ANALYSIS OF THE PERFORMANCE OF A SUSTAINABLE HOUSE, INCLUDING CONSUMER BEHAVIOUR

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ENG460 – Engineering Thesis

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This thesis is submitted to the School of Engineering and Information Technology, Murdoch University, in partial fulfilment of the requirements of the ENG460 Engineering Thesis and for the degree of Bachelor of Engineering.

I, Jamie Andrew Stephen, declare that the work presented herein has been completed in accordance with Murdoch University policy. The work is original except where indicated by reference. No part of this work has been submitted elsewhere or in any other course.

Signed:

Jamie Andrew Stephen

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To Josh Byrne, thank you for the original idea for this project, and for subsequently making your family home available to be studied in this project. I sincerely hope your vision drives positive change.

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Executive Summary

Growing populations and diminishing water supplies are a major cause of concern for the future of cities around the world, including Perth. In order to support a larger population, it is necessary to decrease the amount of water and energy consumed per person.

This report analyses the performance of a Perth house designed to consume significantly less water and energy than the metropolitan average, through the introduction of sustainable technologies and efficient appliances and behaviours. By collecting and analysing data from 55 sensors in the house, it was possible to accurately quantify water and energy performance over the period of this project.

It was found that the house consumed 90-94% less scheme water than a standard Perth household, due to the alternative water sources in place, including rainwater, grey water reuse and bore water. With no hard surfaces on-site, the site recharges more water to the superficial aquifer than the bore draws. The house also consumed 38% less electricity than the Perth average, and was a net exporter of electricity (6.3kWh/day) owing to a 3kW solar PV system. A life cycle analysis showed an operational energy reduction of 111% over the business as usual approach, due to solar passive design, low-energy lighting and appliances, absence of mechanical heating or cooling, and the presence of solar hot water and PV systems.

As well as technology improvements, consumer behaviour was found to be significant in water and energy conservation. It was estimated that by being highly engaged users in terms of both energy and water, the occupants of Josh’s House would save approximately 20% on both energy and water through behavioural efforts alone. The relationship between attitudes and actual behaviours was investigated, and a new model for delivery of future behaviour change programs was proposed.
Citation

Contents
Acknowledgements ................................................................................................................................... ii
Executive Summary ............................................................................................................................... iii
Citation ................................................................................................................................................ iv
1.0 Introduction ...................................................................................................................................... 1
  1.1 Aims ............................................................................................................................................... 3
2.0 Literature Review – Life Cycle Assessment ......................................................................................... 5
3.0 Literature Review – Consumer Behaviour .......................................................................................... 11
  3.1 Rebound Effect ............................................................................................................................... 15
4.0 Methodology ..................................................................................................................................... 18
5.0 Results & Discussion ........................................................................................................................ 22
  5.1 House Water Usage ....................................................................................................................... 22
  5.2 House Energy Usage ...................................................................................................................... 28
  5.3 Water-Energy Nexus ..................................................................................................................... 32
  5.4 Water-Energy-Food Nexus ............................................................................................................ 36
  5.5 Site Water Balance ....................................................................................................................... 38
  5.6 Scaled-Up Results ......................................................................................................................... 41
  5.7 Survey/Consumer Behaviour ......................................................................................................... 47
6.0 Conclusions ...................................................................................................................................... 49
  6.1 Further Work .................................................................................................................................. 51
  6.2 Policy Implications .......................................................................................................................... 52
References ............................................................................................................................................... 53
Appendix A – Schedule of Sensors in Josh’s House ................................................................................. 59
Appendix B – eTool Life Cycle Assessment Report for Josh’s House ....................................................... 61
Appendix C – Consent Form, Information Letter and Questionnaire designed for survey .... 69
Appendix D – Photos of Josh’s House and Monitoring System ............................................................... 76
Figure 1: Life Cycle Assessment framework based on ISO 14040: 2006. (ISO, 2006). .......... 5
Figure 2: Carbon footprint comparison of Josh’s House with the business as usual approach. ................................................................. 8
Figure 3: Proposed CBSM model for future behaviour change program delivery. .............. 15
Figure 4: Daily water consumption at Josh’s House. ................................................................. 22
Figure 5: Daily water consumption showing the transition from scheme water consumption to rainwater consumption. ......................................................... 24
Figure 6: Annual scheme water consumption at Josh’s House compared to an average Perth household, and the Perth average for 4 people (Water Corporation, 2013)................. 25
Figure 7: Grey water produced from water consumed in Josh’s House. .............................. 26
Figure 8: Breakdown of scheme water savings from different sources at Josh’s House.... 27
Figure 9: Breakdown of electricity use in Josh’s House when all water systems are operational. ............................................................................. 28
Figure 10: Josh’s House temperature data - summer............................................................. 29
Figure 11: Josh’s House temperature data - winter............................................................... 30
Figure 12: Typical daily PV generation and energy consumption profile of Josh’s House.... 31
Figure 13: Energy intensity per unit volume for various water sources............................... 32
Figure 14: 5-minute power usage of the bore pump............................................................. 33
Figure 15: 5-minute power usage of the rainwater system.................................................. 34
Figure 16: Construction of the permeable driveway (left) and the finished result (right) (Byrne, 2014) ........................................................................ 38
Figure 17: Monthly aquifer recharge vs bore uptake during and after garden establishment. ......................................................................................... 40
Figure 18: Cluster 1 Water Usage.......................................................... 42
Figure 19: Cluster 2 Water Usage.......................................................... 42
Figure 20: Cluster 1 Water Sources.......................................................... 42
Figure 21: Cluster 2 Water Sources.......................................................... 43
Figure 22: Cluster 2 Rainwater System Performance......................................................... 43
Figure 23: Monthly water profile of water sources in a Josh’s House cluster and in a Business as Usual cluster.......................... 45
Figure 24: Monthly wastewater discharge volumes in a Josh’s House cluster and in a Business as Usual cluster.......................... 46
Table 1: The direct and indirect drivers of water saving behaviour (from Jorgensen et al, 2009) .................................................................................................................................................. 11

Table 2: Potential energy savings due to measures targeting behaviour (from European Environment Agency, 2013). ....................................................................................................................................... 48
1.0 Introduction

The Josh’s House project involved the design and construction of two 10-star Nationwide House Energy Rating Scheme (NatHERS) rated homes on typically sized Western Australian blocks (≈600m^2). Importantly, this was achieved using common construction materials and in a comparable timeframe (<12 months) and cost (≈$1,200/m^2) to standard residential constructions in Perth. This was done to demonstrate that more sustainable housing could be achieved under current conditions, while remaining aesthetically pleasing and functional to a modern family. The homes are expected to meet exceptionally high energy (90% energy reduction) and water efficiency (60% water reduction) criteria (Byrne et al., 2014). The project was undertaken by environmental scientist and sustainability expert Josh Byrne in the Fremantle suburb of Hilton, and the construction was completed in June 2013. The homes demonstrate a novel approach to the integrated design and implementation of residential urban water management.

Western Australia’s growing population is expected to increase annual scheme water demand by 230GL between 2008 and 2060, or an average annual increase of 4.4GL, at a time when our groundwater resources are already stretched (Water Corporation, 2009). The importance of a home designed with 60% reduction in water consumption is therefore clear, and at Josh’s House, this is achieved through the integration of water efficient technology and behaviour, alternative water sources and grey water reuse. The two homes are connected to scheme water, and share a bore.

The home of Josh Byrne and his family (two adults, two children) has sensors incorporated throughout the building to collect power and water use data. Whilst numerous modelling exercises and projections of potential water savings have previously been undertaken, limited studies quantifying actual savings from integrated water systems at the single residential scale exist. Most similar work has been carried out overseas or on Australia’s east coast (e.g. Beal and Stewart, 2011), which cannot be directly translated to Western Australia due to our unique climate.

Beal and Stewart (2011) used high resolution smart meters to quantify and characterise end uses of scheme water in a sample of 252 residential dwellings located in South East Queensland. It was found that installation of water efficient appliances within the home (shower heads, low flow taps, front loader washing machines, etc.) can significantly reduce
scheme water consumption, but that campaigns targeting water efficient behavioural change are equally important. There have also been numerous studies on decentralised systems at a development scale (e.g. Sharma et al, 2010), which have suggested that more research into decentralised systems at a lot scale is needed.

The principle scheme water saving methods at Josh’s House are:

- Water sensitive design
- Water efficient appliances and fixtures
- Rainwater harvesting
- Grey water reuse
- Bore water use

Of equal importance as these water saving technologies is the behavioural change of inhabitants of the building. An innovative program conducted by Sinclair Knight Merz (SKM, 2012) for the Water Corporation of Western Australia demonstrated that households could achieve a 17-19% decrease in water consumption by using voluntary behaviour change techniques alone. When combined, more efficient behaviour patterns and technological upgrades will greatly improve the performance of a residential household’s energy and water efficiency.

Technological introductions are effective at facilitating household water consumption, but work best when combined with a targeted behavioural change campaign (AHURI, 2009). That paper acknowledges that although limited research currently exists on behavioural intervention campaigns targeting decreased water consumption, the research which has been done has noted that campaigns targeting specific end uses may be effective. This project will add to the existing body of knowledge, both in terms of consumer behaviour and specific end use of water, by closely monitoring water use at Josh’s House, and by comparing survey results from the residents of Josh’s House to results of nearby residents.

However, as sustainable technologies are introduced, it is important to be aware of the rebound effect. When an efficient new technology is introduced which is expected to reduce energy and/or water consumption, the rebound effect is the behavioural change that occurs which reduces or eliminates the savings that would have been expected from the introduction of the new technology. For example, more efficient shower heads may be installed and expected to save water, but may actually result in inhabitants of the building taking longer showers than before as they feel they are still making some water savings. It is
important to ensure that this negative impact is eliminated, or at least minimised, to get the maximum possible benefit from the combination of water saving technologies and behaviours (Yu et al., 2013).

The monitoring systems in the building are now operational and data is becoming available. This includes sensors to monitor local weather conditions, roof-mounted solar hot water and photovoltaic system performance, in-slab and in-roof temperature, logging of all water sources (scheme, grey water, rainwater and bore), water and power sub-meters. A full schedule of sensors is presented in Appendix A.

1.1 Aims

1) By collecting and analysing this data, and presenting it in a clear and approachable format, the primary aim of this project is to give a clear understanding of the power and water reductions achieved by the building. Detailed analysis will be carried out on the data extracted from the 55 sensors at the site, in order to get a clear idea of the benefits of this type of building design over the business as usual approach. The results will fill a current void in research, by providing accurate, quantitative data at a lot scale.

In a recent study, Umapathi et al. (2013) monitored the performance of 20 detached households fitted with rainwater tanks in South East Queensland for a period of 12 months. An average yearly rainwater usage (or scheme water saving) of 40kL/household was found. This project will build on this by monitoring not only a rainwater collection system, but an expanded system incorporating many technological elements, together with behavioural analysis, to provide more detailed input into strategic urban water planning for sustainable water resource management.

The data collected in this project will give a clear view of quantities of water being used at various points in Josh’s House, and where this water comes from. The associated energy costs will also be calculated, to determine the competitiveness of decentralised technology at a single-residence scale, compared to large-scale technologies such as desalination. This kind of fit-for-purpose design has been championed by many authors over the years as a method to greatly reduce scheme water consumption and wastewater flows (e.g. Dixon et al, 1999).
Additionally, the power consumption of the house will also be analysed. The solar passive design of the house has resulted in an absence of mechanical heating and cooling, which are a large source of energy consumption in an average Perth household (Synergy, 2014). It is also important to verify that savings on one utility do not result in an increased consumption of another.

2) A second aim of this project will be to investigate consumer behaviour and the rebound effect. It is important to achieve the maximum energy and water savings from the house, and this can only be done if new technologies are combined with water efficient behavioural practices (Beal and Stewart, 2011). This report will review the literature in this area, and build upon it by linking water saving technologies with effective water saving behavioural change methods, to determine the ultimate water savings. This will require focusing on behavioural complexity, behavioural groupings and lifestyle types of different people, as this will help determine the strategy that will be most effective in each case (Gilg and Barr, 2006).

3) A final aim of this project will be to analyse Josh’s House from a life cycle assessment perspective, and compare this to a business-as-usual residential build. The building industry uses great quantities of raw materials, which involve high energy consumption in their fabrication. Inferior design and construction materials not only entail a higher initial level of energy consumption, but may also increase future energy consumption in order to fulfil heating, ventilation and air conditioning demands (Bribian et al, 2011).

Although the house was deliberately constructed using common building materials, this analysis will still give a clear picture of the long-term impacts of an innovative building such as Josh’s House. It is expected that Josh’s House will be comparable to a standard construction in terms of initial energy consumption of building materials, but that the house will perform significantly better over the course of its life due to lower operating energy demands. The life cycle assessment will accurately quantify the performance of the house from a whole-of-life standpoint.

By bringing together and analysing the combination of: (1) resource saving technologies; (2) efficient behavioural change; and (3) awareness of life cycle costs and economic implications associated with design and construction, this report aims to provide a clear, quantitative view of the energy and water savings that are currently achievable.
2.0 Literature Review – Life Cycle Assessment

Life cycle assessment ("LCA") is a method of determining the real amount of energy consumed over the entire lifetime of a product. This kind of analysis is important as it provides a basis for comparison between various options. In the case of residential buildings, this energy consumption is made up of two components – the embodied energy and the operational energy. Embodied energy is the energy required to construct, maintain and dispose of the premises. This includes primary resource extraction, processing & manufacturing, transport, and disposal or recycling of the materials at the end of the useful life (Haynes, 2010). The operational energy is the energy used for space cooling and heating, ventilation, lighting, hot water and running electrical equipment in the dwelling during its life (Fay et al, 2000).

LCA methodology is based on the International Organisation for Standardisation’s ISO14040:2006 principles and framework, consisting of four distinct steps shown in Figure 1, below:

1) Defining the goals and scope of the LCA;
2) Life cycle inventory analysis;
3) Life cycle impact assessment; and
4) Interpretation (ISO, 2006).

![Figure 1: Life Cycle Assessment framework based on ISO 14040: 2006. (ISO, 2006).](image)
With increasing concern over the quantity of greenhouse gas emissions from anthropogenic activity, energy efficient construction has become important. Residential operational demand accounts for 9% of total energy demand in Australia (ABARE, 2009), and the embodied energy of the built stock accounts for 10% to 20% of Australia’s total energy consumption (Harrington et al, 2009). Similar proportions are also found in other countries such as India (Dakwale et al, 2011) and China (Jiao et al, 2011).

Until recently, the focus was on operational energy due to its larger proportion in the overall life cycle energy and the relative ease of measurement (Cabeza et al, 2013). However, with the advent of more efficient appliances and more effective insulation techniques now available, the focus is beginning to switch to reducing the embodied energy of building materials (Menzies et al, 2007). Determining embodied energy is more time consuming than operational energy, and there is currently no generally accepted methodology for computing embodied energy accurately and consistently (Miller, 2001).

Furthermore, it has recently been suggested that the service life of materials must also be taken into account when evaluating the life cycle energy demand of residential buildings. Although more research is required in this area, Rauf and Crawford (2012) showed that an increase in the service life of materials results in a reduction in recurrent embodied energy demand of up to 48%, which equates to a reduction in the total life cycle energy demand of up to 15%. Generally, the recurrent embodied energy is included in the initial embodied energy calculation of a dwelling (Karimpour et al, 2014).

Bribian et al (2011) determined that to minimise the embodied energy of construction materials, it is necessary to replace, as far as possible, the use of finite natural resources with the waste generated in different production processes, thereby closing the cycles of the products. This involves committing decisively to reuse and recycling, and always minimising the transport of the starting materials and products, promoting the use of resources available in local areas.

In Perth, substituting the cement in the perennially popular concrete floor slab for a lower embodied energy supplementary material, such as fly ash, blast furnace slag or silica fume, can drastically reduce the embodied energy. The cement portion of concrete accounts for around 15% of the mass, but around 90% of the embodied energy (Grace, 2005).
The carbon footprint of various sources of sandstone was studied by Crishna et al (2011) in the United Kingdom. The high impact of transportation on the carbon footprint of the sandstone stood out, and so the importance of using local material was shown. The same principles are applicable to other building materials in other locations.

It has been noted that Perth has an almost perfect climate for solar passive housing due to mild winters and summer breezes, and that by incorporating solar passive design, the need for mechanical heating and cooling of a building can be reduced, or even eliminated (Grace, 2005). An additional benefit of solar passive design is that high levels of natural light improve the ambience of the spaces, and further reduce energy demand by lighting the building naturally.

The Josh’s House project was deliberately designed with common construction materials used in Perth, for ease of replication. The design goal was to achieve significant operational energy and water savings (90% and 60% respectively) (Byrne et al, 2014). As such, it is expected that the embodied energy will be comparable to the business as usual case for standard residential constructions in Perth (some reduction is expected due to the inclusion of framed walls, reduced size and assumed extended design life), but that the operational energy will be significantly lower over the life of the building.

A professional life cycle assessment was carried out on Josh’s House by eTool, a Perth-based industry leader in life cycle assessment software, and certified in December 2012. The assessment found savings of 23% on embodied carbon and 111% on operational carbon, for a total saving of 90% kgCO$_2$e per year per occupant compared to the business as usual approach for residential construction (eTool, 2012). The breakdown of these savings is shown in Figure 2.
In their report, eTool made several recommendations to further improve the carbon performance of Josh’s House, including (eTool, 2012):

- Customised ventilation for fridge can save up to 15% on energy consumption;
- Use of natural gas for oven instead of fossil electricity (but 100% renewable energy is preferable, therefore keep the electric oven unless a syngas replacement comes);
- Increasing solar PV system to 3.5kW capacity to achieve full carbon neutral; and
- Increasing design life through future proofing and higher density.

Together these recommendations could achieve a saving of up to 116.8t CO$_2$e over the life of the building.

Lower embodied energy recommendations were also made but not progressed due to the requirement of Josh’s House to be built from readily available and commonly employed construction materials. However, in future projects, the following measures would significantly reduce the embodied energy of construction (eTool, 2012):

- Reduce internal finishes with exposed brick on internal walls (though this would have a negative effect on the internal lighting of the building);
- Use of 50% fly ash concrete;
- Use of recycled bricks;
- Rammed earth floors throughout;
- Straw bale external wall construction;
- Timber window frames throughout;
- Recycled timber to framed wall elements; and
- Recycled timber to roof structure.

Together these elements could achieve a saving of up to 34t CO\textsubscript{2}e over the life of the building. The full eTool LCA report is attached as Appendix B.

It would be valuable in future projects to include battery storage for the PV solar panels on the roof of the house. This will give a more accurate estimation of the carbon emissions saved by the house, by reducing reliance on grid power at times where solar power is not being produced. Exporting energy back to the grid in times of surplus generation is beneficial, but grid energy (largely generated by coal fired power stations with large associated CO\textsubscript{2} emissions) is still imported when solar is not being produced. This need could be reduced (and potentially eliminated, if combined with a 3.5kW capacity solar PV system: eTool, 2012) by installing battery storage to draw on in times where solar is not being produced.

The presence of an appropriately-sized lead-acid battery can increase the local use of PV energy generated on-site by 171\% (Parra \textit{et al}, 2014). Based on daily PV generation of 18.7kWh and average daily demand of 12.4kWh, an approximate capacity of 8kWh would be appropriate for a battery at Josh’s House, (Parra \textit{et al}, 2014). A battery system of this size would cost up to $9,000 (McKenna \textit{et al}, 2013; Solar Energy Storage, 2013\textsuperscript{1}). A lead-acid battery has the added benefits of being significantly cheaper than equivalent lithium-ion batteries (approximately 7 times less expensive: Divya \& Ostergaard, 2009), and being highly recyclable, which is in keeping with the whole of life sustainability philosophy employed at Josh’s House.

It would also have been beneficial at the initial design and construction phase to consider the ability of construction materials to be disassembled and reused or recycled at the end of their useful life in the house. The total embodied energy and the carbon footprint of one tonne of residential building construction waste in Perth have been found to be 1,890MJ and 397Mt CO\textsubscript{2} equivalent, respectively. This can be significantly reduced through reuse and recycling of building materials, particularly bricks, which account for 51\% of embodied

\textsuperscript{1} The approximate costs were based on McKenna \textit{et al}'s estimations of £1280 and £1222 for a 10.08kWh battery and inverter, respectively. These figures were scaled down to an 8kWh equivalent, then converted into Australian dollars (£1=$1.80 at the time of writing), and finally reduced by 5\% based on an annual predicted reduction in price of 5\% for this technology.
energy and 76% of the carbon footprint of residential building construction waste in Perth (Biswas, 2008).

Although operational energy has been looked at in great depth in previous studies, there is a gap in analysing the water-related operational energy of an integrated water system, such as that at Josh’s House. This project aims to address this gap by giving an accurate idea of the water and energy savings at a lot scale, and extrapolating this up to a larger scale. It is expected that, on top of water consumption being reduced, additional benefits such as delayed infrastructure upgrades and lower maintenance costs can be expected, as well as shared catchments for rainwater harvesting, having greater areas for grey water irrigation, scheduling for summer holidays and shared battery banks.

In future projects, it would be beneficial to combine the solar passive design principles, energy saving technologies and integrated water system present in Josh’s House with lower embodied energy construction materials and battery storage for excess solar PV produced. By sizing the photovoltaic grid and battery storage accurately, it may be possible to achieve full carbon neutral (Weniger et al, 2014). Although that was not the goal of this house, these further improvements are worth considering in future, to build on the current success.
3.0 Literature Review – Consumer Behaviour

Many studies have shown that the introduction of water efficient fixtures into a dwelling will reduce water consumption in that dwelling (see, for example, Beal and Stewart, 2011). However, the effect of consumer behaviour must also be considered, as it can have a significant impact on the quantity of water consumed by a household, in the absence of any new water efficient fixtures being introduced (Hassell & Cary, 2007).

Previous studies have identified a number of direct and indirect factors which drive water use behaviour in consumers, depending on the factors examined in each study (see Table 1). However, no study was able to associate the whole of the variation in water use to the specific factors they studied, due to the complex nature of human behaviour (Jorgensen et al, 2009). In Australia, a growing body of evidence suggests that consumer attitudes towards conserving water are generally positive, and are driving behavioural changes in water use (Beal et al, 2011b; Willis et al, 2011).

Table 1: The direct and indirect drivers of water saving behaviour (from Jorgensen et al, 2009)

<table>
<thead>
<tr>
<th>Direct drivers</th>
<th>Indirect drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Climate/seasional variability (Berk et al, 1980; Klein et al, 2006)</td>
<td>• Person characteristics (e.g., subjective norm, behavioural control, attitude toward the behaviour) (Leviston et al, 2005)</td>
</tr>
<tr>
<td>• Incentives/disincentives (e.g., tariff structure and pricing, rebates on water saving technologies, etc.) (Campbell et al, 2004)</td>
<td>• Institutional trust (i.e., trust in the water provider) (Lee, 1981)</td>
</tr>
<tr>
<td>• Regulations and ordinances (e.g., water restrictions, local government planning regulations) (Klein et al, 2006)</td>
<td>• Inter-personal trust (i.e., trust in other consumers) (Lee, 1981)</td>
</tr>
<tr>
<td>• Property characteristics (e.g., land size, pool, bore, rainwater tank, house size, house age, etc.) (Campbell et al, 2004)</td>
<td>• Fairness (i.e., in decision-making processes, water restrictions, tariffs, new pipelines)</td>
</tr>
<tr>
<td>• Household characteristics (e.g., household composition, household income, water saving technology, water supply technology) (Campbell et al, 2004; Gilg et al, 2005)</td>
<td>• Environmental values &amp; conservation attitudes (Corral-Verdugo et al, 2002; Syme et al, 2004)</td>
</tr>
<tr>
<td>• Person characteristics (e.g., intention to conserve water, knowledge of how to conserve water) (Corral-Verdugo et al, 2002; Syme et al, 2004)</td>
<td>• Intergenerational equity</td>
</tr>
<tr>
<td>• Socio-economic factors (e.g., income, household composition, age, gender, education, etc.) (Campbell et al, 2004; Nancarrow et al, 2004)</td>
<td></td>
</tr>
</tbody>
</table>
Attempts to reduce residential water consumption are generally delivered via information campaigns aimed at encouraging voluntary water conservation through behaviour alteration to consume less water and/or through installation of water efficient fixtures (Syme et al, 2000). This requires an understanding of human responses to such information campaigns, which can be quite intricate.

Various behavioural models have been employed in voluntary behavioural change campaigns in Australia, with varying degrees of success. No single method works to reduce water consumption in all individuals in all contexts (Rolls, 2001). However, in a review of various behavioural change models, Hassell and Cary (2007) identified the most important elements influencing behaviour from all of the models, with the focus on water conservation:

- facilitating conditions;
- an individual's behavioural intention;
- an individual's capacity to respond;
- anticipated outcomes of change in behaviour;
- attitude to water conservation;
- norms for water conservation;
- strength of, and social support for, existing habits; and
- a positive emotional reaction within individuals.

Having identified these elements, it was concluded that an individual is most likely to change their water consumption behaviour when as many as possible of the following factors are present (Hassell and Cary, 2007):

- External factors, such as appropriate water pricing and policy consistency, encourage appropriate behaviour;
- Individuals have formed a strong positive attitude towards saving water;
- Individuals have the capacity to reduce consumption – technology (e.g. low flow shower heads) or water substitutes are available and are not constrained by inability to purchase or install;
- Individuals believe that the advantages or positive outcomes outweigh the disadvantages or negative outcomes from saving water;
- Individuals perceive more social (normative) pressure to conserve water than to not conserve water; and
• Individuals’ emotional reaction to performing the behaviour is more positive than negative, and individuals perceive that conserving water is more consistent with their self-image and social identification than inconsistent with it.

It has been suggested that, because the environment is a shared resource, people may be reluctant to change their behaviour unless they feel that others are doing the same (Collins et al, 2003). However, a recent analysis of the determinants of pro-environmental behaviour (Bamberg and Moser, 2007) concluded that behavioural intention is the most important determinant of positive environmental behaviour, and that intention is influenced equally by three factors: perceived behavioural control, attitude and moral norm.

Water end use studies are becoming more common as a way of understanding water use in the home, in order to determine where improvements can be made (Beal and Stewart, 2011). Smart metering technology is rapidly developing, and can be used to provide an accurate and timely view of water use to consumers (Anda et al, 2013b). Combined with a community based social marketing program, and feedback to consumers from eco-coaches, the recent H2ome Smart program saw savings of 12% for households in the Margaret River region, 9.9% in the Pilbara and Kimberley regions, and 9.9% (projected) for the Perth region (Anda et al, 2013b; ENV Australia, 2012).

“Water conservation awareness and practice involves understanding the efficiency, opportunities and impacts of certain water saving activities, as well as the desire to continually reduce consumption” (Willis et al, 2011 paraphrasing CSIRO, 2002). It is expected that this report will help to expand the body of knowledge on the opportunities and impacts of certain water saving activities, by gathering detailed information on the performance of a purpose-designed water efficient house and comparing it to the business as usual case. By making these detailed findings public, it is hoped that the opportunities and impacts of introducing water-wise technologies will become clear to consumers and utilities, and that the rate of uptake of these systems (in both new construction and in retrofitting) will increase.

The literature suggests that the focus should be on developing awareness information focused on improving the current level of understanding and impacts of shower, tap use, clothes washing and irrigation behaviours (Willis et al, 2011). Such a targeted information program should result in noticeable reductions in water consumption within the residential
sector. Previous studies also suggest that significant reductions in consumption levels can occur if society at large values water and is actively concerned with how it is being consumed (Willis et al., 2011). It is for this reason that the questionnaire designed for this project focuses on attitudes towards water consumption, as well as actual past actions and intended future actions.

The process of community-based social marketing (CBSM) has been shown to be an effective delivery vehicle for environmental programs, by ensuring that psychological knowledge is available to the persons designing the program (McKenzie-Mohr, 2000). CBSM is made up of four steps: (1) uncovering barriers to behaviours then, based upon this information, selecting which behaviour to promote; (2) designing a program to overcome the barriers to the selected behaviour; (3) piloting the program; and (4) evaluating it once it is broadly implemented (McKenzie-Mohr and Smith, 1999). CBSM merges knowledge from psychology with expertise from social marketing, which emphasises that effective program design begins with understanding the perceived barriers to engaging in an activity (Andreasen, 1995).

The importance of social norms in consumer behaviour has already been noted (Hassell and Cary, 2007), and an important aspect of CBSM is fostering the development of descriptive social norms (Cialdini et al., 1990). CBSM can therefore be effective in influencing members of the community as to what is appropriate behaviour. One proposed model suggests that behavioural change will occur when motivation, ability and a trigger are all present. In the absence of just one of these elements, behavioural change will not occur (Fogg, 2009).

Building on the recent H2ome Smart program (Anda et al., 2013b), and the CBSM conceptual framework (McKenzie-Mohr, 2000), the model in Figure 3 is proposed to deliver water conservation programs to Perth residents in future. Based on the literature, this should be an effective way of delivering a behaviour change program in a water saving context. This project aims to improve public motivation for both behaviour change and adoption of new water-wise technologies, by demonstrating the real results achievable by a household in Perth. This will help future behaviour change programs by facilitating two of the necessary elements for behaviour change: motivation and ability, with the future program itself acting as the trigger.
3.1 Rebound Effect

In conservation, the rebound effect refers to the behavioural responses to the introduction of new technologies designed to improve the efficiency of resource use, which offset or reduce the beneficial effects of the new technology (Grubb, 1990). The rebound effect results in a lower than expected benefit. The full rebound effect can be attributed to three distinct economic reactions to technological changes:

1) The **direct rebound effect** refers to the increase in consumption of a good because of its lower effective cost of use (price effect);

2) The **indirect rebound effect** occurs when the reduced cost of a good or service leads to the increase in consumption of other goods and services, which have their own associated greenhouse gas emissions (income effect); and

3) **Economy wide effects** occur because improved technology creates new production possibilities and promotes economic growth (Sorrell and Dimitropoulos, 2008).
Most of the current body of work on the direct rebound effect has focused on electricity, particularly on space heating and personal vehicles. The previous estimates of rebound effect for space heating are in the range 0-55% for the short-run, and 1.4-60% for the long-run (see review in Yu et al, 2013). For personal transport, the rebound effect is estimated between 10-30% in the long-run (Sorrell et al, 2009). While these rebound effects are significant, some household appliances do not exhibit any direct rebound effect, such as refrigerators, fans, televisions, PC’s and gas showers (Yu et al, 2013).

Murray (2013) suggests that the most promising area for demand-side environmental policies to be effective in the short-term is not new technology, but the adoption of ‘green’ consumption choices. The author found that if rebound effects are ignored when evaluating the environmental benefits from ‘green’ consumption, then they will overstate the actual likely benefits by at least 15% in the case of vehicle fuel consumption, and 6% in the case of electricity conservation. Also, environmental policy directed at changing consumer behaviour is best targeted at high income households, as they generally have greater scope for action (Murray, 2013).

In a recent paper focusing on rebound effects of low-flow devices installed into homes (Price et al, 2014), no statistically significant evidence of a rebound effect was found. This means that the low-flow devices analysed in the study (showerheads, toilets, washing machines and dishwashers) did not become less effective over time due to poor rates of retention or behavioural changes. This outcome is important but not completely unexpected, given that water demand is highly inelastic, and that water expenditures comprise a small amount of total household income. The value of this finding for water utilities cannot be understated, as it means that introduction of low-flow devices into homes will reduce water consumption in the long-run with no rebound effect.

This result is backed up by Beal and Stewart (2011), who found that water consumption of residents in South East Queensland did not revert back to pre-drought levels after restrictions had been relaxed, as was expected, due largely to the introduction of water-saving devices during the time of drought, which resulted in lower long-term water demand in this area. Dumont et al (2013) also concluded that there is no direct rebound effect in relation to water consumption, because water demand is inelastic to price, and therefore the price effect is not applicable.
The findings of previous studies are very relevant to this project. Whilst it has been agreed among academics that the rebound effect exists in conservation, this has regularly been linked to consumer behaviour in the energy sector, particularly space heating and personal transport. Recently published studies focusing on performance of low-flow appliances have shown that no such rebound effect exists in this situation, due to the largely inelastic demand for water within the home. Water savings from Josh’s House as a result of the introduced water-efficient appliances and technologies are therefore going to provide real, long-term water savings to both the occupant and the water utility, as the water consumption behaviours will be inelastic and therefore the rebound effect will be non-existent (Dumont et al, 2013).
4.0 Methodology

The design of Josh’s House incorporated a number of smart meters throughout the property, to record high resolution quantitative data on the performance of the house. By collecting and storing this data, it becomes possible to analyse specific performance metrics within the property, and develop robust conclusions based on actual performance statistics, rather than modelling.

Josh’s House has a total of 55 smart meters present, recording parameters such as:

- Thermal performance
- Energy Use
  - Electricity
  - Gas
- Power Generation
- Water
  - Rainwater
  - Grey water
  - Bore water
  - Scheme water
- Environmental
  - On-site weather
  - Soil moisture

A schedule of sensors, with a description of each, is attached as Appendix A. The location of these sensors formed part of the original design of the house, in order to collect and log data on these parameters.

The data collected is logged on two separate data loggers, located in the laundry of the house. Photos of Josh’s House, including the monitoring system are included in Appendix D. The first is a dataTaker DT80 general purpose data logger. This collects and stores data on temperatures, water and gas flow rates, soil moisture levels and data from the local weather station. Data is cumulative, and each stream resets each day. Data is logged and time-stamped at 30 minute intervals.
The second logger is an Onset Hobo data logger which collects and stores energy use data for the house from the various pumps and circuits. Data is cumulative and logged and time-stamped at 5 minute intervals. Streams do not reset each day.

Data from both logging systems is downloaded periodically to a local computer, in comma-separated value (csv) format. This format is compatible with Microsoft Excel, which has been used to collate, present and analyse the data for this project, and to prepare charts of significant findings for visual interpretation of data.

The water and energy data from December 2013 to June 2014 was analysed in this project, to determine the performance of the house. Although energy data was available earlier than this date, some water data (e.g., grey water quantities) did not become available until later in the project. Problems were also encountered throughout the project with the calibration of various streams, but these were attended to as they arose. The greatest concern was the bore water quantity not being accurately logged. However, due to the nature of this water stream (being on a set reticulation schedule, which only changes for each season), data was able to be recorded manually for a one-week period during summer, and then applied to the other weeks on the same reticulation schedule. In spite of these problems, sufficient data was collected for each stream for analysis and interpretation.

By pairing data from the two data loggers, a detailed analysis was performed on each water stream to determine the water-energy nexus for rainwater, grey water and bore water. By choosing lengthy periods where each stream was in operation, it was possible to calculate an accurate water-related energy use for each stream. This could then be compared to the reported water-related energy use of large-scale, centralised water supply systems, such as desalination plants in Perth.

The standby power of each water system is also analysed. By plotting the power usage of each system over time, it is possible to accurately quantify the minimum energy draw during times where the system is not in use (generally overnight). By calculating the standby power, recommendations can be made for improvement in this area for similar, future projects.

An analysis of previous studies in consumer behaviour including potential rebound effects was also undertaken, as this is a recognised area for potential resource savings. A survey instrument was designed to present to the residents of Josh’s House, as well as some
nearby residents. The design of the questionnaire was based on a previously prepared questionnaire in a study in Queensland (Spinks et al., 2011), in order to determine participants’ attitudes to water conservation, together with their actual past behaviour and future behavioural intentions. The literature review showed that a person's attitude towards water conservation was the strongest indicator of likely behaviour, which is why the questionnaire focused on attitudes. A copy of the questionnaire, consent form and information letter is attached as Appendix C.

The questionnaire was intended to be delivered by visiting residents of the same suburb as Josh’s House, with no barriers to participation other than that the house must be free-standing and owner-occupied. This is to ensure ease of access to water billing records, which can be more difficult to obtain and attribute in a multiple-tenancy complex (Spinks et al., 2011). The questionnaire was to be explained, then left with participants and collected a few days later, once it had been completed.

Unfortunately, due to the delayed addition of the survey to the scope of this project, the requisite approval from Murdoch University’s Ethics Committee was not forthcoming in a timely manner. The survey could not be delivered in time for inclusion in this final report.

The goal of the survey was to apportion the total water and energy savings at Josh’s House partly to the technology present in the house design, and partly to efficient consumer behaviour of the residents. Josh Byrne and his family are highly engaged users who practice efficient water and energy saving behaviours as a matter of habit (Anda et al., 2013a), and would therefore make some savings compared to a standard Perth residence even in the absence of water and energy-wise technology. The savings made through efficient behaviour will instead be estimated from a review of previous behaviour change studies.

The energy data from Josh’s House was also analysed, to determine the proportion of total energy being directed to the water systems. This was done over a long period of time when all systems were operational, to get the most accurate results possible. This allowed the relative proportion of energy consumption by each installed system to be calculated, and a water-energy nexus to be established. This will give a better idea of real savings, because a balance must be struck between saving water and consuming power.

A water balance was also prepared for the site over a three year establishment period for the gardens, to compare the quantity of water drawn by the bore from the superficial aquifer to
the quantity infiltrated on-site from rainfall events. The site was designed to have 100% permeable surfaces to minimise overland stormwater run-off and evaporation, thereby maximising the amount of water recharged to the superficial aquifer from the site. This water balance shows the interaction of the Josh’s House site with the superficial aquifer.

Finally, the results obtained from Josh’s House are scaled up using both Aquacycle software and Microsoft Excel to a cluster scale. This is where the advantages of a construction such as Josh’s House become clear not only to individual households, but to city planners and water providers. The savings in water for each household are the primary benefit, but there are secondary benefits to water utilities in the form of less pressure on the distribution network, lower operating and maintenance costs, and delaying construction of future desalination plants or alternate water sources. In a time where the water network is already under a great amount of stress, these additional benefits cannot be understated.

The energy data was analysed to determine the thermal performance of the house in different seasons, to assess the value of solar passive design principles. The house contains no mechanical heating and cooling, which is a huge source of energy consumption in most Perth households. This was not deemed necessary in Josh’s House at the design phase due to its favourable orientation and design. However, the success of this design (and associated energy reduction) can only be determined by viewing the thermal performance of the house over the course of different seasons to ensure it remains at a comfortable internal temperature for the occupants.

By collecting and analysing the data from the 55 sensors present in Josh’s House, this project accurately quantifies the total water and energy savings available through smart design principles, introduction of efficient appliances and technologies, and efficient consumer behaviours. Also, the real water-energy nexus of rainwater, grey water and bore water systems is determined in situ, which is a recognised gap in the current literature (Sharma et al., 2010). This will give an accurate indication of performance of the systems in place at Josh’s House, which will be of interest to consumers, the housing industry, utility providers and policy-makers.
5.0 Results & Discussion

5.1 House Water Usage

The original design goal of the Josh’s House project was to achieve 60% scheme water saving compared to the Perth metropolitan average (Byrne et al., 2014). This target has been greatly exceeded, as shown in Figure 4. Over the period of this report, Josh's House used 72-86% less water than the Perth average.

The average daily use at Josh’s House over the period from February 9 to May 21 was 209.3L per day. The lower bound of average Perth household consumption of 759L per day is based on a reported annual average use of 277kL per household (Water Corporation, 2010a). The upper bound of 1447L per day is based on an average consumption of 132kL per person per annum in Perth, multiplied by 4 occupants in Josh’s House (Water Corporation, 2009). Using either measure, it is clear that water use in Josh’s House is significantly lower than the Perth residential average, and that the design goal of 60% scheme water saving has been comfortably achieved.

![Figure 4: Daily water consumption at Josh's House.](image-url)
Due to the relatively short period over which this project was carried out, this result does not incorporate water data from the entire year. However, seasonal fluctuation in water use in Perth is predominantly due to external water use for irrigation, which is supplied by 100% bore water at Josh’s House, thereby eliminating the need to augment scheme water use over the hot, dry summer. It is therefore likely that water consumption in the house will remain constant throughout the year. Furthermore, this project covers the end of summer, when it is very dry (February and March), and the transition to winter, when Perth experienced cooler temperatures and rainfall (May). It can be seen from Figure 4 that the average daily use did not noticeably change over this period. This is further evidence that the water use figures calculated in this report can be extrapolated over a whole year.

There are two short periods in Figure 4 where no water use data was logged. The first (18-21 March) was due to a logging failure of the equipment. As such, no data was recorded for these days, and these dates were excluded from calculations of mean daily usages. The second (28-31 March) was due to the house being unoccupied. Due to the short nature of the vacancy, it was not necessary to exclude these dates from mean consumption calculations, as they will not have a significant impact on results, and may, in fact, give a more accurate result by reflecting the normal tendency of a family to take a short trip. Similar periods of no water usage are likely to be seen across Perth households during vacation periods.

The scheme water saving in Josh’s House is even greater than outlined in Figure 4, because the house consumes rainwater harvested on-site during the wet winter months. The 20,000L rainwater tank has been in use since May 4, during which time the scheme water use has dropped to an average of only 4.5L per day, as shown in Figure 5. The reason for this small, ongoing consumption of scheme water is unclear, but could be attributable to the sensitivity of the smart meters installed in the house registering small movements of water in the pipes within the house. This is most likely, because a Water Corporation account received at the house for the 2 month period from September to November 2013 showed a water use of 0kL over that period, as the house was running entirely on rainwater.
The switch to rainwater for a large portion of the year magnifies the scheme water savings. In 2013, the rainwater tank ran out on December 18. Assuming the same period of use each year, this results in the house using scheme water for 138 days per year, and rainwater for 227 days per year. Based on a daily consumption of 209.3L, the annual scheme water use for Josh’s House would therefore be 28.9kL. The average Perth annual household use is 277kL (Water Corporation, 2010) and the average use per annum for 4 occupants is 528kL (Water Corporation, 2009), as shown in Figure 6. This results in scheme water savings of 90-94%, depending on which basis is chosen. Either way, this is an excellent result which is far beyond expectations.
In addition to consuming significantly less water, Josh’s House also reuses grey water generated on-site for irrigation. The grey water produced from showering, clothes washing, dish rinsing and hand washing is diverted for irrigation of 40m$^2$ of garden area. As would be expected, the quantity of grey water produced closely follows the quantity of water consumed within the house, as shown in Figure 7. The Department of Health’s mandated 10L/m$^2$ per day maximum grey water irrigation quantity is also included in Figure 7, for reference (Department of Health, 2010).
Figure 7: Grey water produced from water consumed in Josh’s House.

Over the period of study, 56% of water consumed for internal purposes at Josh’s House (scheme water + rainwater) was diverted and reused as grey water. This was a volume of 6.8kL in 65 days, or an average of 105L per day.

Reusing grey water on-site has three major benefits. Firstly, it reduces the need for additional bore water (or scheme water, in the business as usual approach) to be used for irrigating this large area of garden. Even during garden establishment, these areas were receiving sufficient water to promote growth and propagation of plants. Secondly, the sources of grey water within the house result in the grey water containing nutrients such as nitrogen and phosphorous which are beneficial for plant growth. This reduces the need for additional nutrients in the areas irrigated using grey water. Finally, reusing grey water on site reduces the flows to local wastewater treatment facilities. This reduces the stress on existing infrastructure, reduces treatment costs and could delay or eliminate the future need to upgrade significant wastewater infrastructure.

It is also worth noting that grey water reuse is especially beneficial due to the timing of its use throughout the year. The grey water system was switched off on May 11, and expected
to be switched back on in October. This is to avoid overwatering during the wet winter months. This means that grey water reused for irrigation is being used through the hot, dry summer months as a substitute for bore or scheme water, which is the period during which demand for water is at its peak.

A breakdown of savings in scheme water consumption at Josh’s House compared to a standard residence is shown in Figure 8, which clearly shows the contribution of water efficiency measures (appliances and behaviours), rainwater harvesting, grey water reuse and bore water use for irrigation on annual consumption.

Although grey water only contributed 9% of the scheme water savings at Josh’s House, this is due to the presence of a large rainwater tank and a large quantity of bore water being used. In other studies (e.g. Evans, 2009), grey water has been shown to save up to 30% of scheme water.

![Figure 8: Breakdown of scheme water savings from different sources at Josh’s House.](image-url)
5.2 House Energy Usage

The average energy consumption at Josh’s House over the period of this project was 12.4kWh per day. This is a saving of 38% over the average 4 person household consumption of 20.0kWh per day for Perth (Energy Made Easy, 2014). The breakdown of energy use during November 2013 by different sources within the house is shown in Figure 9. November 2013 was chosen as the best representative period because this was the only extended period of time where all water systems were operational in the house. The rainwater tank stops being used from December to May, by which time the grey water system is switched off and the bore use has significantly decreased.

![Figure 9: Breakdown of electricity use in Josh’s House when all water systems are operational.](image)

The low energy consumption is greatly helped by the solar passive design of the house. The absence of a need for mechanical heating and cooling in the house significantly lowers energy consumption, as appliances such as reverse-cycle air conditioners require a large amount of energy for operation (Grignon-Masse et al, 2011). Passive design uses natural heating and cooling sources, such as warm sunlight and cooling breezes, to achieve a comfortable temperature throughout the house without the need for additional heating and
cooling, even in the peaks of summer and winter. This is demonstrated in Figures 10 & 11, which show inside and outside temperatures at the house in summer and winter, respectively. It is clear that although the outside temperatures fluctuate greatly, and are outside the comfortable limits for family living, the temperature inside the house varies much less, and remains in a comfortable temperature range of 20-25°C.

![Temperature Graph](image-url)

*Figure 10: Josh's House temperature data - summer.*
Figure 11: Josh's House temperature data - winter.

The energy use at Josh's House is offset by the energy generation from the 3kW solar PV array on the north-facing side of the roof. Generated energy is used on-site, if required, and the excess is exported back to the main electricity grid. The average production per day is 18.7kWh, meaning that Josh’s House exports a net average of 6.3kWh per day to the grid.

This result must be interpreted with caution, as it could be read to mean that the house is energy-independent by creating more electricity than it consumes. On-site power generation occurs during the middle of the day, during peak sunshine hours – between 8am and 5pm. However, peak energy use occurs in the mornings and evenings, before and after school/work respectively. This is shown graphically in Figure 12. This results in energy being exported to the grid for most of the day, and being imported in the mornings and evenings to meet peak demand. This is both environmentally and economically disappointing as it still costs money to import energy, and still requires the presence of large, coal-fired power stations to provide electricity.
Introducing battery storage for the PV energy generated on-site will allow for more of this locally produced energy to be consumed within the house. In turn, less electricity will need to be imported from the grid. As previously mentioned in the life cycle assessment literature review, an 8kWh lead-acid battery would be a suitable size for installation at Josh’s House. This would not eliminate the need for connection to the energy grid, but would drastically reduce reliance upon it, by time-shifting the solar power to meet peak energy demands.

Figure 12: Typical daily PV generation and energy consumption profile of Josh’s House.
5.3 Water-Energy Nexus

The most important aspect of this project was to analyse the water-energy nexus of the various water systems in place at Josh's House, to determine how these small, decentralised water systems compare to larger centralised systems such as desalination plants. By pairing up the water consumption data with the energy use data, it was possible to accurately calculate the energy use per unit volume of water delivered by each water system. Figure 13 shows how each water system compares to the reported annual energy use per unit volume by the Water Corporation for the last 4 years, taken from annual reports (Water Corp, 2010b; Water Corp, 2011; Water Corp, 2012; Water Corp, 2013).

The water-energy nexus is even more important because the average energy consumed per kL of potable water delivered by the Water Corporation has slowly risen from 1.2kWh/kL in 2010 to 1.7kWh/kL in 2013 (Water Corporation, 2013 at p.43). This upwards trend is likely to continue as Perth relies more and more on energy-intensive desalination plants to supply the growing population. As a comparison, the Kwinana desalination plant uses 4.1kWh/kL (Water Corp, 2006).

![Energy Intensity per Unit Volume for Various Water Sources](image_url)

**Figure 13:** Energy intensity per unit volume for various water sources.
From Figure 13 it can be seen that the grey water system at Josh’s House is using less energy per kL than the centralised utility. Furthermore, it is not using any energy as standby power. This is a significant finding, because it is important not to focus exclusively on the water-saving benefits of these systems, but to also consider the energy implications. In the case of the grey water system, it is a positive result from both a water and an energy perspective.

The bore water system is comparable to the centralised utility, but the standby energy accounts for 56% of the energy used by the bore pump. This is a substantial amount. To investigate this, the incremental power use of the bore pump was plotted at 5-minute intervals over a typical 24 hour period, and is presented as Figure 14.

![Figure 14: 5-minute power usage of the bore pump.](image-url)

The irrigation schedule at Josh’s House is set to be automatically delivered between 6am and 10am each day. It is not in use for the rest of the day, unless a small amount of hand watering is carried out. Due to the predictable nature of this water use, one possible solution may be to introduce timers which coincide with the irrigation schedule. This would eliminate the standby energy used throughout the rest of the day. The system could be manually switched on at times when hand watering is desired, and then switched off after completion.
Although a little more onerous on the user, this remains a good solution as it will minimise the significant standby energy consumption.

The rainwater system presents a more difficult problem, due to the unpredictable nature of the times at which this water source is used. This can be seen in Figure 15, which shows use over a 24 hour period. It is important to note that the operational portion of energy use of the rainwater system is less than the Water Corporation’s 1.7kWh/kL, which makes it important to minimise or eliminate this standby power energy to make this system more viable from an energy consumption perspective.

![Figure 15: 5-minute power usage of the rainwater system.](image)

The high standby energy (83%) of the rainwater system is largely attributable to the ultraviolet (UV) disinfection lamp in the system. The UV lamp runs non-stop while the system is switched on, with a power consumption of 55-85W\(^2\), resulting in a consumption of 1.32-2.04kWh/day. This lamp cannot be turned off whilst not in use through the day, due to the time required for it to heat up to be effective.

In other houses with a rainwater tank, UV disinfection may not be necessary if dual plumbing is employed. Dual plumbing involves using harvested rainwater for non-potable purposes such as toilet flushing, clothes washing and showering, and scheme water for potable purposes. Because the rainwater is not used as a potable water source, it is not necessary to have a UV disinfection lamp within the rainwater system. Dual plumbing is in place at Josh’s House, but rainwater is used for both potable and non-potable purposes, necessitating the UV disinfection. Other disinfection options such as ozonation, microfiltration, ultrafiltration, nanoalumina, and photodisinfection with high-intensity LED light could be investigated as alternatives in future projects.

Another solution may be to install a smaller, elevated tank on the property which can be periodically filled with disinfected rainwater, thereby eliminating the need for the UV disinfection unit to be constantly running. This tank would deliver the water using the force of gravity and not require additional treatment or pumping. However, caution must be taken not to store water for too long so that it becomes stagnant and potentially dangerous for human consumption.

A final solution to the standby energy problem of the rainwater system may be to supply this energy from a solar PV battery bank. The benefits of a battery bank have already been discussed and although this option does not eliminate the standby energy draw, it does allow the UV disinfection system to run constantly from a renewable source of energy, which can be replenished each day.

The water-energy nexus is important because water-related energy use will become an increasingly important element of meeting the commitment to reduce greenhouse gas emissions 80% below 2000 levels by 2050 (Department of Climate Change and Energy Efficiency, 2012). In a recent study of household water and energy consumption over a period of 3 years, it was found that water-related energy use accounted for 59% of total household energy use, and 35% of total household emissions, excluding transport-related emissions (Kenway, 2013). The significance of water-related energy use at a household scale is therefore evident, as is the need to minimise this source of energy consumption. In order for these reductions to occur, studies such as the current project will play an important role in highlighting not only where water savings can be achieved, but also the energy implications of these water-saving measures. It is only once this entire picture is available that decisions can be fully informed, which will lead to superior policy-making decisions and more effective educational campaigns.
5.4 Water-Energy-Food Nexus

The water-energy-food nexus refers to the interrelationship between water, energy and food, and how the functioning of one depends on the others. There are many links between these three spheres, which must be viewed as interdependent, not independent. Energy and water have already been discussed, but food security is becoming a more important consideration in Australia and internationally due to rapidly increasing populations and urban migration. Traditional farming areas are becoming displaced by urbanisation, and shipping has made international transport of goods safe and affordable, resulting in our food no longer being produced locally (Shuman, 1998). Modern cities around the world almost exclusively rely on imported food and resources to meet their basic daily needs (Grewal and Grewal, 2012).

For these reasons, food security is now a key resilience threat for people living in cities, however urban gardens, agriculture and water management can contribute to long-term food security during periods of energy scarcity (Barthel and Isendahl, 2013). Furthermore, the transport of food over long distances results in the emission of deleterious greenhouse gases. This highlights the importance of local food production, such as the urban gardening at Josh’s House.

The landscape design at Josh’s House includes a productive vegetable patch, a chicken run and compost bays. A wide variety of fruit trees and vines have also been planted around the site, including subtropical species like guava, banana, pawpaw and passion fruit, as well as a range of stone fruit trees and grape vines. Herbs such as thyme, oregano, mint and sage were included to soften hard edges and as an accessible source of organic herbs for cooking.

Minnich (1983) estimated that under average growing conditions during a 130-day growing season, a 10m by 10m plot can provide a household’s yearly vegetable needs. This is not the only benefit of producing food within a city. Doron (2005) calculated that if food was produced and consumed locally in the United Kingdom, the level of carbon dioxide emissions would be reduced by 22% - more than twice the amount under the Kyoto Protocol commitment – and gardening can also increase the rate of carbon sequestration, further mitigation greenhouse gas emissions and slowing climate change. Additionally, the urban heat island effect can be reduced, leading to lower air conditioning costs (and emissions) in cities (United States Environmental Protection Agency, 2008) and kitchen wastes can be reused as fertilisers, resulting in less waste production and less importation of synthetic
fertilisers. Similarly, redirection of stormwater to food production reduces the stress on stormwater infrastructure. Many of these benefits are visible on a small scale at Josh’s House, and could greatly help with long-term sustainability if applied at a larger scale. Indeed, Grewal and Grewal (2012) demonstrated three different scenarios for a typical city in the United States. It was concluded that the city could produce up to 100% of fresh produce needs, 94% of poultry and shell eggs and 100% of honey. The study also showed that this would result in up to $115 million being retained locally per annum.
5.5 Site Water Balance

“A water balance is an application of the principles of mass conservation used to account for the movement of water in the land phase of the hydrological cycle, for a given area of land, and a selected time interval” (Mitchell et al., 2003). These principles were applied at Josh’s House to determine the interaction between the bore and the superficial aquifer.

The surfaces at Josh’s House were designed to be 100% permeable. This is to minimise the effect on local groundwater of using bore water for irrigation, by ensuring that as much rainfall as possible is infiltrated to the superficial aquifer. There are no hard surfaces from which rainfall can runoff into stormwater drains. The driveway consists of pebbles overlaying fast-draining membranes (see Figure 16), with the rest of the landscape being comprised of a combination of turf, mulch, soil, plants and pebbles. An additional benefit of the pebbled driveway is additional security by hearing approaching vehicles/pedestrians.

![Figure 16: Construction of the permeable driveway (left) and the finished result (right) (Byrne, 2014).]
To investigate the interaction of the site with the superficial aquifer, a site water balance was undertaken. Josh’s House is on a 698m$^2$ block, but the roof area of 205m$^2$ must be subtracted as rainwater is harvested from this area. Using annual rainfall statistics for Perth from the Bureau of Meteorology, the quantity of water to fall on the site each year was calculated to be 359kL. Not all of this rainfall will make it to groundwater, as some will be lost to evaporation and some will be taken up by plant roots or held in the soil. As such, a recharge factor of 0.5 is applied, which is the estimated recharge factor applicable to residential sites in Perth (Department of Water, 2009).

There is also some overflow from the rainwater tank each year which is directed to underground sumps on the site. After extensive modelling carried out by Josh Byrne & Associates, this overflow was estimated to be approximately 31.8kL per annum. In total, a small net uptake (18.6kL) was calculated for the first year of inhabitation, due to the larger quantity of water required during establishment of the gardens on the property. Once the gardens are established (year 3+), a net annual recharge of 47kL is expected. The exact number will fluctuate from year to year due to climatic variations, but an average of 47kL per annum recharged to the superficial can be expected in the long-run. This number would be even higher when surplus irrigation (beyond evapotranspiration) is included, but has been left out here due the highly engaged nature of the occupants and the presence of soil moisture sensors. This will reduce any excess irrigation at Josh’s House, but needs to be taken into account in other properties. The water balance between the site and the local groundwater supply is shown in Figure 17.

This is an important finding because it means that not only is scheme water being saved by using bore water for garden irrigation (as discussed earlier), but that the bore water being drawn up from the superficial aquifer is being more than replenished by having 100% permeable surfaces at the property, resulting in a net recharge to the aquifer each year.
Figure 17: Monthly aquifer recharge vs bore uptake during and after garden establishment.
5.6 Scaled-Up Results

Aquacycle is a water balance model developed to simulate the urban water supply, wastewater and stormwater systems (Mitchell et al., 2001). By viewing potable water, stormwater and wastewater as one integrated system, rather than three distinct systems, it is possible to analyse the positive and negative (if any) effects of a house consuming significantly less water than the metropolitan average. On its own, the effect will be insignificant at a city-scale. However, by scaling the results from this project up using simulation software, the future effects can be predicted and taken into account in city planning and policy decision-making.

The results from this project were used to run a simulation using Aquacycle to compare two suburbs, each with 1000 houses. The first (Cluster 1), adopted the business as usual approach, whereas the second (Cluster 2), included the technology present in Josh’s House. The results are presented in Figures 18-22. It is clear that the introduction of rainwater tanks and grey water reuse systems greatly reduces the quantity of scheme (“reticulated”) water required at a cluster scale.

Figure 19 shows that more of the water requirements are met from grey water and black water than in Figure 18 – due to the presence of the water saving technologies at Josh’s House. Figure 20 shows that, under the business as usual approach, all of a household’s water requirements must be met with scheme water. With the technology present in Josh’s House, Figure 21 shows that the reliance on scheme water is drastically reduced at a cluster scale. Finally, Figure 22 shows that appropriately sized rainwater tanks are capable of meeting a large proportion of water required by the cluster in most years.
Figure 18: Cluster 1 Water Usage.

Figure 19: Cluster 2 Water Usage.

Figure 20: Cluster 1 Water Sources.
Caution must be taken when analysing these Aquacycle results. Firstly, the software utilises climatic assumptions from the Woden Valley catchment, located in the Australian Capital Territory, which cannot be changes with the current version of the software. Although the same basic principles will apply, rainfall and evapotranspiration data and patterns will be significantly different for Perth. Secondly, the software uses the same input for household water consumption for both clusters. In reality, Josh’s House (Cluster 2) uses significantly less water than the business as usual approach (Cluster 1). This would again drastically change the results, amplifying the savings in Cluster 2 water usage (Figure 19).

The results from the Aquacycle simulation can therefore be viewed as indicative at best. They do not provide accurate estimations of the quantities of water to be saved at a cluster scale from introducing the technology and behaviours in place at Josh’s House. They do, however, give an indication of the possibilities. Although the figures are not accurate it is still
possible to ascertain the benefits of introducing rainwater tanks and grey water reuse systems. Figure 21 demonstrated that alternative water sources greatly reduce the quantity of scheme water supplied to the cluster, and Figure 22 shows the performance of the rainwater systems in Cluster 2 over a 10-year period, showing that it meets the water demands of the cluster in most years over the period.

Because these simulations were not accurate, a spread sheet was designed in Microsoft Excel to attempt to more accurately quantify the savings from Josh’s House when scaled up to 1000 households. The water use profiles of two 1000-house suburbs – one employing the technologies and behaviours present at Josh’s House, and the other using the Business as Usual approach, are represented in Figures 23 & 24. Average monthly water usages were scaled using relative values from a publication by the Water Corporation (2003). The most striking result is the drastic reduction in scheme water use in the Josh’s House cluster, due to the varied water sources available, as shown in Figure 23.

The additional benefit of lower wastewater discharged to sewer can be seen in Figure 24. Although the grey water reuse system is switched off at Josh’s House for the winter period (mid-May to mid-October), the wastewater flows are still much lower due to the lower water consumption for internal use. During summer, when a maximum quantity of grey water is reused for irrigation, the Josh’s House cluster (2 houses) discharges approximately 80% less wastewater than the Business as Usual approach. This lower flow will reduce the costs and energy associated with wastewater treatment. It also has the benefit of cutting down the amount of treated wastewater being discharged to waterways after treatment at a centralised treatment facility – this can be seen in Figure 24.
Figure 23: Monthly water profile of water sources in a Josh’s House cluster and in a Business as Usual cluster.
Figure 24: Monthly wastewater discharge volumes in a Josh's House cluster and in a Business as Usual cluster.
5.7 Survey/Consumer Behaviour

Due to the survey being unable to be delivered, as explained earlier in the Methodology section, the quantity of water and energy savings at Josh’s House will instead be estimated by analysing the results of previous studies in this area. This will provide a reasonable substitute, as a large body of work exists in this area, including previous studies in which Josh Byrne and his family participated (e.g., Anda et al, 2013a).

One Melbourne study showed that, by introducing a Smart Shower Meter with real-time feedback, shower users made sustained savings of 15% on water over a 6-month period (Smart Water Fund, 2006). However, in that study meters were voluntarily taken up by interested participant households, meaning that the individuals participating in the study were likely already somewhat inclined towards conserving water. Results may not as high for the wider community, but can be estimated using existing behavioural change program data (Rogers, 2003):

- Champions (Innovators)  First 5-10% that adopt a product
- Early Adopters  Next 10-15%
- Early Majority  Next 30%
- Late Majority  Next 30%
- Laggards  Remaining 20%

An individualised Water Smart Pilot program was trialled in 2004 by Yarra Valley Water (Socialdata, 2005). That program encouraged households to determine their own targets for water savings, and offered help to assist them make behaviour changes to reach those targets. Over the course of the study, participants achieved average savings of 12%.

Recently in Western Australia, smart metering technology was combined with a community based social marketing program and feedback to consumers from eco-coaches in the H2ome Smart program. Savings of 12% for households in the Margaret River region, 9.9% in the Pilbara and Kimberley regions, and 9.9% (projected) for the Perth region were achieved (Anda et al, 2013b; ENV Australia, 2012).

In terms of energy, Seligman and Darley (1977) investigated the effectiveness of constant daily feedback on participants’ energy consumption. By providing daily feedback on energy use levels, a 10.5% saving was achieved by the study group compared to the control group,
due to the encouragement of effective behaviours and the reinforcement of seeing the savings being made.

A recent review of available literature targeting energy savings through consumer behaviour identified a number of ways to save energy, and estimated the potential savings of each (European Environment Agency, 2013). The results of that review are presented in Table 2.

**Table 2: Potential energy savings due to measures targeting behaviour** (from European Environment Agency, 2013).

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Range of Energy Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedback</td>
<td>5-15%</td>
</tr>
<tr>
<td>Direct feedback (including smart meters)</td>
<td>5-15%</td>
</tr>
<tr>
<td>Indirect feedback (e.g. enhanced billing)</td>
<td>2-10%</td>
</tr>
<tr>
<td>Feedback and target setting</td>
<td>5-15%</td>
</tr>
<tr>
<td>Energy audits</td>
<td>5-20%</td>
</tr>
<tr>
<td>Community-based initiatives</td>
<td>5-20%</td>
</tr>
<tr>
<td>Combination interventions (of more than one)</td>
<td>5-20%</td>
</tr>
</tbody>
</table>

Based on the literature, it will be assumed that, by being highly engaged users in terms of both energy and water, the occupants of Josh’s House would save approximately 20% on both energy and water through behavioural efforts alone. This is at the high end of literature estimates, which is appropriate because the behaviour of Josh Byrne and his family is close to representing best-practice ( Anda et al, 2013a).

This must be kept in mind whilst reading the results in this project, as the energy and water savings are not entirely attributable to the intelligent design of Josh’s House, and introduction of efficient technologies and alternate water sources. This does not diminish the results in any way, as it was shown from the literature reviews that the most effective method to save energy and water is a combination of new technology and delivery of a behaviour change campaign.
### 6.0 Conclusions

This report successfully quantified the performance of Josh’s House, a sustainable housing project, over the period from February to June 2014. The house was analysed in terms of its water and energy performance, on a life cycle assessment basis, and the water-energy nexus of the systems in place was investigated.

In terms of water consumption, the house consumes 72-86% less water than the Perth metropolitan average (Aim #1), due to the inclusion of alternate water sources and the presence water efficient fixtures and appliances. This figure rises to a 90-94% scheme water saving over the business as usual approach when the savings made from internal rainwater use are included. This has the additional benefit of decreasing associated wastewater flows to treatment facilities, lowering costs and energy consumption associated with treatment and discharge.

This very large water saving is especially significant in Perth due to the hot, drying climate and expanding population. With water supply infrastructure already under a great deal of stress, the importance of the results of this project is clear. More new constructions and retrofits must follow the lead of Josh’s House in order to save water and reduce reliance on the centralised provider.

The energy results are equally important. Josh’s House uses 38% less energy than the Perth average (Aim #1), largely due to intelligent solar passive design of the house. The house has no mechanical heating and cooling, and still remains at a comfortable internal temperature zone of 20-25°C year round. Energy-efficient fixtures and appliances also help to achieve this result. Josh’s House is also a net exporter of energy, generating, on average, a 6.3kWh/day excess from the 3kW solar photovoltaic system on the north-facing roof, which is sent back to the grid. This result is even more notable when it is considered that the energy consumption of a rainwater pump, grey water reuse system and bore pump are included, which are not present in a standard Perth household.

The water-energy nexus was also investigated in this project, helping to address a recognised void in the existing literature by accurately quantifying the performance of decentralised water systems at a lot scale (Sharma et al, 2010). By pairing energy and water
datasets from Josh’s House, and comparing the results with Water Corporation’s reported
statistics, it is seen that the operational energy of the rainwater system (1.3kWh/kL), grey
water reuse system (0.44kWh/kL) and bore pump (0.64kWh/kL) were all lower than the
Water Corporation’s water-related energy use for 2013 (1.7kWh/kL) and significantly lower
than the water-related energy use at the Kwinana desalination plant (4.1kWh/kL).

However, the standby energy of the rainwater system was excessively large (6.3kWh/kL).
This is due to an ultraviolet disinfection system which operates non-stop, which may not be
necessary in other circumstances. Suggestions have been made to address this problem, as
the standby energy needs to be reduced for this water source to be viable from an energy
perspective. The bore system standby energy was also noticeable (0.82kWh/kL), although
not excessive.

The life cycle analysis carried out on Josh’s House showed a 23% embodied energy saving
and a 111% operational energy saving (Aim #3). The house was purposely designed to use
standard building materials and methods, for ease of replication, so the lesser embodied
energy saving was expected. The operational energy saving is attributable to the absence of
mechanical heating and cooling, installation of efficient lighting and appliances, and the
power generated by the solar PV system. The house achieved an overall saving of 90% on
kgCO₂e per occupant per year.

The water balance showed that by incorporating 100% permeable surfaces instead of hard
surfaces, the site was able to infiltrate 39% more rainwater to the superficial aquifer than is
drawn up by the bore each year, once the gardens are established. There is a small net
uptake during the first year, due to the higher initial water requirements, which becomes a
net recharge of 47kL/annum thereafter. This more than offsets the bore water utilised for
irrigation, which is important because it means that scheme water consumption is not simply
being replaced with bore water consumption.

Although the questionnaire designed for this project was unable to be completed, the in-
depth analysis of consumer behaviour (Aim #2) showed that the effective delivery of a
behaviour change program is an important aspect of water and energy conservation
measures – up to 20% of water and energy can be saved through engaging occupants. A
new model for community based social marketing campaign was proposed, based on the
strong link between consumer attitudes and actual behaviours.
Overall, the results presented in this project are significant for future house design in Perth, and around the country, as the water and energy savings over the business as usual approach are very large, at a time when utilities are becoming more and more stretched. The need for more houses like Josh's House is amplified by a drying climate, and, importantly, was achieved at a similar cost to a standard Perth residential construction, making replication a viable option at a larger scale. This would greatly reduce the strain on centralised utility providers, at a time when such a reduction is most needed.

6.1 Further Work

It would be beneficial to carry on the work within this project over a longer period of time. Due to the short nature of this project, data was only analysed for a short period of the year, and conclusions were based thereupon. By continuing the project over a whole year (or more), a detailed analysis of the house's performance could be obtained through each season. Furthermore, more robust conclusions could be drawn due to the longer timeframe and larger dataset available.

Additionally, a more detailed analysis of the grey water system would address a current gap in literature. Grey water systems can reduce scheme water consumption and wastewater flows, but performance varies over the course of the year. For example, they are switched off during winter to prevent overwatering, thereby increasing wastewater flows on a city-wide scale. This effect needs greater study. Also, the current Department of Health guidelines for application (10L/m².d) are conservative, especially during the hot summers in Perth. More detailed analysis of this restriction is required to determine whether it is appropriate.

Also, a specific life cycle assessment of each alternate water system would add to the current body of work in this area. Although a life cycle assessment of Josh’s House as a whole was carried out, a specific focus on each water system (rainwater, grey water and bore water) would be beneficial to determine how well these systems perform from a whole-of-life perspective.

It would also be beneficial, once more data is available over a longer period of time, to calculate payback periods and returns on investment for the technologies introduced at
Josh’s House. This would require a financial analysis of the initial capital cost of the technologies, and the ongoing savings generated over a period of time (years, not months).

6.2 Policy Implications

1) Josh’s House uses 72-86% less water than the Perth average yet still maintains a high quality of life and thriving garden. The Perth average water consumption is twice as high as other major cities around the world, which shows that WA is not doing enough to conserve water.

2) The Western Australian government, together with the Department of Water and Synergy, needs to lead the way in water and energy saving programs aimed at behaviour change and technological improvements. This is not only a matter of social & environmental justice, but of economic prosperity.

3) The Water Corporation and electricity retailers must roll out massive retrofit and behaviour change programs to combat WA’s poor historical performance in water and energy consumption. These programs are long overdue, and the need for them will only increase the longer it takes to introduce them.

4) Policy needs to be developed accordingly, recognising the problems that we face and addressing them. Simple measures such as mandating solar PV systems and small (~3kL) rainwater tanks on every new residential construction can have a significant lasting impact.
References

• Evans, C., 2009. Greywater reuse: An assessment of the scheme water savings that can be achieved at a household scale. Murdoch University, Perth, WA.


- Smart Water Fund, 2006. Development and Trial of Smart Shower Meter Demonstration Prototypes. Project Smart1. Invetech Pty Ltd.


## Appendix A – Schedule of Sensors in Josh’s House

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Living Room Slab Nth (°C)</td>
<td>Temperature of north side of living room concrete slab</td>
</tr>
<tr>
<td>2. Living Room Slab Mid (°C)</td>
<td>Temperature of middle of living room concrete slab</td>
</tr>
<tr>
<td>3. Living Room Slab Sth (°C)</td>
<td>Temperature of south side of living room concrete slab</td>
</tr>
<tr>
<td>4. Master bedroom wall (°C)</td>
<td>Temperature of wall in master bedroom</td>
</tr>
<tr>
<td>5. Bedroom 2 wall (°C)</td>
<td>Temperature of wall in second bedroom</td>
</tr>
<tr>
<td>6. Bedroom 3 wall (°C)</td>
<td>Temperature of wall in third bedroom</td>
</tr>
<tr>
<td>7. Living area Sth wall (°C)</td>
<td>Temperature of south wall in living area</td>
</tr>
<tr>
<td>8. Living area West wall (°C)</td>
<td>Temperature of west wall in living area</td>
</tr>
<tr>
<td>9. Activities room wall (°C)</td>
<td>Temperature of wall in activity room</td>
</tr>
<tr>
<td>10. Living room ceiling (°C)</td>
<td>Temperature of ceiling above living room</td>
</tr>
<tr>
<td>11. Roof cavity (°C)</td>
<td>Temperature in the roof cavity</td>
</tr>
<tr>
<td>12. Roof surface (°C)</td>
<td>Temperature at the surface of the roof</td>
</tr>
<tr>
<td>13. Spare 1 Temp (°C)</td>
<td>Not currently in use</td>
</tr>
<tr>
<td>14. Spare 2 Temp (°C)</td>
<td>Not currently in use</td>
</tr>
<tr>
<td>15. Spare 3 Temp (°C)</td>
<td>Not currently in use</td>
</tr>
<tr>
<td>16. Greywater 1 (%VWC)</td>
<td>Volumetric water content of first soil moisture sensor in grey water irrigated zone</td>
</tr>
<tr>
<td>17. Greywater 2 (%VWC)</td>
<td>Volumetric water content of second soil moisture sensor in grey water irrigated zone</td>
</tr>
<tr>
<td>18. Greywater 3 (%VWC)</td>
<td>Volumetric water content of third soil moisture sensor in grey water irrigated zone</td>
</tr>
<tr>
<td>19. Turf 1 (%VWC)</td>
<td>Volumetric water content of first soil moisture sensor in turf irrigated zone</td>
</tr>
<tr>
<td>20. Turf 2 (%VWC)</td>
<td>Volumetric water content of second soil moisture sensor in turf irrigated zone</td>
</tr>
<tr>
<td>21. Turf 3 (%VWC)</td>
<td>Volumetric water content of third soil moisture sensor in turf irrigated zone</td>
</tr>
<tr>
<td>22. Vegetables 1 (%VWC)</td>
<td>Volumetric water content of first soil moisture sensor in vegetable patch irrigated zone</td>
</tr>
<tr>
<td>23. Vegetables 2 (%VWC)</td>
<td>Volumetric water content of second soil moisture sensor in vegetable patch irrigated zone</td>
</tr>
<tr>
<td>24. Vegetables 3 (%VWC)</td>
<td>Volumetric water content of third soil moisture sensor in vegetable patch irrigated zone</td>
</tr>
<tr>
<td>25. Fruit Trees 1 (%VWC)</td>
<td>Volumetric water content of first soil moisture sensor in fruit tree irrigated zone</td>
</tr>
<tr>
<td>26. Fruit Trees 2 (%VWC)</td>
<td>Volumetric water content of second soil moisture sensor in fruit tree irrigated zone</td>
</tr>
<tr>
<td>27. Fruit Trees 3 (%VWC)</td>
<td>Volumetric water content of third soil moisture sensor in fruit tree irrigated zone</td>
</tr>
<tr>
<td>28. Natives Verge 1 (%VWC)</td>
<td>Volumetric water content of first soil moisture sensor in native plants irrigated zone on verge of property</td>
</tr>
<tr>
<td>29. Natives Verge 2 (%VWC)</td>
<td>Volumetric water content of second soil moisture sensor in native plants irrigated zone on verge of property</td>
</tr>
<tr>
<td>No.</td>
<td>Description</td>
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<tr>
<td>30.</td>
<td>Natives Verge 3 (%VWC)</td>
</tr>
<tr>
<td>31.</td>
<td>Spare 1 Moisture (%VWC)</td>
</tr>
<tr>
<td>32.</td>
<td>Spare 2 Moisture (%VWC)</td>
</tr>
<tr>
<td>33.</td>
<td>Spare 3 Moisture (%VWC)</td>
</tr>
<tr>
<td>34.</td>
<td>Rainwater tank (L)</td>
</tr>
<tr>
<td>35.</td>
<td>Solar radiation (W/m²)</td>
</tr>
<tr>
<td>36.</td>
<td>Nursery Temperature (°C)</td>
</tr>
<tr>
<td>37.</td>
<td>Nursery Humidity (%RH)</td>
</tr>
<tr>
<td>38.</td>
<td>House Gas (L)</td>
</tr>
<tr>
<td>39.</td>
<td>Solar Gas (L)</td>
</tr>
<tr>
<td>40.</td>
<td>Mains Water (L)</td>
</tr>
<tr>
<td>41.</td>
<td>Rainwater (L)</td>
</tr>
<tr>
<td>42.</td>
<td>Greywater (L)</td>
</tr>
<tr>
<td>43.</td>
<td>Bore Water (L)</td>
</tr>
<tr>
<td>44.</td>
<td>Hot Water (L)</td>
</tr>
<tr>
<td>45.</td>
<td>Tap Line (L)</td>
</tr>
<tr>
<td>46.</td>
<td>Local Weather Station</td>
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<tr>
<td>47.</td>
<td>Voltage RMS, mV 3-phase supply – Red</td>
</tr>
<tr>
<td>48.</td>
<td>Voltage RMS, mV 3-phase supply – White</td>
</tr>
<tr>
<td>49.</td>
<td>Voltage RMS, mV 3-phase supply – Blue</td>
</tr>
<tr>
<td>50.</td>
<td>Voltage RMS, mV Lights 1</td>
</tr>
<tr>
<td>51.</td>
<td>Voltage RMS, mV Lights 2</td>
</tr>
<tr>
<td>52.</td>
<td>Voltage RMS, mV Rainwater</td>
</tr>
<tr>
<td>53.</td>
<td>Voltage RMS, mV Grey water</td>
</tr>
<tr>
<td>54.</td>
<td>Voltage RMS, mV Bore water</td>
</tr>
<tr>
<td>55.</td>
<td>Voltage RMS, mV Oven</td>
</tr>
</tbody>
</table>
Appendix B – eTool Life Cycle Assessment Report for Josh’s House

eTool Life Cycle Assessment

Josh Byrne Residence
Grigg Place, Hilton, Western Australia

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40-44 Pier St Perth
Western Australia
+61 8 6364 3805
info@etool.net.au
Josh Byrne Residence
Grigg Place, Hilton, Western Australia

A Life Cycle Assessment has been carried out on the proposed design, calculating the carbon emissions due to materials’ manufacture, materials’ transport, building construction, maintenance and operations. The boundary of the assessment includes the foundations, floors, walls, roof, internal finish, external finish, services and basic fittings. The results measured against a benchmark are summarized below:

Building Embodied Carbon: 757 kgCO₂e per year per occupant. Saving of 23%

Building Operational Carbon: -342 kgCO₂e per year per occupant. Saving of 111%

Total Building: 420 kgCO₂e per year per occupant. Saving of 90%

Assessed by Henrique Mendonca
4th December 2012

Certified by Richard Haynes

The Ratings Explained:
- Bronze Medal: 0 - 30% Carbon equivalent greenhouse gas emissions (CO₂e) saving against the applicable benchmark
- Silver Medal: 30 - 60% CO₂e saving
- Gold Medal: 60 - 90% CO₂e saving
- Platinum Medal: More than 90% CO₂e saving. Gold must be achieved in all categories for an overall Platinum rating.
Life Cycle Assessment: Josh Byrne - Base Design

Executive Summary

In order to quantify and improve the design of the Strata Lot 2 - Rear a life cycle assessment (LCA) has been conducted. Three LCAs were conducted, each representing an alternative design:

- A business as usual or benchmark design, "Strata Lot 2 - Rear Brick Veneer, BCA Climate Zone 5, Perth NEV"
- Base case design, "Strata Lot 2 - Rear Josh Byrne - Base Design"
- Improved design with modeled recommendations, "Strata Lot 2 - Rear Josh Byrne - eTool recommendations"

Design life is a critical factor in LCAs of buildings and infrastructure. In this case, the estimated design life of the benchmark was 35 years whilst the maximum durability of the building is 150 years. The estimated design life for the subject building "Strata Lot 2 - Rear Josh Byrne - Base Design" is 65 years whilst the maximum durability is 175 years.

The Global Warming Potential impact associated with the base case design totaled 68,693 kgCO2e.

Taking into account the functional units of the building, this is equivalent to 408 kgCO2e/year/occupant. This represents a 90% or 3,684 kgCO2e/year/occupant saving compared to the benchmark.

With recommendations a saving of 114% or 4,326 kgCO2e/year/occupant can be achieved.

Having quantified the impacts associated with the base case design, this enabled a number of recommended design improvements to be identified. These are summarized below:

- Customised ventilation for fridges can save up to 15% on energy consumption and represents a total of 9.2t CO2e over the life of the building.
- Use of natural gas for oven represents a total savings of 5.8t CO2e over the life of the building.
- Increase solar PV system to 3.5kW capacity to achieve full carbon neutral, saving a total of 101.7t CO2e over the life of the building.
- The following recommendations have also been provided for consideration on future projects where more flexibility exists to change the functionality of the buildings:
  - Increase design life through future proofing. Further design options that would enable to house to be extended, retrofitted or modified for increased density or an alternative use. For example, enabling a dwelling to be split into two smaller living spaces at a later date by retrofitting the required plumbing under the slab could significantly increase the expected design life of the dwelling by making it more attractive in the future. (not modelled in the design)
  - Increase design life through higher density. Increase the density of the building to reduce the embodied emissions. By increasing density, the expected design life of the dwelling would increase. This is due to it becoming a less unattractive target for redevelopment than lower density surrounding buildings. Stacked walls also mean less the embodied impacts per dwelling for the wall. (not modelled in the design)
  - Better utilisation of materials through increased ability to de-conconstruct. Use materials that can be de-conconstructed such as timber / steel frame floors, walls and roof systems in preference to materials that can’t be re-located and re-used (eg, brick walls). If masonry walls are used, consider using a lime based mortar that enables the bricks or blocks to be cleaned and re-used after the building is demolished (rather than concrete mortar). Not modelled in the design
  - Previous to the LCA report, the following lower embodied energy recommendations were made but not progressed due to the project requirements to build with readily accessible and available products and methods:
    - Reduce internal finishes with exposed brick on internal walls will save a total of 3.2t CO2e over the life of the building.
    - Use of 50% of fly ash concrete will save 3.2t CO2e over the life of the building.
    - Use of recycled bricks represents a saving of 3.1t CO2e over the life of building.
    - Rammed Earth Floors throughout - 10t CO2e saving (assumed 200mm slab thickness)
    - Straw Bale External Wall Construction - 10t CO2e saving
    - Timber window frames throughout - 2t CO2e saving
    - Recycled timber to framed wall elements - 1.3t CO2e saving
    - Recycled timber to roof structure - 1.2t CO2e saving

The following charts provide some further information regarding the comparative impacts of the three designs. A comparison has also been provided of the largest embodied and operational impacts. The detailed percentage split of impacts sources relating to the base case design have also been provided.
Life Cycle Assessment Report Information

Introduction

Life Cycle Assessment (LCA) is a method used to determine the real cost and/or environmental impact of a product over its life. This LCA accounts for impacts and costs from cradle to grave (recycling and environmental costs are not yet within the scope of eTool LCAs). In the case of buildings, the total life cycle energy consumption is made up of two components:

- Embodied Impacts
- Operational Impacts

This life cycle assessment compares the life cycle impacts of design options to a chosen benchmark. Where recommendations are made, their purpose is to reduce the impacts of the design.

LCA Goals

The goals of this life cycle assessment are to:

- Quantify the environmental impacts of the clients design (normal eTool assessments pay particular attention to CO2 equivalent emissions, CO2e)
- Compare these impacts against a typical 'business as usual' benchmark
- Provide recommendations that will ideally reduce the total impacts of the building
- Conduct this in a cost effective, auditable and repeatable manner

A typical eTool assessment allows reporting of numerous impacts. This report only details the Global Warming Potential impacts of the design options. It is the goal of eTool to estimate impacts with enough accuracy to compare different design options. The aim is to be vague right not precisely wrong. Estimating impacts to high levels of confidence requires detailed resources. In the case of buildings, this will usually be overshadowed by the influence of occupant behavior on operational impacts, or the actual building life that will deviate significantly from that estimated in this assessment. The assessment does not attempt to predict the effects of future changes to:

- Grid Power Sources (which hopefully by the time this building is actually nearing it’s design life will be predominantly renewable)
- Inflation of building materials (for maintenance), labour costs or energy costs

The assessment therefore represents a snapshot in time, all else being equal, of the building performance.

LCA Scope

A number of impact categories have been isolated for reporting. Furthermore, the extent to which these categories are measured are detailed in the scope. Both the system boundaries and specific detail of the scope are found below.

System Boundaries

The system boundary of the assessment is detailed in Figure 1. The system boundary is quite broad for this LCA, however the omission of demolition and recycling impacts must be noted as this has potential to be significant in an unbounded LCA. The eTool database does however store an estimated percentage of recyclable materials used in the construction of the building which can be reported on separately. Please contact us for more information.

![Diagram of System Boundary of LCA](image)

**Figure 1: System Boundary of LCA**

Specific Details of Scope

In relationship to the building envelope itself, the scope is further defined in Table 1. The impact categories are listed in the first column. The items falling in and out of scope are listed in detail. Factors that would greatly influence the total LCA GHG emissions of the designs include:

- Non-permanent building fixtures such as furniture and appliances
- Operational transportation (transportation of building occupants to and from the building to workplaces, recreational areas and retail outlets)
- Embodied carbon relating to building planning and sales
These factors listed are not considered significant to the conclusions of the LCA however please contact eTool if you would like to discuss these impacts could be included in your assessment.

<table>
<thead>
<tr>
<th>Materials</th>
<th>In Scope</th>
<th>Out of Scope</th>
<th>Fit-outs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Foundations</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Foundations and Footings Room</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Doors</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Windows</td>
<td></td>
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<tr>
<td></td>
<td>6. Insulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7. Structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8. Doors</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9. Windows</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10. Insulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11. Paint</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12. Work Coverings</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13. Commerical / Display</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14. Wall Coverings [by plaster]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15. Setting boards</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16. Wash areas and walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly</td>
<td>Site Preparation and Extravagance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recurring</td>
<td>Replacement of materials used in the categories listed In Scope above</td>
<td>Maintenance of materials used in the categories listed In Scope above</td>
<td>Recurring assembly impacts associated with maintaining and replacing building components in scope above</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport and Travel</td>
<td>Transport of materials associated with all material categories listed In Scope above</td>
<td>Transport of building occupants after construction</td>
<td>Operational Transport Energy</td>
</tr>
<tr>
<td></td>
<td>Transport of materials associated with all material categories listed In Scope above</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transport of equipment and staff associated with all scope assembly categories</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transport associated with recurring aspects</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Specific detail of scope in relation to the building envelope.

Data Sources and Assumptions

Embodied Impacts

The life cycle inventory data chosen for this assessment includes:

- The default cradle to factory gate embodied impacts of materials are derived from the inventory of Carbon and Energy (Mammon). Alternative LCI sources can be chosen in eTool and may have been implemented in whole or part in this report.
- National Greenhouse Accounts Factors for GHG coefficients for fossil fuel combustion (Department of Climate Change and Energy, 2011).
- In selecting data sources for eTool software, efforts have been made to identify significant items and cross check these against second or third sources for consistency and relevance. For example, the embodied GHG coefficient for clay bricks was cross checked against the Think Brick Australia – LCA of Brick Products (Energistics, 2010) for geographical relevance to Australian based LCAs and found to be appropriate.

Operational Impacts

For residential buildings, operational energy demand was modelled using a range of data sources. Australian primary energy consumption (ABARE, 2009) was interpreted to establish the average energy demand in Australia. This data was then cross referenced against other international residential building energy statistics (IBPSI International LTD, 2009) and US Energy Information Administration, 2011). Once adjusted for climatic influence, the comparisons supported this method of estimating overall energy demand for average households. In the case of residential buildings, demand categories were then modelled using information from such as:

- Year Home Technical Manual (Department of Climate Change and Energy Efficiency, 2010)
- Energy use in Provision and Consumption of Urban Water in Australia and New Zealand (Kinnery et al., 2018)
- Nationwide House Energy Rating Scheme (NABERS) starbands (www.nabers.gov.au) for average thermal performance

In the case of commercial buildings, operational energy demand was benchmarked using the following sources:

- Sustainability in the Commercial Property Sector (Department of Environment and Climate Change NSW)
- NABERS Office Energy Calculator
- Actual commercial buildings energy consumption (both predictive and surveyed data)
Functional Units
In order to normalise assessments between building types the impacts were measured per occupant. Furthermore, in order to normalise assessments between different building ages, the impacts were measured per year.

The Total Global Warming Potential for each of the designs assessed is outlined below:
- Josh Byrne - Base Design: 68,693 kgCO2e
- Brick Venner: BCA Climate Zone 5, Perth NEW: 339,689 kgCO2e
- Josh Byrne - eTool recommendations: -123,435 kgCO2e

The design life of buildings has a very large effect on their comparable sustainability. Although difficult to predict, eTool uses a methodology aimed at producing fair and repeatable comparisons between buildings designs. Individual building life spans will deviate significantly from the design lives calculated using this methodology; however the aim is to predict the mean expected life of all buildings with similar characteristics and circumstances.

Although studies that quantify the actual life span of buildings are lacking, the reasons for demolition of buildings are quite well documented. Studies conducted in Australia (Kapambwwe, Ximenes, F. Vinden, & Keenan, 2009) and the US (Aherne Institute, 2004) indicate that less than 10% of buildings are demolished due to reaching the end of their structural service life. It is other factors that usually dictate service life, namely:
- Redevelopment for economic reasons (surrounding land has increased in value to the extent that it is more profitable to increase the density or use of the building)
- Redevelopment for aesthetic reasons (the building is no longer in fashion)
- Fire or other disaster

For this reason the following characteristics are also considered when estimating design life:
- Building density
- Density of the surrounding suburb
- Design quality

Best practice building design attempts to match the durability with the redevelopment potential of the building.

In this case, the estimated design life of the benchmark was 35 years whilst the maximum durability of the building is 150 years. The estimated design life for the subject building "Strata Lot 2 - Rear Josh Byrne - Base Design" is 65 years whilst the maximum durability is 175 years.

The eTool estimated design lives often differ compared to industry perceptions of buildings life span. Architects in Australia for example expect detached residential buildings to last over 60 years (Kapambwwe, Ximenes, F. Vinden, & Keenan, 2009).

Life Cycle Inventory
A summary of LCI outputs is found on the first page of this report. For further details on the life cycle inventory (both inputs and outputs) which are all stored in the eTool database please contact eTool.

eTool Design Recommendations
- Customised ventilation for fridges can save up to 15% on energy consumption and represents a total of 9.2 t CO2e over the life of the building.
- Use of natural gas for oven represents a total savings of 5.8t CO2e over the life of the building.
- Decrease solar PV system to 3.5 kW capacity to achieve full carbon neutral, saving a total of 101.7 t CO2e over the life of the building.
- The following recommendations have also been provided for consideration on future projects where more flexibility exists to change the functionality of the buildings:
  - Increase design life through futureproofing. Further design options that would enable to house to be extended, retrofitted or modified for increased density or an alternative use. For example, allowing a dwelling to be split into two smaller living spaces at a later date by installing the required plumbing under the slab could significantly increase the expected design life of the dwelling by making it more attractive in the future. (not modelled in the design)
  - Increase design life through higher density, increase the density of the building to reduce the embodied emissions. By increasing density, the expected design life of the dwelling would increase. This is due to it becoming less unattractive target for redevelopment than lower density surrounding buildings. Shared walls also mean half the embodied impacts per dwelling for the wall, (not modelled in the design)
  - Better utilisation of materials through increased ability to de-construct. Use materials that can be dis-constructed such as timber / steel frame floors, walls and roof systems in preference to materials that can’t be re-located and re-used (e.g. brick walls). If masonry walls are used, consider using a lime based mortar that enables the bricks or blocks to be cleaned and re-used after the building is demolished (rather than concrete mortar). Not modelled in the design
- Previous to this LCA report, the following lower embodied energy recommendations were made but not progressed due to the project requirements to build with readily accessible and available products and methods:
  - Reduce internal finishes with exposed brick on internal walls will save a total of 3.2 t CO2e over the life of the building.
  - Use of 50% fly ash concrete will save 3.2 t CO2e over the life of the building.
  - Use of recycled bricks represents a saving of 3.7 t CO2e over the life of building.
  - Reused Earth Floors throughout - 10 t CO2e saving (assumed 200mm slab thickness)
  - Straw Bale External Wall Construction - 10 t CO2e saving
  - Timber window frames throughout - 2 t CO2e saving
  - Recycled timber to framed wall elements - 1.3 t CO2e saving
  - Recycled timber to roof structure - 1.2 t CO2e saving

Sensitivity
Estimating impacts to high levels of confidence requires costly resources, and in the case of buildings, is very likely to be overshadowed by the influence of occupant behaviour on operational impacts, or the actual design life (both of which on a case by case basis will deviate significantly from the estimates in the LCA). eTool LCA software aims to be vague right not precisely wrong. The accuracy is sufficient to ensure that informed design decisions can be made by
quantifying and comparing options. The conclusions drawn in this LCA are sensitive to the data sources and assumptions which should be understood carefully to ensure confidence in design decisions. Please contact eTool for clarification on the sensitivity of any conclusions drawn from this report.

List of Major References


Department of Climate Change and Energy, National Greenhouse Account Factors, Australia Government, 2011.


Dynamics of Carbon Stocks in Timber in Australian Residential Housing, The University of Melbourne and NSW Department of Primary Industries, Forest and Wood Products Australia, 2009.

EnergyTools, Think Brick Australia - LCA of Brick Products, Energistics Pty Ltd, 2010.


Inventory of Carbon and Energy (ICE), Sustainable Energy Research Team, Department of Mechanical Engineering, University of Bath, UK, 2008.


NSW Department of Environment and Climate Change, Sustainability in the Commercial Property Sector, 2009

Appendix C – Consent Form, Information Letter and Questionnaire designed for survey

Consider Form

Research Title: Analysis of the performance of a sustainable house including consumer behaviour

Researcher: Jamie Stephen (4th Year Engineering Student)

I have been given information about the analysis of the performance of a sustainable house including consumer behaviour and discussed the research project with Jamie Stephen who is conducting this research as part of a Bachelor’s Degree in Engineering supervised by Dr Martin Anda in the department of Engineering at Murdoch University.

I have had an opportunity to ask Jamie Stephen any questions I may have about the research and my participation. I understand that my participation in this research is voluntary, I am free to refuse to participate and I am free to withdraw from the research at any time. My refusal to participate or withdrawal of consent will not affect my treatment in any way and any answers already provided will be destroyed.

If I have any enquiries about the research, I can contact Jamie Stephen (jamiestephen85@hotmail.com, 0415 860 003) or Dr Martin Anda (m.anda@murdoch.edu.au, 9360 6123) or if I have any concerns or complaints regarding the way the research is or has been conducted, I can contact the Chair of the Human Research Ethics Committee, Murdoch University, A/Professor Tanya McGill (T.Mcgill@murdoch.edu.au, 9360 2798).

By signing below I am indicating my consent to (please tick):
☐ answer question in the survey
☐ have my answers anonymously pooled with others for analysis

I understand that the data collected from my participation will be used for a thesis publication and I consent for it to be used in that manner.

Signed ___________________________ Date …/…/……

Name (please print) ………………………………………………………………………..
Dear Participant,

I invite you to participate in a research study looking at the effects of consumer attitudes and behaviour on household water consumption. This study is part of my Bachelor’s Degree in Environmental Engineering, supervised by Martin Anda at Murdoch University.

**Nature and Purpose of the Study**

It is common practice to look at the effect of efficient appliances on household water consumption. However, many the importance of attitudes and behaviour of consumers is now also recognised as a major contributing factor, which can play a significant role in water consumption.

Therefore the aim of this study is to investigate how consumer attitudes and behaviour affect actual water consumption to find out what proportion of the water savings at Josh’s house (a local sustainable house) can be attributed to the efficient technologies present in the house, and what proportion is attributable to efficient behaviours.

If you consent to take part in this research study, it is important that you understand the purpose of the study and the tasks you will be asked to complete. Please make sure that you ask any questions you may have, and that all your questions have been answered to your satisfaction before you agree to participate.

**What the Study will Involve**

To participate in this study, you must own the home in which you currently reside, and have at least one previous water bill.

If you decide to participate in this study, you will be asked to complete the following:

- Complete 1 questionnaire that asks about your attitude and behaviour towards water consumption.
- To provide the quantity of water used on one previously received water bill.

It is estimated that the questionnaire will take approximately 15 minutes.

It is possible that you may experience some level of anxiety or stress during the session as a result of some of the questions in the questionnaire. You are free to withdraw at anytime during the questionnaire.

**Voluntary Participation and Withdrawal from the Study**

Your participation in this study is entirely voluntary. You may withdraw at any time without discrimination or prejudice. All information is treated as confidential and no names or other details that might identify you will be used in any publication arising from the research. If you withdraw, all information you have provided will be destroyed.

**Benefits of the Study**

It is possible that there may be no direct benefit to you from participation in this study, however upon completion of the questionnaire I will be able to advise you on potential water saving behaviours and technologies that you may be able to adopt in order to reduce your water consumption, should you so desire.
While there is no guarantee that you will personally benefit, the knowledge gained from your participation may help others in the future by providing a better understanding of the effect on consumer attitudes and behaviours on actual water consumption.

Possible Risks
There are no specific risks anticipated with participation in this study. However, if you find that you are becoming anxious as a result of any of the questions in the questionnaire, we ask that you withdraw from this survey immediately.

If you have any questions about this project please feel free to contact either myself, Jamie Stephen on mbi. 0415 860 003 or my supervisor, Dr Martin Anda, on ph9360 6123. My supervisor and I are happy to discuss with you any concerns you may have about this study.

Once we have analysed the information from this study we will mail a summary of our findings. You can expect to receive this feedback in August 2014.

If you are willing to consent to participation in this study, please complete the Consent Form.

Thank you for your assistance with this research project.

Sincerely

Jamie Stephen

This study has been approved by the Murdoch University Human Research Ethics Committee (Approval 2014/104). If you have any reservation or complaint about the ethical conduct of this research, and wish to talk with an independent person, you may contact Murdoch University's Research Ethics Office (Tel. 08 9360 6577 or e-mail ethics@murdoch.edu.au). Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.
QUESTIONNAIRE

In this survey, you will be asked about two methods of conserving water:
1) Engaging in everyday actions to save water around the house and garden
2) Installing water efficient appliances around the house and garden

The following are examples of everyday actions to save water around the house and garden:
- Check and fix leaking taps
- Collect rainwater to use on garden
- Only run dishwasher if it is full
- Have shorter showers
- Use half flush or don’t flush the toilet every time
- Wash cars with minimal water
- Turn off taps when brushing teeth
- Only run the washing machine if it is full
- Use minimal water in the kitchen
- Collect and use grey water on the garden
- Be water-wise in the garden

The following are examples of water efficient appliances that your household may install in order to conserve water:
- Low-flow taps and/or shower heads on all fittings
- Pool cover
- Hose with trigger or timed sprinklers
- Water-wise plants and/or gardens
- Dual-flush toilet
- Shower timer
- Grey water system
- Rainwater tank
- Water-wise washing machine
- Water efficient dishwasher

When answering the questions in this questionnaire please use the following scale to rate your answer:
1. Strongly disagree
2. Disagree
3. Neither
4. Agree
5. Strongly agree
SECTION 1: EVERYDAY ACTIONS

Q1: I think engaging in everyday actions to save water around the house and garden is beneficial:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Q2: I feel a strong personal obligation to save water around the house or garden:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Q3: I am willing to put extra effort into saving water around the house and garden:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Q4: I am confident I could save water around the house and garden if I wanted to:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Q5: In the last six months, how often did you do each of the following:

<table>
<thead>
<tr>
<th></th>
<th>Never</th>
<th>Rarely</th>
<th>Sometimes</th>
<th>Almost always</th>
<th>Always</th>
<th>Not applicable</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Check and fix leaking taps</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>b) Collect rainwater to use on garden</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>c) Only run dishwasher if it is full</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>d) Have shorter showers (4 minutes or less)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>e) Use half flush or don’t flush toilet every time</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>f) Wash cars with less water (i.e. use a bucket or at an efficient car wash)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>g) Only run the washing machine if it is full</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>h) Use minimal water in the kitchen (i.e. cooking, washing up, rinsing)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>i) Collect and use grey water on garden</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>j) Turn off taps when brushing teeth</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>k) Be water-wise in the garden (only water at night, less watering, use a bucket, plant drought-tolerant plants)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>NA</td>
</tr>
</tbody>
</table>


SECTION 2: WATER EFFICIENT APPLIANCES

Q6: I think installing water efficient appliances in the house and garden is beneficial:

1 Strongly Disagree 2 3 4 5 Strongly Agree

Q7: I feel a strong personal obligation to install water efficient appliances around the house and garden:

1 Strongly Disagree 2 3 4 5 Strongly Agree

Q8: I am willing to put extra effort into installing water efficient appliances around the house and garden:

1 Strongly Disagree 2 3 4 5 Strongly Agree

Q9: I am confident I could save water around the house and garden using water efficient appliances if I wanted to:

1 Strongly Disagree 2 3 4 5 Strongly Agree

Q10: Over the next six months, will your household install the following items:

<table>
<thead>
<tr>
<th></th>
<th>Definitely not</th>
<th>May not</th>
<th>Unsure</th>
<th>May</th>
<th>Definitely will</th>
<th>Already Installed</th>
<th>Not applicable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low flow taps and/or shower heads on all fittings</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Al</td>
<td>NA</td>
</tr>
<tr>
<td>Pool cover</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Al</td>
<td>NA</td>
</tr>
<tr>
<td>Hose with trigger or a timed sprinkler</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Al</td>
<td>NA</td>
</tr>
<tr>
<td>Water-wise plants and gardens</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Al</td>
<td>NA</td>
</tr>
<tr>
<td>Dual-flush toilet</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Al</td>
<td>NA</td>
</tr>
<tr>
<td>Shower timer</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Al</td>
<td>NA</td>
</tr>
<tr>
<td>Grey water system</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Al</td>
<td>NA</td>
</tr>
<tr>
<td>Rainwater tank plumbed into the house</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Al</td>
<td>NA</td>
</tr>
<tr>
<td>Rainwater tank <em>not</em> plumbed into the house</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Al</td>
<td>NA</td>
</tr>
<tr>
<td>Water-wise washing machine</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Al</td>
<td>NA</td>
</tr>
<tr>
<td>Water efficient dishwasher</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Al</td>
<td>NA</td>
</tr>
</tbody>
</table>
SECTION 3: BELIEFS

Q11: I consider myself to be well informed about water conservation and the risk of water shortages:

| Strongly Disagree | 1 | 2 | 3 | 4 | 5 | Strongly Agree |

Q12: I believe that everyday actions to save water around the house and garden are effective in reducing the risk of water shortages in my local area:

| Strongly Disagree | 1 | 2 | 3 | 4 | 5 | Strongly Agree |

Q13: I believe that installing water efficient appliances to save water around the house and garden is effective in reducing the risk of water shortages in my local area:

| Strongly Disagree | 1 | 2 | 3 | 4 | 5 | Strongly Agree |

Q14: Water conservation is important to our household:

| Strongly Disagree | 1 | 2 | 3 | 4 | 5 | Strongly Agree |

Q15: Do you think your household is a (please tick one):

- □ High water user
- □ Medium water user
- □ Low water user
- □ Don't know

Q16: On your rates bill you receive information about the average daily water use of your house. Looking at your last rates notice, what was the average daily use?

Average daily use ____________________________________________
Appendix D – Photos of Josh’s House and Monitoring System

Satellite image of the two lots at the Josh’s House site. Josh’s House is Lot 2 (Byrne, 2014).

Original modelled design of the two houses and landscaping (Byrne, 2014).

One of the sensors in place at Josh’s House.
DT 80 data logger in a cupboard in the laundry (Byrne, 2014).

All gutters and downpipes are directed to the rainwater tank (Byrne, 2014).
The 20,000L rainwater tank at Josh's House (Byrne, 2014).

The pump and UV disinfection system for the rainwater tank.
The covered pump and UV disinfection system for the rainwater tank, to protect from weather.

The grey water irrigation drip lines, uncovered (Byrne, 2014).
Grey water system with filter and sensor visible.

Functional landscaping at Josh’s House (Byrne, 2014).
Solar hot water system and 3kW photovoltaic system on the north-facing roof (Byrne, 2014).

Sunlight flooding the solar passive living and dining area (Byrne, 2014).
The local weather station at Josh's House.