined, and finally, an investigation of people's perceptions of low-cost, low-carbon housing, and their willingness to live in it is conducted.

1.3 Research Questions

The specific research questions to address the thesis question are set as a group of transitions that can be seen to have global significance. These are the global renewables transition, the local renewables transition, the construction transition and the housing transition. The questions are as follows:

1. **The global renewables transition.** How would disruption to the traditional electricity market from renewable energy and storage impact global electricity demand forecasts and what implications do these have for fossil fuel assets? Under which scenarios could renewable energy fulfil the majority of global energy demand?
2. **The local renewables transition.** What opportunities in Perth can be used to demonstrate the residential solar transition? When will solar and battery systems reach retail grid parity³ in Western Australia? What effect does the installation of solar panels have on a household's utilisation of grid electricity? What further reductions are seen when a battery is installed? What is the role of the grid combined with a distributed energy system and what are the changes to incumbent utility business models? How can utilities respond to this transition? Is solar-storage a disruptive innovation?
3. **The construction transition.** How do modular buildings compare against traditional buildings when considering cost, time and sustainability performance? What role can they play in delivering low-cost and low-carbon housing? What are the barriers and opportunities for traditional builders to become part of this transition? Can modular construction be considered a disruptive innovation?
4. **The housing transition.** What governance, ownership, and financing arrangements are possible that will facilitate renewable energy and storage uptake in strata housing developments? Does sustainability influence actual medium-density housing preferences in Perth, Western Australia? What is the relative importance of sustainability features when compared against other dwelling and location features in determining purchasing and rental decision-making? What is the role of disruptive commercial and governance models in enabling disruptive innovations?

³ Retail grid parity is defined as the point when solar-storage can generate electricity at levelised cost of electricity (LCOE) that is less than or equal to cost of purchasing electricity from the electricity grid.

2. LITERATURE REVIEW

A great amount of research has already been undertaken in the field of low-carbon and sustainable housing (Lovins 1991; Karolides 2003; Buys, Bendewald and Tupper 2010; Newman and Matan 2013; Archambault, Wang and Yardi 2004; Droege 2010; Droege 2011; Preservation Green Lab 2011; Newman, Beatley and Boyer 2009; Beatley with Newman 2009; von Weizsacker et al 2011; Droege 2009; Deng, Prasad and He 2008; Rauland and Newman 2015; Hoornweg and Freire 2013; Seba, 2013a,b,c and 2014). This research has identified various barriers related to the development of low-carbon built environments, including public opposition to high-density housing and cost implications of sustainability technologies. The literature does not provide a lot of hope that the goal of 80 per cent less greenhouse gas emission by 2050 is likely to be fulfilled, as the majority of the existing built environment seems to be fossil fuel dependent. Even the IPCC (2014a) sees path dependence as being the fundamental barrier to a rapid transition towards the goals that global governments are now setting. Path dependence is the idea that what happens is dependent on what immediately precedes before it.

The need for rapid mainstreaming of low-cost and low-carbon alternatives requires a dramatic intervention, otherwise the need to reach 80 per cent less carbon by 2050 and 100 per cent less by 2100 are not going to be feasible. Such rapid change may not have been fully considered as potentially feasible, as most scientific and economic assessments of the transition tend to look back and not see the opportunities for rapid disruption. The following sections outline the business and market theories of disruptive innovation that offer a potentially powerful intervention for global markets. This will then be applied to two disruptive technologies: solar-storage technologies that could disrupt traditional electricity generation and transmission systems, and modular construction methods that have the potential to be disruptive to traditional construction systems. After outlining the disruptive technologies, the review will examine disruptive business models and then disruptive culture and behaviour change.

2.1 Disruptive Innovation

Disruptive innovation theories are not based on a single school of thought. They aim to describe the phenomenon of a new product entering an established market and quickly capturing market share in a way that is unexpected. In doing so, it completely changes the sector and leaves the incumbent products defunct and stranded (Bower and Christensen 1995).

This can be a cheaper product, though it may just be more effective, and is characterised most of all by rapidly capturing market share. This results in consumer demand declining for incumbent offerings, ultimately leaving them and the systems that have grown around them stranded. The Christensen approach to disruption suggests that innovation is demand-led rather than being supply-led.

Disruption theories date back to the early 20th century when economist Nikolai Kondratieff published his ideas on cycles of innovation. He conceived that these cycles lasted for 50 to 60 years before a new technology becomes mainstream (Kondratieff 1925 in Schumpeter 1939). Typically, at the beginning of a new Kondratieff cycle, entrepreneurs require a considerable amount of capital to make a new product, e.g. a steam engine. High interest rates are no obstacle, as entrepreneurs increase their earnings by implementing more productive systems. But eventually, after several years, the new technology networks begin to offer diminishing returns on investment. This means demand for credit grows more slowly and real interest rates move towards zero in the end.

Economist Joseph Schumpeter expanded upon Kondratieff's work. He coined the term 'creative destruction', which outlines how within the economy, the tendency towards equilibrium is constantly displaced by entrepreneurial initiative that drives the economy along new and unexpected pathways (Schumpeter 1942). In his theory displacement can be driven by any actions, including policy changes, but are primarily driven by technology.

This is distinct from Clayton Christensen's later theories around disruptive innovation, where Christensen purports that technological changes are only disruptive if they are present independently of supportive policy (Bower and Christensen 1995). Christensen's work at Harvard Business School was pioneering in examining the micro-technological changes that occur within the larger cycles of innovation and how new companies create products that erode the market share of larger players by innovating in their market segment (Bower and Christensen 1995). Christensen holds that technologies, in order to be considered disruptive, must offer basic, everyday options for consumers, sometimes at a cheaper price than the incumbent technologies but always in a way that attracts consumer demand (Christensen et al 2015). The disruption is more than a new market; it brings about change in the whole system surrounding that market. He gives the example of 3.5-inch floppy discs that were more expensive per unit of storage memory than 5.5 inch discs, but they were more portable and

hence were favoured; this led to the popularity of portable notebook computers, which changed the nature of the computing system. Christensen thus believes that disruptive innovation, at its core, will also bring about a change in related industries (Baumann et al 2006). By establishing new business models, disruptive innovation presents established and incumbent companies with an opportunity to enter a new growth stage and not die out with the disruption. Competing companies left with the old products, like 5.5 inch discs, are left with stranded assets and soon disappear.

Tony Seba, an American public academic who lectures at Stanford University, expands on Christensen's work to include all and any phenomena (including policy and business models) that result in disruption. Seba (2014a, b and c) outlines three modalities of disruption: disruption from below, from above, and big bang disruption. Seba suggests that there will be dramatic shifts towards renewable energy and electric vehicles as their disruptive changes begin to filter into the mainstream. Using this expanded definition of disruption, solar-storage systems and modular construction systems have the potential to disrupt the traditional housing sector as well as the centralised, fossil fuel-based electricity generation and transmission sector.

Seba's research builds on the same notions of transition using the Kondratieff model. He has shown that the time between the cycles or waves of innovation are shortening to 25 to 40 years and the likelihood of companies being able to recover their previous market dominance once they have been disrupted is declining (Seba 2013). However, not all innovations are disruptive. As an illustrative example, microwaves, though considered an innovation, did not disrupt convection ovens and are both considered to be staple household items today.

An example of a company responding and surviving a disruption is IBM's shifting business models with the advent of the portable laptop. IBM started off by manufacturing mainframe computers and later, more commercially successful desktop computers. However, anticipating increased competition in the retail market, they ceased desktop computer production to focus on mainframe operations. This has resulted in them being the dominant supplier in the mainframe market but missing out on the substantial growth in the portable computer market popular today (DRR 2016).

IBM's perception of market drivers and future trends enabled it to be well placed to take

advantage of disruption in their part of the computer market. However, many other businesses fail to recognise the core signs of disruption or respond sufficiently to stop or capitalise on these changes. Disruption typically cannot be identified through a single event. Instead, it is built through a chain of events, a system of activity, which is derived from competitors responding to market demands or innovative ideas (Bower and Christensen 1995; Seba 2013).

These aspects of disruption are covered in more detail in **Journal Papers 2 and 3**.

Contemporary thinking on innovation explains disruption in a more nuanced way, incorporating a wider set of factors that are not simply creating change in a linear fashion, but as a system. Transition theory provides a framework that can be used to evaluate major transitions in electricity and housing systems (Geels, 2010; Geels, 2013; Rip & Kemp, 1998). Geels, Rip and Kemp refer to them as ‘socio-technical’ transitions owing to simultaneous and related changes in markets, market practice, policy, culture, as well as technology (Geels 2010). Geels holds that in relation to housing, changes will not manifest easily due to incumbent systems having strong roots underpinned by investments, policy and culture (Geels 2010).

Transition Innovation Systems (TIS) is another alternative heuristic framework (Coenen et al 2012), which originates from evolutionary economics through work by Nelson and Winter (1982). TIS focuses on identifying the catalytic features that support emerging sustainability technologies such as modular construction and solar storage (Coenen and Truffer 2012).

The transition process has also been examined using a Multi-Level-Perspective (MLP) heuristic framework. MLP takes a broader approach than TIS by looking at transformative societal processes and was developed to help understand the transition in socio-technical systems (Rip and Kemp 1998; Geels, 2004; Geels, 2002; Geels and Schot 2007 and Coenen and Truffer, 2012). It incorporates three contexts to understand transitions: a (macro) landscape level taking account of profound cultural, economic and political patterns; a regime (meso) level that looks at market practises and prevailing rules; and niche (micro) where new innovations are trialled and break into the status quo.

Thus, technologies, business models and broader social systems are all involved in the disruption process. To best position companies in the face of disruption, Wessel and

Christensen (2012) propose that they should identify the strengths of their competitors, especially those emerging in the light of these factors. They should also identify their own relative advantages and then evaluate the conditions, which would see their business' relative advantages turn into disadvantages; the final stage of the disruption. Understanding how the disruption may occur will place companies in a better position to maximise any market or consumer changes that may eventuate or even lead to them developing their own disruptive innovation. Aghion et al (2014), examines the role that social factors, like path dependence, can play in preventing the innovation process, but when recognised and acted on will expedite the transition to a low-carbon future in ways which traditional modelling has not taken account of. This is further emphasized by Zenghelis in Jacobs and Mazzacuto (2016).

In TIS transition theory, disruption can occur incrementally, radically or systemically. This thesis, examines how the transition of the two disruptive technologies is taking place. E.g. Is solar-storage and modular construction disruptive innovations? What is the test? Is change appearing as a more incremental change that will ultimately be at a systemic level? Are there places that a systemic shift is already evident? How is the shift in energy towards alternative energies and away from fossil fuel energy manifesting? Often with disruptive, there is a path dependency (Arthur 1989) and technology 'lock in' (Twomey and Gaziulusoy 2014) that is indicative of impending disruption. This is examined for both solar-storage and modular construction.

Therefore, by assessing solar-storage and modular construction, this research broadens the field of knowledge and literature around disruption and innovation to encapsulate three contexts: technologies, business models, and culture and behaviour change. This analysis provides an opportunity to examine not only the technologies, but the broader socio-technical systems, which are part of the disruption process. The way these factors interact will be an important part of the thesis.

2.2 Disruptive Technologies

Both innovations, solar-storage and modular construction, require significant digital skills that will disrupt traditional workforces unless they are updated through training; this aspect will not be pursued in detail in the thesis, though there is awareness of the need in the literature

(Hajkowicz et al 2016; Karoly and Panis 2004 and Johnston et al 1987).

Both solar storage and modular technologies appear, in certain countries, to be disruptive innovations to traditional centralized and largely fossil fuel-based electricity systems and traditional housing industries. There is more at stake than merely low-cost and low-carbon housing. As housing, including the built form and the electricity consumed within them, represents a large component of cities, having them operate efficiently will contribute to wider economic benefits (Krugman 1991; Hoornweg and Freire 2013). Thus, the thesis will examine how they can influence forecasting for the future, as well as more focused policies for the sectors. My local city of Perth will be used as the case study, as set out below, which appears to be a leader in solar-storage innovations and has some initial case studies for modular construction that enables me to evaluate the potential for and implications of disruption.

It is important to recognise that disruption is actually necessary if Paris climate objectives (of holding global average temperatures to well below 2 degrees Celsius above pre industrial levels and to pursue efforts to limit temperature increase to 1.5 degrees Celsius above pre industrial levels) (COP 21 2015) are to be realised. Moreover, incumbent fossil fuels are to be disrupted and a transition to a low-carbon economy will become a reality.

2.2.1 Solar-Storage

In Australia and most developed nations, electricity generation and transmission systems have largely remained unchanged since their inception around a century ago and have been built in stages, as urban and regional centres experience population fluctuations. This has resulted in generators being located far away from where electricity is consumed in households, requiring the construction and maintenance of long and costly transmission and distribution lines. These assets are mostly owned by utilities that recover the costs of upgrades through electricity service charges to customers.

In Perth, electricity generation and transmission structures are now several decades old, and require considerable maintenance and upgrades to provide regular service to consumers. The South-West Interconnected System (SWIS) that services Perth and regional surrounds is also disadvantaged due to the large geographical area that it covers with a low population density. Perth has the lowest proportion and the lowest growth rate of medium and high-density

dwellings (Bankwest Curtin Economics Centre 2014; Department of Housing and Planning 2013) often for reasons of cost, and existing perceptions and barriers that will be examined in this thesis.

There are three main components of electricity bills: wholesale costs, network charges and retail margin. Underlying much of the price rise in electricity (as shown in Figure 1 below) was the high amount of capital expenditure on the aging network system. A great deal of this expenditure was because the network was over-specified and also due to perverse market incentives given to network operators (Wood, Carter and Harrison 2013). There has been much speculation about impropriety, which ultimately resulted in a senate inquiry into electricity prices (Australian Parliament House 2012). Maintaining and expanding this system has been a major contributor to the price of electricity increasing at a faster rate than the consumer price index (see for example the Australian price rises in Figure 1 below) in Australia over the past decade.

The steep rise in the retail price for electricity seen over the past decade cannot solely be attributed to the costs for network infrastructure maintenance, though it is a large part of the story.

In Australia, grid electricity experienced strong growth in demand at the beginning of the century but began declining in the latter part of the 21st century (Stanwix 2015). Network regulators erroneously forecasted an increase in grid electricity demand in line with the increase of gross domestic product, when the two variables have actually begun to decouple (Wood, Carter and Harrison 2013). This decoupling is a result of advances in energy efficiency, changes in composition of the economy to less energy intensive sectors, as well as the uptake of renewables including solar photovoltaic cells by Australian households (Palmer 2015). Based on this erroneous assumption, much large-scale generation capacity built was predicted upon demand growth. Many utilities entered into long-term power purchase agreements (PPAs) that they have to pay for whether the demand materialises or not. These costs are added to the price of electricity and has been particularly prevalent in the SWIS (Martin 2016).

Further, since the repeal of Australia's climate laws the wholesale price of electricity in Australia has increased dramatically, which is predominantly driven by limited gas supplies

on the National Electricity Market (Morton 2017) and the retirement of aging generation capacity (AEMC 2016).

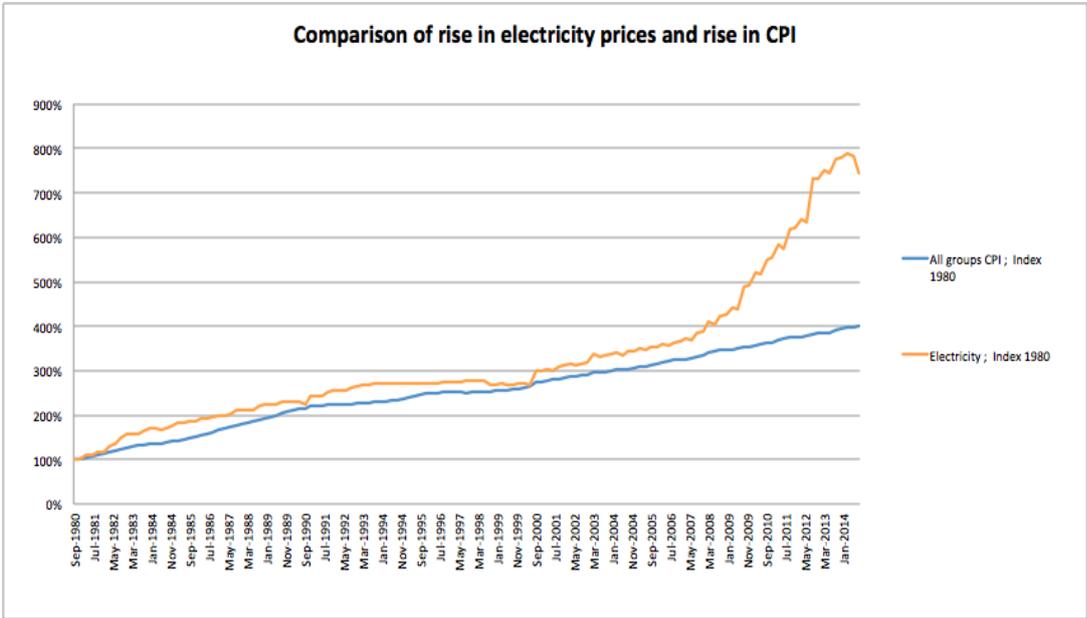


Figure 1: The large inflation of retail electricity prices in Australia in comparison to the Consumer Price Index (author created, based on ABS 2015b).

It should also be noted that in Western Australia, the state government subsidises electricity prices up to AU\$510.3 million per annum (Electricity Market Review Steering Committee 2014). Therefore, even though prices are high, they are not cost reflective. This creates an issue, as pricing acts as a signal to consumers to change their behaviour as prices fluctuate. Electricity prices in Australia are in the process of becoming cost-reflective, as state governments no longer wish to continue to subsidise electricity (AEMC 2014). Rising electricity prices in Australia have been an important catalyst for the uptake of solar photovoltaic (PV) and battery systems, as it accelerates the date at which solar and storage will reach retail grid parity, which is defined as the point when solar-storage can generate electricity at levelised cost of electricity (LCOE) that is less than or equal to cost of purchasing electricity from the electricity grid. Australia has been growing rapidly in its adoption of solar PV with more than 1.5 of the 9 million households in Australia having rooftop installed solar PV (and projected to rise to over 18 million kW by 2031) (Flannery and Sahajwalla 2013).

The rise of electricity prices has been coupled with the decline in price of solar PV technology. This has played a considerable role in the large demand for household solar panels, especially in Perth in the past eight years, which was subject to a large mining boom that created large amounts of wealth for middle-class workers living in the suburbs. Solar electricity was an obvious way to buy something useful for the future, as it paid for itself in five or six years. This period corresponds to stagnant economic growth in the rest of the developed world where new markets were struggling to become viable. Thus Perth's growth in solar becomes an important prototype for the rest of the world, as it offers a case study in disruptive innovation from solar electricity.

Solar uptake in Western Australia has been fuelled by a variety of other factors. In part it is due to already high electricity prices (Deutsche Bank 2015; AEMOb 2016), but another prescient condition to consider is the near-300 days of sunshine a year that the state experiences (BOM 2016). Further, in 2001, the federal government created the Renewable Energy Target (RET), in which the Solar Homes and Communities Plan provided installers of small-scale solar systems with a financial incentive. Initially, as prices of solar systems were high, the uptake was relatively low, however this changed in 2009 when the government changed the Plan to Solar Credits. Solar Credits provided upfront capital cost subsidy, worth around AU\$7,500 by applying a multiplier to certificates generated from small generation units. At the same time, solar costs fell rapidly whilst the value of the Australian dollar increased, and states and territories put in place generous feed-in tariffs. This coalescing of factors contributed to a large increase in the installation of rooftop solar PV as well as large-scale solar systems. Consequently, the rapid increase of certificates caused certificate prices to fall dramatically, creating price uncertainty. The government responded by legislating to separate the RET into two schemes: the LRET for large-scale projects, and the SRES to assist households and businesses with the upfront costs of small-scale solar PV (Climate Change Authority 2017).

Another important condition is that in the past, a generous feed-in tariff was imposed but then was quickly dropped. In Australia and globally, solar PV prices have declined so much in recent years that PV electricity can compete with grid pricing without subsidisation (Deutsche Bank 2015). With prices continuing to decline, solar PV has already eaten into the market share of incumbent utilities (Economist 2013).

Globally, locations that have seen high penetration rates of solar PV have experienced a number of different drivers for the uptake of renewables, including government subsidisation, high electricity prices, and behavioural drivers (such as a desire to lower individual carbon footprints), the rapid lowering in price of solar PV systems, and the high availability of sunshine (Deutsche Bank 2015; REN21 2016). In 2015, Deutsche Bank examined the price of electricity in 60 global locations, finding that grid parity for solar electricity had already been realised in half of the places (Shah and Booream-Phelps 2015). The key factors to facilitate solar penetration, as well as grid parity, were noted to be high levels of sunshine and high electricity prices.

In Western Australia, like many other locations around the world, the first influential driver for the uptake of solar PV systems took the form of government subsidisation, a policy that was remarkably effective. Government-owned utilities initially committed to purchasing excess electricity generated by these systems at AU\$0.40/kWh in order to create a more attractive payback period for solar panels owners (Synergy 2016). However, the significant and unexpected uptake of panels in the SWIS meant the government had to cut the rate to what it is today, AU\$0.07/kWh, because they could no longer afford the high initial subsidisation price (Synergy 2016; King 2011). Around the world, it is expected that renewable will globally be able to compete with traditional sources of electricity without government subsidisation by 2020 (BNEF 2015a). It appears to have already crossed this line in Western Australia.

Solar PV in Australia, and indeed in other parts of the world, have benefited from subsidies and received criticism for this, as though it has obtained 'unfair advantage'. However, it is important to note that fossil-fuel dependent sources of electricity do not pay for the full impact of their externalities, also commonly referred to as a Pigouvian tax (Baumal 1972), these subsidies could instead be considered a quid-pro-quo market equalizer.

However, despite the declining payback period for this technology, solar generation still suffers from its primary drawback; that it cannot provide electricity when the sun is not shining. Thus the development of storage options is a major part of the disruptive trend that is being analysed in this thesis.

Presently, solar PV panels allow households to generate power during the day while the sun is shining and sell any excess power they have to the grid. Then at night, households purchase electricity from the grid, when their solar PV panels are unable to generate power. This is not desirable for two reasons. The first being that peak demand for power usually occurs in the evenings when solar PV panels are unable to generate electricity. The second is that solar PV owners sell their electricity for a much lower rate than they buy it back at night. A solar PV owner could therefore still accrue a large bill from a utility despite generating far more electricity than they consume (Green and Newman 2016). Cost-competitive storage rectifies both these shortcomings, as it allows consumers to store electricity for consumption at night. A detailed case study of this will be examined in the thesis.

April 30 2015 saw the launch of US company Tesla's Powerwall, a lithium-ion-phosphate battery, sized to facilitate household electricity needs at a low price that set a new benchmark for the market (Debord 2015). Even though these batteries were not available until late 2015, Tesla received US\$800 million in pre-orders during the week post launch (Randall 2015). Other battery manufacturing companies have also benefitted from the increased interest. As batteries enter the market and are demanded by consumers, their prices will decrease, and Bloomberg New Energy Finance asserts that battery prices are already experiencing a similar rapid decline in price to solar PV technology (BNEF 2015b), with forecasts for prices to halve between 2015 and 2020. The mass utilisation of battery technology in smart phones, laptops, electric vehicles and household energy storage has and will continue to work to lower the price of batteries.

When cost-competitive batteries are paired with solar PV systems, they can provide a localised alternative to grid-sourced electricity. As battery prices further decline, these systems will approach price parity with conventional electricity. Solar PV panels are already disrupting utilities' business models during periods of the day when the sun is shining, and this is only set to increase to all periods of the day as batteries experience mass-market uptake (Chambers and Rozali 2014).

Many incumbent electricity utilities have not adequately considered the impact that battery storage will have on their traditional business model of centralised electricity generated in one place and utilised in another (Koh and Baker 2015), or as Schumpeter called the 'creative destruction' (Schumpeter 1942). Battery storage technology is not limited to lithium-ion-

phosphate, as other chemistries of battery such as flow, liquid, and zinc-bromine batteries will also enter the market (ARENA 2015). However, this paper is not examining the different technologies and chemistries of batteries, rather, it focuses on those currently being deployed in the mainstream market. It focuses particularly on lithium-ion batteries, as they have been chosen as the battery of choice by Chinese manufacturers, and the resulting mass production has dramatically lowered their price to below the levels of that predicted for the Tesla battery. Therefore, solar PV with lithium-ion batteries is poised to create a truly disruptive influence.

2.2.2 Modular Construction

A great deal of electricity is consumed in the building construction process and the production of the materials used within the buildings (Hammond and Jones 2008; Venkatarama Reddy, 2003; Sartori and Hestnes 2007; Lenzen 1998). Dwellings that are poorly designed from a thermal performance perspective are more reliant on mechanical heating and cooling, which requires electricity. Thus, there is a strong relationship between household electricity costs, the carbon emissions of buildings, and the materials used in the building (Aye et al 2007 and 2012).

Literature suggests modular construction offers cost and time savings, with a reduction of up to 70 per cent of waste compared with traditional building approaches (Rogan, Lawson and Bates-Brkljac 2000) due to efficiencies in design. Construction work hours can be reduced by an estimated 50 per cent (SBEncr 2015) and mitigates the risk of weather delays (Li et al. 2013).

In Australia however, modular construction has not yet reached the mainstream, representing approximately just 3 per cent of the construction market (Green and Newman 2014), despite high construction costs, household electricity prices, and in global terms, high greenhouse gas emissions per capita (Muenstermann 2012).

This thesis asserts that modular construction could be a potentially disruptive technology as it affords a variety of time and financial benefits, as well as being a low-carbon innovation. It also has the potential to assist cities that want to institute urban growth boundaries, or want to respond to rapidly growing demand for better located housing, to do so without causing house

price inflation. Newman and Kenworthy (2015) show that there is an increasing demand for cities to grow at higher densities than to continue grow at low-density. There are also significant agglomeration benefits for cities that grow up rather than out (Glaesser and Gottlieb 2009) including productivity gains and being more innovative. There is both public demand in terms of increased efficiency in use of infrastructure and creation of knowledge economy jobs, as well as private demand to be part of this new economy.

The first manufactured housing plant was created in the United States in 1926 (SBEnrc 2015) followed by the UK, and Japan in 1955 (SBEnrc 2015). The prefabrication of buildings in Australia dates back to the first set of portable iron-clad homes constructed in the UK that were shipped to Melbourne in the 1850's (SBEnrc 2015). The aftermath of World War II included the ready availability of building materials and a need for rapid rebuilding, creating the perfect storm for many countries to employ pre-fabricated construction methods (Maddocks 2011).

Modular construction methods have historically experienced quality issues that have resulted in preconceptions about the products of today's modular construction methods (SBEnrc 2015). During the 1960's and 1970's, Great Britain and Sweden had an initial focus on mass-production instead of fulfilling customers' needs and desires in a building, instead ensuring an efficient and effective prefabrication process, which resulted in poor uptake (SBEnrc 2015). In the past, manufactured buildings have often been perceived to be used only for site huts or temporary transportable rooms or offices, which are common in Australian construction sites, mines, and schools. However, the latest market offerings allow for high-quality precision-designed buildings to be produced that are more thermally efficient and therefore low-carbon (SBEnrc 2015). At present, there is limited literature assessing market acceptance and perception of contemporary modular.

Modular construction harnesses similar technologies to the aerospace, shipbuilding, and automotive industries (Buswell et al 2007; Green and Newman 2014). Harnessing the know-how and technology from other sectors, such as the automotive sector, would be crucial in Australia establishing a domestic modular industry. To start with, the demand for modular in Australia is likely to be stimulated initially because of the rapid growth in building manufacture in the Asia-Pacific region, (Green and Newman 2014) which is lower cost, and is being imported into Australia.

New skills required by the building sector to deliver manufactured buildings include design for manufacture, material innovation, transportation, and erection of modules; the procurement and management of materials, and a re-evaluation of construction techniques to maximise the time saving benefits of modular construction (SBEnc and CRC 2015). Even though modular in high-income OECD countries may not be able to compete with labour costs for similar operations in developing countries, there are advantages to offering a domestic supply. Advantages such as reduced transport time and costs, easier commission, easier defect rectification, and, in general, a greater level of certainty around post-purchase support (SBEnc and CRC 2015).

While Australian cities consider modular construction to be a relatively new technology, Scandinavian countries are seeing modular construction becoming the norm i.e. ‘creatively destructing’ (Schumpeter 1942) the traditional building industry, with 50 per cent of housing in Finland and 74 per cent of housing in Sweden being prefabricated (SBE 2015). Strong international growth can be considered a potential indicator for a domestic industry, and a reported global growth of US\$30 billion between 2011 and 2012 in output from the prefabricated building (Business Wire 2014). The Australian modular industry is aiming to account for 10 per cent of the construction market by 2020 (PrefabAUS 2015). Other countries are on a similar growth trajectory, such as the US and the UK (Business Wire 2016). Thus the time and financial savings as well as market penetration and acceptance of modular in other countries, suggests that modular technology could have a bright and potentially disruptive future both in Australia and on an international basis.

In applying disruptive innovation and transition theory, this thesis examines the potential of modular construction to be a disruptive innovation to the traditional building industry in two ways. Firstly, the potential for a domestic transformation that will see the building industry in Australia up-skill and side-skill with this new disruptive technology, i.e. micro and meso MLP transition context (Twomey et al 2014). Colocation of modular factories and demand for the buildings reduces transport costs and offers a greater opportunity for modular in high-income OECD countries. If the demand for modular housing is met by products made interstate, or even internationally, the local building industry will be affected due to the failure to innovate around this new technology, i.e. a macro transition context (Twomey et al 2014).

The second scenario is where the international growth of the modular construction industry, is not mirrored in Australia, leading to competition between international modular buildings and traditionally constructed buildings in Australia. For this risk to be mitigated and managed, i.e. to create a competitive domestic modular industry, the Australian modular industry would have to overcome a number of barriers to the deployment of modular. From a technological innovation system (TIS) theoretical perspective, actors, institutions, entrepreneurial activity, knowledge development and diffusion, market formation and resource mobilisation (Twomey et al 2014) are all catalytic factors that could underpin disruption and transition.

If modular construction in Australia is enabled it could strengthen both the building and manufacturing sectors. To understand why this isn't yet the case, the socio-technical systems need to be examined as well as the modular technology itself.

In order for countries like Australia to develop a strong modular construction industry, it will need to address a number of barriers. A significant challenge for the domestic modular industry is the availability of bank finance for modular projects. Currently, there is not a *culture* of lending to the modular industry (Curtin University 2016). In Australia, financial institutions are presently reluctant to lend to the modular industry, due to concerns around completion risk and how progress payments are made. Completion risk manifests when a modular manufacturer goes into liquidation prior to the completion of a project. Distinctly, under the same scenario with traditional construction methods, a lender can appoint a new developer to complete the project (Curtin University 2016). Another issue for modular is related to progress payments. These are financial payments made from lenders to developers, commensurate with progress made at the development site i.e. in-situ. However, with a development using modular construction methods, most of the progress occurs in the modular factory. Lenders in Australia are presently reluctant to release payments for progress that takes place in a factory, as opposed to in-situ (Curtin University 2016). Perhaps counter intuitively, the existence of imported modular is, in fact, helpful to the domestic modular industry, as the competition will promote innovation as well as market acceptance from a consumer, developer, and lender perspective.

Within the building and finance industries, new *cultural behaviour change* and *business models* are needed for the disruptive technology of modular construction to reach its full potential domestically. Regulation may need to be reformed. An example of this is that until

recently, schemes such as the Queensland Home Warranty Scheme that protects consumers and builders excluded ‘*offsite prefabrication in a factory of the whole of a building*’ (BSA 2011). In Europe, schemes have been developed to underwrite modular development (EU 2014). In the United Kingdom, a scheme called BOPAS has been developed to underwrite finance to the modular industry (BOPAS 2016). Further, completion-risk could be addressed by modular producers having a backup producer to step in, in the event that the primary producer cannot complete the project (Curtin University 2016). Policy reforms at all levels of government may be required to unlock the potential of modular, either because regulations are explicitly opposed to modular, or have not contemplated it.

If these financing and regulatory barriers are not overcome, the industry will remain constrained and will therefore not be able to grow and compete with established traditional building methods. This would result in Australian cities and other cities globally missing the opportunity that modular could provide to create low-cost, low-carbon housing. That scenario would be a missed opportunity for Australia, as international growth in the industry would see competition with the Australian building industry, whether it adopts modular practices or not.

Aside from the market building opportunity, modular construction can also offer environmental benefits that could contribute to the development of a sustainable, low-carbon Australia (SBEnrc 2015). To achieve this, designs and materials used in the buildings would need to be refined, depending on the location of the development, to achieve optimal thermal performance. Further, lower embodied energy and carbon in the building materials must favourably compare to traditional building equivalents (SBEnrc 2015).

From a planning perspective, when city limits are imposed to contain sprawl, often, consequently, issues around housing affordability emerge due to constrained supply (Sheehan 2001; Glaeser et al 2003; Nelson et al 2004; Donegan and Kelly 2015). However there is a growing market for redevelopment of well-located areas into higher-density housing, though this also suffers from price issues due to land costs, especially in Australia (Newman and Kenworthy 2015; Rowley and Phibbs 2012).

Market acceptance of modular is also crucial to uptake, i.e. demand led disruption. These areas include acceptance of modular products by consumers, which would encourage property

developers to use the product. Long-term lower maintenance costs for modular buildings have to be understood to promote industry acceptance. There is little research in this area to date.

Further, there are limited research case studies comparing the overall performance of both modular construction methods and modular buildings in relation to traditionally constructed buildings. Therefore, in undertaking a case study, this applied research intends to identify some of the barriers and evaluate how the modular industry, developers, and lenders may overcome them.

2.3 Disruptive Business Models

2.3.1 Solar Storage

If alternative energies are able to compete against fossil fuel alternatives both from a cost and reliability perspective, then demand for fossil fuel energies will decline along with the valuations of fossil fuel companies (Carbon Tracker 2015). Many commentators are saying that these assets are overvalued due to a failure to tax or regulate the external costs, such as carbon, and therefore represent an economic bubble (Carbon Tracker 2011). Future investment in new projects is also at risk, due to the long-term outlook for fossil fuels being in structural decline (Carbon Tracker 2015).

According to Carbon Tracker, assets can become stranded for three main reasons: regulation, physical impacts, or change in market demand. These dramatically alter the intended market course of the product (Carbon Tracker 2014; IEA 2013):

1. **Regulatory stranding** of assets occurs when there is a change in government legislation that impacts how an asset is used. This increases the effort and cost required to use the asset in accordance with extensive regulation. This happens to the point where ceasing operations is the easiest or cheapest option for a business. Examples include asbestos products, chlorinated hydrocarbon pesticides, leaded petrol, and incandescent light bulbs.
2. **Economic stranding** occurs when there is a change in the market's appraisal of the asset. Investors' expectation of the probability of future cash flows is altered, and, as

such, the asset is no longer as attractive as before. This can be the result of a new product entering the market or from rising costs relating to regulation or physical changes. The asset suffers from an unanticipated or premature change in market value, becoming worth a lot less in the market than originally planned. It is then converted to a liability for a company and its shareholders. Examples of products that have been stranded due to market changes include walkmans, record players, PDAs, floppy disks, and whale oil for lighting. The disruptive innovation discussed in this thesis is mostly related to this third form of stranded asset due to economic stranding.

Regulatory and economic stranding are correlated and share many of the same drivers.

3. **Physical stranding** occurs when access to the asset is impacted by a change in environmental conditions, such as a flood preventing access, or conditions that will deteriorate the resource faster, leading to a decrease in its lifespan. The physical limitations in accessing the resource, or using it, ultimately overcome the desire or cost behind trying. An example is when farms are no longer viable due to declining rainfall resulting in the land no longer being arable.

Further, **litigation risk** relating to climate change and associated impacts is also a discrete and material concern to a company's survival. This can occur when investors pursue the company they are investing in for not adequately disclosing or addressing climate concerns, or where a third party pursues a company for the impact it is having to the climate. Size of claims relative to market capitalisation could present an existential threat to companies. The Taskforce on Climate Related Financial Disclosures, led by Mark Carney, has prepared a report of recommendations to manage and mitigate these risks.

Irrespective of what drives the decline in demand for a product, the result is ultimately the same: stranding. The previously-valued product becomes redundant and it is no longer viable for the company to continue making it. Current examples of products that are at risk of becoming stranded are those related to the electricity generation and motorised transportation industries, due to the phasing out of carbon-intensive fuels. Although coal and oil are at historic low prices, they are being replaced or 'disrupted' by other energy sources. Assets related to their production and use are becoming stranded as new power production (especially rooftop solar PV) and new transport options (especially electric transit and motor

vehicles) become a demand choice (Newman and Kenworthy 2015). In some places this has been assisted by subsidies, however, incumbent fossil fuel industries are also greatly subsidised (IMF 2015). Hence, this is likely to delay the realisation by investors that the investment in the asset is likely to be stranded and will result in economic loss. Such confusion does exist in the market outlook, though data in this thesis shows that investment is now settling on the alternative technologies, thus rapidly shifting the market to being disruptive.

Global electricity demand forecasts have conventionally been undertaken by electricity market incumbents, which are predominantly fossil fuel companies. Many fossil fuel companies, including Exxon Mobil and Shell, have conducted forecasts for future global energy and electricity demand, concluding that there is a bullish outlook for their sector. Similar projections from the EIA (US Government Energy Information Administration) have been made with assumptions that little change is likely in the growth in consumption of fossil fuels (Carbon Tracker 2016). Therefore, fossil fuel businesses isolate themselves from potential risks to the consumption of fossil fuels, such as climate change policy, or the growth in renewable energy generation due to disruptive innovation (Exxon Mobil 2014; Shell 2014), which runs counter to ideas proposed by Aghion et al 2014 and Zenghelis in Jacobs and Mazzacuto (2016). The bullish outlook for energy and electricity consumption is mainly driven by a view that the industrialisation of the developing world will ensure a continued relationship between the growth in electricity consumption and the growth of GDP.

However, the relationship between electricity consumed and GDP is beginning to show a divergence, as energy efficiency measures and the growth of renewable energy result in significant drops in electricity consumption, especially in OECD countries (BNEF 2015a; IEA 2014a and b; von Weisacker et al 2014; Smith, Hargroves and Desha 2010; Newman and Kenworthy 2015). However, many developing nations are also showing the beginnings of decoupling. Throughout 2014-2015, China's economy grew 7 per cent, yet its electricity intensity only grew 3.8 per cent (Garnaut 2015), with similar trends continuing since. In addition to reducing the amount of electricity consumed, China has made commitments to reduce its greenhouse gas emissions, which are the highest in the world (The White House 2015) by decarbonising its electricity supply.

Conversely, many fossil fuel companies also produce estimates surrounding the growth of renewable energy. None of them have the view that renewables will be able to grow quickly enough to topple fossil fuel generation before 2050. However, in October 2015, BHP Billiton released the first risk analysis on its asset portfolio, assessing the possible impacts of climate change out to 2030. This report is also the first-of-its-kind in sector and represents a shift in the mentality of this multinational fossil fuel corporation. The report concluded that BHP was in a good position, due to the industrialisation of developing countries. It is also concluded that there is post-industrialised demand for its other assets such as copper and uranium. Although a robust analysis in some areas, the assumptions in this report may not necessarily play out, as it doesn't consider the possibility of renewables being able to compete with fossil fuels, the growing trend for countries wanting to become more energy independent by supplying their own fuel, exemplified by India's move to end coal imports (Buckley 2016), or attempts by countries to reduce urban air pollution and associated health issues, as China is pursuing (Sheehan et al 2014). While BHP's assessment of their asset portfolio is by no means certain, the undertaking of such an analysis is still significant.

The view that global electricity demand will rise in concert with GDP is starting to be challenged (Newman and Kenworthy, 2015; Newman, Beatley and Boyer 2017). The developing world may not industrialise in the same way as it has in the past, with new low-carbon technologies entering the market. For example, decentralised renewable energy and storage may enable certain locations to 'leap-frog' the need for an expansive grid, in favour of micro-grids and standalone power systems. Renewable energy, when paired with storage, possesses the characteristics of a disruptive innovation, and so is likely to grow exponentially to challenge centralised fossil fuel electricity generation in the market. Thus, instead of growth in GDP correlating with growth in fossil fuels, as has been seen for the Fourth Wave economic cycle, it is likely that fossil fuels and GDP will decouple materially (Smith, Hargroves and Desha 2010 and Newman and Kenworthy 2015). This perspective underlies the research in **Journal Paper 1** and also parts of the other papers.

2.4 Disruptive Culture and Behaviour Change

In order for innovations to rapidly become adopted, they need to be demand-led. This can be because of product performance, price or a combination of the two (Christensen et al 2015). This means that the consumer culture needs to be supportive and that the behaviour change

requirements are acceptable to consumers or the market. In the analysis of the solar-storage phenomenon, it was clear that the dramatic growth in Perth of rooftop solar was led by consumer demand for a technology that eased household electricity costs and easily fitted into the lifestyles and desires of the population. The thesis, however, pursues a more difficult question about the adoption solar PV in multi-unit housing, where presently there is limited uptake. The research looks at what are the commercial and business models, culture and behaviour change needed to underpin the innovations in this part of the housing market.

In relation to modular construction, this thesis evaluates the technology itself as well as business models, culture and behaviour change needed to facilitate its uptake. Given that modular construction currently represents a small percentage of the overall construction market in Australia, it is important to understand what challenges the modular industry faces now and in the future. For example, is it primarily the financing challenges? Is it cultural shifts for consumers in trying something new? Is it understanding the relative benefits of modular compared against traditional construction? Or is it for governments to see the opportunities for modular construction in delivering affordable housing supply and to create supportive policy settings to facilitate its developer and consumer demand for modular?

The Western Australian Government has infill plans to increase the population density of Perth (WAPC 2010), with around half of the new 700,000 homes to be constructed between now and 2050 targeted to be infill (WAPC 2015). However, the need for regeneration is a highly contested space in cities like Perth that have been built in the low-density car-dependent era of city building (Newman and Kenworthy 2015). Medium-density housing, however, has had limited uptake in Perth's recent history, as it has been relatively more expensive compared with greenfield development (Rowley and Phibbs 2012). Within Perth, presently only 9 per cent of the population lives in flats, units and apartments (ABS 2013b). By 2020 there are expected to be an additional 10,685 apartments added to the market, being approximately 40 per cent of the new housing supply (Y Research 2015). Therefore, there is a need to understand what attributes people want in medium-density housing before undertaking such a large expansion project, instead of relying on stated preference surveys.

Research about low-cost and low-carbon housing in Australia is quite limited. Important examples include Grattan Institute's *Housing We'd Choose*, Curtin University's *Housing We'd Choose for Perth and Peel* and research from AHURI (Kelly, Weidmann and Walsh

2011; Rowley 2013). This research is based on stated, rather than actual preference surveys, where people comment on hypothetical situations. This has resulted in potentially distorted views of people's housing preferences being presented, rather than analysing actual market trends to draw conclusions.

These studies focused on what people would choose in a situation that they have not actually encountered. It is hard to replicate actual market choices, and people often choose options out of the range of their budget in hypothetical situations (Department of Housing and Planning 2013; Jones, Irwin and Roe 2004). Typically, interviews are conducted with only a random sample of the population, regardless of whether they are currently looking to move or to install low-carbon technologies. Therefore, there is not a clear picture of how people would actually react to low-cost, low-carbon housing choices.

The need for affordable and sustainable housing is not a situation unique to Perth, or Australian cities (Kelly et al 2014). Cities around the world have become the economic engines of nations globally (Manyika et al 2012). Owing to concerns around affordability and climate change, the need for low-cost, low-carbon redevelopment has become a global imperative.

While low-cost, low-carbon technologies and housing options may exist in the market, the uptake of them by the population will require mass behavioural changes or changes in demand. Manu (2010) describes culture related innovation as being when a technology changes behaviour, it changes the culture. Therefore, looking at instances where consumers choose low-cost and low-carbon housing could be instructive in identifying what are the *disruptive culture and behaviour changes* that would lead to this outcome.

Clayton Christensen characterises disruption as:

'a process whereby a smaller company with fewer resources is able to successfully challenge established incumbent businesses. Specifically, as incumbents focus on improving their products and services for their most demanding (and usually most profitable) customers, they exceed the needs of some segments and ignore the needs of others' (Christensen et al 2015).

Further, entrants that prove to be disruptive begin by successfully targeting those overlooked segments, gaining a foothold by delivering more suitable functionality, frequently at a lower price. Incumbents, chasing higher profitability in more demanding segments, tend not to respond vigorously, miss the opportunity (Christensen et al 2015) and therefore their underlying assets becoming stranded.

The Australian market has seen sky-high rates of household rooftop solar penetration with forecasts for this to continue (Flannery and Sahajwalla 2013). This has almost completely been focussed on low-density housing for a number of reasons. These dwellings are often tenanted and (ABS 2014) investors have had little incentive to provide expensive renewable energy infrastructure when tenanted as it does not benefit the dwelling's purchaser. Designing a shared energy system adds a level of complexity and additional upfront cost to developers. At present, established models for strata development companies to utilise rooftop solar and batteries are lacking, as well as most other sustainability innovations that operate at a precinct scale (Bunning et al 2014). The market for this renewable energy in strata is substantial, as Australia has an estimated 3 million strata and community owned developments (Altmann 2012). Owing to how strata is often developed, with a developer designing and constructing the buildings, and then selling them to a third party, the Principle-Agent problem (Jensen et al 1976) can also be cause for limited innovation of electricity within strata buildings. The Principle-Agent dilemma holds that one person or organisation (the 'agent') makes decisions on behalf of, or that impact, a third party: (the 'principal') This dilemma exists in situations where agents are motivated to act in their own best interests that are contrary to those of their principals. To see electricity system innovation in strata, this dilemma or problem would need to be overcome.

If modular construction is able to deliver higher-density dwellings at a lower cost and to a more efficient carbon standard, then it could make a considerable contribution to cities' economic prosperity and sustainability. When human behaviour engages technology in an innovation outcome and value is exchanged, this exchange creates a *disruptive business model* (Manu 2010). For this 'creative destruction' (Schumpeter 1942) to occur, developers and consumers would need to see the modular product being of a similar or better quality to traditional construction alternatives to choose it in favour of traditionally constructed homes. Without this, the product demand would not be there (Foxon 2010). Citizens' engagement

with new technologies is therefore a manifestation of innovation as a behaviour outcome and the trigger for an innovation behaviour cycle (Manu 2010).

Whilst there may be commercial opportunities in pursuing innovations in the construction sector (Fang 2016), these innovations may have transformative potential (Kahkonen 2015), pre-existing cultures and behaviours that present challenges could also need to be overcome for them to be adopted (Twomey 2014) and ‘creatively destruct’ (Schumpeter 1942) or ‘strand’ (Carbon Tracker 2014) the incumbent traditional building sector.

From a developer perspective, the literature suggests that modular construction can deliver advantages in terms of construction times, which allow the product to get to market faster, thus modular also has cost and timing advantages (Steinhardt et al 2013). Modules are built away from the final site, minimising the impact on the surrounding roads and community from construction noise and site movements. In sustainability terms, modular construction typically produces around 50 per cent less waste, and the thermal performance of the building can be improved at a lower cost than in traditional buildings (Rogan, Lawson and Bates-Brkljac 2000). Modules can more readily be designed to contain less embodied energy over their lifecycle, reducing the overall greenhouse gas impact (Aye et al 2012).

These advantages, however, don’t guarantee a market for modular buildings. Disruptive innovation and transition theories hold that consumers have to demand a product i.e. to be willing to purchase modular, developers would need to choose modular construction methods, and financiers need to lend and invest in modular projects (Twomey et al 2014). These cultural (macro) preconditions need to be met for an innovation to be disruptive. For modular construction, one hypothesis is that the consumer market may see modular being of lower quality, hence culture and behavioural factors present a challenge. Around business models, finance, in the UK, for example, lenders are able to insure their loans to modular projects using a scheme called BOPAS (BOPAS 2016), which has created a culture of lending to the modular industry.

There is clearly a relationship between the presence of disruptive innovations and whether incumbent assets become stranded. In relation to solar-storage and modular construction, this thesis examines to what extent the presence of stranded assets a test of whether there has been a disruption.

If disruptive innovations like solar-storage and modular construction are to be facilitated then it is important to address any barriers to deployment of renewables and modular housing, as well as understanding what other systemic conditions and the market conditions for incumbent technologies, need to alter to facilitate such a transition.

Thus all three factors - evaluating a technology, examining culture and behaviour changes, and analysing business models – are needed to help mobilise technologies that deliver low-cost and low-carbon housing. Only in this way is it possible to see whether technologies are likely to be disruptive innovations.

3. RESEARCH DESIGN AND METHODOLOGIES

This section outlines the research design for the thesis, the different methodologies used, and assumptions made for the journal papers. Figure 3 below includes an outline of the original research undertaken over the course of this doctorate grouped under each paper.

Research Question	How can disruptive innovation contribute towards low cost and low carbon housing?					
Key Area of Research	Disruptive Technologies		Disruptive Business Models	Disruptive Culture Behaviour Change		
Paper	Stranded Assets and forecasting renewable energy futures	Citizen Utilities: The Emerging Power Paradigm	Modular Construction vs Traditional Construction: An Australian case study	Governance of decentralised energy assets in strata developments	How does sustainability influence actual medium density housing preferences?	
Research Questions	How will the disruption to the traditional energy market from renewable energy and storage impact global energy demand forecasts, and what implications does this have for fossil fuel assets? Under which scenarios could renewable energy meet the majority of global energy demand?	When will solar and battery systems reach grid parity in Western Australia? What effect does the installation of solar panels have on a household's utilisation of grid electricity? What further reductions are seen when a battery is installed? What is the role of the grid in a distributed system and what are the changes to the utility business model, especially in retailing electricity? Is solar-storage a disruptive innovation?	How do modular buildings compare against traditional buildings? Is modular construction a disruptive innovation?	What governance, ownership and financing arrangements are possible that will facilitate renewable energy and storage uptake in strata?	What is the relative importance of sustainability features when compared against other dwellings features and location features in determining purchasing and rental decision making?	
Case Studies	Global Energy & Renewable Energy Forecasts	Josh's House	Adara	Gen Y Housing Development	27 medium density developments	
Publication	Journal of Sustainable Finance Investment	Energy Policy	Energy & Buildings	Urban Policy & Research	Cities	
Publisher	Taylor & Francis	Elsevier	Elsevier	Taylor & Francis	Elsevier	

Figure 3: PhD research design

3.1 Research Design & Methods Journal Paper 1 Global Energy Forecasts out to 2050⁴

The research questions addressed in this paper are focused on the global renewables transition: How will disruption to traditional energy markets, from renewable energy and storage, impact global energy demand forecasts? What implications does this have for the value of fossil fuel assets? Under which scenarios could renewable energy meet the majority of global energy demand?

These questions are addressed through the following steps:

1. Using historical energy data from BP and the IEA baseline scenario from 1980 to 2014, the research mapped past global energy demand, and then forecast a number of scenarios in which demand decouples from GDP at a rate of 10, 20, 30 and 40 per cent out to 2050.
2. Using historical energy data from the IEA baseline scenario from 1990 to 2010, the research mapped the growth in renewable generation and then forecasted three different scenarios. It demonstrated that the rate of growth of renewables was increasing by 6, 7 and 8 per cent above IEA baseline scenario forecasts, out to 2050.
3. All these scenarios are then compared, identifying which permutations will see renewable generation accounting for 100 per cent of global energy demand by 2050.

Global Energy Forecasts and scenario analysis to 2050

This research uses energy consumption data and GDP predictions from the International Energy Association forecast out to 2050. This shows energy demand decoupling from GDP at a rate of 10, 20, 30, and 40 per cent to 2050. The second variable is the growth of renewable energy, which is plotted using historical data out to 2050 with increases of 6, 7 and 8 per cent above the IEA baseline scenario forecast. These two factors are analysed in conjunction with each other to determine what would need to happen in global energy efficiency and global renewable growth to see renewable energy account for 100 per cent of global energy demand by 2050.

⁴ Published in the Journal of Sustainable Finance & Investment December 2016

3.2 Research Design & Methods Journal Paper 2 Citizen Utilities

The overarching research question for this paper is about the local renewables transition: What is happening in Perth with its opportunities to demonstrate the residential solar transition? When will solar and battery systems reach retail grid parity in Western Australia? What effect does the installation of solar panels have on a household's utilisation of grid electricity? What further reductions are seen when a battery is installed? What is the role of the grid in a distributed system and what are the changes to the utility business model, especially in retailing electricity? How can utilities respond to this transition? What are the different responses that incumbent utilities could have in dealing with the disruptive nature of solar-storage? What responses are most likely to see their continued relevance? What role will consumers have in the new electricity system paradigm?

What size solar-storage system is needed to be 'off grid'?

Using data collected over a year from June 2014 to June 2015, sourced from a house with a 3kW solar PV system installed, this research evaluated how much electricity the house consumed in that year, what percentage of the electricity was sourced from the grid, and what percentage from the solar panels. A 10kW battery was then installed, which has an optimum usage of 8kWh. At the time, this was the only residential battery installed in Perth.

The combined capacity of both the solar panels and the battery are then used to evaluate the amount of electricity that would need to be drawn from the grid, with the household first prioritising the electricity sourced from the solar panels and then from the battery. An optimisation test for the energy load demanded by the house during that year-long period was then conducted to see what was required for the house to be entirely grid independent.

Another key research question examined in this paper is: When will solar and battery systems reach retail grid parity in Western Australia? To address this question, this research uses a linear-regression forecasting model to predict the price of the A1 tariff in the future. For past prices and to forecast the price of solar-storage systems, a consensus estimate is used. During the forecasted period for the cost of electricity from solar-storage, this information is sense-checked against market forecasts by undertaking a logarithmic regression.

3.3 Research Design & Methods Journal Paper 3 Modular Construction

Hickory Case Study

A part Hickory-designed modular building called Adara and its equivalent of traditional design were compared and evaluated from three perspectives: time, cost and sustainability performance. To determine the financial performance, construction costs, funding costs, and return on investment were evaluated.

To evaluate the sustainability performance, the thermal performance, operating energy, construction, and operational greenhouse gas emissions and waste during construction were examined. To evaluate the thermal performance, comparisons between the modular building and a traditionally constructed building were made in three different geographical locations: Melbourne, Perth and Port Hedland, in order to examine the role of local context and climate.

The overarching questions this research on the construction transition seeks to answer are:

How do modular buildings compare against traditional buildings when considering cost, time and sustainability performance? What role can they play in delivering low-cost and low-carbon housing? The approach is set out in the research model in Figure 4 below.

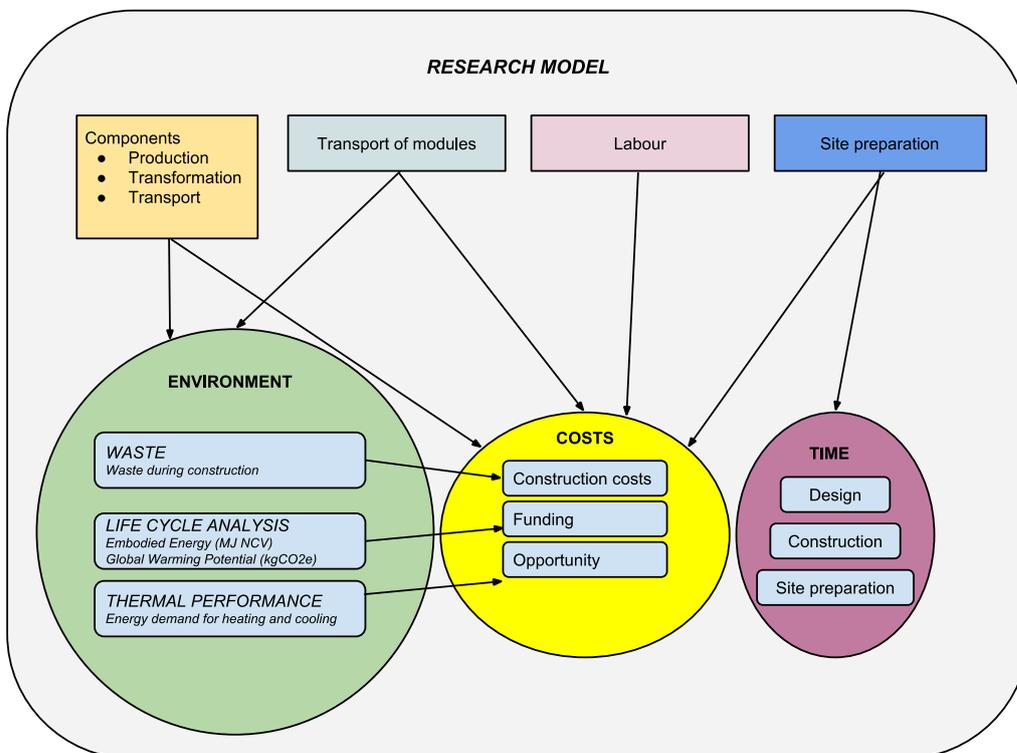


Figure 4: Research model for modular versus traditional building analysis

As well these questions the paper seeks to answer: **What are the barriers and opportunities for traditional builders to become part of this transition? How can the barriers be overcome? How can modular buildings be optimised for context specific thermal performance, and therefore low-cost and low-carbon housing?**

3.4 Research Design & Methods Journal Paper 4 Solar-Storage in Strata: The Gen Y Case Study⁵

The overall research question for this housing transition paper is: **What governance, ownership, and financing arrangements are possible that would facilitate renewable energy and storage uptake in strata housing developments?**

This question was answered using action research methods where researchers work with participants in a study to trial new practices, ultimately helping the development of new commercial models, strategies and technologies, and contributing to guidelines for best practice. The case study for this paper is the WGV development located in White Gum Valley in the City of Fremantle, Western Australia. As a result of this action research, this development has specific electricity network designs using state-based strata legislation.

This action research, to design the building's electrical system and governance framework, took into account the following factors:

- a) The fair charging by reference to consumption of electricity for both the apartments and the common areas;
- b) The fair apportionment of capital to a sink-fund for maintaining and replacement of assets at end-of-asset-life;
- c) Accurate sub-metering with automated billing capability;
- d) Compliance with the Strata Title and Residential Tenancies Acts;
- e) Compliance with the regulations for Western Power, Synergy and the AEMC;
- f) A strata company willing to manage the assets and billing; and
- g) Owners and tenants willing to buy and live in the dwellings with these assets and governance system.

⁵ Accepted for publication in Urban Policy & Research August 2016

Interviews were conducted with key stakeholders, strata companies, developers, involving the CRC for Low Carbon Living, architects, CSIRO, LandCorp and Balance Energy to develop the battery system tested in the strata complex.

3.5 Research Design & Methods Journal Paper 5 Demand Drivers for Medium Density Housing⁶

The question that this research aims to address in the housing transition is: **How does sustainability influence actual medium-density housing preferences in Perth, Western Australia? And what is the relative importance of sustainability features when compared against other dwellings features and location features in determining purchasing and rental decision-making?**

This research is based on surveys of residents and an assessment of the features of the development's location using a multi criteria analysis. MCA is a way of evaluating complex problems by breaking the problem into more manageable components to allow objective data and subjective judgements to be brought to bear on the pieces and then reassembling them to present a coherent overall picture. This approach explicitly considers multiple criteria in decision-making in both qualitative and quantitative measurements (Gamper & Turcanu 2007). MCA has been an active area of research since 1976 (Delft & Nijkamp 1977) and is widely used by governments and businesses to understand optimal solutions and designs for problems which include multiple inputs.

From 27 developments, a minimum of four residents from each were surveyed on their reasons for choosing that particular dwelling and location. The surveys gathered information on demographics, reasons for choosing that dwelling, a rating of aspects that influenced their decision and some decision trade-offs the residents made. Each development was assessed based on location, amenity and facilities, affordability, and sustainability. These covered aspects such as distance to the CBD, school selection, amenities, parking options and the

⁶ Accepted for publication in Urban Policy & Research July 2016

design of the dwelling, as well as sustainability features such as public transport options, bike paths, walkability and energy efficiency.

A comparison of 28 dwelling and location attributes between 27 developments provided insight into the factors influencing an individual's decision to reside there. This multi criteria analysis does not attempt to be predictive, instead, it gives attributes equal weighting and allows the individual's decisions to drive the results. This approach to research has more recently been used to analyse the impact of sustainability attributes on decision-making and informed government policy reviews (Gamper and Turcanu 2007).

4. SUMMARY OF RESULTS

The research in this thesis examines how disruptive innovations can contribute towards rapid deployment of low-cost and low-carbon housing, what the challenges are to the deployment of these technologies, and how these technologies can be mainstreamed. The results from each paper are summarised below.

4.1 Results from Journal Paper 1 Global Energy Forecasts out to 2050⁷

Below are the consolidated views on future energy demand from a variety of organisations into condensed this data in to Figure 5 below. These organisations are: The IEA, Shell, World Energy Council, BP, MIT, Exxon Mobil, EIA, Bloomberg New Energy Finance and the University of Western Australia.

⁷ Accepted for publication in Journal of Sustainable Finance & Investment January 2016.

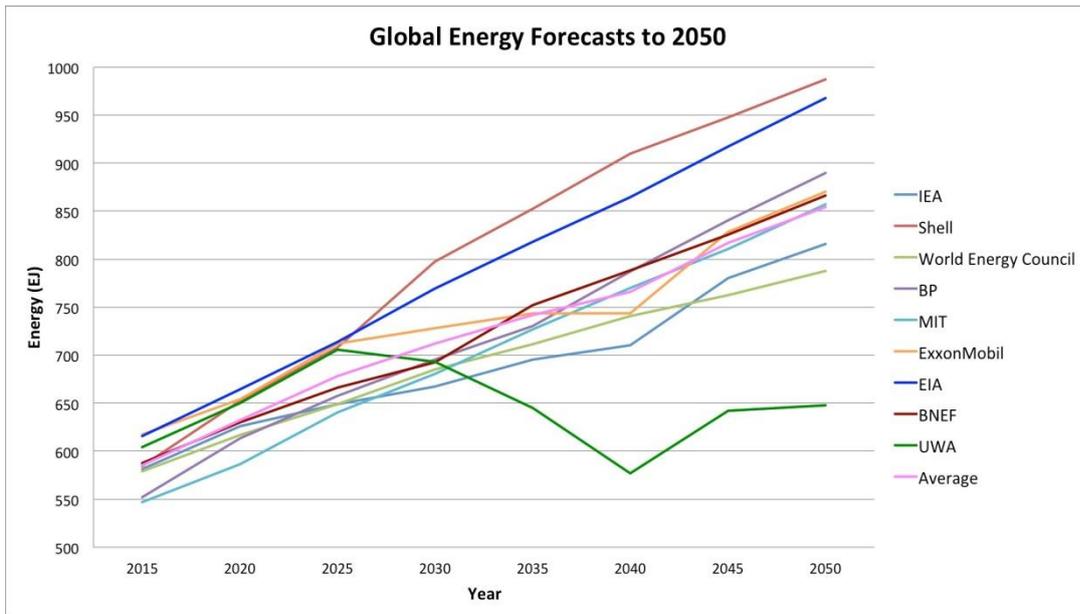


Figure 5: Energy organisations’ global energy demand forecasts

The global energy demand scenarios of the various organisations range from 769 EJ (UWA) to 988 EJ (Shell). While it would be expected that sources would aim to be as accurate as possible, it should be noted that the petroleum-related organisations account for the figures at the higher end of the spectrum.

Next a comparison of the renewable energy forecasts of the same set of organisations out to 2050 is undertaken (Figure 6 below).

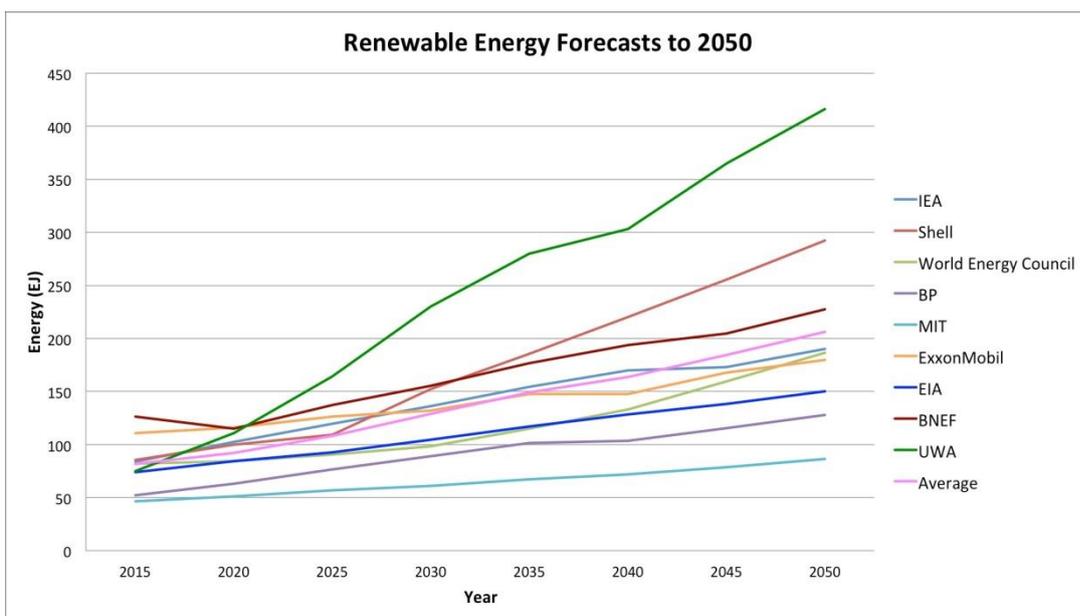


Figure 6: Energy organisations’ global renewable uptake forecasts

The range of predicted global renewable installation forecasts are from 86.2 EJ (MIT) to 415.9 EJ (UWA). The range is larger between these forecasts than from the global energy demand forecasts. There is also a diverse range of views from the petroleum-related organisations. However, these graphs demonstrate that these energy companies are basing their risk analyses for their assets on assumptions that global energy demand will continue to grow. While they acknowledge that renewables will also grow, their views hold that it will not be at a rate that will allow them to fulfil global energy demand before 2050. These assumptions may or may not transpire. Using TIS transition theory, disruption can occur incrementally, radically or systemically. The shift in energy, towards alternative energies and away from fossil fuel energy, in the global context, is presently taking place incrementally (although radically in certain countries e.g. Norway). As more incremental change unfolds, this will appear at a systemic level. Systemic shifts are already evident in many places including Europe and China. In these locations there is a path dependency (Arthur 1989) and technology ‘lock in’ (Twomey and Gaziulusoy 2014) that is occurring, ensuring incremental change in perpetuity i.e. ultimately systemic change, disruption, stranded assets and transition away from fossil fuel energies.

Next, scenarios are developed for the growth of global renewable energy generation and compared against forecasted global energy demand. This includes identifying a number of permutations in which renewables could account for 100 per cent of global energy demand before 2050. The scenarios that examine global energy demand decoupling from GDP growth rates of 10, 20, 30, 40 and 40 per cent. IEA baseline data from 1990-2014, (IEA 2014b) is used to forecast the growth of renewables out to 2050 at simple rates of 6, 7 and 8 per cent above the IEA baseline scenario forecast during that same period, which implies a growth rate of 4 per cent per annum. See Figure 7 below.

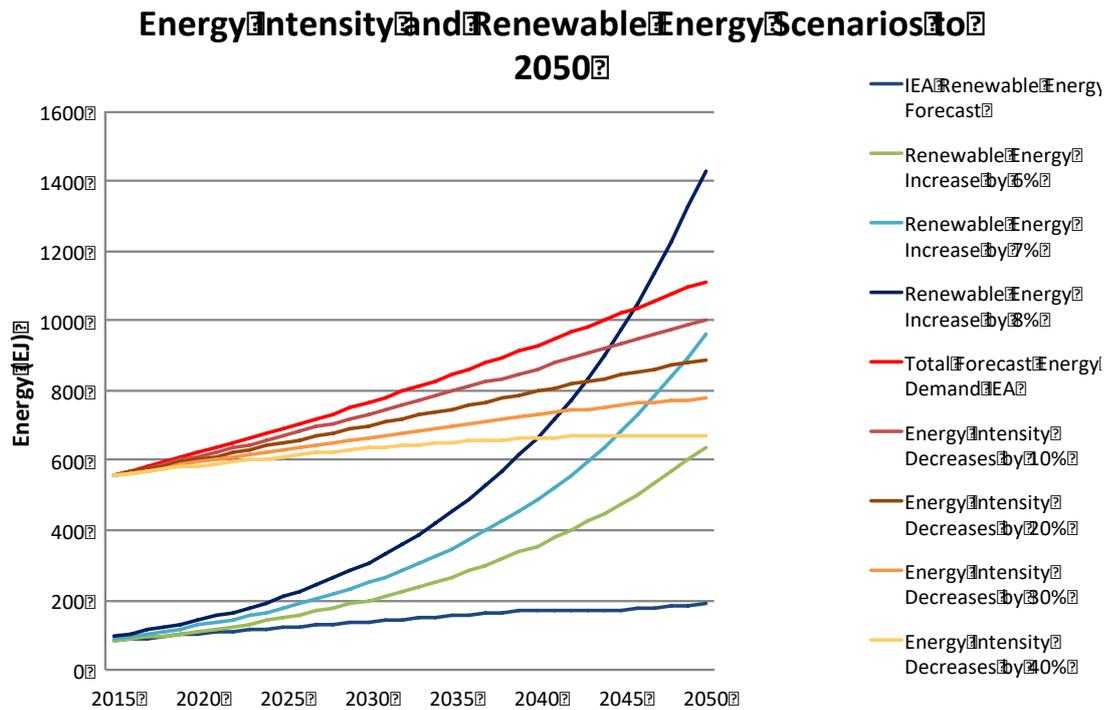


Figure 7: Energy intensity and renewable energy scenarios to 2050.

To compare these scenarios, seven potential permutations are identified in different years in which 100 per cent of global energy demand would be met by renewable generation (Table 1 below). There are two scenarios considered most feasible. The first is in 2044, from an 8 per cent per annum additional renewable energy growth rate (above the IEA baseline scenario forecasted growth rate) along with the relationship between energy demand and GDP decoupling 10 per cent over the period 2015 to 2044. The second is in 2049, from a 6 per cent per annum additional renewable energy growth rate along with the relationship between energy demand and GDP decoupling 20 per cent over the period 2015 to 2049.

Energy Intensity and Renewable Energy Scenarios to Meet by 2050				
Year	Rate of decline energy intensity vs GDP	Simple annual growth rate renewables	Compound annual growth rate renewables	Global Energy Demand (EJ)
2040	40%	8%	27%	664
2042	30%	8%	30%	741
2043	20%	8%	31%	825
2044	10%	8%	32%	918
2045	40%	6%	19%	670
2047	30%	6%	20%	766
2049	20%	6%	21%	881

Table 1: Scenarios for renewable energy accounting for 100 per cent of global energy demand

These scenarios are based on conceivable assumptions as data from 1990 to 2015 shows high levels of decoupling in countries and growth in renewables (Newman and Kenworthy 2015; Newman, Beatley and Boyer 2017). Both scenarios would see renewable energy coupled with storage supply 100 per cent of global energy demand, which would effectively render all fossil fuel assets stranded.

Geopolitical changes may occur to alter certain countries resolve to reduce carbon emissions and increase the use of renewables. However, given there are many other drivers that determine the uptake of renewable energy both for electricity and transportation, e.g. the price of renewable energy and the price of electric vehicles declining rapidly with strong demand present, policy shifts protecting fossil fuels may not stymie the low carbon transition. The author believes that the disruptive preconditions are already present in many major economies and are likely to intensify growth rates, therefore placing a good likelihood of 100 per cent renewable energy by 2050.

4.2 Results from Journal Paper 2 Citizen Utilities

For the optimisation test of electricity load demand of the house during the year-long period, it was found that an increase from 3kW to 5kW of solar PV panels and from 8kWh to 14kWh of battery storage, a 66 per cent and 75 per cent increase respectively, would see the house be 100 per cent load defective during the year long period. This was sufficient to draw the house completely off grid, but did not present an attractive payback period. This was because the infrastructure upgrade would not be utilised at all times of the year, but just for those consecutive cloudy days in winter and for the remainder of the time, the surplus electricity would be sold back to the electricity retailer for a low feed-in-tariff. If the house were off-grid, then this electricity would not be sold to anyone and would therefore have an even longer payback period.

A limitation of this study is that the electricity usage data was taken in 30 minute intervals and if during any interval, more power was being demanded than could be provided by the solar and battery system, all of the demand would be provided for by the grid. This is thought to be of minimal consequence as it would only be at times when high-power-demand appliances were running such as hair dryers, kettles and vacuums, which are used infrequently. Another

limitation of the analysis is that the reference period was only 1 year. Household electricity consumption and sunshine may vary from year-to-year, therefore to optimally size the system, a longer period would be required.

For the evaluation of when solar-storage would compete against grid-sourced electricity in Perth, the modelling suggests electricity price growth of 7.5 per cent per annum. However, for conservative estimates, this was reduced to 5 per cent price growth per annum. While this research makes a conservative estimation, it is quite likely that electricity prices will increase into the future. This is due to the West Australian state government's move toward cost-reflective pricing through the reduction of subsidy, the age of the electricity network's poles and wires, which will require significant upgrades and therefore expenditure, as well as the network needing to service a large geographic area. This model does not consider the cost of capital, which can be large across users.

In determining the point at which solar-storage would compete against grid-sourced electricity in the SWIS, Figure 8 below shows a crossing over of the price of electricity in Perth at around 2017/2018.

Note, the below diagram, shows only a partial evolution of costs. Network effects and political economy effects, could further reduce costs and provide a tipping point to switch to renewables and storage in a more favourable global environment. For example, where business lobbies in new sectors and successfully push for more favourable policies and international agreements as they are seen as in a nation's self-interest. It is not expected that at that point mass uptake of battery storage would be seen, but as the delta between the two lines becomes greater, this is likely to manifest. The solar-storage cost is flattening from 2019 onwards as their prices are predicted to have reached optimal economies of scale at that point.

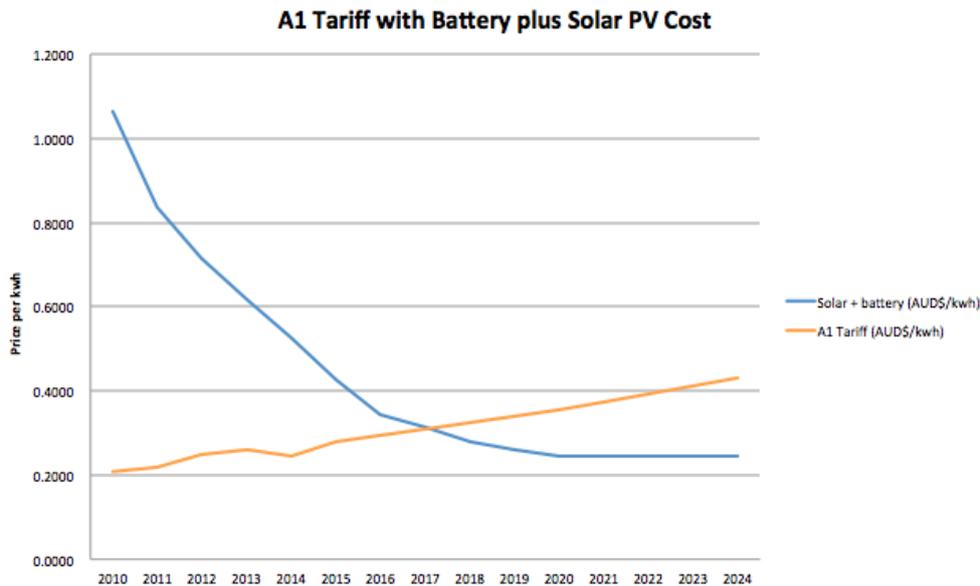


Figure 8: Electricity prices in Perth, Western Australia with solar PV and battery storage against the most commonly charged tariff. Retail grid parity will be reached around 2017/2018.

For the analysis of electricity use at the house with solar-storage, the house is highly energy efficient, using approximately 10 kWh of electricity per day and does not have mechanical air conditioning or heating. The results of monitoring show that when the house only has rooftop solar PV and no battery storage, the household was sourcing 55 per cent of its electricity from the grid and 45 per cent from its solar panels. The house has a lower peak demand than normal households due to not having air conditioning, and, with the rooftop solar PV, is producing 75 per cent more power than it is consuming over the course of the year – see left pie chart in Figure 9 below, showing the reduction in electricity drawn from the grid annually with 3 kW of solar PV.

With a solar and storage system in place, some of the power collected from the sun during the day can be stored in the battery and then consumed during the evening, instead of purchasing electricity from the grid.

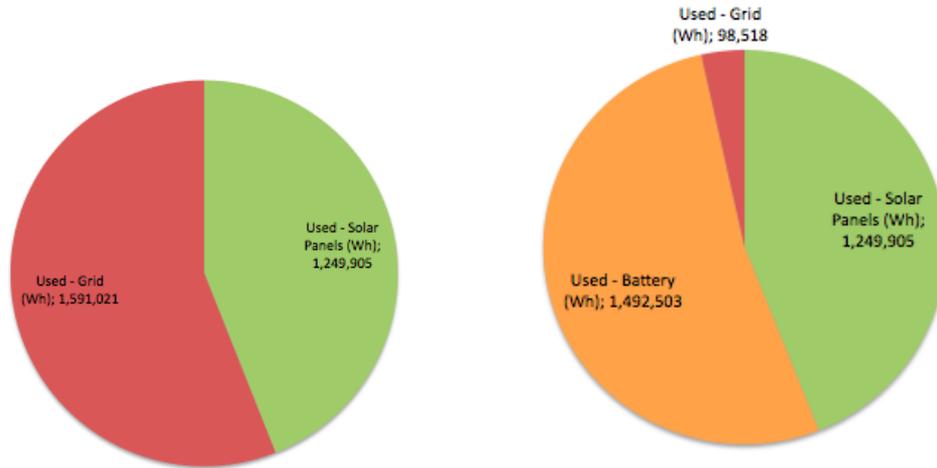


Figure 9: Results of monitored Perth household with 3kW solar panels and then impact of incorporating an 8kWh battery. Annual energy usage, between June 2014 and June 2015.
Source: Author's calculations with data from joshshouse.com.au

The pie chart on the right in Figure 9 above shows the reduction in demand of grid-sourced electricity from the installation of a battery system. The incorporation of a solar PV and battery system reduced this highly energy efficient household's reliance on the grid from around 55 per cent to less than 10 per cent, whilst still uploading 75 per cent surplus electricity to the grid. The household would therefore only draw electricity from the grid during the few periods of the year with consecutive cloudy days, but this would still be significant on the household, if, for some reason, the house was not grid connected.

There are three potential responses that governments and incumbent utilities can have in reacting to the disruption of electricity markets: *Fight, flight or innovate*. These responses are outlined separately below, but may be displayed concurrently, i.e. a company could simultaneously lobby against battery storage and also employ innovative strategies to adapt their business model (See Figure 4).

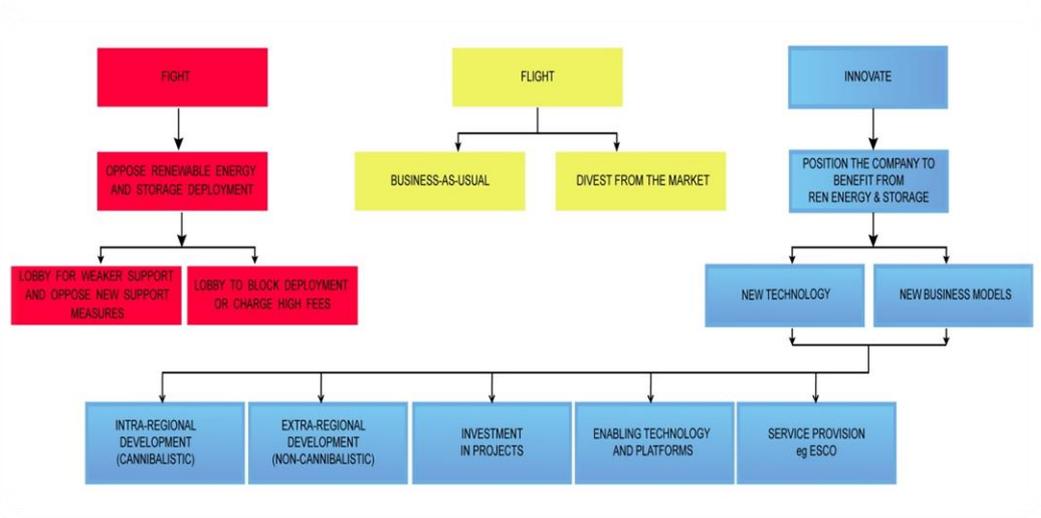


Figure 10: ‘Fight’, ‘Flight’ or ‘Innovate’ options for businesses threatened by decentralised electricity business models (Green & Newman 2016 with some information from BNEF).

Fight

Government and utilities may take a resistant position against renewables and storage, implementing protectionist policy that maintains the market share of utilities, effectively ‘fighting’ this new wave of technologies. In this scenario incumbent players lobby government to implement policy reform that would protect their business models, for example, setting a higher fixed charge. Regulators could also place restrictions or limit the ability of customers to connect renewables or batteries up to a certain point, or altogether. A strong fight response may cause a negative consumer reaction, seeing households retaliate by utilising household solar PV and battery systems to dramatically reduce their dependency on incumbent utilities and go ‘off grid’. This will result in a dramatic increase in stranded assets.

Flight

The ‘flight’ response could see governments and utilities take one of two actions. First, they could do nothing, and let solar and battery products disrupt electricity markets, severely impacting their business models and commercial viability. Alternatively, the flight response could see companies sell their position and divest from electricity markets altogether. Divestment could take the form of investors selling their shares in a utility, or a utility selling their fossil fuel based assets. This response will also see assets stranded on a micro-level, and on a systems level will result in utilities becoming insolvent as they struggle to adapt.

Innovate

Finally, utilities could adapt their business models to profit from these new products, ‘innovating’ through a number of different mechanisms. Likewise, regulators could implement policies that foster the uptake of renewables. Whilst the innovate response would be no guarantee of success, as some companies will offer better products and services than others, and some more quickly than others, this course of action would give companies the best chance of surviving market disruption and to avoid becoming a stranded asset.

The three DI core features of solar PV and other renewables with batteries suggest that it is indeed a disruptive innovation. This means it is likely to dramatically impact the market, necessitating the development of tools that can help predict the point at which assets could become stranded and also the extent of the renewable energy transition in the electricity sector.

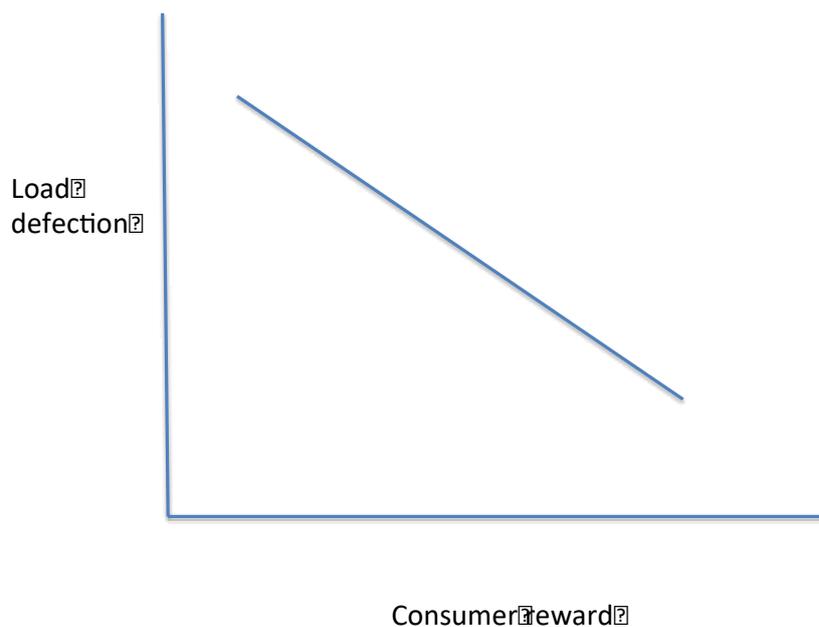


Figure 11. Threshold for grid maintenance.

4.3 Results from Journal Paper 3 Modular Construction Hickory Case Study

Time

The assessment of the modular building in Perth, benchmarked against a traditional equivalent building, found that the modular method reduced the time of the project by 50 per cent. The

reduction in the time of the project also translates into differences from both a cost and return on equity perspective.

Cost

Where construction costs are the same, the faster build time of the modular project provides a 5 per cent return-on-equity uplift, and where construction costs are 10 per cent less in the modular building, the difference in construction times results in an equity uplift on return for the modular project of 25 per cent. In this particular case study, the modular building cost 10-12 per cent less than a traditional equivalent building, with 35-40 per cent less aggregate funding costs.

The below two graphs give an overview of capital expenditure and funding cost profiles under both scenarios.

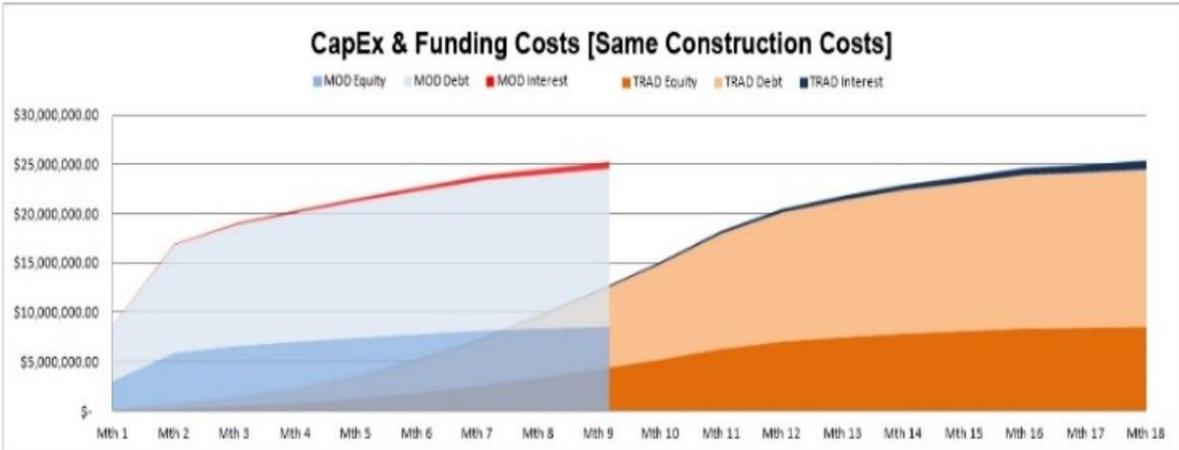


Figure 12: Equity and debt drawdown and interest paid for modular and conventional, assuming both approaches has the same construction costs.

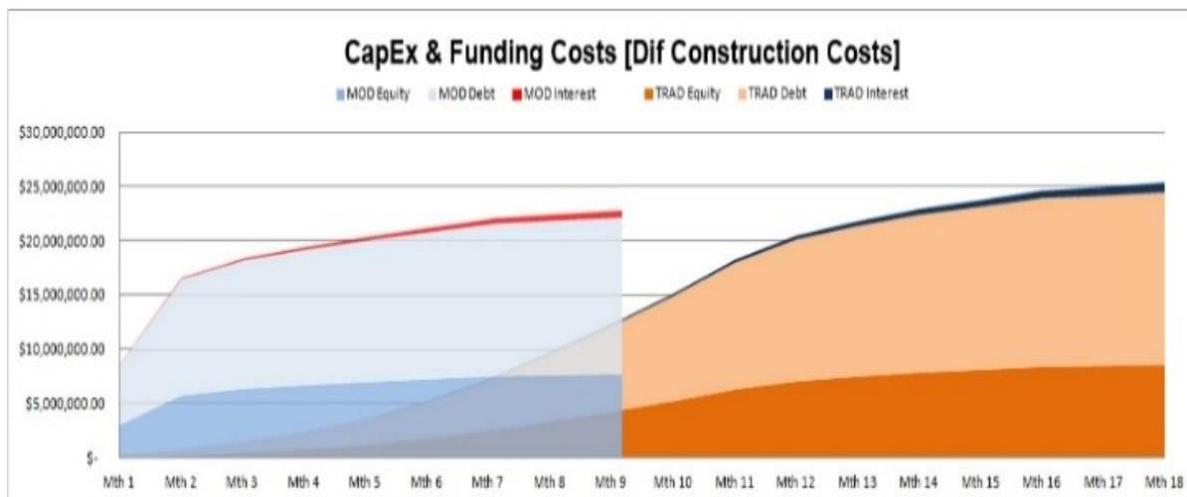


Figure 13: Equity and debt drawdown and interest paid for modular and conventional, assuming the modular project construction costs are 10 per cent less than the traditional.

In both analyses, we assume the debt to equity ratio (D/E) to be 65 per cent debt to 35 per cent equity and the interest rate to be fixed at nominal rate of 7 per cent.

Figure 13 below shows the difference in funding costs, based on the difference in construction costs. Due to a faster build time, the cash-flow profile for modular is significantly different to the traditional building. For modular, equity and debt drawdown is accelerated, but as the project is completed earlier, debt is paid out faster. For Adara, even with more capital being used sooner, and therefore attracting interest rate costs, there are 35-40 per cent savings on aggregate funding costs. The modular funding costs were \$638, 374 and the traditional funding costs were \$891,696, which although substantially different, are a relatively small difference in percentage terms when considering the total project costs, being \$25, 138, 374 versus \$25,391, 696, or around 1 per cent difference.

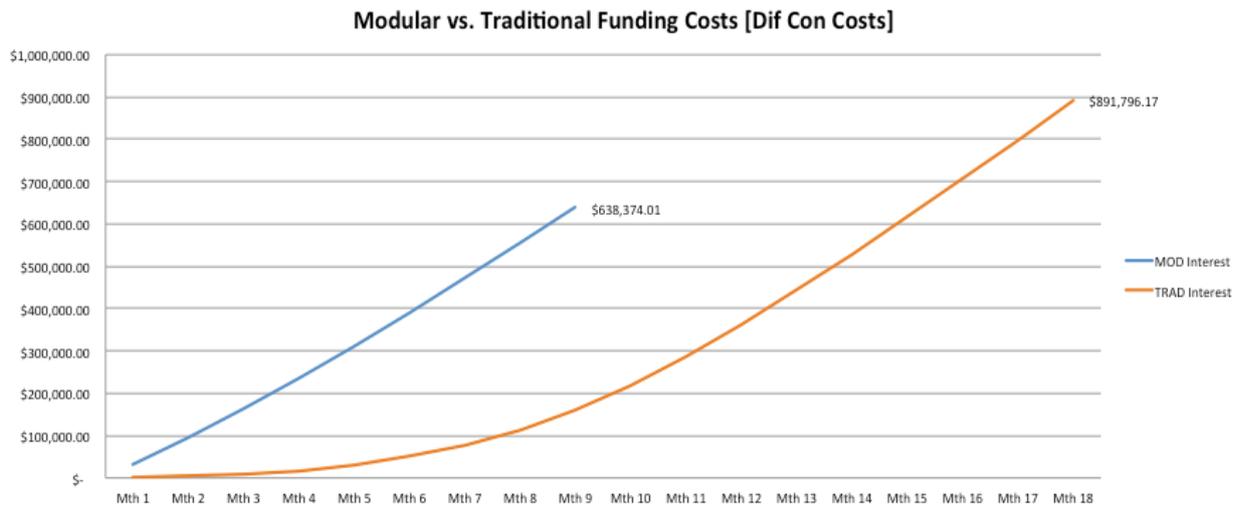


Figure 14: Illustration of funding cost savings with 10 per cent lower construction costs.

Figure 14 shows that where modular construction costs are 10 per cent less than a traditional equivalent building, funding costs during the construction period are more than 45 per cent less. In the below graph (Figure 13), we analyse the difference in funding costs, based on the assumption that construction costs between modular and traditional are the same.

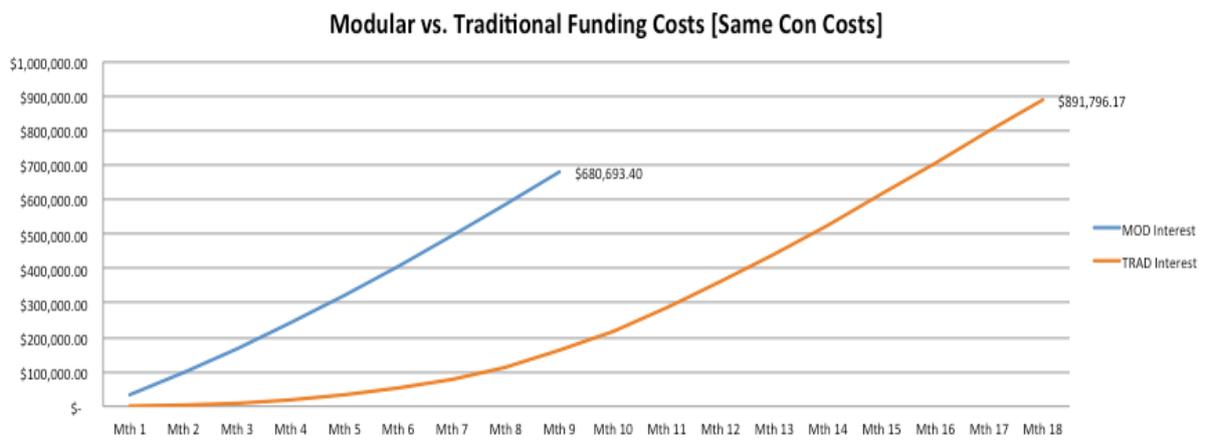


Figure 15: Illustration of funding cost savings with the same construction costs.

Figure 4 shows that in a like-for-like costing situation, due to the faster pace of construction, the modular project funding costs would be approximately 31 per cent less. While this is not a significant cost saving, faster construction times and lower funding costs lead to the sale of dwellings to market sooner, resulting in a return-on-equity (RoE) uplift, discussed in further detail below.

For this analysis, the expected RoE for the modular construction sector was compared with apartments and the hotel developer markets. We assume RoE targets, based on the inner-city investment market seeking RoE of 25-35 per cent. Due to the faster speed of construction, and therefore, sales, in the modular building approach we evaluate the potential for modular to provide a significant equity uplift. Figure 13 shows that where construction costs are the same, the faster build time of the modular project provides a 5 per cent equity uplift on return and where construction costs are 10 per cent less in the modular building, the difference in construction times results in an equity uplift on return for the modular project of 25 per cent.

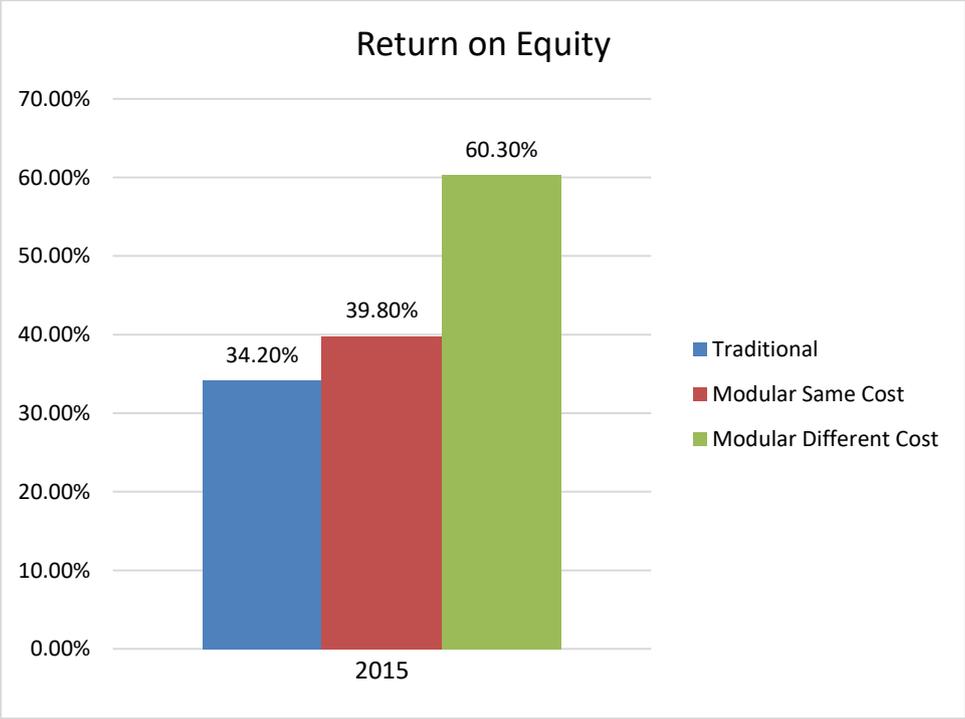


Figure 16: Illustration of RoE comparison between traditional construction, modular with the same construction cost, and modular with 10 per cent less construction cost than traditional.

In dollar terms, for a \$24,500,000 project cost, investors would contribute \$15.9 million in equity. The traditional project would return \$5.4 million and the modular project would return \$6.3 million. If the modular product were to cost 10 per cent less, the RoE would be \$8.6 million.

Sustainability Performance

Using the design provided by Hickory, the traditional equivalent building performs more effectively in the summer but worse in the winter. This results in an overall thermal performance being 8 per cent more efficient than the modular building (see Table 2 below).

	MODULAR		TRADITIONAL	
	[MWh]	[kWh/m ²]	[MWh]	[kWh/m ²]
Heating	26.59	4.94	39.78	7.39
Cooling	340.59	63.28	268.20	55.44
TOTAL		68.22		62.83

Table 2: Thermal performance of Adara comparison

This modular design performs worse from a thermal perspective, in comparison to its traditional equivalent, due to a lack of thermal mass. Designing modular buildings for the particular context is where the biggest potential exists for them to deliver low-carbon outcomes. When the local context is included in design, then low-cost, low-carbon disruption can happen.

Simulation results for Port Hedland

Port Hedland is a town 1,300km north of Perth, Western Australia. The town experiences a typical semi arid and tropical savanna environment in which the minimum temperature is 17.5°C and maximum is 42.0°C. When tested in these conditions, the modular and traditional buildings generated the following results (Table 5).

MODULAR	PERTH		PORT HEDLAND	
	MWh	kWh/m ²	MWh	kWh/m ²
Heating	26.59	4.94	0	0
Cooling	340.59	63.28	1113.22	206.83
TOTAL		68.22		206.83

TRADITIONAL	PERTH		PORT HEDLAND	
	MWh	kWh/m ²	MWh	kWh/m ²
Heating	39.78	7.39	0	0
Cooling	298.39	55.44	1175.65	218.43
TOTAL		62.83		218.43

Table 3: Thermal performance of Adara in Port Hedland compared to Perth.

In this location, the thermal mass isn't as critical to the thermal performance of the building in summer because there is not as significant of a difference in temperature between night and day. Subsequently, the modular building performs 6 per cent better than the traditional construction.

Simulation results for Melbourne

For Melbourne, the thermal performance results are summarized below.

MODULAR	PERTH		MELBOURNE	
	MWh	kWh/m ²	MWh	kWh/m ²
Heating	26.59	4.94	182.84	33.97
Cooling	340.59	63.28	119.16	22.14
TOTAL		68.22		56.11

TRADITIONAL	PERTH		MELBOURNE	
	MWh	kWh/m ²	MWh	kWh/m ²
Heating	39.78	7.39	268.20	49.83
Cooling	298.39	55.44	83.53	15.52
TOTAL		62.83		65.35

Table 4: Thermal performance of Adara in Melbourne compared to Perth.

Melbourne has a cooler climate and in these weather conditions, the added insulation of the modular building represents the most important feature contributing to thermal performance, particularly in winter. During winter, the modular building performs much better than the traditional building, saving 16 per cent in electricity demand.

Modular building approaches can more readily surpass the energy efficiency of traditional buildings by designing modular for the specific geographical context or making adjustments as suggested afterwards. This study has shown that if the local geographical context is not considered or climate-appropriate materials are not chosen wisely, then a prefabricated modular building can easily prove to be more carbon intensive than a traditional equivalent.

Sales for the modular building are consistent with market norms during the same period, suggesting that there is market acceptance for this relatively underutilised construction method. However, comparable sales is the not the only precondition that needs to be met for modular to compete with traditional building approaches. Developers would need to overcome financing challenges and perhaps see superior demand due to perceptions of quality, to be willing to take on the risk of trying new this new technology.

4.4 Results from Journal Paper 4 Solar-Storage in Strata: the Gen Y Case Study⁸

This research produced a governance framework for how a solar PV and battery storage systems can be designed, installed, managed and financed in strata developments. Microgrids in these developments can utilize economies of scale to provide electricity to households. Residents will access electricity directly from solar PV panels, solar generated electricity stored in the batteries, and then from the grid. This research charged the same price tariff for electricity sourced from the microgrid, however, strata companies may choose to offer this electricity at a discounted rate as a market incentive to tenants. Funding mechanisms for installing renewable energy generation and storage in strata are outlined to complement the governance model. By demonstrating a financial incentive for developers to include solar and battery infrastructure in medium density housing, this research intends to facilitate the mainstreaming of these systems for medium density housing, where there is currently a gap in the market.

Figure 15 outlines the energy system and model of governance in strata to enable a ‘citizen utility’ structure to emerge.

⁸Published in Urban Policy & Research March 2017

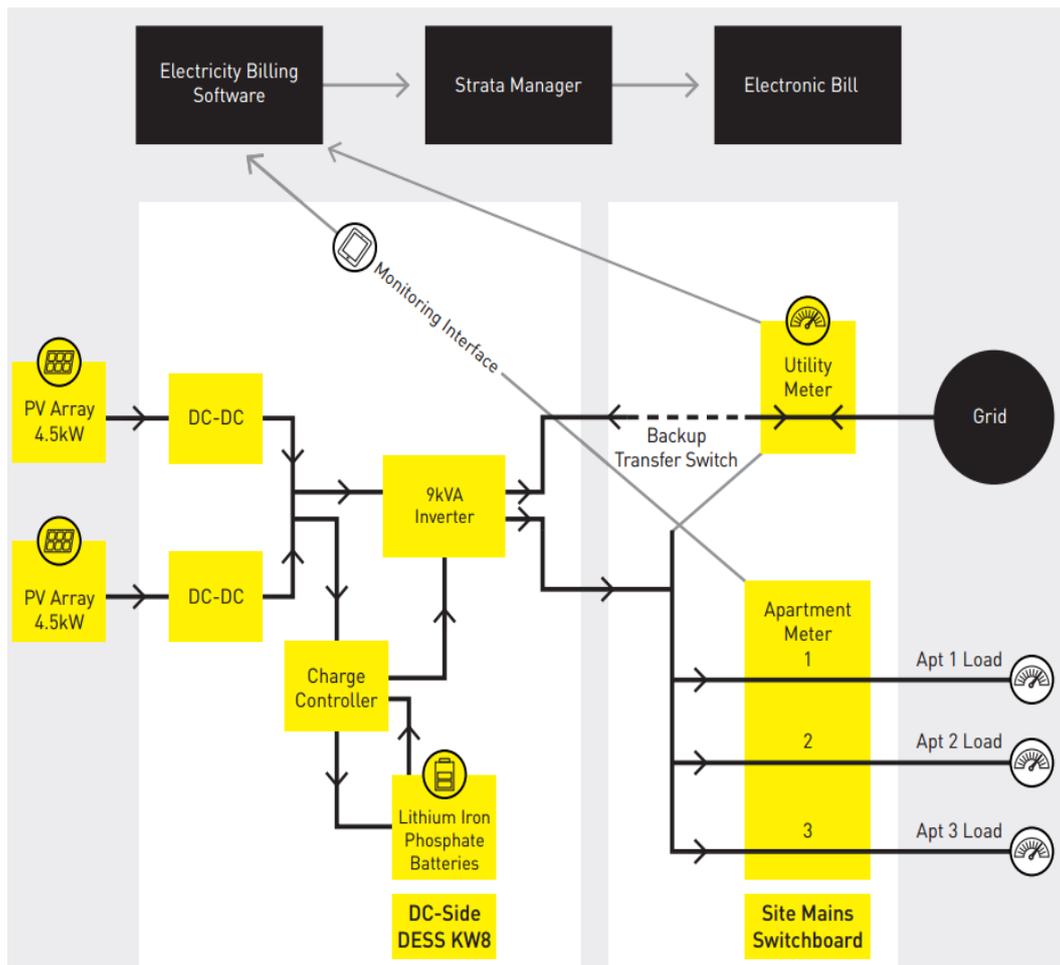


Figure 17. Design and metering options for strata with solar PV and battery systems for electricity provision.

The following are the core elements for the governance framework:

- 1) **Sub-metering:** Accurate tariff quality sub-metering of electricity consumption.
- 2) **By-laws:** By-laws for the strata notifying of:
 - a) Intent to charge for power and the pricing regime and the payment requirements; and
 - b) The electricity usage to be monitored for the purposes of:
 - i) Charging owner-occupiers (usage, maintenance and replacement), landlords (maintenance and replacement), and tenants (usage only).
 - ii) Behaviour modification, if necessary, based on how the community handles critical peak time and other periods when solar-storage may be low.
- 3) **Tenanted apartments to pay strata company:** Tenanted dwellings will need their lease agreements to contain an addendum requiring tenants to pay their electricity costs to the dwelling owner. The owner will then pay the electricity bill to the strata company.

- 4) **Monitoring and billing managed by the strata:** In the WGV Gen Y development, proprietary software will be used.
- 5) **Pricing:** The billing arrangements are managed under state legislation. For example, for tenanted properties the Western Australian Residential Tenancies Act 1987 allows for the sale of electricity to strata dwellings at a tariff no greater than the residential retail tariff offered by Synergy, which is the sole electricity retailer in the SWIS. The Strata Titles Act 1985 allows for similar provisions.
- 6) **Maintenance:** This can be managed by the strata company, sub-contracting it out, or even coordinating it by a commercial arrangement with an energy services company.

Precinct-scale renewable energy and storage can be implemented, financed, and funded for strata through a variety of mechanisms. Planning systems can take account of these mechanisms and promote them to developers.

For decentralised electricity projects to proceed, finance has to be sourced. There are various potential ownership and electricity billing arrangements that can enable this market. A variety of different approaches are identified, including investor funding, ownership of infrastructure by homeowners, and a hybrid ownership management, as explained below (see Figure 16).

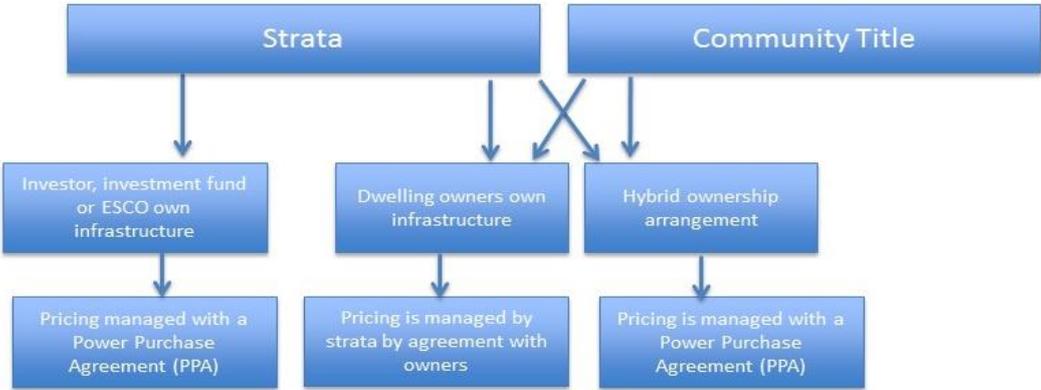


Figure 18. Renewable energy funding arrangements for strata developments.

The three potential financing, funding, and ownership approaches that could be taken to secure decentralised electricity in precinct scale developments are:

1. **Dwelling owners own the infrastructure, funded by either of the following:**
 - a) The developer finances the construction phase, then passes on the costs to the buyer as a part of the overall purchase price; or

b) Residents purchase the infrastructure pre-construction, as a part of their dwelling financing arrangements, or from a standalone credit facility as an add-on to the dwelling base cost; paying upfront.

2. Investor, investment fund or ESCO finances and owns the infrastructure.

3. Hybrid ownership arrangement between the dwelling owners along with investor, investment fund or ESCO:

a) Developer finances the infrastructure during construction and then passes on the costs to the dwelling owners, investors, investment fund, or ESCO post construction; or

b) Investor, investment fund or ESCO finances the infrastructure during the construction phase and then sells a portion to dwelling owners on purchase of dwelling.

In approach two and three, there is the potential for securitised instruments to be structured to finance such a market. These financial instruments could invest a diverse selection of assets, and operators, to reduce risk and provide liquidity to enable the market. With any of the above approaches the grid can provide backup power if necessary, and excess power generated from the solar PV arrays can be sold to the grid.

4.5 Results from Journal Paper 5 Demand Drivers for Medium Density Housing

Location

The average number of dwellings in each development is 51, with the maximum reaching 137 dwellings in Beaufort Central.

Fifteen of the twenty-seven developments are under a 10 km drive from the CBD, which are desirable locations to interviewees who work in or close to the city. A third of the developments are less than 2 kms from the city and eleven are within 3 kms. Almost three-quarters of the developments are within 15 kms of the CBD, which requires residents to either commute further to work or rely on public transport.

Affordability

Affordability was the most influential attribute for these dwellings (figure 1), confirming global research stating that the affordability of a location is consistently a driving factor of where people choose to live. In this study, over one-third of the developments are sold at market rates without any governmental assistance to buyers.

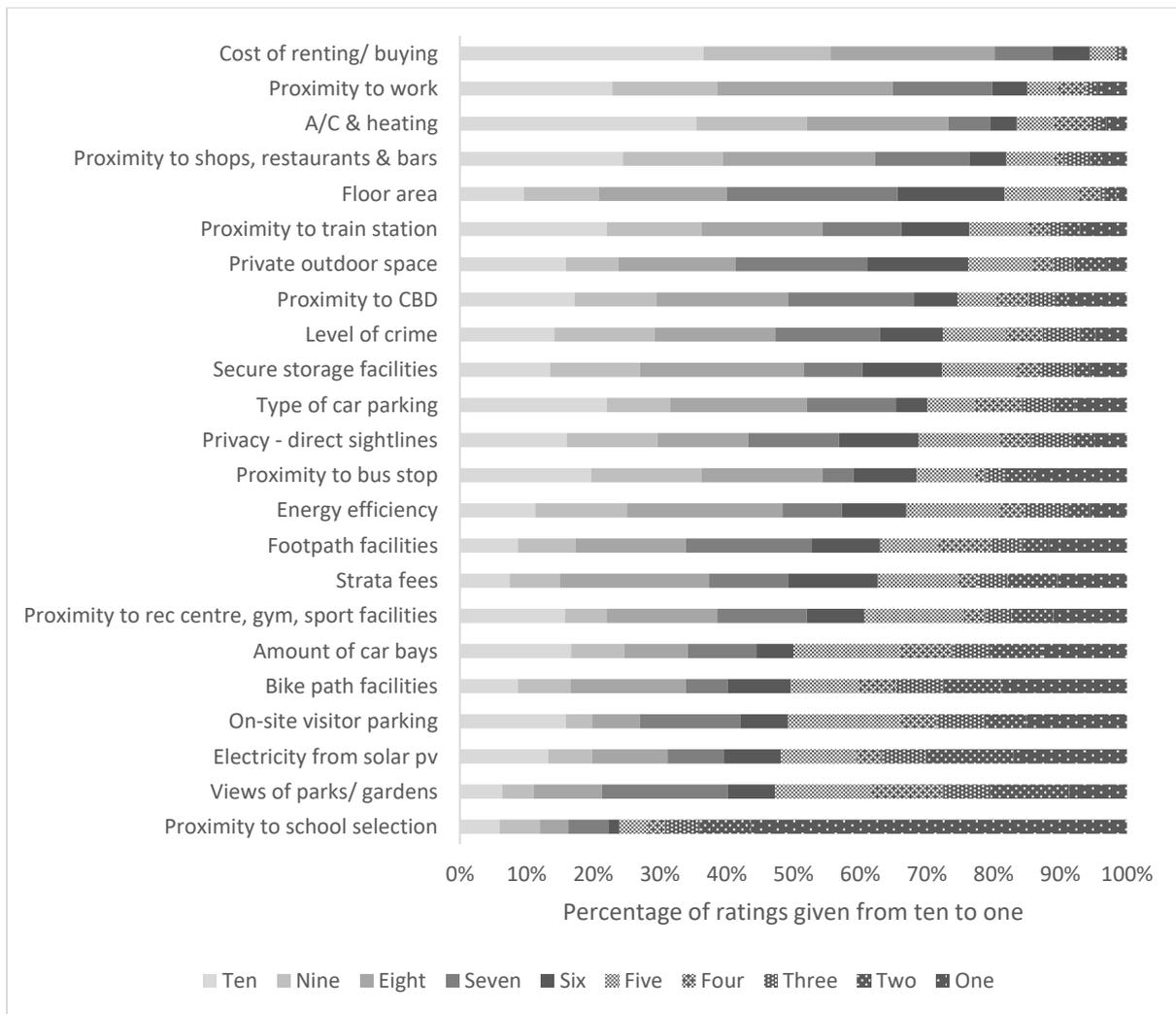


Figure 1. Residents’ ratings of the importance of dwelling attributes in influencing their choice of housing. Affordability is the most important factor for residents, with comfort features such as floor size and temperature control, and sustainability features such as public transport, proximity to work and amenities, and energy efficiency also being major influencers.

Transport Access

Within the survey locations residents live closer to bus stops, at an average distance of 138m, than train stops, with the average distance of 929m. All dwellings had a transit stop within 280m. The preference for public transport options is reflected in statements by residents saying that proximity to transport was quite influential in their choice, with twenty per cent rating public transport access as one of the most influential features of their choice of location (figure 2). Train proximity is somewhat more desirable than bus proximity.

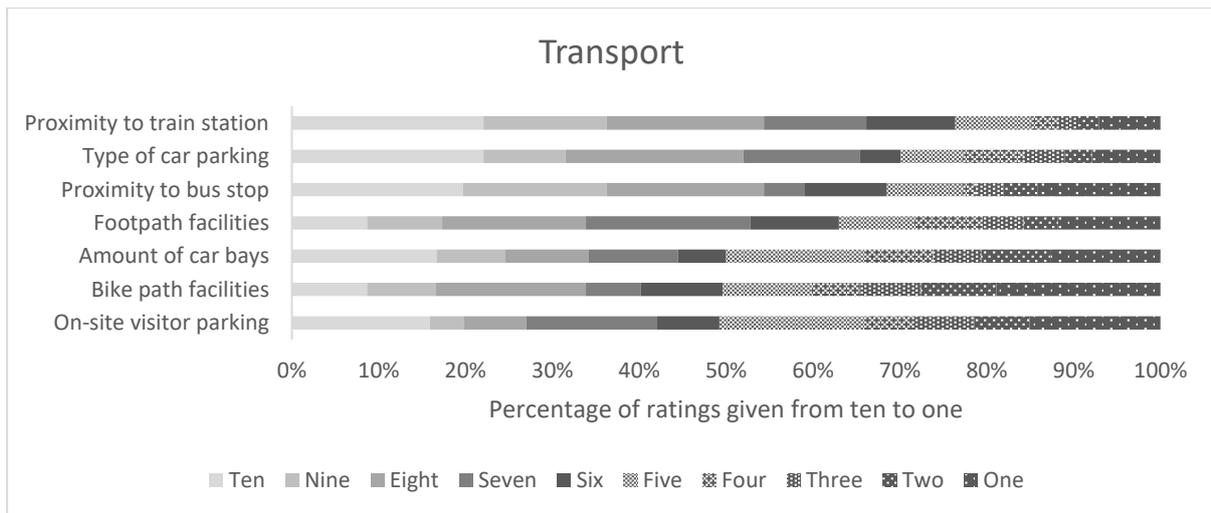


Figure 2. Preference for transport for dwelling residents. The proximity to train stations was highly influential of residents' choice of dwellings, more so than buses. The availability of parking bays was still considered very important, despite the increased use of public transport, walking and cycling in Perth (Ngo 2015).

Proximity to footpaths was rated as more desirable than closeness to bike paths (figure 2), although bike infrastructure in the studied locations were not of particularly good quality. Less than three quarters of roads surrounding the properties have bike friendly lanes, routes or connections to train stations or the CBD nearby. Only six of the developments have dedicated bike routes into the CBD within 300 metres. The most common option was bike lane connections to train stations, where bikes can be left for the day and collected after work. The 54% rise of the number people working in the Perth CBD since the mid-1990s (Ngo 2015) has not seen a commensurate rise in the amount of parking bays or people driving in to the city; the growth has entirely been supported by increased use of public transport, walking and cycling (Ngo 2015). The provision of even limited parking, however, was valued as important by survey respondents who owned a car (figure 2). While all the developments except one provide some form of parking, most of these have only one bay per unit regardless of the number of bedrooms each dwelling has, and just over a third provide some form of visitor parking. Most parking provided is in secure garages or undercover areas, which respondents found desirable for increased security. The only development that does not provide parking is located in the workers' precinct in East Perth, a dedicated low-income housing property close to the CBD and trains and buses.

Access to Amenities and Facilities

All the developments in the study are within walking distance to schools and parks, encouraging less car use and promoting healthier living and stronger community interaction (Gehl 2010). While the majority of residents surveyed did not have children, all of the developments have at least two primary schools and one high school within a 3km radius. Despite this, most of the residents rated the proximity to school selection low among the reasons for choosing the development, even if they planned to have children in the future (figure 1, figure 3). The only residents who did rate proximity to schools highly were ones who already had children (figure 4).

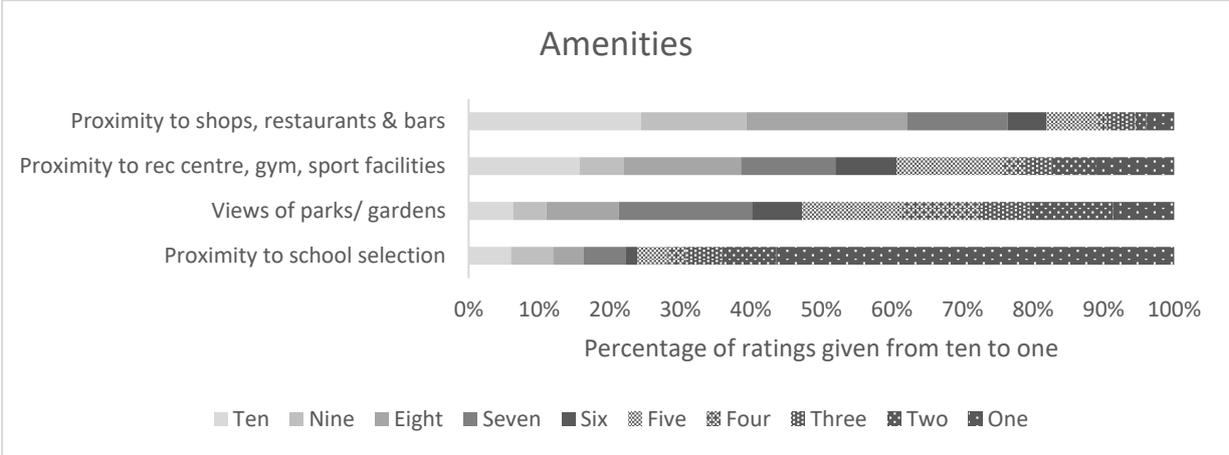


Figure 3. The importance of access to amenities for residents’ choice of dwelling. Proximity to shops, restaurants and bars are the most important amenities to residents, while the proximity to school selection has little influence, even for residents that planned to have children in the future.

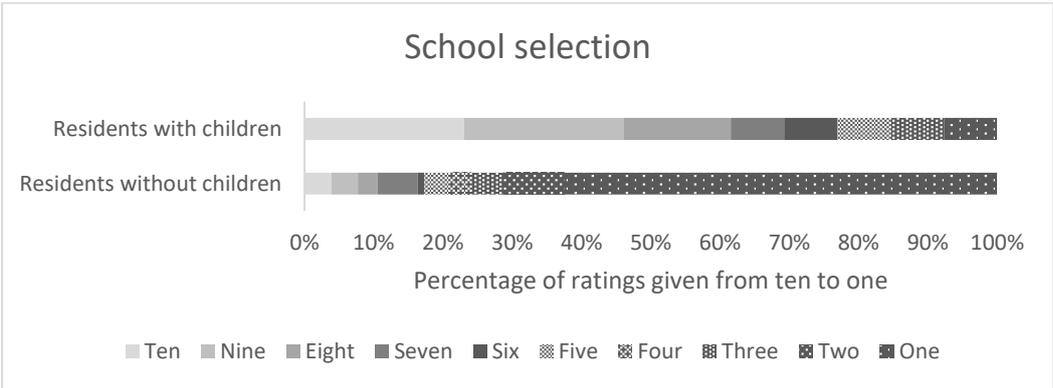


Figure 4. School selection had a low level of influence for residents’ choice of dwelling. Only residents that already had children rated it as an important factor.

The proximity to retail shops, restaurants, pubs and cafes is in high demand while choosing a place to live in, particularly by those under 50 years of age with no children. Sixty-three per

cent of residents under 50 years of age rated the proximity as very important (figure 5). Residents between 40 and 50 years of age rated being close to shops as one of the most influential factors in their final decision to live in their dwelling. All developments have some service within 500 metres of their house with the average distance being 200m, a comfortable walking distance. While these services vary, their close location to the dwellings highlights the desire of people to be located within hubs of activity.

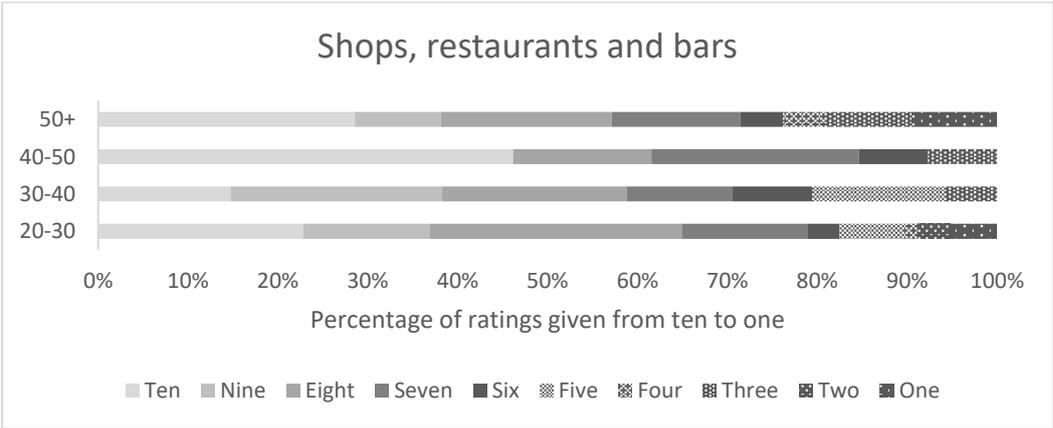


Figure 5. Residents’ ratings of the importance of dwelling attributes in influencing their choice of housing. Affordability is the most important factor for residents, with comfort features such as floor size and temperature control, and sustainability features such as public transport, proximity to work and amenities, and energy efficiency also being major influencers.

Over three-quarters of the respondents live less than 1km from food shops, making them easily accessible on foot, by bike or car by all respondents.

Indoor community facilities of various functions are all situated within 3km of each development, including community centres, recreation halls, libraries, health services, museums and gyms. The average distance to the closest facility is 904m, which is well over the Walk Score walkability guideline of 400m, although a walkable distance of 1km for less commonly required activities is often used as a benchmark. The importance of facilities by residents was quite varied from very low to very high, with residents below 40 years of age rating it higher than those above 40 (figure 6).

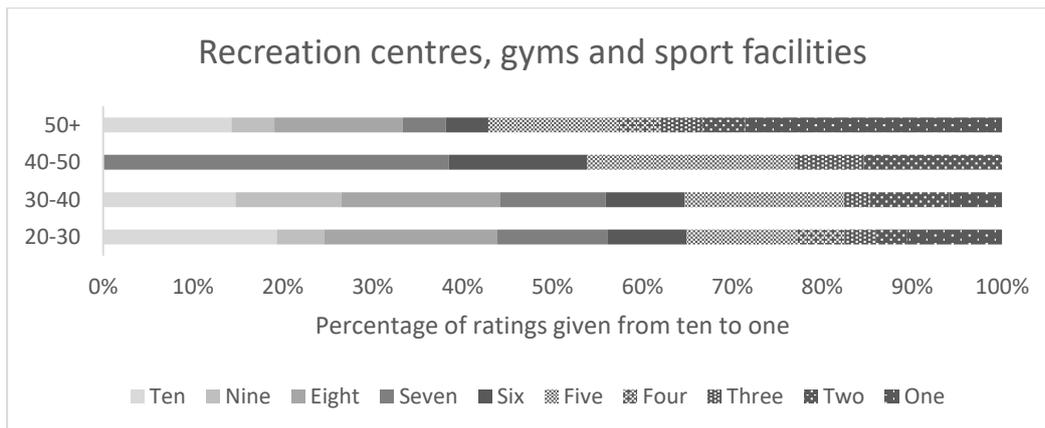


Figure 6. The proximity to recreation centres, gyms and sport facilities are more important to residents below the age of 40.

Three quarters of the developments have mature trees in the surrounding streets that provide shade for the area, lowering the temperature on the surface and within houses. Fifty-nine per cent of respondents rated the influence of views of parks and gardens as 5 or above (out of 10), however, only twenty-one per cent gave a rating of 8 or higher (figure 3).

Security

For these locations, the range of incidences is between 32 and 1,246 per year. Prior to this survey, the average number was 580 incidents per year with twenty suburbs having fewer than 1,000 incidents (WA Police 2014). Survey respondents reported the level of crime to be a strong overall concern. Ninety three per cent of respondents rated it important to their decision (5 or higher out of 10), though responses don't show a relationship between level of concern and level of incidents (figure 1). Secure (lockable) storage facilities for residents are almost always provided for each development.

Other Factors

All but two properties (East Perth Workers Housing and Highgate) have air-conditioning and heating installed with reverse cycle systems being the most popular. The result show that people still prefer the option of air-conditioning (figure 1) even in dwellings with sustainability features that may improve thermal performance. Lack of privacy from neighbours was a concern for just under 70% of respondents, however, only two of the surveyed apartments had sight lines into one another.

Seventeen per cent of respondents stated that the size of the dwelling was one of the most influential factors in their housing choice, while forty per cent rated it 8 or higher out of 10 in

importance (see figure 1). With a warmer climate in Perth, unsurprisingly, most respondents rated private outdoor space as important in a dwelling, with forty-one per cent rating it 8 or higher out of 10 (see figure 1).

Energy Efficiency and Energy from Solar

Sixty per cent of these dwellings have some sustainability attributes that go above and beyond compliance with legislation. Respondents said that these sustainability attributes did have an influence on the overall decision to live in the dwelling.

Energy efficiency had an equal response between respondents who lived in dwellings with sustainability attributes, and respondents in dwellings without; it was considered a very important factor to almost half of respondents in both types of dwellings (see figure 7 and figure 8). Solar PV for electricity supply was rated very important by only 30 per cent of respondents (see figure 1), however, within the medium density market there are very few instances where solar power is connected directly to the dwelling due to the lack of a governance system to enable this (Green & Newman 2016). Within the scope of this study, only three dwellings generated electricity from solar PV. Therefore, actual preferences for renewable energy are more difficult to ascertain.

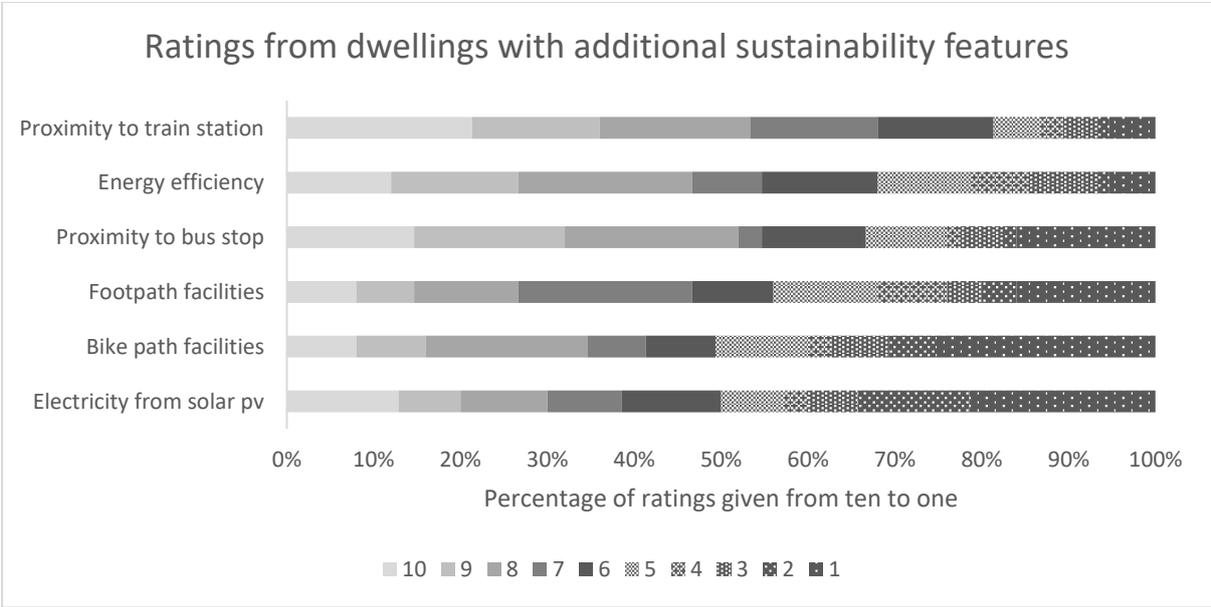


Figure 7. Of the dwellings with additional sustainability features, residents prioritised proximity to train stations and the energy efficiency out over other sustainability features.

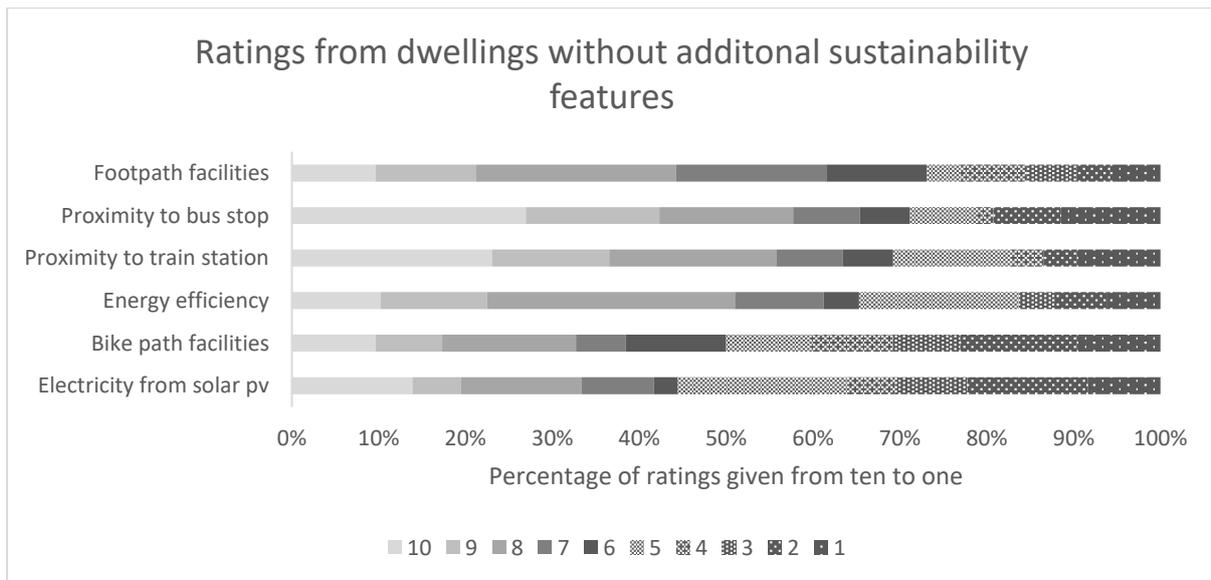


Figure 8. Of the dwellings without additional sustainability features, residents prioritised footpath facilities and proximity to bus stops over other sustainability features, however, more residents considered bus stops, train stations and energy efficiency to be highly influential.

The few respondents who ranked energy efficiency as of low importance did not reveal an overall trend as to what was of greater importance in choosing a dwelling. For the six developments offering rental affordability schemes as well as comprising sustainability attributes, the results were generally supportive of the sustainability attributes, especially where they lowered household costs. The presence of bike paths, which allow another form of low-cost transport, was rated more highly in these areas than interviewees from non-subsidised dwellings. Privately arranged car sharing was undertaken by twenty per cent of interviewees in both the more sustainable and less sustainable developments. No commercially arranged car sharing was found in any of the developments.

5. DISCUSSION

This thesis examines disruptive innovation – disruptive technologies, disruptive business models, disruptive culture and behaviour change – to determine how they can contribute to low-cost and low-carbon housing. The two disruptive technologies examined are modular construction and solar PV panels paired with lithium-ion batteries. This section will discuss the significance of the primary results in the journal papers and identify how the research adds

original contributions to the literature surrounding mainstreaming low-cost, low-carbon housing and disruptive innovation.

5.1 Discussion Journal Paper 1 Global Energy Forecasts out to 2050⁹

The renewable energy and energy efficiency scenarios illustrate that with rapid increases in energy efficiency and a substantial increases in the rate of deployment of renewables and storage, i.e. with disruptive innovations, the potential to meet global energy demand by 2050 is not being contemplated by most forecasting. There is an emerging trend that suggests a decoupling of GDP and energy demand, which would further support the achievement of this outcome as less energy per unit of GDP is needed over time. The paper suggests that it would be prescient to consider the impacts of disruptive innovation to be included in energy forecasting. If such positive scenarios are not provided, then incumbent fossil fuel industries may assume they are safe to continue business as usual under all scenarios, as though demand for their product will remain and continue to grow.

Presently, most research suggests that global energy demand will grow in line with global population growth and growth in GDP. Owing to this, fossil fuel companies predict that due to the continued forecasted rise of energy consumption, their products will meet the majority of this demand. However, this thesis evaluates the potential for renewable energy to meet future energy demand, considering scenarios of increased energy efficiency, the declining price of electric vehicles and the rise of renewable generation with storage.

The significance of this analysis is that it shows how disruptive innovations such as solar-storage, as well as global megatrends around energy efficiency, and the declining price of electric vehicles (BNEF 2017), can individually and collectively change forecast trajectories. Although some fossil fuel companies, financial analysts, and investors may view energy projections from organisations such as the US Energy Information Administration (EIA) as being forecasts, the EIA makes clear their reference case is a projection of current trends, not a forecast (EIA 2016), though this is quickly lost when companies do their projections for business into the future (Carbon Tracker 2016).

⁹ Published in Journal of Sustainable Finance & Investment December 2016.

This research suggests that fossil fuel companies and investors that own assets related to the fossil fuels industry will need to undertake more sophisticated assessments of the risk of stranded assets and to understand risks in a more nuanced way.

Whilst there are presently a small-set of examples of incumbent utility assets becoming stranded, there are a number of moves by utilities to separate the more at risk assets from total asset portfolios and also divest them. In addition, investors are choosing to divest from fossil fuel assets, due to perceptions of risk around the assets becoming stranded (Baron and Fisher 2015). Therefore, there appears to be a notional relationship between the presence of disruptive innovations and whether incumbent assets become stranded. This could be an area of further research.

5.2 Discussion Journal Paper 2 Citizen Utilities

The first key conclusion from the disruption due to solar-storage is that the grid is unlikely to be abandoned by most consumers in cities. Total grid defection is a disconnection of the household from the grid with a sole reliance on renewables and battery storage (Bronski et al 2015). The evidence from the research shows that the solar-storage system cannot carry the household throughout the year even in Perth, a city characterized by high solar irradiance. Instead, the option of load defection would allow consumers to be significantly less reliant on electricity from the grid while still being connected. The economics of total grid defection outlined in this scenario therefore are not as compelling as the more than 90 per cent load defection scenario with the smaller system. Achieving grid defection is exponentially more costly as the system approaches 100 per cent. This suggests that households who optimise the size and cost of their system will still rely on the grid in some periods throughout the year and in cities, where the grid is already installed, the grid will remain an important piece of infrastructure.

Australian Energy Market Operator, in their *Deferred 2015 Electricity Statement of Opportunities*, have analysed what the deployment of solar and storage would have on network utilisation and tariffs in Perth. Additional displaced network energy represents 8- 16 per cent of energy currently provided to small business and residential customers (RT1 – RT4 tariffs). This group accounts for AU\$1,104 million of network revenue for 2016/17 (out of a total of AU\$1,520 million). Assuming the current tariff structure is retained, revenue leakage

would be AU\$54 – \$112 million per annum. Alternatively, the variable network tariff would need to increase by 10 – 22 per cent, or up to 2c/kWh to compensate (AEMO 2016). Given these profound impacts on costs at a low level of deployment, if there was mainstream household defection of load, under the current system, the unit cost of residual power from the grid would be substantial. This energy system will require a different shape of grid, alongside write-offs of some assets and new pricing models.

The main impact of solar-storage is that bi-directional electricity flows are rapidly becoming popular. If utilities adopt fight responses, offering a low return for this electricity, consumers are likely to store as much electricity as they can behind the meter and consume it, as opposed to spilling this electricity out onto the network. The former scenario would result in a decline in network utilisation and retailer demand.

The third conclusion from the emerging new electricity systems associated with solar-storage is that consumers are likely to create their own way of managing the majority of their electricity needs and the way they dispose of their excess electricity. This is because these households would prefer to sell their surplus directly to other consumers. This will enable consumers to potentially become electricity traders, only selling electricity back to the grid when the buyback price is what they desire (Reposit Power 2015). I have coined this emerging phenomenon ‘citizen utilities’. This will put downward pressure on electricity prices and bring with it new economic opportunities for individuals, communities, and network utilities who can make use of this new revenue source.

Diminished use of the grid as a result of the increasing attractions of distributed solar PV and storage will increase costs for others, leading to increased incentives for others to use the grid. This potential source of a “death spiral” may or may not be fully offset or more than fully offset by increased value of local exchange. The death spiral is the scenario where consumers reduce their reliance on grid-sourced electricity, by installing solar PV and batteries, and as a result the remaining consumers’ electricity unit prices go up. Consequently more consumers install solar PV and batteries, further exacerbating the problem. Over time, the cost of the grid becomes too high and becomes economically unviable to maintain. As an alternative, if consumers are economically rewarded for providing electricity, capacity and ancillary services to the grid and other consumers, they may size their systems to self-supply electricity, but will also increase the size to maximise the return available and monetise their

roofspace. This scenario would see greater relevance of the distribution network, but declining need for the transmission network, which could lead to asset writedowns and stranded assets.

The evidence for these bottom-up responses to solar-storage is that already technology platforms are being invented to sell excess local electricity, such as Reposit and Local Volts. Companies such as Grid Singularity and Solar Coin are using the Bitcoin's underlying programming protocol, called 'the blockchain', to transact electricity (Extance 2015). This is a distributed consensus-driven infrastructure, which enables trust between counterparties. Using the blockchain, grids can become more resilient, with a commonly-used database for managing transactions. This platform can be used to both manage electricity and the financial transactions associated with it (Rutkin 2016). The future for electricity in cities would appear to be an integration of these smart city systems with sustainable city systems (Newman, Beatley and Boyer 2009; Hargroves and Smith 2005).

These conclusions have not been able to be made before, as no other city has the unique situation of high electricity prices, a great deal of sunshine, and has so extensively delivered solar PV. Therefore, the likelihood of rapid mass grid defection due to cheap Li Ion battery storage is very low, and, indeed, the grid will become more important wherever communities can be linked by citizen utility mechanisms. The research, therefore, has significance well beyond Perth, as it shows that electricity grids and solar-storage will be an important part of the disruptive electricity transition we are entering globally.

5.3 Discussion Journal Paper 3 Modular Construction Hickory Case Study

As cities around the world grow in size, there are aspirations to implement city limits and urban growth boundaries (Newman and Kenworthy 2015). The result is often characterised as a constraint to affordable housing supply and consequent increases to the cost of housing (e.g. Cox 2005 and Troy 2012). Particularly for commercial projects such as medium and high density housing, modular construction has the potential to deliver product to market at a much faster rate than traditional building approaches and to create a cheaper housing product due to the construction process. This will therefore address housing affordability concerns associated with redevelopment (e.g. Jordan 1995). Thus, modular construction can be seen as a financial

instrument, which can be used to control housing supply and, furthermore, housing affordability. It will also be able to further demonstrate sustainability benefits and it has the potential to disrupt the traditional construction industry in the process of achieving the low-cost, low-carbon outcomes that are in demand.

Our analysis demonstrates that the use of modular construction could rapidly grow, and leave the traditional construction industry in Australia (and likely in most parts of the world) with stranded assets in the workforce and in the traditional supply chains for the brick-on-brick/stick building industry.

In applying disruptive innovation theory, an analysis is given for the responses that traditional industry and government agencies can make to disruption as either *'fight'* *'flight'* or *'innovate'* (Green and Newman 2016a and b). The same analysis can be applied in terms of modular construction.



Figure 19: Potential responses the traditional building industry can take to modular construction

Source: Green, J., Newman, P., with information from BNEF

In Figure 19 above, three possible responses are outlined to the disruptive innovation from modular construction that can be made by government agencies responsible for the construction industry and incumbent players in the construction industry.

Fight

If incumbent construction businesses *fight* against the market uptake of modular, they can lobby for protectionist policies that maintain their market share and lock out domestic or imported modular. If there is market demand and supportive policy settings for modular, *fighting* will continue to lead to reduced demand for traditional buildings, asset write-downs and stranded assets.

Flight

The *flight* approach would see traditional builders taking no action, or divesting investments in traditional construction markets altogether. Inaction leaves traditional builders exposed to the market changes. Not managing the transition effectively between the old and the new paradigm will likely lead to asset write-downs and stranded assets.

Innovate

Incumbent players can embrace this new reality and continue to play to their strengths as established brands with a wide customer base and technical experience. They can adapt their product offerings and services to this new market. *Innovate* approaches take the form of deployment of new modular technologies. The new modular market is attracting participants such as component providers and technology and software companies, along with financial institutions backing the industry. *Innovative* strategies may therefore include incumbent builders continuing to build traditionally but including modular components in the building, or embracing an entirely modular approach.

Although *innovation* isn't an assurance of survival, some will survive by innovating, whilst others will be unable or unwilling to adapt. If incumbents 'fight', they are unlikely to succeed, as imported modular building product is high quality and cost competitive and free trade deals are likely to support them being imported. If they adopt 'flight' approaches in taking no action, the domestic building sector will be disrupted, creating stranded assets and bankruptcy. Therefore, 'innovate' approaches to modular innovations are those most likely to provide net benefit to the incumbent construction sector, as well as for cities in delivering low-cost and low-carbon housing.

For innovation to occur, the financial services sector will need to become more willing to lend to the modular industry. This may involve business models around underwriting financial risk, using systems like BOPAS in the UK. Government housing and land development agencies can help in the short term by underwriting pilot projects to create market acceptance and disruptive culture and behaviour change. The Adara project is an example of consumer demand for modular and illustrates how the project risks can be adequately mitigated and managed. There is greater demand for modular in Perth, after seeing the results of this project (Curtin U2016).

The potential for domestic modular construction to compete against imported modular construction exists, particularly where the transportation costs are very high, countering the lower costs of foreign labour. Imported modular construction could assist the development of a domestic modular construction industry by building market acceptability for the product and viable projects, thereby increasing bank willingness to finance modular.

As modular construction can be produced much faster than traditional construction methods, it could be used to provide housing in greenfield areas, to rapidly deploy infill projects, to counter the effects on house prices where urban growth boundaries are put in place and when redevelopment is the only option or the preferred option.

Until the barriers to modular construction's deployment in Australia are addressed, it is difficult to see it as a 'live' disruptive innovation, albeit with latent potential. Were this to manifest, the incumbent traditional building approaches may cease, but many of the materials used will be instead used in modular and will not become 'stranded'. Some, such as bricks, may do. The presence of traditional materials becoming 'stranded' due to different building approaches such as modular becoming 'mainstreamed', could legitimately be seen as an indicator that 'disruption has occurred'.

5.4 Discussion Journal Paper 4 Solar-Storage in Strata the Gen Y Case Study

If the model of decentralised electricity and storage is realised, there will be significant implications for Australia's electricity system, cities, and utilities' business models. The business models of incumbent electricity companies must alter otherwise incumbent companies will not survive the change. Kodak knew that digital photography was the future but it was their lack of understanding of the business models that lead to their bankruptcy (Seba 2014c).

It is no longer possible for utilities and regulators to ignore the disruption, nor can planners see this as outside their scope of responsibility. Planning systems, including those used in Perth, are trying to enable multiple housing developments and want to help create a more sustainable future (Newman and Kenworthy 2015; WAPC 2015). A good planning and

governance framework to enable higher density precincts in managing sustainability innovations is required to make this possible.

For housing, public-private partnerships (PPP) between developers and the private sector allow for greater pooled investment to facilitate the establishment and maintenance of strata networks (Bunning et al 2013). Residents owning solar-storage infrastructure will lower household costs for residents, thus lowering the lending risk for banks, which, if incorporated into the bank's credit assessment, could result in their becoming the lender of choice for residents of battery and solar powered dwellings. The utilisation of these innovative governance and financing approaches will result in greater uptake of renewable energy in the housing market in Australia and other cities around the world. To deliver low-cost and low-carbon housing, planning systems in cities globally need to enable such services by ensuring that policies have the ability to implement a flexible governance structure that allows for the creation of a localised utility. There is no similar model that has been proposed in other parts of the world to enable solar-storage in multi-unit dwellings.

5.5 Discussion Journal Paper 5 Demand Drivers for Medium Density Housing¹⁰

The following key findings are suggested from the survey of residents in Perth's new medium density dwelling market.

- 1) Sustainability attributes are important to the market.

Energy efficiency is rated more highly than solar PV, but given that there is not a lot of solar PV presently in the medium density property market, *actual* preferences are difficult to garner. These results suggest that if the market will provide more options of housing with sustainability attributes, people would choose them and developers would have a larger range of buyers.

- 2) Location Location Location

The location of a dwelling in respect to amenities such as food shops, schools, public transport and place of work are the next most influential factors after affordability of the dwelling. This confirms the desire of planners in many cities, including Perth, to prioritise redevelopment over fringe development however, the market for greenfields still outstrips

¹⁰ Published in Urban Policy & Research March 2017

redevelopment due to built-in momentum in the planning system (Newman & Kenworthy 2015).

3) People in Perth love air-conditioning

The presence of air-conditioning and heating features in a dwelling is consistently important to all surveyed, even in properties with energy efficiency and passive cooling/heating design. This highlights the perception in the market that there must be these additional climate control systems to live in comfortable conditions throughout the year.

4) Public transport proximity is highly valued

Proximity to at least one form of public transport is very highly valued by almost all residents, except those who work close by (aged 20-30) or are in their 50s-60s. Those who did not rate at least one form of public transport as fairly, or very important (6 or above out of 10, which was seventeen per cent of respondents), rated provision of car parking very highly, surpassed only by price, location to amenities and air-conditioning features. People in sustainability-oriented dwellings, who rated public transport access as important (45 per cent), also rated energy efficiency attributes highly. Public transport remains a fundamental amenity for medium and high density living in Perth.

5) Importance of green space and recreational centres varies

Proximity to green space, over recreational centres, was more highly valued in the central areas of Perth/East Perth than elsewhere. Conversely, proximity to recreational centres was more highly valued in the suburbs (outside CBD proximity) than proximity to green space, despite being more green space in proximity in the suburbs. Overall, the amenity of green space remains important for medium and high-density living.

6) Proximity to schools is only important to those who have children

All the developments examined have multiple school options surrounding them, many at walking distance, however only people with children stated this to be an important factor in their decision. Those who did not plan to have children in the foreseeable future did not take the proximity to schools into consideration in their decision. Developers could infer that for medium density dwellings, proximity to schools is of lesser importance than other factors.

7) Walkability is valued

There exists a large variation in people's preferences for footpath and bike path proximity to their dwellings. Locations where most daily errands can be completed on foot were most desirable.

Consolidated discussion

There are some important links to be drawn between the micro-economics of papers 2, 3 and 4 and the big picture of paper 5. Paper 5 shows that where consumers are offered sustainability features in their housing, they prefer it. The principle-agent dilemma or problem is potentially having an impact on developers (principle) including sustainability features for the buyer (the agent). Solar-storage is a technology that could be deployed in medium-density housing, by dealing with this split incentive issue. As illustrated in paper 4, developers could co-own or entirely own the solar-storage system and provide reduced price power to residents. If this disruption was planned for i.e. not fought against, it could result in avoiding or reducing the instance of stranded fossil fuel assets. In paper 5, if the financing challenges for modular are overcome, the principle could use modular, which would be beneficial for both principle and agent.

Although system innovation and transition theories such as TIS and MIS look at different types of change, including incremental, radical system innovation, these are an analysis *ex post*. There are not tools that identify earlier on in the process that ‘disruption is assured or highly likely even’. Whilst solar-storage appears to have more preconditions for disruption, with path dependency and lock-in (Twomey and Gaziulusoy 2014), modular has been successful in disrupting traditional building approaches in certain countries, e.g., Finland and Sweden. In this respect it has the potential to be disruptive in Australia but does not appear to be manifesting presently.

In terms of what tips the balance towards disruption, this research finds that it is a variable combination of: the technology, consumer behaviour change, enabling business models and supporting policy. Further work could entail analysing in context specific cases, what is the relative importance of variables and where a technology lie in the pathway to disruption.

6. CONCLUSIONS, IMPLICATIONS AND RECOMMENDATIONS FOR FURTHER WORK

6.1 Conclusions

The overall purpose of this thesis was to conduct research to answer the following question:

“How can disruptive innovation contribute towards mainstreaming low-cost and low-carbon housing?”

To address multiple aspects of this question, different research questions were developed to elucidate the global renewables transitions, the local renewables transition, the construction transition and the housing transition. The conclusions presented in this thesis are:

The global renewables transition. *How will the disruption to the traditional electricity market from renewable energy and storage impact fossil fuel assets? Under which scenarios could renewable energy fulfil the majority of global energy demand?*

Traditional electricity utilities generation, transmission and distribution assets are at risk of becoming stranded due to the uptake of distributed solar-storage systems. Fossil fuel companies have bullishly forecast the growth of global energy demand, drawing conclusions that their asset portfolios have little or no risk. Innovation factors, such as increased energy efficiency causing the decoupling of GDP and energy demand, and the faster rate of uptake of renewable energy underpinned by low storage costs have not been adequately considered, and, as such, their assessment of portfolio risk lacks the requisite sophistication. Global demand forecasts that do consider these factors suggest that low-cost renewables could account for global energy demand before 2050, leaving many fossil fuel assets stranded. Fossil fuel risk assessments should therefore be revisited with these factors incorporated into the scenario analysis.

The local renewables transition. *What is happening in Perth with its opportunities to demonstrate the residential solar transition? When will solar and battery systems reach retail grid parity in Western Australia? What effect does the installation of solar panels have on a household’s utilisation of grid electricity? What further reductions are seen when a battery is*

installed? What is the role of the grid in a distributed system and what are the changes to the utility business model, especially in retailing electricity? How can utilities respond to this transition?

The impact that distributed renewable energy and storage will have on household electricity usage and cost was examined. It has been found that there is an economic advantage to load defecting and reducing a household's reliance on the grid to a certain point. Solar and battery technology can see very significant reductions on a household's electricity demand from the grid, up to 90 per cent in this case study. This paired with forecasts for the continued decline of solar and battery prices to fall below retail grid parity, occurring in 2017/18 in Perth, Western Australia. Although at that moment, disruption of incumbent utilities will not consequently manifest, further price decline in solar and storage and further price rises to grid sourced electricity will result in the former becoming relatively cheaper in the near term. As this occurs, solar-storage installations are likely to increase, reducing demand for electricity from centralised fossil fuel generation sources, negatively impacting asset values. Consequently the transmission network is likely to be utilised less, impacting its value. Utilisation of distribution networks could be maintained. This scenario would suggest that large-scale fossil fuel generation utilities and transmission networks could be facing a disruptive threat to their business models and would need to innovate to survive.

For the past century in Australia and indeed in most developed cities around the world, consumers have been at the end of a long production line of electricity. Notwithstanding that, in less than a decade, with mass deployment of solar PV rooftop installations in Australia, they've moved from consumers to consumer-producers, much like citizen journalists in social media. With middle-income rooftop-installed solar PV now the largest power station in the grid in Australia, there is significant disruption, as householders seek to not only reduce their power bills, but to sell their excess power to other local users via micro utilities and enabling technologies like the blockchain. Residential building managers and local communities are able to become citizen utilities, providing their groups of households with solar power and profits from the excess.

This research has demonstrated that the grid will still be needed in this new distributed system and that citizen utilities will need to be accommodated. This is a challenge to all conventional utilities, especially in their retail function. This is the first version of a new kind of electricity

market, operated by consumers, or *prosumers* (Toffler 1980), which will change the way electricity is generated, consumed, and transacted.

Facilitating this transition can enable significant economic advantages to a city. The Perth transformation suggests that the change from an old economy orientation with fossil fuels and centralised power can rapidly shift to distributed, citizen utility-based power on a foundation of new economic localism and the democratisation of power.

The attractiveness of going ‘off grid’ or reducing grid reliance, saving and distributed renewable energy will increase to the extent that policies raise electricity bills to tax carbon or to subsidise renewables. Policies around this are a key method for channeling expectation in the market place and encouraging investment.

The extent to which consumers are remunerated for the real contribution that their electricity and energy makes to the grid at different times of the day will also impact the utilization of the grid, as indicated in Figure 11. The threshold for grid maintenance needs to be kept in mind as indicated by AEMO 2016. The window for addressing the systemic reform needed has been represented below in Figure 20.

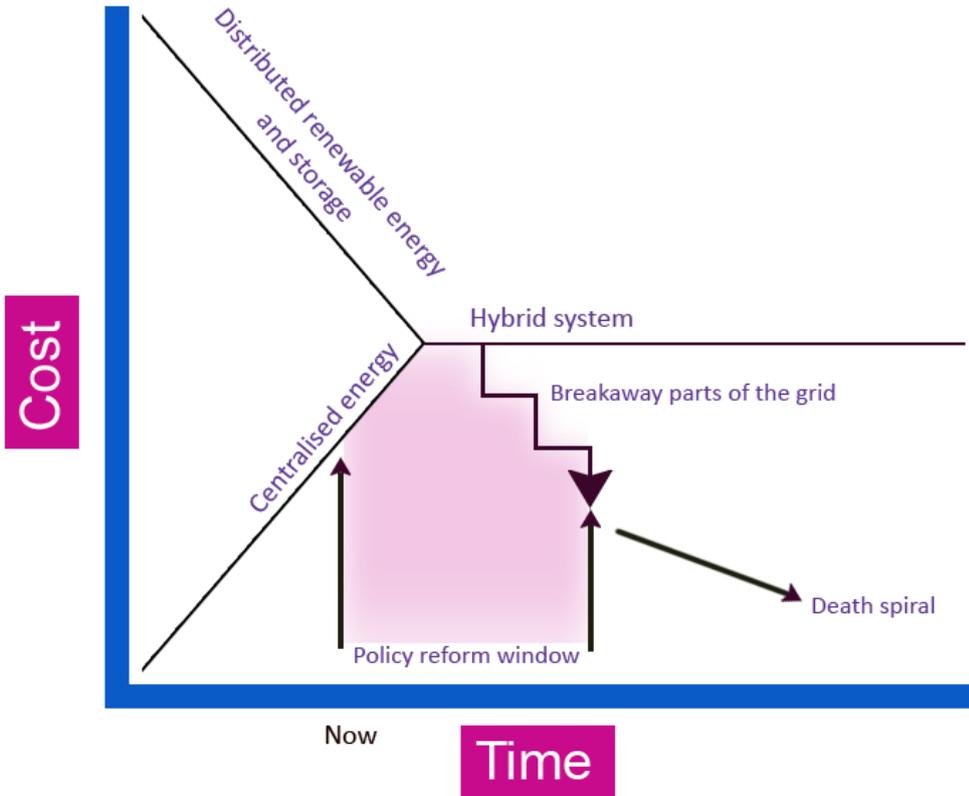


Figure 20: Systemic reform window of opportunity

The construction transition. How do modular buildings compare against traditional buildings when considering cost, time and sustainability performance? What role can they play in delivering low-cost and low-carbon housing? What are the barriers and opportunities for traditional builders to become part of this transition?

Modular construction methods can substantially reduce the time spent on construction, waste generated, and construction costs, while increasing the thermal performance of the building in comparison to traditional construction methods. There is also significant potential for carbon emission reduction from freight if materials can be domestically sourced and modular factories established in close proximity to development sites.

Modular construction has many benefits, which were demonstrated in this analysis of the Adara building, one of the first to be built from modular techniques took place in Perth, Western Australia. Construction costs, return on equity, and construction times are materially better, and waste is substantially reduced. Energy efficiency can be improved from traditional building approaches, by designing modular for the specific geographical and climatic context.

This study has shown that if the local context is not considered or the climate appropriate materials not chosen wisely, then a prefabricated modular building can easily prove to be more carbon intensive than a traditional equivalent.

By overcoming these kinds of issues, Australia and other countries with traditional construction sectors, have the potential to compete against imported modular construction and to disrupt the local traditional construction firms, which will result in resilience within the domestic building industry.

Overall, there is great potential for modular buildings to deliver low-cost and low-carbon housing. There are a number of challenges that must be overcome, such as refining products to suit the Australian climate and resolving challenges as regards the financial sector providing finance for modular construction. However, the results would support the contention that modular construction is likely to be a disruptive innovation.

***The housing transition.** What governance, ownership, and financing arrangements are possible that will facilitate renewable energy and storage uptake in strata housing developments? Does sustainability influence actual medium-density housing preferences in Perth, Western Australia? What is the relative importance of sustainability features when compared against other dwellings features and location features in determining purchasing and rental decision-making?*

In Australia, solar PV and battery systems have not seen the same high uptake rates in residential, medium-density developments as they have in standalone residences. This is because there has been little incentive for developers to include these systems that solely benefit occupiers. This thesis has developed a new business model for strata developers that would see solar and battery technology installed in strata as a part of a micro-grid to provide economies of scale. Electricity produced behind the meter would then be sold to residents to pay back the capital investment in the electricity infrastructure, with developers having the option to provide cheaper electricity than that provided by the grid as an attractive feature for residents. Innovative business models such as this can provide new commercial opportunities for residential developers, while also promoting low-carbon technologies and lifestyles.

Cost-competitive solar and storage have significant implications for incumbent utilities and their business models, due to the reduced utilisation of their network and generation assets. Utilities will hopefully move from *'fight'* and *'flight'* responses to *'innovate'* responses. Planning systems need to ensure they too can accommodate *'innovate'* responses in their strategic and statutory schemes, and development appraisal in general. For developers, significant opportunities lie in avoiding project electricity headworks costs for infrastructure e.g. transformers and substations. This involves reducing a development's reliance on the grid through solar and storage infrastructure. This also creates a new market proposition for developers to offer dwelling buyers.

There are challenges to deployment of this model, which the case study has sought to overcome. This research provides a planning, commercial and governance framework from which more decentralised renewable electricity generation, namely solar PV, and storage assets can be deployed in Australia and internationally, using the principles developed,

especially in high-density urban areas where current practice provides limited incentives for the uptake of renewable generation and storage. The application at WGV needs to be trialled in other jurisdictions and markets. Part of this should be an attempt to put this within the planning system using the WGV Structure Plan and a WGV Local Planning Policy as references.

Additional larger-scale versions of this approach to electricity systems are now being considered for deployment on different kinds of strata developments, such as commercial and retail operations. If successful, it may be that the model can be extended to non-strata housing through design linkages and use of connecting technologies such as the Internet of Things (using, for example, blockchain software). Thus, the model may release the ‘hidden potential’ of precinct-scale local utilities, and help create a city of distributed power (Maloney 2015).

Sustainability attributes of a medium-density dwellings have an influence on actual market choices and there is a market for their inclusion in developments. Features that reduce a household’s electricity have a material impact on people’s choice of dwelling, and the medium-density housing market in Australia are demanding green features. Developers that have included green features in their developments have attracted a greater number of buyers.

6.2 Implications of the Research

It is anticipated that the findings of the research will have implications within the global and local community, the full extent of which is not known. However certain things can begin to be seen:

- 1) The examination of disruptive innovations and how rapidly they can enter global markets has demonstrated the risk of incumbent’s business models based on continued growth and reliance on fossil fuel electricity generation and centralised distribution systems. It is anticipated that this will support other such findings and lead to a shift in perception about the capabilities of renewable generation and storage, and ultimately the mainstream uptake of renewables. It will hopefully assist incumbent utilities make the transition by recognising that the traditional forecasts may be misleading in an age of disruptive electricity and housing innovations.
- 2) Through understanding the full impacts that solar and battery systems will have on centralised, fossil fuel-based power systems, this thesis aims to highlight the risks in not

innovating in this area, as well as outline strategies that utilities and fossil fuel companies may use as result of market disruption. The need for the electricity grid in the cities of the future, albeit with a more distributed electricity generation, means that utilities will need to develop new commercial business models, such as leasing solar-storage to consumers and utilising storage within the grid for balancing the power system and enabling peer-to-peer electricity trading. Blockchain interactions will grow into a major mechanism for facilitating citizen utilities and enabling incumbent utilities to survive.

3) The contextualisation of solar and battery technology as a disruptive innovation aims to, first, better understand the phenomenon of disruptive innovation, and second, better understand and anticipate market changes in the electricity sector. The adaptation of business to this phenomenon will be greatly influenced by the understanding of where change is occurring and how to take new opportunities from the disruptive process.

4) Demonstration of the benefits and barriers of modular construction in this thesis demonstrates that the finance and modular industries need to work together to come up with a solution that facilitates funding for modular projects. This is obvious in Australia and is likely to be the same wherever traditional construction is present. Imported modular can assist in creating market acceptance for modular product. The development of a domestic modular industry will assist in the transition of any traditional construction workforce and make it more resilient to competition from international business. It will also promote local innovation and deliver low-cost and low-carbon housing.

5) The model for medium-density buildings will provide strata managers and owners with a robust tool to develop a new business offering that not only creates new revenues but also differentiates the consumer offering in the market, by providing lower-cost electricity to residents. The development of viable revenue streams aims to overcome financial and perception barriers around the uptake of renewable and storage technology in medium-density housing developments. This should be applicable to any part of the world, as no other model seems to exist for multi-owner dwellings.

6) By demonstrating actual market preferences and demand for sustainability features in dwellings, this thesis intends to highlight the economic benefits to developers and homeowners to include low-carbon features in their dwellings. For these sustainability features, the economic case, i.e. their contribution to affordable living, is vital to their demand and therefore their inclusion in the Australian housing market and is likely to be applicable to many other parts of the world struggling to see how sustainability markets can emerge in housing choices.

6.3 Future Research Questions

As with all research projects, there have been many questions raised during the duration of this research. The following list outlines some of the areas that warrant further investigation:

- *Where can modular construction methods best be applied to fully utilise the benefits of this technology?* A domestic modular industry has many potential benefits, as outlined in this thesis. Further research should be conducted to determine what type of buildings would best benefit from modular construction, as this thesis has mainly focussed on residential applications. Research into demand for modular buildings may also work to promote market acceptance and be indicative of where best to establish modular factories.
- *What financial and governance structures are possible to facilitate renewable energy and storage uptake for business?* This thesis has mainly examined renewable electricity generation in residential buildings. Renewable energy uptake within the business context will be equally important including offices, shopping centres and industrial areas. While many similar principles in this thesis are applicable to business as well as residential developments, commercial properties will have unique financial and governance barriers, especially as many businesses rent their office space rather than owning the buildings outright.
- *What are the economics for load and grid defection in other parts of Australia and the world?* Perth, Western Australia, has a coalescence of ideal conditions for the uptake of solar and storage systems, which means that retail grid parity for solar and battery systems will be reached earlier relative to other locations, both in Australia and abroad. Factors such as access to sunshine, electricity prices, whether houses are located in a grid, or off grid, will all affect grid pricing, the pricing of solar and storage systems, and their market penetration. Further research to determine when this will happen would be useful to electricity providers, consumers, market analysts, and solar and storage developers. This research on Perth should continue to be evaluated as the technology is further improved, and more households install storage, or other changes occur due to unpredictable *'fight, flight or innovate'* responses. Responses of utilities should be analysed to further assess what measures are effective or not in surviving market disruption.
- *At what rate have solar and batteries penetrated the electricity market and has this resulted in a more distributed electricity generation model, and what does this model look like? How can companies best position themselves to survive disruption?* At the time of publication of this thesis, the combination of solar and battery systems had only just begun to

penetrate the market, thus many of the effects of this new technology have been based on predictions. The actual effects of this technology on the electricity system should be closely monitored, as suggested above, and a more detailed evaluation carried out of which market segments are finding solar-storage to be most effective.

- *What is the threshold for grid maintenance versus and off-grid world? What policy reforms are needed and by when to minimise grid defection and therefore maximise economies of scale from the grid? In the Australian context, the window of opportunity for maintenance of the grid is in the next 5 years. Policy reforms that are essential to ensure its ongoing relevance include time of day feed in tariffs, and consumers receiving payment for providing capacity and ancillary services to the grid. The built form has enormous potential to provide considerable generation and storage capacity, therefore, policies for new buildings that mandate roof optimisation for solar will also assist this transition.*

- *Solar and battery technology as a case study of micro-level disruption.* Much of the literature on disruptive innovation occurs on a macro level, looking at waves of innovation with examples of specific products. However, little has been done on a micro level. Solar and battery disruption could serve as a case study of micro-level disruption, allowing for a micro-economic analysis.

- *What other tools can be utilised to facilitate the uptake of renewable energy and storage in multi-unit dwellings?* This thesis highlights a number of barriers to the uptake of renewables and storage in medium-density housing. While the governance tool in this thesis can provide a practical framework for developers, which creates a financial incentive for the installation of these systems in a micro-grid, other strategies may prove equally as beneficial. This could include market analytics to determine actual consumer demand, the development of marketing strategies, and suggestions for sustainability benchmarks in the industry.

- *What assets are at a greater risk of being stranded? What examples of stranded assets exist already and why did that stranding occur in that context?* In this thesis, stranded assets are described as a result of the growing economic preference for renewables (as well as the potential for modular to be preferred over traditional construction). In reality, there will be a number of factors that contribute to certain assets being stranded. A useful tool would be a framework to discern and classify how at-risk assets are, that could then be applied industry-wide. Case studies of assets that have already been stranded would also work to illustrate fully the impacts for stakeholders, such as the labour market and investors.

- *What are the preconditions for disruption and transition to occur? How can it be known if disruption or transition is 'on track'. What is the relationship between the presence of disruptive innovations and whether incumbent assets become stranded?*

6.4 Concluding Comments

Returning to the main question, using the results and conclusions analysed above it can be suggested that solar-storage and modular construction are disruptive innovations that show significant potential to cause rapid mainstreaming of low-cost, low-carbon built environments. The demand is there and the scientific analysis of their ability to create significantly better carbon and cost outcomes would suggest that they are disruptive. However, they can also be prevented from disrupting energy, electricity and housing markets if *fight* or *flight* strategies are adopted by governments and incumbent industries. There are barriers to be overcome to enable *innovate* strategies to become the mainstream agenda. More work can be done to enable the disruptions to be facilitated, rather than interventions that could stop them. However, the thesis suggests that a future of significant decarbonisation in the built environment can now be envisioned, especially in the mainstreaming of low-cost, low-carbon housing through solar-storage and with some policy reform, with modular construction.

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8. RESEARCH PAPERS

Journal Paper 1: Disruptive innovation, stranded assets and forecasting: the rise and rise of renewable energy

Jemma Green and Peter Newman

Curtin University Sustainability Policy Institute, Western Australia

Publisher: *Taylor & Francis: Journal of Sustainable Finance & Investment* (Published
December 2016)

**This Chapter is an exact copy of the journal paper referred to above
<http://www.tandfonline.com/eprint/ACYyK7JHVepTdAjDuJcT/full>**

Journal Paper 2: Citizen utilities: The emerging power paradigm

Jemma Green and Peter Newman

Curtin University Sustainability Policy Institute, Western Australia

Publisher: Elsevier: *Energy Policy* (Published March 2017)

This Chapter is an exact copy of the journal paper referred to above

<https://authors.elsevier.com/a/1UmCX14YGgTsH0>

**Journal Paper 3: Is modular construction a disruptive innovation? An
Australian case study**

Jemma Green, Lionel Hebert, Peter Newman, Roberto Minunno and Francesca Geromino

Curtin University Sustainability Policy Institute, Western Australia

Publisher: *Elsevier: Energy & Buildings* (Submitted July 2016)

This Chapter is an exact copy of the journal paper referred to above

Is modular construction a disruptive innovation? An Australian case study

Jemma Green, Lionel Hebert, Peter Newman, Roberto Minunno, and Francesca Geromino,

Highlights:

- Life cycle analysis of the construction to assess greenhouse gas impacts, waste and thermal performance.
- Faster construction times resulting in higher return on equity compared to traditional building methods.
- Modular construction can increase housing supply and underpin affordable housing strategies in cities.
- Modular construction can be considered a disruptive innovation to traditional building sector and thus become rapidly adopted.

Abstract

We have evaluated construction time, cost, and environmental performance of a steel frame modular apartment complex in Perth, compared against an equivalent building of traditional construction, to also assess whether modular building approaches constitute a disruptive innovation. For this case study, the digital design skills of an Australian construction company Hickory, based in Melbourne, were used, and the modular pods shipped to Perth to create the Adara apartment building. Hickory build using both modular, traditional and hybrid approaches. The local climatic context was evaluated using comparisons of the performance of equivalent building simulations for the climate in Perth versus Port Hedland and Melbourne. Modular construction can be more energy efficient, however the design in this case study did not take sufficiently into consideration the local climate and was relatively less energy efficient, though adaptations can be made. Construction time and cost are found to be significantly better in the modular building, and waste is drastically reduced. As the buildings take less time to construct and assemble, they can be occupied sooner and an enhanced return on investment can be expected for developers. We evaluated the costs of modular construction compared against traditional construction and found significant benefits in terms of construction cost, cost of funding and return on equity investment. There are still challenges to face with the financial sector being risk averse in lending to modular construction, which would need to be overcome for this disruptive technology to manifest significant change in the built environment. We examined the potential for modular construction to be a disruptive innovation to incumbent and traditional building approaches, finding there is significant potential for it to become a larger

proportion of the construction sector and can be used to relieve escalating housing prices.

Key Words: Modular construction; Prefabrication; Low Carbon; Low Cost; Sustainable Housing; Energy Impacts; Greenhouse Gas Impacts; Life Cycle Analysis; Affordable Housing, Disruptive Innovation

Introduction and literature

Disruptive innovation is where rapid change in technology is accompanied by changes to a market that fundamentally alters its traditional base (Bower and Christensen 1995). The result is major change as demand for incumbent technologies are displaced, production assets are stranded and traditional skills and support structures are undermined. This paper attempts to assess whether modular construction is such a disruptive innovation for low cost housing that is also low carbon. The need for both low cost and low-carbon housing is needed if an industry is going to be able to continue into the foreseeable future.

A great deal of research has already been undertaken in the area of low-carbon and sustainable housing, [Newman and Matan (2013), Droege (2011), Droege (2010), Newman, Beatley and Boyer (2009), Beatley and Newman (2012; 2013), Droege Ed. (2009), Deng, Prasad and He (2008)]. This research has identified a wide range of barriers to the development of low carbon precincts including public opposition to high-density housing and cost implications of sustainability technologies.

Research around low-cost and low-carbon housing is more limited. However, important examples include Grattan Institute's 'Housing We'd choose' (Kelly, J.F 2011), Curtin University's 'Housing We'd choose for Perth and Peel' (Rowley, S 2013), AHURI and the National Research Centre for the Sustainable Built Environment.

Off-site prefabrication of building components or fully-finished modules have been used for decades, but this technology was often chosen when traditional alternatives were hardly possible. For example, in remote areas where skilled labour was scarce, or in disaster response when urgent product is needed, or when a limited budget was available to build many similar dwellings such as for mining villages (Steinhardt et al., 2013). Moreover, aesthetic, efficiency or comfort were rarely part of the requirements, let alone other key performance indicators, when choosing prefabrication. Prefabricated modular technology today is chosen for different reasons: it can be applied to almost every building typology (such as residential detached houses to multi-level hospitals and offices) and seems to be able to provide buildings that are at least as aesthetic, efficient and comfortable as traditional construction, while retaining their advantages in construction time and cost (Cartwright, 2011; Jordan,

1995). The literature shows that the largest cost and time savings of modular construction come from the efficiencies in factory production along with a reduction of up to 70 per cent of waste compared with traditional building approaches (Rogan, Lawson and Bates-Brkljac, 2000) due to efficiencies in design. Construction work hours can be reduced by an estimated 50 per cent (SBEnrc, 2015) and mitigates the risk of weather delays (Li et al., 2013).

Modular and traditional building project funding or interest rates are broadly similar, however, as modular buildings can be constructed faster, the length of time of borrowing can be shorter, therefore funding costs less (Curtin, 2016). Modular can provide an enhanced return on equity, as discussed in section 4.2, and the better preparation and supervision of manufactured building helps to keep budgets (as well as quality and time) under control; limiting the risk of unexpected expenses and delays. Modular, however, presents some distinct real and perceived financial risks and opportunities when compared against traditional on site building approaches. On the risk side, as an example, with modular construction, the progress takes place in a factory as opposed to on site, necessitating a different funding payment schedule to traditional construction, which can make obtaining financing a challenge (Li et al., 2013, Curtin, 2016). Lenders are also concerned that if the modular company goes into liquidation, finding an alternative modular company to complete the building will be a lengthy and more costly process. This risk, termed 'completion risk' can leave lenders reluctant to lend to modular projects (Curtin University, 2016).

The literature suggests modular construction has the potential to offer the environmental, economic and social benefits required for the buildings of the future. Evaluations of actual projects are needed to examine all of these aspects. This paper assesses one of the first urban modular commercial projects in Perth, the Adara apartment building. We test the time, cost and sustainability aspects of the development with an emphasis on energy impacts. Low-carbon, low-cost housing is a strong agenda in Europe and Japan where the modular solution has been found to provide many opportunities for achieving these goals as well as market acceptability (Aitchison, 2014). However, in Australia the modular solution has not yet been mainstreamed despite high construction costs, household electricity prices, and in global terms, high greenhouse gas emissions per capita (Muenstermann, 2012). The research in this paper was designed to achieve some certainty about how important modular construction could be for achieving multiple value outcomes.

A great deal of energy is consumed in the building construction process and the production of the materials used within the buildings (Hammond and Jones, 2008; Venkatarama Reddy, 2003; Sartori and Hestnes, 2007 and Lenzen, 1998). Dwellings that are poorly designed from a thermal performance perspective are more reliant on mechanical heating and cooling, which requires electricity. In the past decade in Australia, household energy costs have risen by more than 80 per cent (Green & Newman, 2016a), taking a greater share of the weekly budget and increasing financial pressure on consumers. Presently, the majority of energy in Australia is generated by power stations that run on fossil fuels (NEM, 2016 and DIS, 2015), polluting the atmosphere and exacerbating climate change. Many consumers are also becoming more environmentally conscious, looking for alternative, cleaner, sources of energy (Green and Newman, 2016b). In Australia, people are increasingly turning to medium density dwellings over stand-alone houses that are larger and have higher maintenance costs. In 2012, 38 per cent of home approvals were for medium density dwellings, compared to 31 per cent in the five years previous to that (BankWest 2013; Department of Planning 2010), however very few so far have been modular construction. This paper finds that with Australian cities planning to limit urban sprawl, modular construction can underpin policies to create urban growth boundaries without creating a commensurate constraint in the housing supply, which would push the price of housing up.

To determine the potential for modular construction in delivering low-cost and low-carbon housing and whether it could be a disruptive innovation, we have evaluated several aspects of Hickory's Adara steel-frame modular building, a six storey apartment complex located in Cockburn Central in Perth Western Australia, and compared against an equivalent traditional concrete building from three perspectives: time, cost and environmental performance.

Background to project

Adara is an apartment complex located in Cockburn Central, in Perth Western Australia, built for the Western Australian Government's Department of Housing. It is made up of six floors of 77 apartments and constructed using 96 prefabricated modules. The non-modular elements of the building include the ground floor and two building cores, which are made of concrete.

Adara's modules were designed and prefabricated in Melbourne by construction company Hickory, before being shipped in to Fremantle, and then trucked to site. These modules are constructed of steel frames and are shipped completely finished inside, including furnishings, plumbing and wiring, and external facades. The site works,

slabs, cores, roofing, services to completion and settlement were undertaken by the head contractor, Goodland Group Company.

The location of Adara, next to a train station, is ideal for minimising transport by automobiles. Many local services and shops are within a short walk and residents can reach Perth City in 10 minutes by train. The evaluation does not include expected transport energy savings from this location but there are clearly additional benefits from a low cost and low carbon perspective due to the location of the building (Newman & Kenworthy 2015). The approach to considering the question posed in the title of this paper is to assess the time and cost of the construction as well as the environmental performance of the building, with a focus on energy and greenhouse gas impacts; this is compared to traditional construction as a means of assessing the potential for modular construction to be a disruptive innovation.

1. Methodology

Adara building, and its equivalent of traditional design, were evaluated and compared from three perspectives: time, cost and environmental performance. The following assessments were undertaken:

- * The construction time and cost analysis is based on information provided by Hickory's quantity surveyor and cost estimator, for both the actual modular building and estimated time for an equivalent traditional building.
- * The various costs associated with the modular project are compared against an estimated traditional equivalent.
- * The impact of the different construction time schedules on funding costs and return on investment are also analysed.
- * To determine the financial performance, construction costs, funding costs and return on investment were evaluated.
- * To evaluate the environmental performance, thermal performance, the following were examined: Operating energy, construction and operational greenhouse gas emissions and waste produced during construction process.
- * To compare the thermal performance, comparisons between the modular building and a traditionally constructed building were made in three different geographical locations: Melbourne, Perth and Port Hedland, Australia.

Finally an evaluation of the potential for modular construction to be a disruptive innovation is undertaken by looking at the characteristics of modular, the challenges to its deployment and the likely consequences if there was mainstream deployment.

5. Results and discussion

5.1 Construction time comparison

In July 2014, 96 modules were craned onto the building at a rate of more than 15 per day, with all the modules being installed within 10 days. The construction time for the entire building, using a combination of traditional and modular construction methods, took eleven months. By contrast, with a traditional building approach, this project would take two years to construct. Therefore, for Adara, the modular approach is more than 50 per cent faster than a traditional equivalent.

5.2 Construction cost comparison

The construction cost of the Adara building was found to be 10 per cent less than a traditional building approach (CBRE, 2015). By way of comparison, for the various elements of this costing analysis, we evaluate a scenario where modular costs 10 per cent less, and also one where the construction costs between modular and traditional building approaches are the same.

Construction costs include labour and materials for both the structure and the foundation. The following two graphs (Figure 1 and Figure 2) show a comparison of capital expenditure and funding costs (i.e. interest on debt) between the modular and traditional versions of the project. This evaluation is for both scenarios where the modular project construction costs are the same as traditional, and where the modular project construction costs are 10 per cent less than the traditional. For the Adara project being 10 per cent less, versus traditional analysis, we assume construction costs to be \$22,050,000 and \$24,500,000 respectively. The below two graphs give an overview of capital expenditure and funding cost profiles under both scenarios.

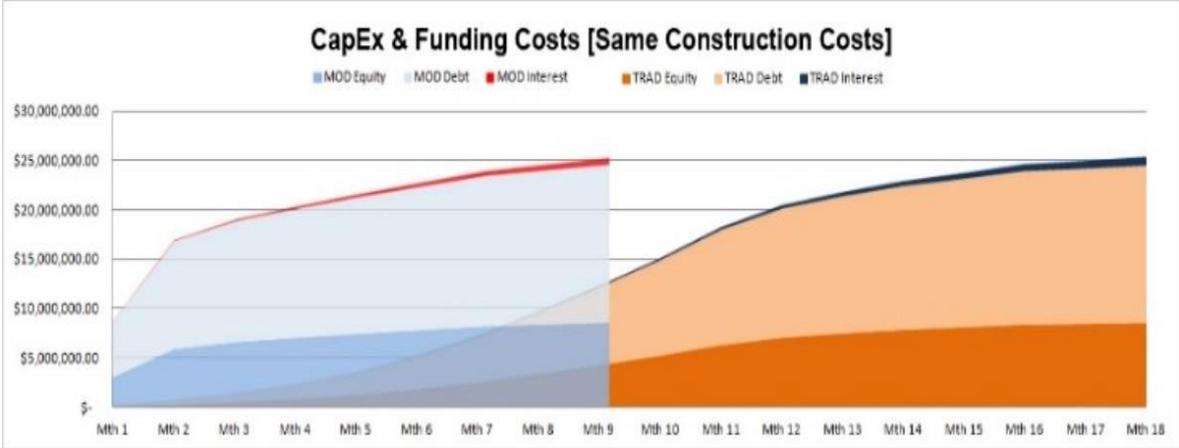


Figure 1: Equity and debt drawdown and interest paid for modular and conventional, assuming both approaches has the same construction costs

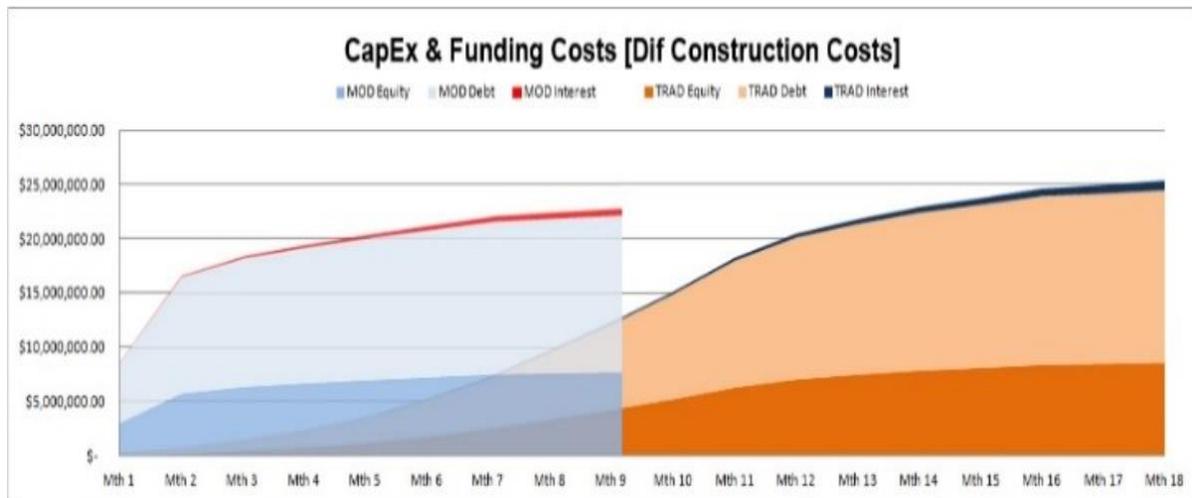


Figure 2: Equity and debt drawdown and interest paid for modular and conventional, assuming the modular project construction costs are 10 per cent less than the traditional.

In both analyses, we assume the loan-to-valuation ratio (LVR) to be 65 per cent debt to 35 per cent equity and the interest rate to be fixed at 7 per cent nominal rate.

5.2.1 Cost of capital

Figure 3 below shows the difference in funding costs, based on the difference in construction costs. Due to a faster build time, the cash-flow profile for modular is significantly different to the traditional building. For modular, equity and debt drawdown is accelerated, but as the project is completed earlier, debt is paid out faster also. For Adara, even with more capital being used sooner, and therefore attracting interest rate costs, there are 35-40 per cent savings on aggregate funding costs. The modular funding costs were \$638,374 and the traditional funding costs were \$891,696, which although substantially different, are a relatively small difference in percentage terms when considering the total project costs, being \$25,138,374 versus \$25,391,696, or around 1 per cent difference.

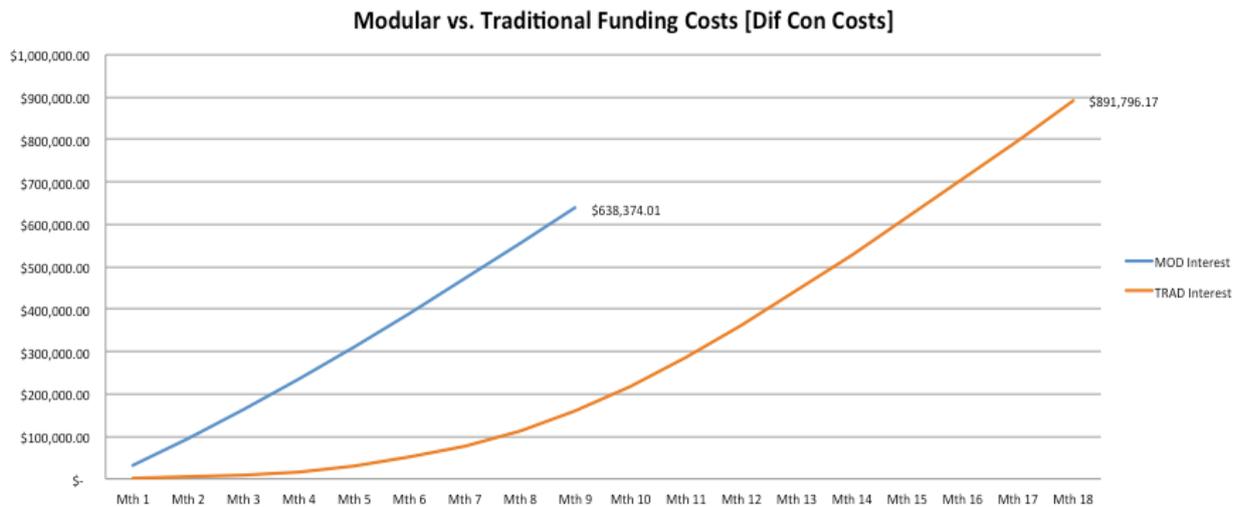


Figure 3: Illustration of funding cost savings of 45.6 per cent from modular construction with 10 per cent lower construction costs

Figure 3 shows that where modular construction costs are 10 per cent less than a traditional equivalent building, funding costs during the construction period are 44 per cent less. In the below graph (Figure 4), we analyse the difference in funding costs, based on the assumption that construction costs between modular and traditional are the same.

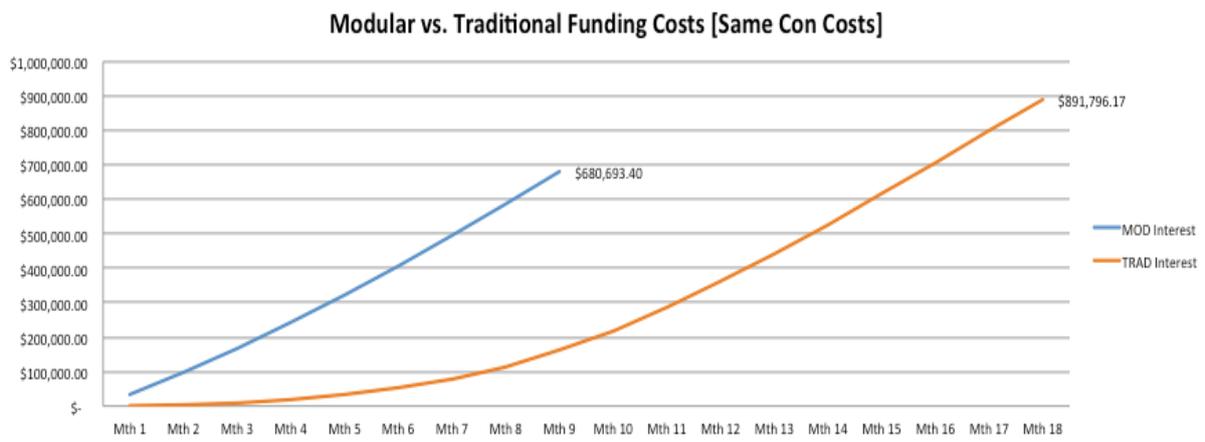


Figure 4: Illustration of funding cost savings of 45.6 per cent from modular construction with the same construction costs

Figure 4 shows, that in a like-for-like costing situation, due to the faster pace of construction, the modular project funding costs would be approximately 31 per cent less. While this is not a significant cost saving, faster

construction times and lower funding costs lead to the sale of dwellings to market sooner, resulting in a return-on-equity (RoE) uplift, discussed in further detail below.

5.2.2 Predictability, yield enhancement and return on equity

The risk of time delays for modular construction is greatly reduced due to the controlling of variables in the factory by one contractor. Hickory delivered the Adara project on time, and this is consistent with previous modular projects they have constructed. For this project, the modular system allowed for more apartments to be constructed without raising the per-apartment cost (i.e. the marginal additional cost). In using the traditional building system 60 apartments would have been constructed for Adara, whereas using the modular building system 77 apartments could be constructed, resulting in a 28 per cent dwelling yield enhancement. This of course requires greater capital, but improves RoE. Further, market demand for this product is high and in line with sales consistent with industry norms for non-modular buildings (CBRE, 2015).

For this analysis, the expected RoE for the modular construction sector was compared with apartments and the hotel developer markets. We assume RoE targets, based on the inner-city investment market seeking RoE of 25-35 per cent. Due to the faster speed of construction, and therefore sales, in the modular building approach, we evaluate the potential for modular to provide a significant equity uplift. Figure 5 shows that where construction costs are the same, the faster build time of the modular project provides a 5 per cent equity uplift on return and where construction costs are 10 per cent less in the modular building, the difference in construction times results in an equity uplift on return for the modular project of 25 per cent.

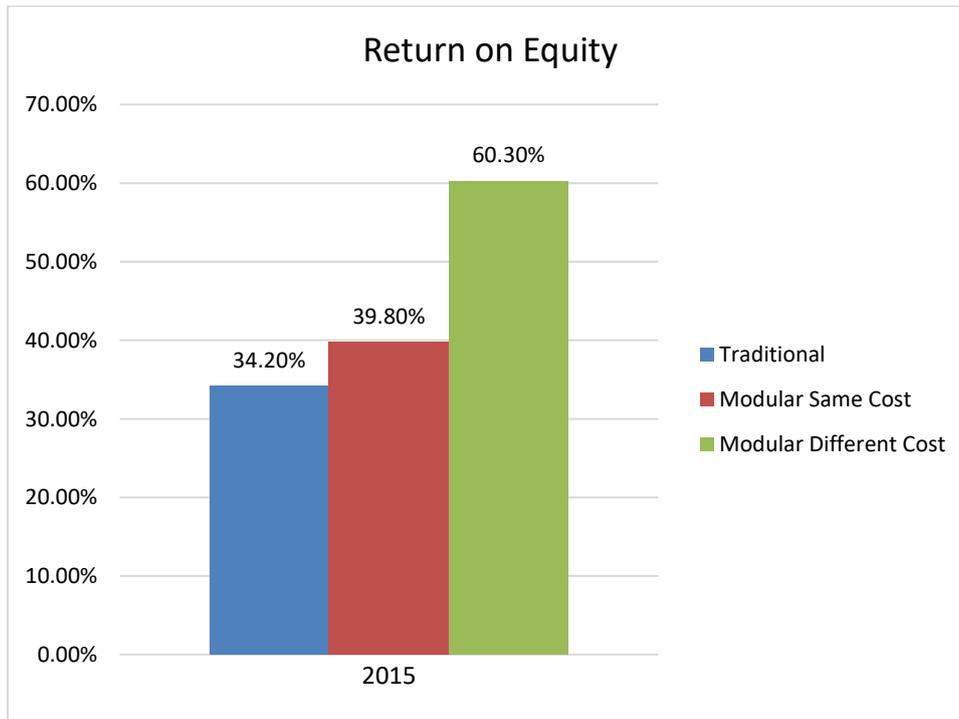


Figure 5: Illustration of RoE comparison between traditional construction, modular with the same construction cost, and modular with 10 per cent less construction cost than traditional.

In dollar terms, for a \$24,500,000 cost of construction, investors would contribute \$15.9 million in equity. The traditional project would return \$5.4 million and the modular project would return \$6.3 million. Were the modular product to cost 10 per cent less, the RoE would be \$8.6 million.

5.2.3 Financing challenges for modular

For lenders to modular projects, a perceived risk exists around progress payments (Curtin, 2016). In traditional construction projects, banks would release funds based on progress that has taken place in-situ, i.e. at the project site. In this situation, senior lenders take charge of the project land titles and as more progress is made, the value of the assets increases commensurately. Alongside that, the lender disperses progress payments to the developer (Fergus and Nothaft, 1995). By contrast, much of the progress of a modular project takes place in a factory, so lenders are not able to see a rise in the value of the land over which they have title, and are therefore reluctant to make progress payments for progress that happens in a factory. This presents a significant challenge for the modular industry as without bank lending, developers are constrained by capital in the amount of projects they can undertake.

The financial services sector has found ways of dealing with certain risks. For the modular building sector, banks manage ownership risk by using a personal property securities register (PPSR) which has a unique identifier for modules for their project in the modular factory, placing legal caveats over their assets to ensure they are not assigned to other projects (Australian Personal Property Security Register, 2016). However, in the situation where not all modules are completed and the modular company goes into liquidation, banks are concerned about which other companies could complete the modules to complete the project. This is particularly of concern where the modular company has a proprietary system of construction. This situation could potentially be remedied by modular companies, in having a backup-modular-producer that could step into the project in the event the primary producer could not complete the work (Curtin, 2016) or underwriting systems that are used in the UK called BOPAS (Bopas, 2016).

5.3 Environmental performance

5.31 Waste

Bossink and Brouwers (1996) were referred to as a benchmark of traditional construction waste. They suggest an overall percentage of waste equal to 9 per cent of a building’s mass. For Adara, waste was calculated from it’s inventory of waste. From this data we calculated the percentage of waste from the production of the modular component of the Adara building.

Because Adara is partially built in a traditional way, we calculated the waste of the traditional component of Adara by using the 9 per cent benchmark. We subsequently added these two figures together to calculate the Adara waste figures and compare these against the 9 per cent waste benchmark for traditional buildings.

5.31.1 Waste from modular

By evaluating the data provided by Hickory on the weight of the bins collected during the construction of the modules, it was possible to calculate the overall amount of waste produced during the entire module’s production. This value is equal to 95.7 tons. This value was used to calculate the percentage of total waste with respect to the overall weight of the modular building. The amount shown in Table 1 below summarises these findings, giving the total amount of waste produced.

	GROSS TOTAL	NET TOTAL
	MASS [tons]	MASS [tons]

PLASTER	80.2	68.3
TIMBER	7.1	5.6
CARDBOARD*	13.9	12.3
GENERAL**	3.6	3.2
PLASTIC	4.5	4.5
PRIMER	2.1	1.8
TOTAL	111.4	95.7

Table 1: Mass of waste produced to build 96 modules into Hickory’s factory

*Cardboard waste is gathered in uncompacted bins. As only waste volumes have been provided by Hickory, an assumed density of 0.1 tons/m³ is used to evaluate these weights, which was referenced from recent research conducted in by Sustainable Learning Australasia for the Environment Protection Authority Victoria.

**General waste means any food waste, contaminated cardboard, waxed paper/paper towel, and tissue paper. This is determined by volume, and assumes a density equal to 0.1 tons/m³.

The weight of a module is 280kg/m², plus two more tonnes per unit, one for roof structure and another for the sidewall cladding. The dimensions of a module are 70.5m² (16.4x4.3), with the total weight for each module being 21.74tons (0.280x70.5+2.0). Therefore, the overall weight for the modular part is approximately 2,100tons (21.745x96 modules).

For the parts of Adara that were built using traditional building methods, the first floor and cores are made of 2,847tons of concrete so we assume 9 per cent of waste (Bossink & Bouwers, 1996) or 256 tons (2,847*9/100) of waste. For the entire modular building, waste produced is calculated as follows:

$(\text{WasteConv} + \text{WasteMod}) / (\text{MassConv} + \text{MassMod}) * 100 = (256 + 95.7) / (2,847 + 2,100) = 7.14$ per cent. Therefore, Adara produced 23 per cent less waste than an equivalent traditional building.

5.31.2 Construction waste

Globally, buildings consume around 30 per cent of produced raw materials (DSEWPC, 2012). In Australia, more than 20 million tonnes of waste is produced each year. Of the construction waste component, 42 per cent went to landfill (ABS, 2010). Rounce (1998) found that the major source of construction waste is due to design changes, finding that designers often fail to pay specific attention to dimensions and standard sizes of products available on the market, resulting in products being ordered which are not suitable for the project. This is also because the

client, architects and designers also make changes to the design while construction is in progress, resulting in previous works being abandoned.

For modular, all designs need to be finalised before construction begins and changes are not able to be implemented. For modular, more detailed design work is undertaken upfront, and in a controlled facility such as a factory it is possible to minimise the waste by using building information modelling (BIM), design for manufacturing and assembly (DfMA) and just in time (JIT) software technologies (Lu and Korman, 2010).

In modular construction, theft, vandalism and weather damage are less of a risk because the factory is enclosed and modules fabricated in undercover areas are protected from weather events (Chua, 2006).

For these reasons, modular buildings are more efficient at reducing the waste produced during construction than traditional buildings. By containing the construction in a secure building, reducing vandalism and theft, modular construction can reduce waste when compared against traditional building approaches.

5.32 Operating energy analysis

Operating energy (OE) includes all sources of energy used to operate the building. However, we limit our analysis to the operating energy used to heat and cool the building to measure the thermal performance. Thus, OE is calculated from the energy demand for heating and cooling over the life of the building. The thermal performance (TP) of 3D models of the two buildings created using BIM was calculated taking into account several factors such as the design and orientation of the building and the materials used to achieve thermal mass and insulation. The energy demand was calculated using dynamic simulation with hourly time steps, taking into account the occupancy of the building in terms of sensible and latent heat, lighting, ventilation, set temperatures, as well as climate conditions.

The software used for estimating energy was CYPECAD MEP, which is a program for the design of the building envelope, distribution and services of the building using a BIM integrated 3D model. CYPECAD MEP uses EnergyPlus, a program developed by the U.S. Department of Energy, to run the dynamic simulation of energy demand.

5.33 Carbon lifecycle analysis

A carbon lifecycle assessment (LCA) for a building is typically calculated by the amount of greenhouse gases emitted from the production of the building materials to the deconstruction and disposal or recycling of the building, including the GHG emitted during the life of the building.

The impact of the greenhouse gas is measured by its global warming potential (GWP) in kilograms of carbon dioxide equivalent (kgCO₂e) for a LCA, which means the volume of gases emitted by that product throughout its life, relative to the impact of one kilogram of carbon dioxide equivalent (CO₂e) (Brown and Herendeen 1996; US EPA 2013).

The LCA of this project was evaluated through an Australian web-based software tool called eTool that is an open-use system designed to evaluate the LCA of a building's performance.

5.34 Embodied energy

Embodied energy (EE) is evaluated as a part of the eTool LCA. In this case study, the EE of the two buildings will not be calculated on a standalone basis but rather aggregated as a part of the carbon footprint i.e. GWP of the energy emissions.

6. Energy, greenhouse gas emissions and waste

6.1 Operating energy

This thermal performance evaluation aims to calculate the overall annual energy required to achieve and maintain a comfortable temperature. The thermal performance results are collected in terms of megawatt hours (MWh) annually for both cooling and heating, and the overall thermal performance is then measured in kWh/m².

The thermal efficiency of a building is dependant on the building design and orientation of the building, the materials used, the energy efficiency of air conditioning and heating, the occupancy (number of occupants, running appliances and lights, air recycling and set interior temperatures) and the outside weather conditions (Wilde and Tian, 2009; Crawley et al, 2008).

6.1.1 Modelling specifications

A 3D model of Adara is reproduced in CYPECAD MEP and contains all of the technical characteristics related to thermal performance, including thermal conductivity, specific heat capacity of the materials and other characteristics.

Weather conditions are factored into the thermal performance modelling to consider how the building will perform in a particular climatic scenario. In CYPECAD MEP, the weather data files are taken from the database of the American Society of Heating, Refrigerating & Air-conditioning Engineers (ASHRAE) and the average

daily global solar irradiance from the NASA Langley Research Centre Atmospheric Science Data Centre.

Internal comfort temperatures have been set to 21°C in winter and 24°C in summer. For the sake of the comparison between the two construction approaches, the heating and cooling equipment’s efficiency was set to 100 per cent.

6.1.2 Simulations results for Perth

Using the design provided by Hickory, the traditional equivalent building behaves better in the summer but worse in the winter, leading to an overall thermal performance 8 per cent more efficient than the modular building (see Table 2).

	MODULAR		TRADITIONAL	
	[MWh]	[kWh/m ²]	[MWh]	[kWh/m ²]
Heating	26.59	4.94	39.78	7.39
Cooling	340.59	63.28	268.20	55.44
TOTAL		68.22		62.83

Table 2: Thermal performance of Adara comparison

This difference in thermal performance is because of thermal mass. To verify the influence of thermal mass, a layer of 50mm bricks was added to the load bearing walls in the modular simulation. This test brought the load down to 62.71kWh/m², bringing the modular building to the same level of traditional buildings in terms of energy demand. Clearly using bricks in a modular building to achieve mass is suboptimal, therefore alternative materials that provides building mass, such as phase change materials, would need to be used.

TEST 1: Adding thermal mass in the modular building						
	MODULAR		TEST 1		TRADITIONAL	
	[MWh]	[kWh/m ²]	[MWh]	[kWh/m ²]	[MWh]	[kWh/m ²]
Heating	26.59	4.94	28.90	4.67	39.78	7.39
Cooling	340.59	63.28	297.59	58.04	298.39	55.44
TOTAL		68.22		62.71		62.83

Table 3: Results of Test showing the impact of adding thermal mass

6.1.3 Modular improvements

Alternatives to bricks in achieving thermal mass are evaluated below. The second factor that influences cooling energy demand is solar gain, which is the amount of heat that penetrates inside the building through the windows. Reducing solar gain can easily be achieved by tinting the windows once installed, or a more durable and cost effective option is to tint them at the glass factory. Therefore, the next five other tests have been undertaken by assessing tinted windows in isolation to other interventions (Table 4).

Solar rays penetrate the building the most when the sun is the lowest in the sky, at sunrise and sunset, through the east facing and the west facing sides of the building.

TEST	Heating [MWh]	[kWh/m²]	Cooling [MWh]	[kWh/m²]	Total [kWh/m ²]
TEST 2: Tinting windows in north and east sides	31.38	5.83	299.09	55.57	61.40
TEST 3: Tinting windows in east side	30.03	5.58	310.50	57.69	63.27
TEST 4: Tinting windows in east and west sides	33.37	6.20	280.36	52.09	58.29
TEST 5: Tinting windows in west side	29.44	5.47	309.70	57.54	63.01
TEST 6: Tinting windows in north and west sides	30.73	5.71	298.23	55.41	61.12
TEST 7: West and east windows fitted with shutters	57.05	5.47	172.23	32.00	37.47

Table 4. The impact of window tinting on thermal performance.

Table 4 confirms that tinting the east and west facing windows produces the most effective results for reducing energy used for cooling in this modular building. The cooling load dropped by 18 per cent and the annual energy demand for heating and cooling is reduced by 15 per cent.

To further test the ability of the modular building in controlling solar gain, the modular building was simulated featuring obscuring shutters on the east and west facing windows.

As shown in Test 7, the installation of shutters reduces the energy demand for cooling Adara from 63.28 kWh/m² to 32.00 kWh/m², or by 49 per cent. With this solution, the modular building has the potential to perform up to 45 per cent better over the whole year. Note: In this simulation, shutters were assumed closed during summer days. This is a theoretical situation to confirm, by simulation, the influence of solar gain on cooling load.

6.1.4 Simulation results for Port Hedland

Port Hedland is a town 1,300km north of Perth, Western Australia. The town experiences a typical semi arid and tropical savannah environment in which the minimum temperature is 17.5°C and maximum is 42.0°C. When tested in these conditions, the modular and traditional buildings generated the following results (Table 5).

MODULAR	PERTH		PORT HEDLAND	
	[MWh]	[kWh/m ²]	[MWh]	[kWh/m ²]
Heating	26.59	4.94	0	0
Cooling	340.59	63.28	1113.22	206.83
TOTAL		68.22		206.83

TRADITIONAL	PERTH		PORT HEDLAND	
	[MWh]	[kWh/m ²]	[MWh]	[kWh/m ²]
Heating	39.78	7.39	0	0
Cooling	298.39	55.44	1175.65	218.43
TOTAL		62.83		218.43

Table 5: Thermal performance of Adara in Port Hedland compared to Perth

In this location, the thermal mass isn't as critical to the thermal performance of the building in summer because there is not such a significant difference in temperature between night and day. Subsequently the modular building performs 6 per cent better than the traditional construction.

6.1.5 Simulation results for Melbourne

For Melbourne, the thermal performance results are summarized in Table 6.

MODULAR	PERTH		MELBOURNE	
	[MWh]	[kWh/m ²]	[MWh]	[kWh/m ²]
Heating	26.59	4.94	182.84	33.97
Cooling	340.59	63.28	119.16	22.14
TOTAL		68.22		56.11

TRADITIONAL	PERTH		MELBOURNE	
	[MWh]	[kWh/m ²]	[MWh]	[kWh/m ²]
Heating	39.78	7.39	268.20	49.83
Cooling	298.39	55.44	83.53	15.52
TOTAL		62.83		65.35

Table 6: Thermal performance of Adara in Melbourne compared to Perth

Melbourne has a cooler climate and in these weather conditions, the added insulation of the modular building represents the most important feature for thermal performance, particularly in winter. During winter, the modular building performs much better than the traditional building, saving 16 per cent in energy demand. This means there is significant application in temperate climates of superior winter heat retention in modular buildings.

6.2 Carbon footprint

6.2.1 LCA of the shell of the modular and traditional building

For the LCA, we first decided to focus on the shell of the buildings, therefore excluding operating energy and operating water from the evaluation.

Several elements were identical in the traditional and modular construction; including service equipment, fittings (e.g. electrical and plumbing), carpet, concrete for the foundations, roof covering, floor tiles and bathroom finishes.

To focus on the elements that differentiate modular and traditional construction, the following analysis excludes elements that were identical for both construction types.

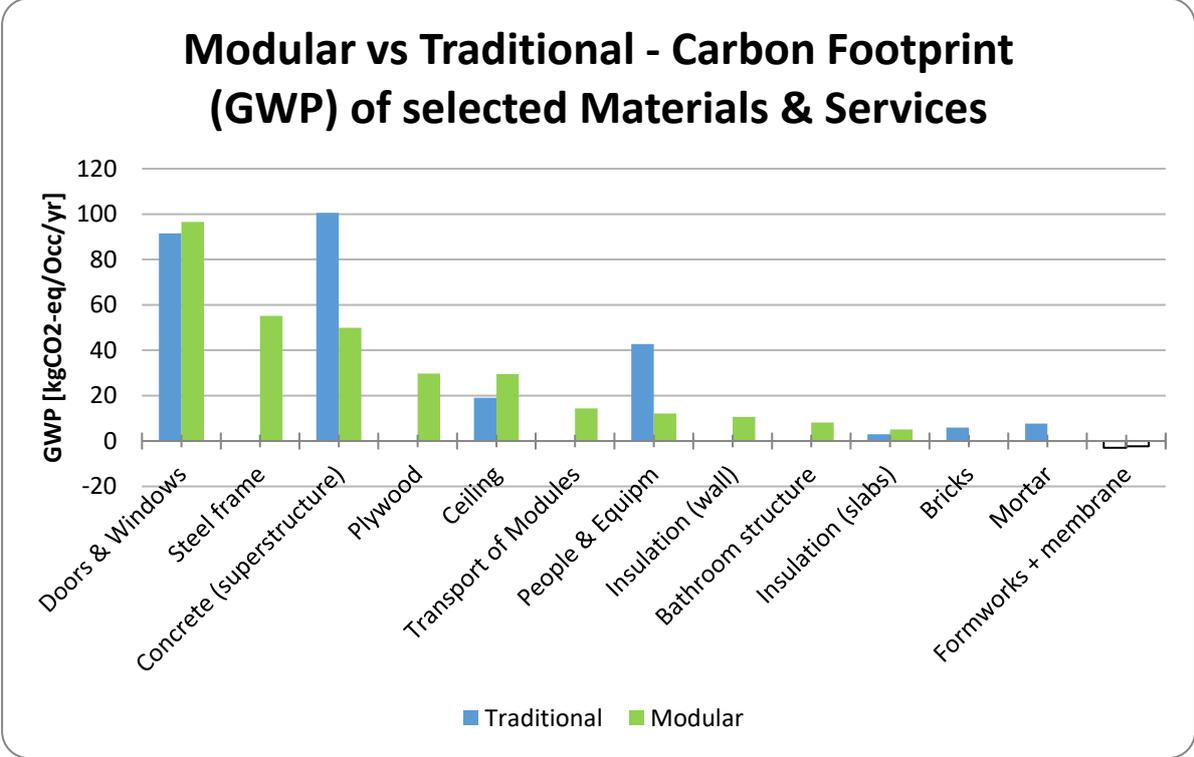


Figure 6: Comparison of selected materials and services of traditional and modular buildings

6.2.2 Interpretation of the findings

The traditional building’s LCA is 268 kgCO₂e/occ/yr, whilst the traditional building’s is 309, resulting in a 13 per cent difference.

The doors of both construction types are considered identical, but while the traditional windows are single glazed, the modular windows are double glazed, resulting in a 5 per cent higher GWP for modular. Despite this, the double glazed windows will be beneficial to modular thanks to the improved thermal performance and consequent reduction in operating energy.

The module’s skeleton is made of a steel frame with steel sheets for the floors and steel sheets for the floors. Steel is a very carbon intensive material but fortunately the volume needed to achieve the structure of the modules is small compared to concrete used for the same function in traditional. Moreover, the plywood boards covering the floors happens to be quite carbon intensive for a timber-based material, because of the added manufacturing processes (lathing and curing) and additives (resins and wax). The bathroom structure is made of carbon intensive aluminium, while the traditional construction would use plasterboards for the partitioning walls.

These three elements account for almost 30 per cent of the total GWP of the “selected materials”, while the timber of the formworks has a negative GWP due to the fact that trees are capturing carbon while they grow.

Though Adara uses half as much concrete and reinforcement as the equivalent building in traditional construction, its concrete accounts for 22 per cent of the total GWP of the materials evaluated.

Modular benefits from a more industrialised fabrication process involving less workers and less equipment. The reduced construction time also leads to a reduction of carbon emissions from worker’s vehicles making less round trips for one project. This results in an overall GWP saving of 72 per cent for modular from the people and equipment category.

In a traditional building there is insulation on the underside (exposed side) of the ground concrete floor, the attic floor and in the roof, while modular has additional insulation on the underside of every internal floor and 52mm of insulation in the walls of every module. This creates the 41 per cent difference between the two construction methods. Even if the additions to the walls resulted in 11kgCO_{2e} pre occupancy per year to the building, this is the most significant feature that sets modular way ahead of traditional for heating energy requirements.

6.2.3 Recommendations on materials and services

The total LCA for Materials and Services of Adara shows an additional 41kgCO_{2e}/occ/year from the traditional building carbon footprint, which represents about 6 per cent difference. This section will attempt to recommend practical improvements to reduce the carbon footprint of future projects.

The doors of the two buildings are made of timber but the window frames are in aluminium. Switching to timber-framed windows would reduce the GWP from 97kgCO_{2e}/occ/y to 47kgCO_{2eq}/occ/y, saving 51 per cent in this category and 7 per cent from all materials and services. This could also increase the buildings’ thermal performance, as wood acts as an insulator.

A wood floor is also recommended instead of the carpet. In the case of Adara, this improvement will drop the GWP compared against carpet from 62 to 10kgCO_{2e}/occ/y, a saving of 84 per cent for the carpet category and 8 per cent of all materials and services. If carpet is required to satisfy market demand, a more basic nylon base carpet also has a longer life span (15 years instead of 10 years for wool) could be used, so that it requires replacing less frequently.

In Adara, the walls of the modules and the ceilings are made of plasterboards. Although not currently mainstream, alternatives can be used in their place by specifying a more sustainable product such as Fermacell

from Xella in Europe, which contains 20 per cent recycled paper (cellulose). Switching to a locally sourced low-GWP alternative for the walls and the ceilings will drop the GWP of plasterboard from 83 to 38kgCO₂e/occ/y, a saving in GWP of 55 per cent for this category and 7 per cent against all materials and services. An alternative to the carbon intensive concrete required for the core of the building is the use of fly ash from coal-fired power stations. By using 50 per cent fly ash in the concrete used within Adara, the GWP of this category would drop from 71 to 60kgCO₂e/occ/y, a saving of GWP of 17 per cent for this category and 2 per cent against all materials and services.

To reduce the GWP from transporting the modules, using local factories is recommended. Several factories exist in Perth and if Hickory had its own local factory, the transport of modules would be reduced to a few kilometres by truck. In that case, the carbon footprint of transport would be reduced from 14 to 2 kgCO₂e/occ/y, bringing a 2 per cent reduction to the materials and services categories.

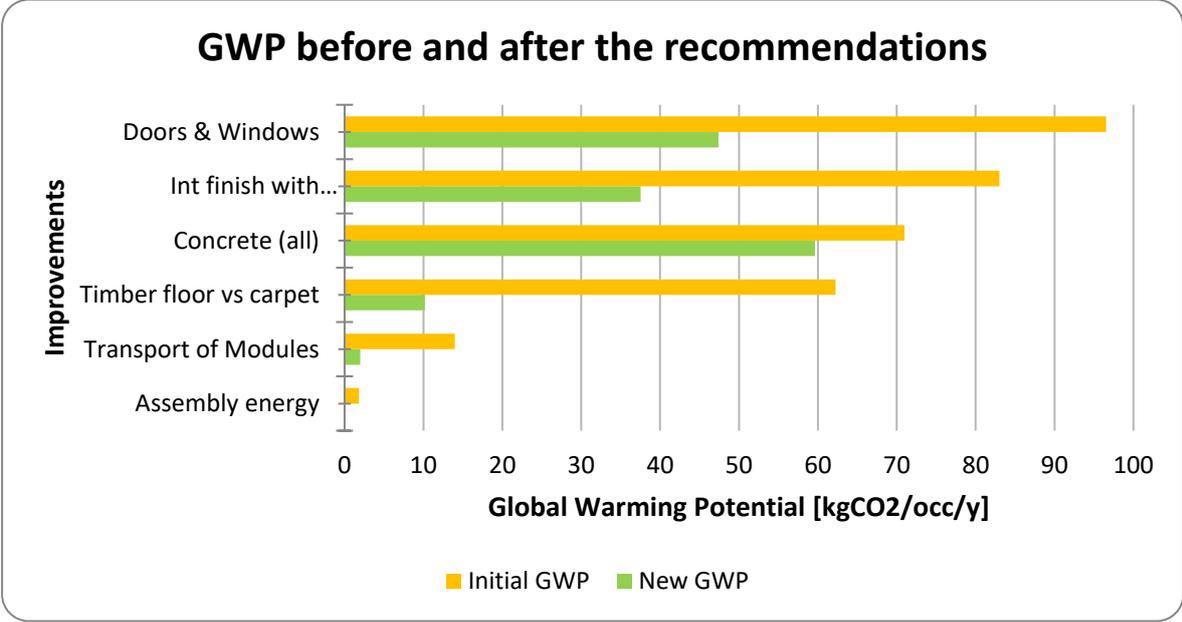


Figure 7: GWP before and after the recommendations

If all of the above recommendations would be implemented, the GWP of materials and services would improve by over 25 per cent which would result in the modular building being 20 per cent more carbon efficient than a traditional building.

7. Discussion

As Australian cities and cities around the world grow in size, there are aspirations to put city limits and urban growth boundaries in place (Newman and Kenworthy, 2015). The result is often characterised as a constraint to housing supply and consequent increases to the cost of housing (e.g. Cox, 2005; Troy, 2012). Modular construction has the potential to deliver product to market at a faster rate than traditional building approaches and to create a cheaper housing product due to the construction process, thereby addressing housing affordability concerns associated with redevelopment (e.g. Jordan, 1995). Modular construction can therefore be seen as a financial instrument with which to control housing affordability. It can also demonstrate better sustainability benefits and hence it has the potential to disrupt the traditional construction industry, although that does not make it disruptive.

Modular construction presently represents only 3 per cent of the construction in Australia presently, but a far greater proportion in other countries (Business Wire, 2016). Our analysis shows that this could rapidly change and leave the present traditional construction industry in Australia (and probably in most parts of the world) with stranded assets in the workforce and in the traditional supply chains for the brick-on-brick and stick building industry.

Modular construction is unlikely to replace traditional construction in entirety, but there are a number of scenarios where it could, for example in medium and high-density scenarios. As cities seek to densify, this could represent a material proportion of the construction industry.

In applying disruptive innovation theory we have analysed the responses that traditional industry and government agencies can make to disruption as either 'Fight' 'Flight' or 'Innovate' (Green & Newman, 2016a and b). The same analysis can be shown in terms of modular construction.

In Figure 8 we have set out the three possible responses of the traditional industry. In 'fight', traditional building companies and industry bodies could oppose the use of modular buildings, particularly those built in other markets, both domestically and internationally. Incumbent builders could lobby government to regulate against modular or make protectionist policies to keep out competition. Traditional builders could advocate that lenders maintain or put up barriers to financing modular construction as a way of keeping with the present system that they know well and therefore see as low risk. In 'flight', traditional builders could do nothing, or sell out of or divest from the construction sector. In 'innovate', incumbent players could begin to use modular components or

make modular buildings, in addition to continuing traditional building approaches, eventually being able to transition to the new products as the market grows.

Figure 8 Potential responses the traditional building industry can take to modular construction.



Source: Green, J., Newman, P., with information from BNEF.

7.1 Fight

If incumbent businesses ‘Fight’ against the market uptake of modular, they can lobby for protectionist policies that maintain their market share. Traditional developers could run scare campaigns around the quality of modular product or that it is depriving local market jobs. They could lobby for import taxes and duties to increase the cost of imported alternatives. Prohibition rarely works in the long term with disruptive innovations, as consumers will try and circumvent the system entirely, whereby incumbents choosing not to reform ultimately suffer more as a result. For example, traditional taxi drivers adopting *Fight* strategies have ultimately not stopped the deployment of Uber taxis and the impact it has had on the traditional market. ‘Fighting’ will still lead to asset write-downs and stranded assets.

The ‘Fight’ response can be explained by Nobel laureate Daniel Kahneman’s theories of behavioural economics; he suggests that under certain conditions people and corporations do not behave in the way that economic models have traditionally assumed to maximize utility, instead the market is resistant and wilfully ignorant to the new paradigm that is emerging (Gilovich, Griffin and Kahneman, 2002).

7.2 Flight

The ‘Flight’ approach would see traditional builders taking no action or divesting investments in traditional construction markets altogether. Inaction leaves traditional builders exposed to the market changes. Not managing the transition effectively between the old and the new paradigm will likely lead to asset write-downs and stranded assets.

7.3 Innovate

Incumbent players can embrace this new reality and continue to play to their strengths as established brands with a wide customer base and technical experience. They can adapt their product offerings and services to this new market. ‘*Innovate*’ approaches take the form of deployment of new technologies. This new market is attracting participants such as component providers, technology and software companies along with financial institutions backing the industry. *Innovative* strategies may therefore include incumbent builders continuing to build traditionally but including modular components in the building or embrace an entirely modular approach.

Although *Innovation* isn’t an assurance of survival, some will survive by innovating, whilst others will be unable or unwilling to adapt. If they ‘fight’, they are unlikely to succeed, as imported modular building product is high quality and cost competitive. If they adopt ‘flight’ approaches, the domestic building sector will be disrupted creating stranded assets and bankruptcy. Therefore ‘innovate’ approaches are those most likely to provide net-benefit to the construction sector as well as for cities.

For innovation to occur, the financial services sector will need to become more willing to lend to the modular industry and government agencies can help with that by reducing the risk over modular developments. To facilitate this, new approaches to mitigating project and therefore financial risks will need to be adopted. This Adara project is an example of how the risk can be minimised by the West Australian Government undertaking a demonstration project that shows there are multiple benefits in enabling, not hindering, this technology.

8. Conclusion

Modular construction has many benefits, which were demonstrated in this analysis of the Adara building, one of the first to be built from modular techniques in Perth, Western Australia. Construction costs, return on equity and construction times are materially better and waste is substantially reduced. Energy efficiency can be considerably better than traditional building approaches by designing modular for the specific geographical context or making adjustments as suggested afterwards. This study has shown that if the local geographical context is not considered or climate-appropriate materials chosen wisely, then a prefabricated modular building can easily prove to be more carbon intensive than a traditional equivalent. Overall, there is a great deal of potential for modular buildings to deliver low cost, low carbon housing.

There are a number of challenges which must be overcome such as refining products to suit the Australian climate and resolving challenges with the financial sector providing finance for modular construction. There is

significant potential for it to become a larger proportion of the construction sector and can be used to relieve escalating housing prices by providing affordable housing supply to the market faster. We examined the potential for modular construction to be a disruptive innovation to incumbent and traditional building approaches. The results support the contention that modular construction is likely to be a disruptive innovation.

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**Journal Paper 4: Governance of decentralised energy assets in medium-
density housing: The WGV Gen Y case study**

Jemma Green and Peter Newman

Curtin University Sustainability Policy Institute, Western Australia

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**Journal Paper 5: Demand drivers for medium density housing and the
relative importance of sustainability attributes**

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Curtin University Sustainability Policy Institute, Western Australia

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Demand drivers for medium density housing and the relative importance of sustainability attributes

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This research evaluated *actual* housing preferences in the Australian city of Perth, to provide a realistic interpretation of what drives consumer behaviour, by examining 27 property developments through a multi-criteria analysis. Affordability, location and size were found to be the key drivers of dwelling choice, while approximately half of respondents rated sustainability attributes as very important factors in choosing a home. For developments that performed high from an energy innovation perspective, 46 per cent of consumers rated these attributes as a major influence in their decision-making. These findings run counter to perceptions that there is no mainstream market for sustainability-orientated dwellings, supporting the inclusion of more sustainability attributes in medium density developments to enhance the buyer base, sales and return on investment.

Keywords: Energy independent precincts; medium density housing; renewable energy; sustainability features; demand drivers; stated and actual preferences.

Introduction

Previous studies examining housing preferences in Perth, elsewhere in Australia and globally (Dunse et al. 2013; Jansen 2013; Kelly et al. 2011; Kleit & Galvez 2011) have focused on *stated* preference market choices (Department of Housing and Planning, 2013; Kelly et al., 2011) as distinct from what people have actually chosen. There is often a large variation in

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what people would state they would buy versus what they actually do buy (Department of Housing and Planning 2013; Frederiks et al. 2015). Therefore, less emphasis can be laid on findings from *stated* market preference studies (Department of Housing and Planning, 2013; Jones et al., 2004) versus studies of *actual* market preferences. *Stated* market preferences were originally used to examine the difference between preferences revealed in surveys or experiments and those observed in actual behaviour. Their use has evolved from economic theories in 1953, to the study of transportation preferences in the 1980s and 1990s, and are being used to examine environmental preferences (Bateman et al. 1999). Stated housing preference studies in the Australian city of Perth and globally have concluded that people are most influenced by type of housing, affordability, location and size of dwelling while choosing where to live (Dunse et al. 2013; Jansen 2013; Kelly et al. 2011; Kleit & Galvez 2011). This study focuses on *actual* market preferences in relation to the demand drivers of retail medium density housing demand in Perth in 27 recently constructed sites around the metropolitan area.

Home ownership in Australia is increasingly becoming out of reach for young people, migrants and low income earners (UDIA 2014). Rising housing costs to more than six times the median household income are resulting in high mortgages or longer reliance on rental and public housing schemes (UDIA 2014). While Australian cities such as Sydney, Melbourne and Adelaide have shifted towards higher density living, urban growth continues outwards, following a long-held perception that high density living is somehow of a lower quality than living in detached houses. However, decades of introducing planning policies to increase density have resulted in some change to these attitudes about apartment living (Palmer 2014). In most American and Australian metropolitan cities, including Perth, urban sprawl is driving people outwards for affordable land, stretching infrastructure requirements and having detrimental impacts on the economy, social wellbeing and the environment (Newman & Kenworthy 2015). While searching for a place to live, consumers are predominantly faced with minimal choice dominated by low-density housing, new suburbs with little supporting infrastructure and services, and long commute times along with associated transport costs due to urban sprawl. Research shows that it is difficult for the generations of people looking to enter the housing market or those downsizing to find small and affordable homes that suit their needs (Department of Housing and Planning, 2013), but this hasn't necessarily resulted in property developers meeting this latent demand.

Historically, Perth has had limited medium and high-density dwelling choices, remaining at the lowest proportion overall and the lowest level of growth in Australia (Bankwest Curtin

Economics Centre 2014; Department of Housing and Planning 2013). With strong population growth, from 1.97 million in 2013 to a predicted 3.5 million by 2050, Perth has the fastest population growth than that of any Australian city and is set to outgrow the size of Brisbane by 2028 (ABS 2013). Perceptions of different types of housing vary considerably around the world, though the UK and new-world Anglophile cities struggle with bad perceptions of medium and high density housing (Newman & Kenworthy 2015). In Perth, perceived negative attitudes towards apartment living have resulted in limited choice in the apartment market for standard one and two bedroom apartments (Kelly et al. 2011). In 2015 only 9 per cent of the Perth population lived in flats, units or apartments, however the market is expected to increase to 20 per cent by 2020 (Y Research & MBA 2015). This shift will be driven by a range of economic and cultural factors expressed in the development plans for Perth, *Directions 2031 and Beyond* (WAPC 2010), which aims to have 47 per cent of all new housing built within urban areas, increasing density, infilling urban areas and establishing transport, commercial and retail hubs. However, between 2010 and 2014 only 28 per cent of all new housing was infill. The latest planning document *Perth & Peel @ 3.5 million* (WAPC 2015) is again trying to influence this upward trend of apartments, envisioning a well serviced, accessible and connected city, which has positive perceptions towards medium density living.

This study examines the transition that Perth is now going through and looks at the extent to which the *actual* market is demanding more sustainability based and less car based housing. Using stated preferences, Brennan et al (2014) found that people in Perth are willing to pay a six to eight per cent premium for houses close to shops, schools, railway stations and the Central Business District (CBD). This premium increases to 20 to 25 per cent for houses in a higher quality neighbourhood with similar attributes. McIntosh et al (2015) found that the land values (i.e. actual willingness to pay) were eighteen per cent higher around Perth's heritage rail lines compared to areas away from stations, and increased 42 per cent around stations along the new fast train line to the south in the first five years after the announcement of the rail line. This suggests that there is a strong market for residential development to be near rail station locations. However, achieving greater density isn't simply a matter of building the houses and the people will come. Designing and building dwellings tailored to market preferences is vital to reaching this goal.

Method

The evaluation methodology used in this *actual* preference study is a Multi-Criteria Analysis (MCA). MCA is a way of evaluating complex problems by breaking the problem into more

manageable components to allow objective data and subjective judgements to be brought to bear on the pieces and then reassembling them to present a coherent overall picture. MCA's purpose is to aid thinking and decision-making but not to make the decisions for the interviewee. This approach explicitly considers multiple criteria in decision-making in both qualitative and quantitative measurements (Gamper & Turcanu 2007). MCA has been an active area of research since 1976 when it was pioneered by Keeney and Raiffa and expanded on by Delft and Nijkamp (1977) and is widely used by governments and businesses to understand optimal solutions and designs for problems which include multiple inputs. Previous MCA applications have led to government policy reviews, as outlined in Zhu et al (2005). There is no normative model of how individuals make multi-criteria choices that are without critics, however MCA comes closest to universal acceptance by researchers as it provides powerful theoretical insights, while not claiming to be predictive. MCA was chosen over other research processes such as informal judgement because it is open and explicit. It also allows scores and weights to be used that provides an audit trail, although each attribute in this study was given an equal weighting. Finally, MCA allows for comparison of attributes between developments, see Kowalski et al (2009), Stagl (2007), Linkov et al (2006) for in depth reviews on the benefits of MCA in sustainability analysis.

To counter the limits of *stated* market choice surveys, this study interviewed residents of 27 newly constructed, medium density developments, once they had chosen a place to live; it sought to determine why they chose a particular dwelling and a particular location. This type of study is unique to Perth and other Australian contexts as we have analysed the impacts of residential attributes on the choice-of-dwellings' post-purchase or lease uptake. This study also has a specific focus on the sustainability attributes of properties to investigate their relative importance against other attributes on the final choice of dwelling. Stated preferences indicate that people are hypothetically willing to pay more for properties with attributes such as energy efficiency, solar panels and walkability, but these have upfront and associated costs that many do not want to, or feel they cannot pay (Department of Housing and Planning, 2013). Sustainability innovations such as good access to natural light, solar panels, insulation, water efficiency, and green spaces are said to be desirable, but lose their relative importance when ranked with other dwelling attributes in stated market perception studies. Previous research in the United States has indicated that home buyers are consistently willing to pay for solar PV systems, but similar research has not yet been replicated in the Australian market (Hoen et al. 2015).

One key sustainability feature rarely provided in new buildings is solar PV for electricity generation, yet the market for solar PV in established housing is growing very rapidly. In the metropolitan area of Perth 22.5 per cent of households have rooftop solar PV (AEMO 2016) and this continues to grow rapidly. This growth in solar suggests there is an increased acceptability of demand for renewable energy in dwellings, however the rhetoric of the land development industry continues to maintain that such demand is minor. Most of these PV systems are on freehold dwellings, with low penetration in the multi-unit market due to issues with strata management companies. Developers, however, could install PV's onto roofs if it seemed like there was a preference for them. Perhaps, like other sustainability features, solar PV on apartments has been avoided until now as developers did not believe that it would add sufficient value, coupled perhaps with erroneous *stated* perceptions that consumers will not pay for it. This research seeks to answer that question along with others associated with such sustainability attributes.

Scope of Study

The paper provides a comprehensive overview of factors that influence dwelling choice from interviews with people who have chosen to live in one of the 27 newly constructed, medium-density developments in the mid-pricing range for Perth of \$350 000 to \$600 000. A greater proportion could have been used if a larger geographical area or radius around Perth was chosen or if older developments could have been included. However, it was felt that this would result in less clarity around what is driving demand in the new housing market in Perth.

In this study, we've examined the interest and willingness of the market to buy properties with sustainability attributes with a goal to reduce the perceived risk of investment in these innovations. The evaluation methodology used in this study is a survey of *actual* preferences. The 27 developments were evaluated through objective features of the development and its surrounding location attributes. The study examined 28 objective attributes of dwellings built within the past seven years and chosen for their mid-market price range and proximity to hubs of activity and amenities (Appendix 1). There are eighteen suburbs represented, within twelve local government areas. Attributes examined included location of the dwelling in relation to the CBD, public transport accessibility, bike and foot paths and parking provided for residents, affordability, access to amenities and facilities rated using the Walk Score (Walk Score 2016), security of the suburb in relation to the number of police incidents; and other attributes including the size of the dwelling, storage space and outdoor areas. Within these attributes, sustainability features above and beyond legal compliance were also included

in the survey, which include energy efficient lighting, energy efficiency, water efficiency and renewable energy.

The Walk Score for access to amenities and facilities was used to calculate the walkability of the dwelling's location. The score is calculated by how many amenities are within a 30-minute walk of a given location, along pedestrian friendly streets.

Walk Score

90-100	Daily errands do not require a car
70-89	Most errands can be accomplished on foot
50-69	Some errands can be accomplished on foot
25-49	Most errands require a car
0-24	Almost all errands require a car

(Walk Score 2016).

For the evaluation of the 27 developments, location data was sourced from Google Maps and confirmed with site surveys, and dwelling attributes were sourced from the developers.

Interviews were conducted with the residents of at least four to five dwellings from each location, through postal surveys, telephone, or in person. Eighty five per cent of respondents were interviewed in person, whereas secondary methods of phone and post surveys were used to collect the remaining data. Questions were asked about housing attributes, and then respondents were asked to rank the top five in order of importance, i.e. trading off the features against each other. Attribute preferences were ranked from 1-10 with 1 being least influential in the decision-making and 10 being the most influential in the decision-making process.

The environmental attributes of the sixteen dwellings with sustainability features above and beyond legal compliance, have been examined in further detail, including solar energy provision and water efficiency measures, to assess whether they impacted the overall decision-making process of the residents.

Discussion of Results

Location

The average number of dwellings in each development is 51, which is quite high based on the current unit per development numbers in Perth (Cresp et al. 2015), with the maximum reaching 137 dwellings in Beaufort Central. These dwellings are located close to existing hubs of services and facilities in Joondalup, Cockburn, Success, Viveash and Perth CBD. Many of the developments have a combination of apartment types with variations in the number of bedrooms and bathrooms. A limitation of the study is that the property developers

were not interviewed to determine their motives for choosing particular design features in their dwellings.

Fifteen of the twenty-seven developments are under a 10 km drive from the CBD, which are desirable locations to interviewees who work in or close to the city. A third of the developments are less than 2 kms from the city and eleven are within 3 kms. Almost three-quarters of the developments are within 15 kms of the CBD, which requires residents to either commute further to work or rely on public transport.

Affordability

Global research shows that the affordability of a location is consistently a driving factor of where people choose to live, and the findings in this study further confirms this (figure 1.). In this study, over one-third of the developments are sold at market rates without any governmental assistance to buyers. Three developments come under the National Rental Affordability Scheme (NRAS) that allows dwellings to be leased at below twenty per cent of the market value to lower-income earners. One development consisted of social housing that is government-subsidised accommodation for people on low to moderate incomes. Three developments had a combination of affordability schemes allowing a broader demographic of the population access to the development.

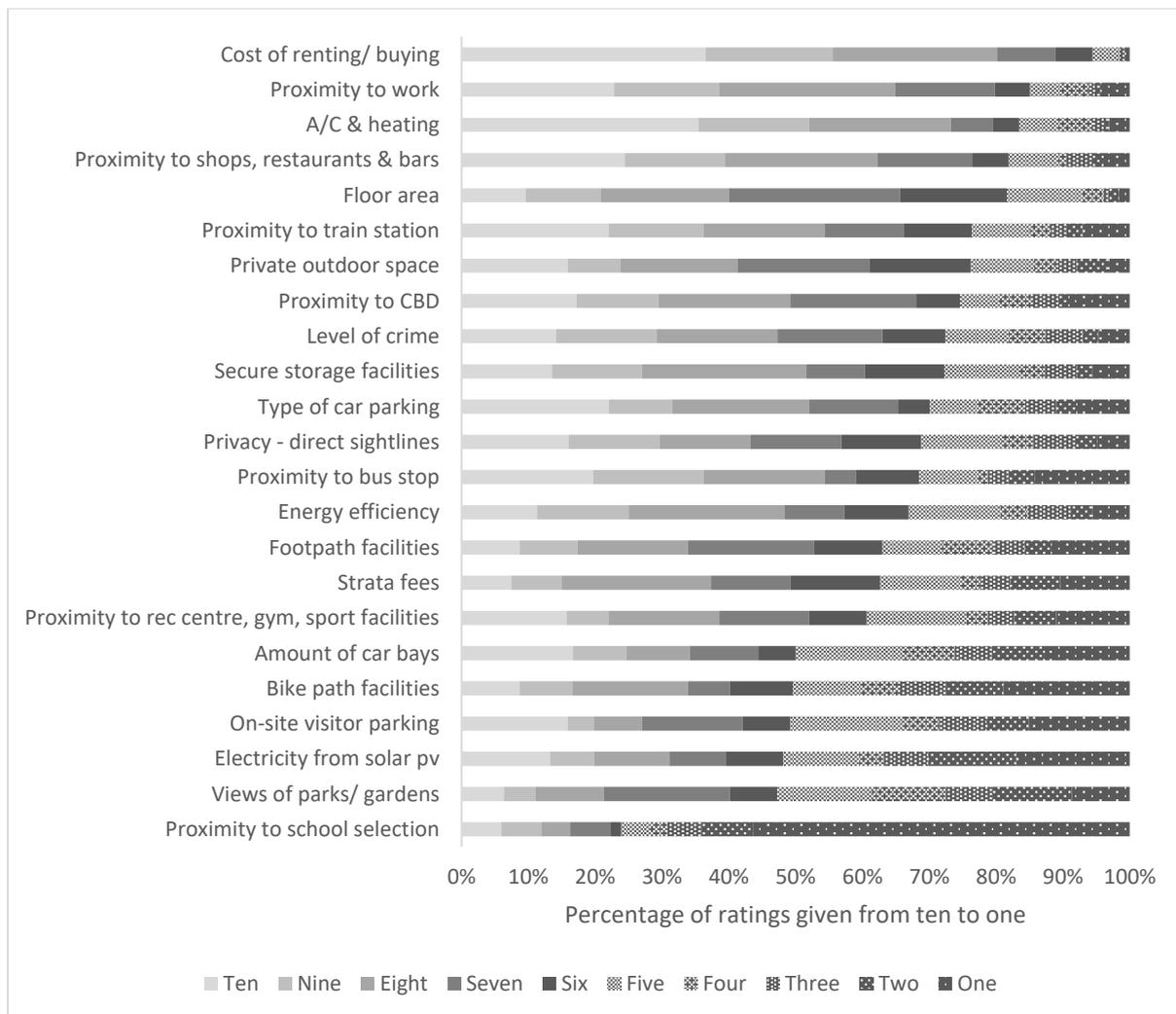


Figure 1. Residents' ratings of the importance of dwelling attributes in influencing their choice of housing. Affordability is the most important factor for residents, with comfort features such as floor size and temperature control, and sustainability features such as public transport, proximity to work and amenities, and energy efficiency also being major influencers.

Transport Access

As Perth's population grows, in order to avoid long commutes and traffic congestion, public transport systems will become increasingly relied upon to move people around (Newman & Kenworthy 2015). This can be seen in areas where high quality public transport is available. Within the survey locations residents live closer to bus stops, at an average distance of 138m, than train stops, with the average distance of 929m. All dwellings had a transit stop within 280m. The preference for public transport options is reflected in statements by residents saying that proximity to transport was quite influential in their choice, with twenty per cent stating public transport access was one of the most influential features of their choice of location (figure 2). Train proximity is somewhat more desirable than bus proximity.

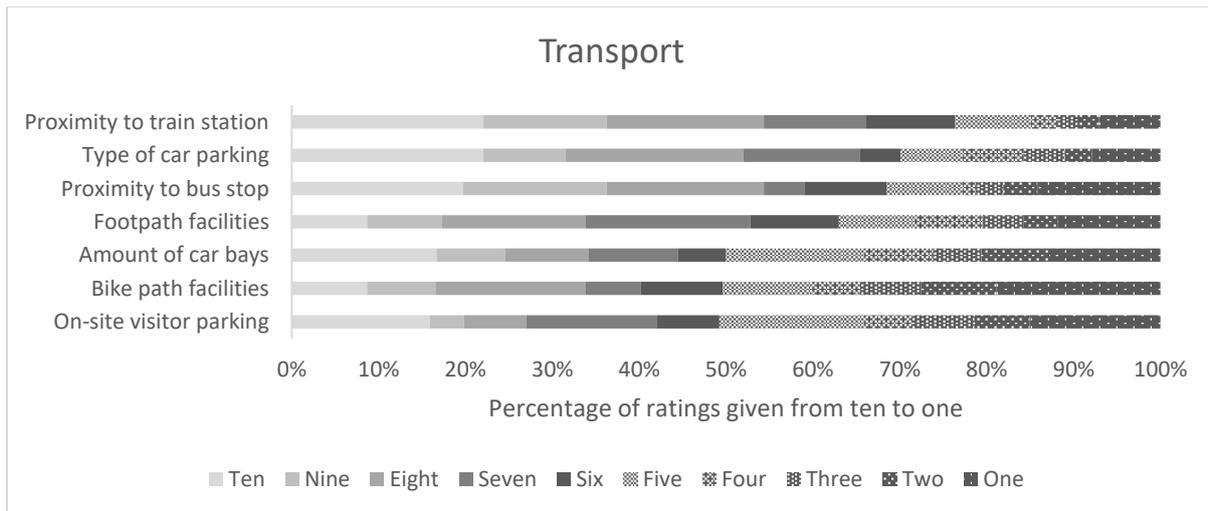


Figure 2. Preference for transport for dwelling residents. The proximity to train stations was highly influential of residents' choice of dwellings, more so than buses. The availability of parking bays was still considered very important, despite the increased use of public transport, walking and cycling in Perth (Ngo 2015).

All the developments have streets with footpaths surrounding them, and people generally choose locations where more errands can be accomplished on foot each day, reducing dependence and cost on cars. Proximity to footpaths was rated as more desirable than closeness to bike paths (figure 2), although bike infrastructure in the studied locations were not of particularly good quality. Therefore, it is reasonable to assume that the market in Perth does not yet have an *actual* experience of what good bike infrastructure consists of to be able to prioritise it. Less than three quarters of roads surrounding the properties have bike friendly lanes, routes or connections to train stations or the CBD nearby. Only six of the developments have dedicated bike routes into the CBD within 300 metres. The most common option was bike lane connections to train stations, where bikes can be left for the day and collected after work.

Since the mid-1990s the number of people working in the Perth CBD has risen from 65,000 people to around 100,000 people (Ngo 2015). However, this rise has not seen a commensurate rise in the amount of parking bays or people driving in to the city. The growth has entirely been supported by increased use of public transport, walking and cycling (Ngo 2015). The provision of even limited parking, however, was valued as important by survey respondents who owned a car (figure 2). While all the developments except one provide some form of parking, most of these have only one bay per unit, regardless of the number of bedrooms each dwelling has. Most parking provided is in secure garages or undercover areas, which respondents found desirable for increased security. Over a third of the developments also provide some form of visitor parking options. The only development that does not

provide parking is located in the workers' precinct in East Perth, a dedicated low-income housing property close to the CBD and trains and buses.

Access to Amenities and Facilities

All the developments in the study are within walking distance to schools and parks, encouraging less car use and promoting healthier living and stronger community interaction (Gehl 2010). While the majority of residents surveyed did not have children, all of the developments have at least two primary schools and one high school within a 3km radius. One third has at least one kindergarten, three primary schools and two high schools within 3km, with some having up to nine primary schools and five high schools close by. Although this analysis shows a range of school options available in close vicinity to the developments, most of the residents rated the proximity to school selection low among the reasons for choosing the development, even if they planned to have children in the future (figure 1, figure 3). Residents, who were not planning on having children in the foreseeable future often stated proximity to schools as the lowest influence in choosing the dwelling. The only residents who did rate proximity to schools highly were ones who already had children (figure 4).

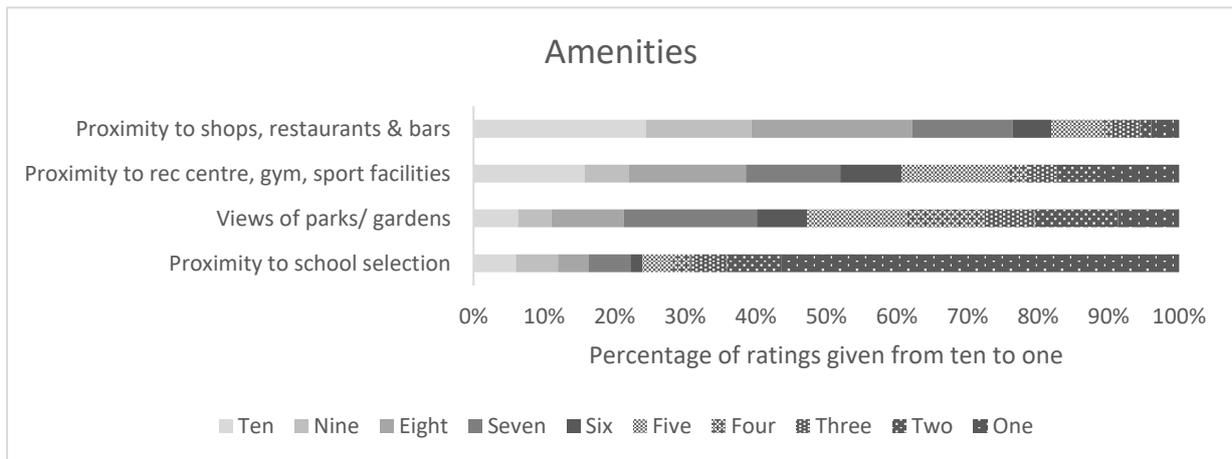


Figure 3. The importance of access to amenities for residents' choice of dwelling. Proximity to shops, restaurants and bars are the most important amenities to residents, while the proximity to school selection has little influence, even for residents that planned to have children in the future.

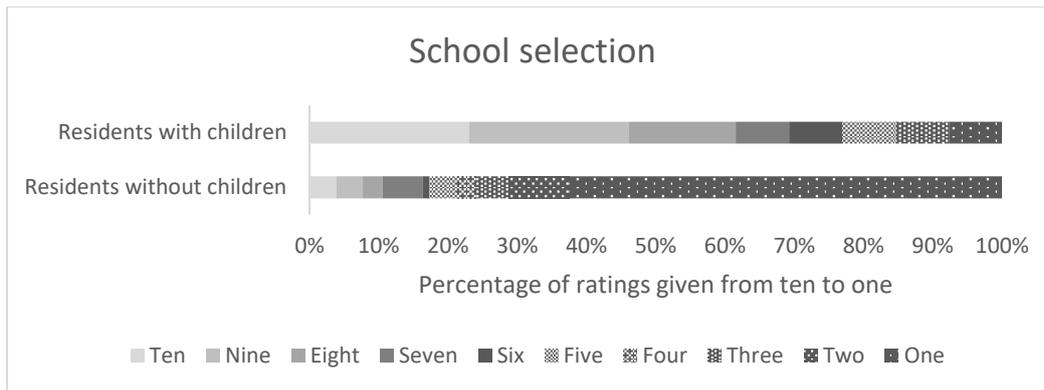


Figure 4. School selection had a low level of influence for residents' choice of dwelling. Only residents that already had children rated it as an important factor.

The proximity to retail shops, restaurants, pubs and cafes is in high demand while choosing a place to live in, particularly by those under 50 years of age with no children. Sixty-three per cent of residents under 50 years of age rated the proximity as very important (figure 5). Residents between 40 and 50 years of age rated being close to shops as one of the most influential factors in their final decision to live in their dwelling. All developments have some service within 500 metres of their house with the average distance being 200m, a comfortable walking distance. Three developments have a service (petrol stations and fast food outlets, cafes and pubs or even hospitals and major shopping centres) adjacent to the property, whereas eight have a service within 100m. While these services vary, their close location to the dwellings highlights the desire of people to be located within hubs of activity.

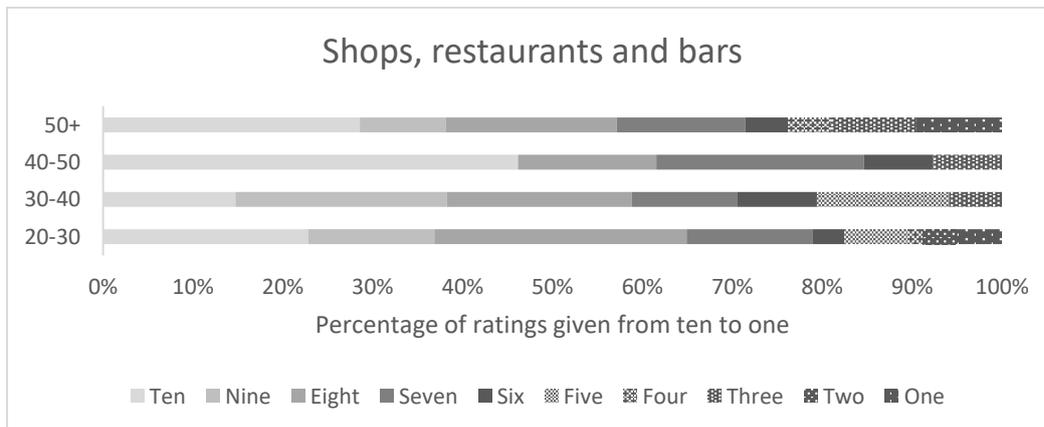


Figure 5. Residents' ratings of the importance of dwelling attributes in influencing their choice of housing. Affordability is the most important factor for residents, with comfort features such as floor size and temperature control, and sustainability features such as public transport, proximity to work and amenities, and energy efficiency also being major influencers.

Most respondents choose to live within walking distance to food supermarkets. Thirteen developments (i.e. 48 per cent) are within the 400m range and six of them are closer than 250m to shops where daily food supplies can be purchased. Over three-quarters of the

respondents live less than 1km from food shops, making them easily accessible on foot, by bike or car by all respondents.

Indoor community facilities of various functions are all situated within 3km of each development. Twelve have more than five facilities, while the average is three facilities per development. The range of facilities includes community centres, recreation halls, libraries, health services, museums and gyms. The average distance to the closest facility is 904m, which is well over the Walk Score walkability guideline of 400m, although a walkable distance of 1km for less commonly required activities is often used as a benchmark. The importance of facilities by residents was quite varied from very low to very high, with residents below 40 years of age rating it higher than those above 40 (figure 6)

The provision of recreational facilities was within 3km for all the developments. Twenty of the twenty-seven developments (74 per cent) are within 2km of a number of parks and half are near sporting facilities. These facilities include cricket, tennis, golf, soccer and bowling clubs, with a quarter of the developments having two or more of these facilities within 2km.

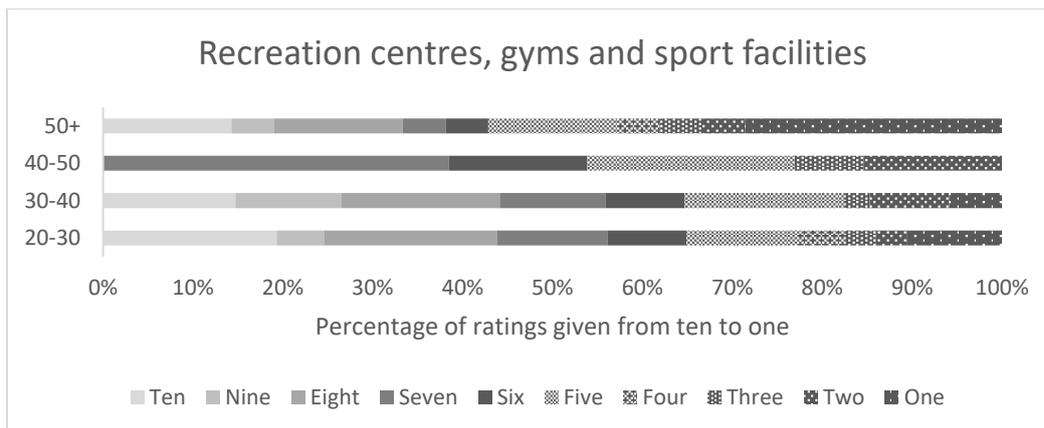


Figure 6. The proximity to recreation centres, gyms and sport facilities are more important to residents below the age of 40.

In Australia, medium density housing is more likely to have green and recreational space surrounding it, which encourages increased walking by residents (Giles-Corti et al. 2013). Perth requires ten per cent of green space in every suburb (WAPC 2012) and has delivered this since 1955; this is the highest rate of any Australian city and is the case in both more affluent and lower income suburbs, though access to regional open space varies by location and is higher in wealthier suburbs. Proximity to parks provides residents with outdoor green space, reducing the demand for these facilities within the development. Three quarters of the developments have mature trees in the surrounding streets that provide shade for the area, lowering the temperature on the surface and within houses. Fifty-nine per cent of respondents

rated the influence of views of parks and gardens as 5 or above (out of 10), however, only twenty-one per cent gave a rating of 8 or higher (figure 3).

Security

Security is measured by the annual incidents that occur in the suburb, not by the perceived safeness as rated by survey respondents. For these locations, the range of incidences is between 32 and 1,246 per year. Prior to this survey, the average number was 580 incidents per year with twenty suburbs having fewer than 1,000 incidents (WA Police 2014). The seven suburbs that had over 1,000 incidents were all located within the local government area of Perth City, in close proximity to the popular entertainment precinct of Northbridge. A quarter of suburbs had fewer than 200 incidents per year. Survey respondents reported the level of crime to be a strong overall concern. Ninety three per cent of respondents rated it important to their decision (5 or higher out of 10), though responses don't show a relationship between level of concern and level of incidents (figure 1). Secure (lockable) storage facilities for residents are almost always provided for each development. Of the 25 dwellings that do have these facilities, most of them are external to the unit, reducing the need to house boxes and bicycles inside the dwelling.

Other Factors

Although 'location location location' may be touted as the most important feature of a dwelling by real estate agents, the interior comfort of the resident's houses also plays an influential role. In these developments, all but two properties (East Perth Workers Housing and Highgate) have air-conditioning and heating installed with reverse cycle systems being the most popular. Air conditioning is present even in the developments that have energy efficiency measures installed in them, showing that even if the properties may be cooler than others, people still prefer the option of air-conditioning (figure 1). Lack of privacy from neighbours is a concern raised in the literature as a negative perception of apartments. However, all but two of the surveyed apartments have been designed in such a way that there are no sight lines into one another, or there are only very limited views.

The floor size of the dwellings varies between developments. One-bedroom apartments have a range of 41m² to 84m² floor space, the average being 60m². Two-bedroom apartments average 70m², with a range of 62m² to 120m². Seventeen per cent of respondents stated that the size of the dwelling was one of the most influential factors in their housing choice, while forty per cent rated it 8 or higher out of 10 in importance (see figure 1).

With a warmer climate in Perth, unsurprisingly, most respondents rated private outdoor space as important in a dwelling, with forty-one per cent rating it 8 or higher out of 10 (see figure 1). Only two properties have no outside space for their residents to use. Balconies are the most common, with nineteen properties having one ranging between 6-51 metres², averaging a sizable 21 metres². Four developments have courtyards and two have some shared sheltered space between residents.

Energy Efficiency and Energy from Solar

In relation to the energy aspects of housing, sixty per cent of these dwellings have some attributes that go above and beyond compliance with legislation. Respondents said that these sustainability attributes did have an influence on the overall decision to live in the dwelling. Eleven of the developments (i.e. forty per cent) do not have any form of energy or water efficiency technology installed. Nine developments have a 6-star NATHERS rating for energy efficiency, with the remaining houses being more efficient than others in their area. Three developments have a combination of solar PV systems (individual or communal), efficient lighting, solar hot water and water efficient appliances included in dwellings, as well as rainwater harvesting. Other sustainability initiatives that properties feature include compact size dwellings to reduce the need for construction materials, double glazed windows and doors, native landscaping to reduce water use, solar passive architecture to reduce energy use and insulation. Privately arranged car sharing was undertaken by twenty per cent of interviewees in both the more sustainable and less sustainable developments; this provides further opportunities for households to reduce their expenditure and environmental impact. No commercially arranged car sharing was found in any of the developments.

Energy efficiency had an equal response between respondents who lived in dwellings with sustainability attributes, and respondents in dwellings without; it was considered a very important factor to almost half of respondents in both types of dwellings (see figure 7 and figure 8). Solar PV for electricity supply was rated very important by only 30 per cent of respondents (see figure 1), however, within the medium density market there are very few instances where solar power is connected directly to the dwelling due to the lack of a governance system to enable this (Green & Newman 2016). Within the scope of this study, only three dwellings generated electricity from solar PV. Therefore, actual preferences for renewable energy are more difficult to ascertain.

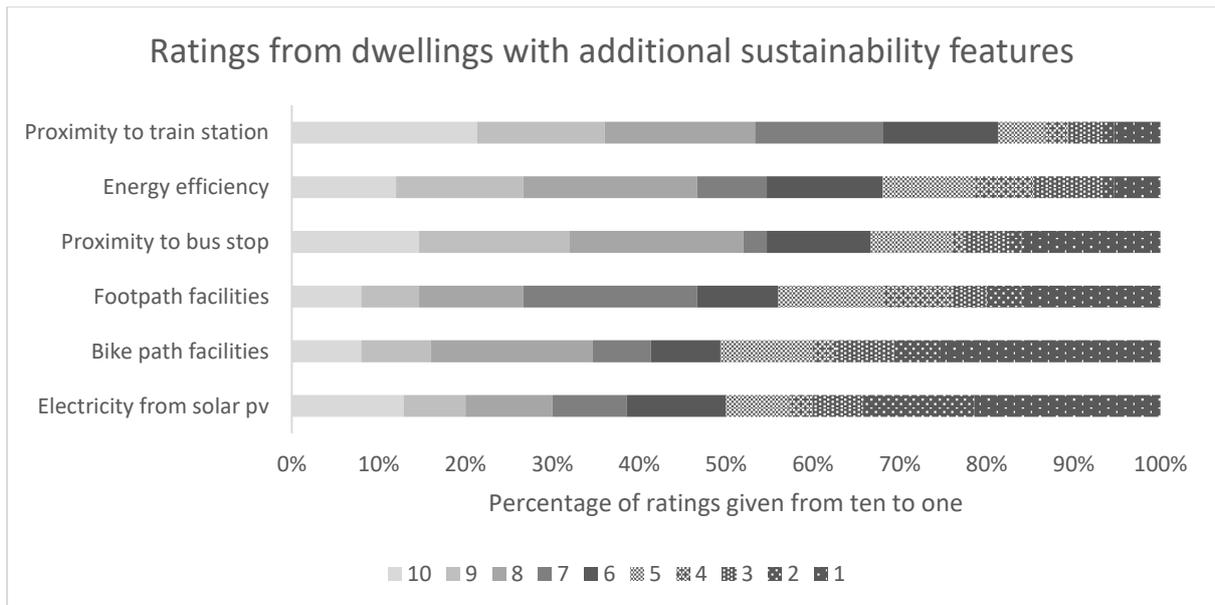


Figure 7. Of the dwellings with additional sustainability features, residents prioritised proximity to train stations and the energy efficiency out over other sustainability features.

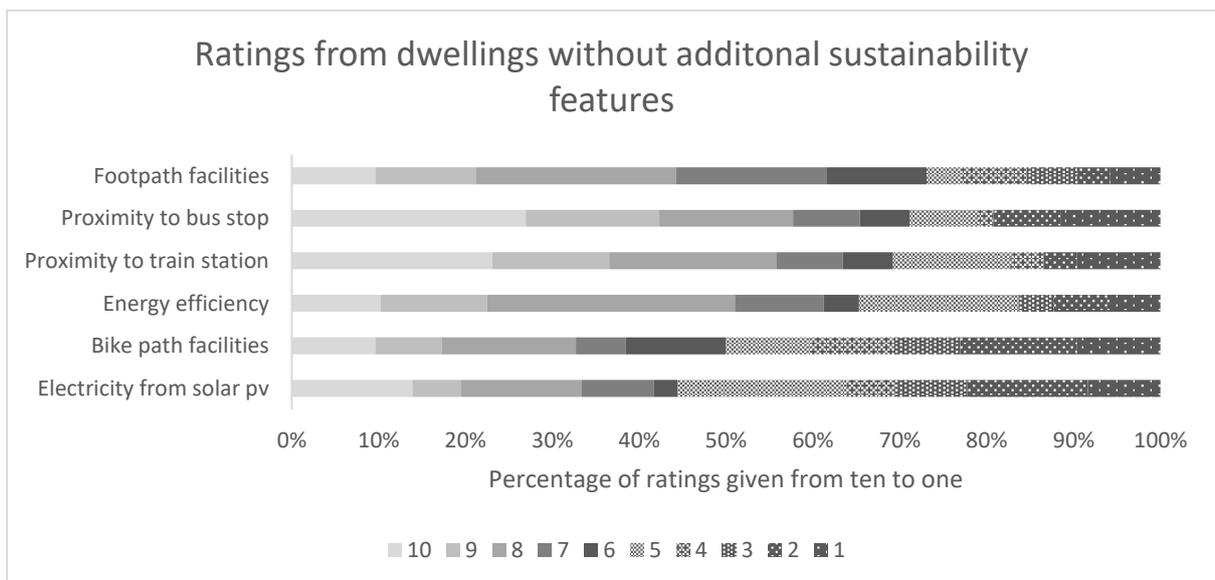


Figure 8. Of the dwellings without additional sustainability features, residents prioritised footpath facilities and proximity to bus stops over other sustainability features, however, more residents considered bus stops, train stations and energy efficiency to be highly influential.

The few respondents, who ranked energy efficiency as of low importance did not reveal an overall trend as to what was of greater importance in choosing a dwelling.

It is reasonable to say that energy efficiency relates to the overall amount of money spent on electricity by households and is a larger proportion of overall household expenditure for lower-income households. While the availability of the dwelling, cost and was the most

important influencing factors, proximity to amenities and transportation, comfort, and energy efficiency were also very important to residents. For the six developments offering rental affordability schemes as well as comprising sustainability attributes, the results were generally supportive of the sustainability attributes, especially where they lowered household costs. The presence of bike paths, which allow another form of low-cost transport, was rated more highly in these areas than interviewees from non-subsidised dwellings. This would suggest that sustainability features that lower household operation costs are valued highly by those on lower-incomes.

Within the medium-density new housing market, the product is heavily segmented with many different types of dwellings. A limitation of this research is that it has not segmented each of the sub types of housing within this product class. This research has focused on pricing within the mid-pricing ranges of \$350-600,000. With a large pricing delta, the product at the higher end of the market may be materially different to the lower end of this range and some residents may have had constraints in finding affordable housing that also had all or most of the features that were important to them. This research has a limited analysis of the trade-offs between features that respondents may have considered when choosing their home.

Overall, affordability and location are the predominant factors for where a person chooses to live. Therefore, other attributes that contribute to economic savings are likely to be desirable to prospective residents. Residents who currently live in medium-density dwellings with sustainability attributes rate these attributes highly. The findings suggest strongly that as the market offers more developments with these attributes, prospective resident's acceptance and demand for them will also increase. In the case of energy efficiency and solar panels, the results suggest that half of the respondents that did prioritise these attributes were not able to move into dwellings that provided them, whether due to location, financial constraints, or because there simply weren't any available at the time that also had other features important to them. Therefore, measures to reduce household bills such as energy efficiency and solar PV present a low risk initiative in which developers would be wise to engage.

Discussion

The following key findings are suggested from the survey of residents in Perth's new medium density dwelling market.

- 1) Sustainability attributes are important to the market.

Energy efficiency is rated more highly than solar PV, but given that there is not a lot of solar PV presently in the medium density property market, *actual* preferences are difficult to garner. These results suggest that if the market will provide more options of housing with sustainability attributes, people would choose them and developers would have a larger range of buyers.

2) Location Location Location

The location of a dwelling in respect to amenities such as food shops, schools, public transport and place of work are the next most influential factors after affordability of the dwelling. This confirms the desire of planners in many cities, including Perth, to prioritise redevelopment over fringe development however, the market for greenfields still outstrips redevelopment due to built-in momentum in the planning system (Newman & Kenworthy 2015).

3) People in Perth love air-conditioning

The presence of air-conditioning and heating features in a dwelling is consistently important to all surveyed, even in properties with energy efficiency and passive cooling/heating design. This highlights the perception in the market that there must be these additional climate control systems to live in comfortable conditions throughout the year.

4) Public transport proximity is highly valued

Proximity to at least one form of public transport is very highly valued by almost all residents, except those who work close by (aged 20-30) or are in their 50s-60s. Those who did not rate at least one form of public transport as fairly, or very important (6 or above out of 10, which was seventeen per cent of respondents), rated provision of car parking very highly, surpassed only by price, location to amenities and air-conditioning features. People in sustainability-oriented dwellings, who rated public transport access as important (45 per cent), also rated energy efficiency attributes highly. Public transport remains a fundamental amenity for medium and high density living in Perth.

5) Importance of green space and recreational centres varies

Proximity to green space, over recreational centres, was more highly valued in the central areas of Perth/East Perth than elsewhere. Conversely, proximity to recreational centres was more highly valued in the suburbs (outside CBD proximity) than proximity to green space, despite being more green space in proximity in the suburbs. Overall, the amenity of green space remains important for medium and high-density living.

6) Proximity to schools is only important to those who have children

All the developments examined have multiple school options surrounding them, many at walking distance, however only people with children stated this to be an important factor in their decision. Those who did not plan to have children in the foreseeable future did not take the proximity to schools into consideration in their decision. Developers could infer that for medium density dwellings, proximity to schools is of lesser importance than other factors.

7) Walkability is valued

There exists a large variation in people's preferences for footpath and bike path proximity to their dwellings. Locations where most daily errands can be completed on foot were most desirable.

Conclusions

This study has shown that the retail property market in Perth is demanding medium-density dwellings with sustainability attributes, especially when these attributes decrease additional living costs from electricity or water bills and minimise the need for travel by car. The market is interested in and willing to pay extra for attributes that reduce their electricity costs.

Attributes that are highly valued include renewable energy, energy efficiency design, water innovations and greenery within and surrounding the development as well as the dwelling's location allowing for reduced car dependence and more walkable living.

For developments that performed highly from an energy innovation perspective, 46 per cent of consumers rated these attributes as a major influence in their decision-making. While sustainability features are not presently in mainstream medium density properties in Perth, this study highlights the latent demand that exists in the market for these attributes.

Therefore, the incorporation of sustainability attributes in any redevelopment will likely attract a greater number of buyers to a development.

Perth has traditionally had very little medium to high density dwellings available in the housing stock and it continues to have the lowest proportion of the few big cities in Australia (Bankwest 2014). The transition that Perth is now going through to provide for more urban, sustainability-based, less car-dependent housing has often been described as having no real market. This paper suggests that the transition is well underway and needs to be facilitated not dampened.

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Appendix 1.Dwellings studied

Development name	Location	Local authority	Number of dwellings	R-code*	Walk Score	Energy Efficiency average importance rating (out of 10)	Solar PV average importance rating (out of 10)	Footpath facilities Average importance rating (out of 10)	Bikepath facilities average importance rating (out of 10)
Bent Street	21 Bent St, Cannington, 6107	City of Canning	20	R60	58	4.6	3.2	2.8	1.6
Ivanhoe Street	26 Ivanhoe St, Bassendean, 6054	Town of Bassendean	16	R20/40	78	7.2	4	4.8	5.2
2 Downey Drive, Como	2 Downey Dr, Como, 6152	City of South Perth	12	R80	67	6.6	5.4	5.6	3.6
Living Space	20 Signal Terrace, Cockburn 6164	City of Cockburn	130	Not assigned* *	80	7.4	2.7	5.2	5

Juniper Gardens	10 Keane St, Midland, 6056	City of Swan	46	Not assigned* *	80	6	4.5	4.4	3.4
Walk on Wilson	13 Wilson St, Bassendean, 6054	Town of Bassendean	20	R20/60	80	5.2	2.4	4	4.2
Park Square Apartments	696 Albany Highway, East Victoria Park, 6101	Town of Victoria Park	24	R60	87	7.8	6.4	7.2	7
Kingston The Fourth	2 Signal Terrace, Cockburn Central, 6164	City of Cockburn	64	Not assigned* *	83	5.4	3.6	5.6	3.8
Stella Apartments	34 Malta Crescent, Success, 6164	City of Cockburn	109	R106	83	6.6	5	6.8	6.8

Somersault Apartments	57 Beach St, Fremantle, 6160	City of Fremantle	58	RAC3	47	5.2	2.2	6.6	6.6
Key City Workers Housing	111 Goderich St, East Perth, 6004	City of Perth	48	R160	88	5.8	5.8	5.4	3.8
Verde Apartments (2010)	70 Wittenoom St, East Perth, 6004	City of Perth	27	Not assigned* *	89	9	8.75	8	8.25
M Square (2013)	140 Parry St, Perth, 6000	City of Vincent	48	RC80	93	6.5	5.25	5.5	6.25
Metropol (2013)	179 Parry St, Perth, 6000	City of Vincent	57	RC80	93	6.5	6	7	7.25
Soda Apartments	17 Lindsay St, Perth, 6003	City of Vincent	13	Not assigned* *	97	7.75	8.75	6	7.25

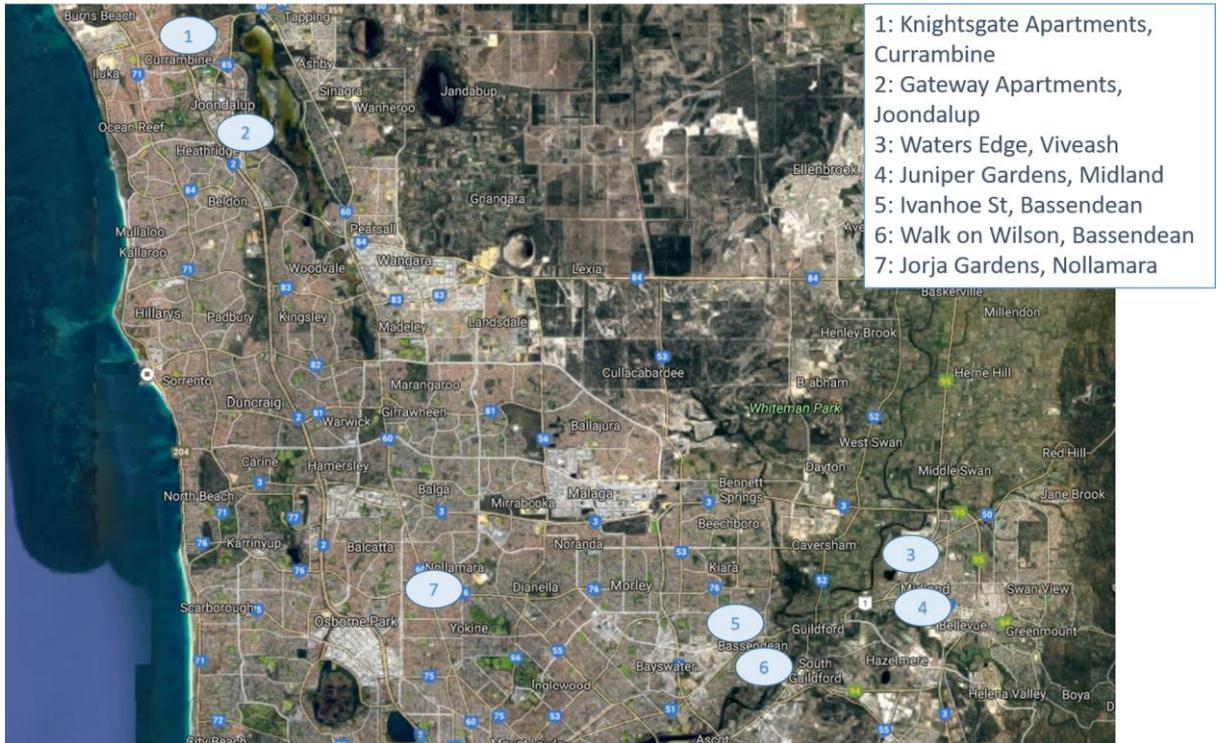
Square One Apartments	14 Money St, Perth, 6000	City of Vincent	35	Not assigned* *	96	9.25	9.25	5.5	4
Jorja Gardens	86 Harrison St, Nollamara, 6061	City of Stirling	17	R40	78	N/A	N/A	6	6
Q Central	154 Railway Parade, Queens Park, 6053	City of Canning	53	R40	63	N/A	N/A	7.8	6.6
Waters Edge	61 Elvire St, Viveash, 6056	City of Swan	106	Not assigned* *	45	N/A	N/A	5.4	4
Wright Street	6 Wright St, Perth, 6000	City of Vincent	15	R80	85	N/A	N/A	6	3.6
Knightsgate Apartments	9 Citadel Way, Currambine, 6028	City of Joondalup	43	R80	50	N/A	N/A	7.8	5.6

Samphire Apartments	15 Tanunda Dr, Rivervale, 6103	City of Belmont	43	Not assigned* * but in a R80-R100 area	47	N/A	N/A	4.4	4.2
Beaufort Central	250 Beaufort St, Perth, 6000	City of Vincent	137	RC80	97	N/A	N/A	7.2	6
Gateway Apartments	6 Walsh Loop, Joondalup, 6021	City of Joondalup	102	R50	57	N/A	N/A	5.6	2.6
Iamgo 2 (2009)	38 Fielder St, East Perth, 6004	City of Perth	22	Not assigned* *	84	N/A	N/A	8.75	8.5
Pavillion Apartments (2009)	59 Brewer St, Perth, 6000	City of Vincent	40	RC80	87	N/A	N/A	8	7.25
Tyne Square (2009)	154 Newcastle	City of Vincent	83	Not assigned* *	97	N/A	N/A	5.75	6.75

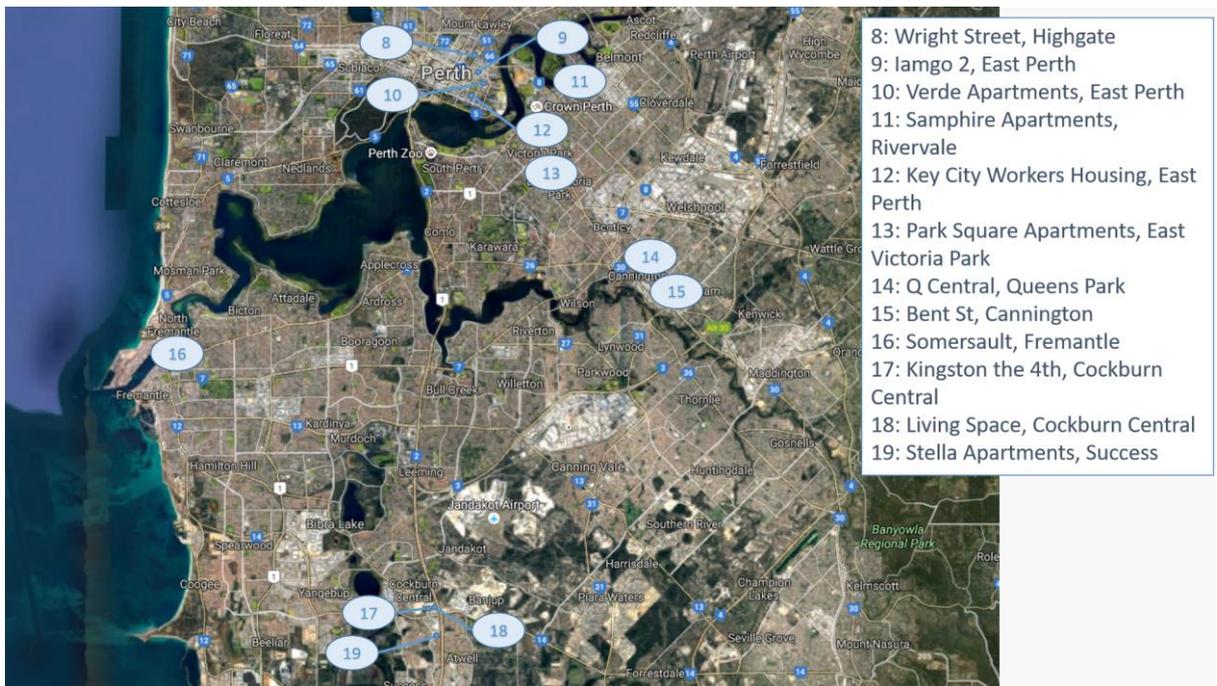
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*R-Codes are the Residential Design Codes containing the development provisions for residential development in Western Australia.

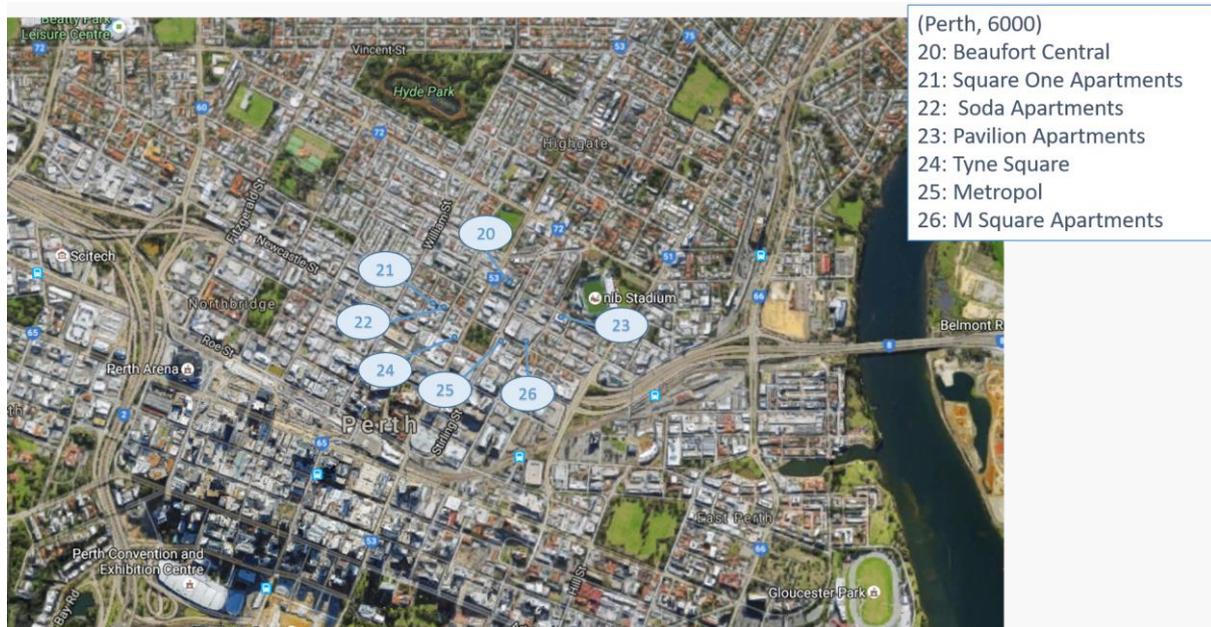
**These developments have not been assigned an R-code by the local government or development authority, which assessed the development based on the plot ratio for the specific application in accordance with the design guideline.



Appendix Figure 1. Locations of apartments found in the Northern and Eastern suburbs of Perth.



Appendix Figure 2. Locations of apartments found in the Western, Central and Southern suburbs of Perth.



Appendix Figure 3. Locations of apartments found in the Inner City of Perth.

APPENDIX 1: STATEMENT FROM THE JOINT AUTHORS

Modular Construction vs Traditional Construction: An Australian case study

Submitted to Elsevier Energy & Buildings, August 2016

Statement of Contributions of Joint Authorship

Green, J

(PhD Candidate)

(50% Contribution)

Writing and completion of manuscript, established paper methodology and theoretical framework, financial modelling and analysis, policy analysis, preparation of tables and figures.

Jemma Marie Green, PhD Candidate

Newman, P (Principle Supervisor) (5% Contribution)

Supervised and assisted with manuscript compilation, editing and co-authorship of manuscript.



Professor Peter Newman, Principle Supervisor

Hebert, L (Engineering Technical Advisor) (35% Contribution)

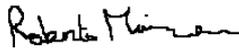
Supervised and taught Roberto Minunno and Francesca Geromino in undertaking the carbon lifecycle assessment, thermal performance and waste analysis, and authoring these sections of the manuscript.



Lionel Hebert, Engineering Technical Advisor

Minunno, R (Masters Student) (10% Contribution)

Undertaking the carbon lifecycle assessment, thermal performance and waste analysis, and authoring these sections of the manuscript.



Roberto Minunno, Masters Student

Geromino, F (Masters Student) (5% Contribution)

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Francesca Geromino, Masters Student

Citizen Utilities: The emerging power paradigm

Submitted to Elsevier Energy Policy, June 2016

Statement of Contributions of Joint Authorship

Green, J (PhD Candidate) (75% Contribution)

Writing and completion of manuscript, established paper methodology and theoretical framework, financial modelling and analysis, policy analysis, preparation of tables and figures.



Jemma Marie Green, PhD Candidate

Newman, P (Principle Supervisor) (25% Contribution)

Supervised and assisted with manuscript compilation, editing and co-authorship of manuscript.



Professor Peter Newman, Principle Supervisor

Governance of decentralised energy assets in strata development

Accepted by Urban Policy & Research, May 2016

Statement of Contributions of Joint Authorship

Green, J (PhD Candidate) (75% Contribution)

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Jemma Marie Green, PhD Candidate

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Supervised and assisted with manuscript compilation, editing and co-authorship of manuscript.



Professor Peter Newman, Principle Supervisor

How does sustainability influence actual medium density housing preferences?

Accepted by Urban Policy & Research, July 2016

Statement of Contributions of Joint Authorship

Green, J (PhD Candidate) (75% Contribution)

Writing and completion of manuscript, established paper methodology and theoretical framework, financial modelling and analysis, policy analysis, preparation of tables and figures.



Jemma Marie Green, PhD Candidate

Newman, P (Principle Supervisor) (25% Contribution)

Supervised and assisted with manuscript compilation, editing and co-authorship of manuscript.



Professor Peter Newman, Principle Supervisor

Stranded assets and forecasting renewable energy futures

Accepted by Journal Sustainable Finance & Investment, January 2016

Statement of Contributions of Joint Authorship

Green, J (PhD Candidate) (75% Contribution)

Writing and completion of manuscript, established paper methodology and theoretical framework, financial modelling and analysis, policy analysis, preparation of tables and figures.



Jemma Marie Green, PhD Candidate

Newman, P (Principle Supervisor) (25% Contribution)

Supervised and assisted with manuscript compilation, editing and co-authorship of manuscript.



Professor Peter Newman, Principle Supervisor

APPENDIX 2: COPYRIGHT PERMISSIONS

Copyright permissions sought from and given by Nicholas Felton for his image “Consumption Spreads Faster Today.”

I, Nicholas Felton, am the copyright owner of the image “Consumption Spreads Faster Today,” originally published in the New York Times February 10, 2008 edition. I grant permission to Jemma Green and Peter Newman to reprint this image in their journal article “Disruptive innovation, stranded assets and forecasting: the rise and rise of renewable energy,” and permission to Jemma Green to reprint this image in her thesis, “Disruptive innovation and mainstreaming low-cost and low-carbon housing.”

Sincerely,

Nicholas Felton

A handwritten signature in black ink, appearing to read "N. Felton", with a stylized flourish at the end.

9. CONSOLIDATED LIST OF REFERENCES

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