LIFE-CYCLE IMPACT OF WATER SUPPLY SYSTEM SELECTION ON TYPICAL NEW ZEALAND HOUSES

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ABSTRACT

Life-cycle studies of houses have concentrated on the physical building, excluding the support systems that are essential for the successful operation of the house, while studies of support systems, such as water supply, usually concentrate on performance improvements and not on the implications of the use of a particular system on the overall residential development. Life-cycle analysis is capable of evaluating competing alternatives based on their environmental performance. This paper examines the impact of water supply systems selection on the environmental performance of individual houses in urban New Zealand using a life-cycle analysis model. The analysis is based on life-cycle energy, environmental impact and cost.

Results suggest that the impact of the water supply system on the total performance of the house is negligible when other operating energy uses such as space and water heating are considered. Nevertheless, rain water harvesting systems supplying a household's total water demand could be used as an environmentally friendlier and cheaper alternative to conventional water supply systems for larger individual houses located in Auckland. For smaller houses, however, continued use of mains water supply systems with reduced consumption is the most environmentally efficient.

Keywords: life-cycle analysis, life-cycle energy, life-cycle cost, embodied energy, rain harvesting, carbon dioxide emissions

1. INTRODUCTION

The life-cycle consideration is vital in evaluating sustainable development activities that continue to provide significant operating as well as maintenance energy and cost savings over long periods. Life-cycle analysis is a framework capable of evaluating competing alternatives based on their life-cycle performance. Although infrastructure systems are essential for successful operation of buildings, integration of infrastructure with buildings is seldom considered in life-cycle studies. However, integration of infrastructure with buildings in life-cycle studies could provide greater opportunities to achieve improved sustainability. Limited building-related life-cycle studies that include certain aspects of infrastructure such as roads and parking facilities [1], waste water treatment [2-4] etc., have recently been conducted. This paper examines the relative performance of alternative water supply systems and the impact of water supply systems selection on the performance of individual houses in urban New Zealand.

According to published data, 62% of the total volume of water supplied by the reticulated supply system in Auckland is currently used in the domestic sector [5]. Any increase in population could also increase the demand for water. It has already been estimated that current daily water use will increase by a further 80,000 m^3 by the year 2022. Wastage of water due to leaks and bursts from a mains water supply network can be significantly reduced by using rain tanks to supply all domestic water needs for individual houses. To satisfy the demand generated by the population increase and the current trend in declining household occupancy, a further 201,000 new dwellings are required in the Auckland region by the year 2021 [6]. Apartments currently comprise 23% of all consents issued for new constructions [7]. However, due to the practical difficulties of collecting sufficient volumes of water and accommodating storage tanks, rain tank systems may not be suitable for medium- and high-density apartment developments and as such those developments will have to continue to rely on reticulated water supply. However, it is reasonable to assume that some of this future demand for housing in the Auckland region will have to be located in new greenfield sites lacking existing water (and other) infrastructure. This paper concentrates on these new developments on greenfield sites. This study investigates the use of rain tanks to satisfy all domestic water needs and to replace mains supply. The resources considered in this instance would be energy, materials and the environment (in terms of CO_2 emissions). Further, the relative significance of the water supply system in the overall performance of individual houses is evaluated by analysing the life cycle resource use for construction, maintenance, replacement and operating requirements over the useful life. The paper is structured as follows. First, the need for the study is established by highlighting the value of the alternative approach in using rain tanks for all domestic needs. The life-cycle analysis undertaken is then described, along with the assumptions used. Results, on relative performance followed by system choice, are presented and conclusions are drawn. Finally, directions for future research are proposed.

1.1 Background

Rain tanks have already been considered in international research for residential developments. However, the main focus has been the reduction of surface water runoff by reducing the volume used from the mains supply incorporating rain tanks to supplement the mains supply [8-10]. This approach leads to a duplication of systems and a higher than normal use of resources.

Although rain water is generally regarded as clean, when collected off roof surfaces especially in urban locations rain water could contain impurities such as dust and other emissions, bird droppings, leaves, etc. Therefore health issues are a concern with regards to the use of rain water for all domestic purposes as has already been highlighted [11]. In the Autonomous House in the UK, all rain water collected is pumped to a slow sand filter before being used inside the house, while cooking and drinking water is in addition filtered using a silver impregnated filter candle [12]. Rain harvesting systems readily available in the market today could be used to screen rain water and to reduce suspended matter. Leaves can be excluded by using leaf mesh on the gutters, and by sending collected water through a leaf guard (gutter head with wire meshing) before entering the tank, which can further exclude any remains. The first few litres of rain water could also be diverted away from the tank each time it rains using a first flush device before any rain water is collected. The volume that needs to be diverted depends on the roof area. It has been shown possible to conform to National Health and Medical Research Council Guidelines (1991) for drinking water in Australia simply by adding a sump with fine mesh to the rain harvesting system detailed above [13]. Further, according to the New Zealand Ministry of Health, of the 300 litres/capita/day used in residential buildings in New Zealand, only the 5 litres/capita/day used for drinking (2 litres), cooking (2 litres) and food preparation (1 litre) needs to be of a safe quality, which could be achieved by boiling water for a minute [14]. Once these measures necessary to achieve safe drinking quality water are in place, life-cycle performance assessment of water supply systems becomes an important decision criterion.

Common materials used for rain tanks in New Zealand are plastic and concrete, with some use of galvanised iron in rural areas. Current average water use in an Auckland house is $387m^3$/annum [15]. An earlier study [16] of alternative water supply systems established that this consumption cannot be sustained with rain tank systems in Auckland. However, studies have already established that the use of simple technical measures such as low-flow shower heads, flow restrictors, front loading washing machines and dual-flush cisterns could reduce water consumption by 50% without any behavioural changes [17]. Therefore the former study [16] considered the life-cycle performance of alternative water supply systems (reticulated supply and rain tank systems with both concrete and plastic tanks of 25 m^3 capacity) over a 100 years period at 50% water consumption scenario. This indicated that the life-cycle performance of plastic rain tank systems in terms of energy and CO_2 emissions is inferior to reticulated supply and concrete tank systems. Further, the plastic rain tank system was found to be more expensive compared with the other options. This paper builds on that previous work by evaluating the relative contribution of water supply system to the total life-cycle performance of typical houses in the Auckland region of New Zealand. Since the volume of water that may be collected depends on the house size, the life-cycle performance of water supply systems are considered for varying house sizes.

There has been a 37% increase in the New Zealand housing stock between 1981 and 2001, with 55% of the current housing stock being built since 1970. The floor area of the average new house in New Zealand has also increased by 25% between 1970 and 2000 [7]. The Building Industry Advisory Council (BIAC) Standard House repeatedly used for research to represent an average house in New Zealand has a floor area of 94 m^2 and therefore would now represent older and smaller houses in New Zealand. Details of current New Zealand housing stock and the volume of rain water that may be collected if located in the Auckland region are shown in Table 1 below. Roof eaves of New Zealand houses tend to vary from non-existent to over a half a metre, and the volumes indicated were calculated based purely on the floor area with no allowance for roof eaves, which could add a further 3-14% to the roof area and hence to the volume of water collected. The rain water volume that can be collected from the BIAC house with 94-m^2 floor area is only 27% (105 m^3) of the current water use. Since technical measures can only reduce the water use by 50%, behavioural changes would also be necessary if rain tanks alone are to be used to supply the total domestic water demand in smaller New Zealand houses. However, as argued by Burkhard et al. [18], alternative systems that require behavioural changes are not embraced by society without resistance, although one could also argue that the domestic water use varies widely [19].

Current NZ housing stock and capacity to collect rain water			
Year of construction	**% of the total stock**	**Average floor area (m^2)**	**#Volume of water that may be collected (m^3/house)**
BIAC	-	94	105
1970s	18.7%	146	163
1980s	13%	149	166
1990s	13.2%	173	193
Since 2000	10.3%	194	217

assuming houses are located in Auckland

Table 1. Details of current housing stock in New Zealand

(Based on: Centre for Housing Research, *Changes in the Structure of the New Zealand Housing Market*, 2004)

2. METHODOLOGY

2.1 Water Supply Systems

Table 1 suggests that only the post-2000 house is capable of collecting more than the 193 m^3 of water regarded as necessary for all water demands in an average New Zealand house that has implemented technical measures to reduce water consumption. The water consumption would vary in all houses and would be similar to the volume collected, but to match the demand to the amount of water collected would require some behavioural changes by the occupants of older and smaller houses. The life-cycle energy use by the water supply systems can be divided into the embodied energy of the system (construction and maintenance) and the operating energy (for pumping water from the rain tank or energy used for the reticulated system operation). For rain tank systems, the embodied energy would be similar for all houses, because the basic system size is usually not dependent on house size, while operating energy would depend on the volume of water to be pumped. However, both embodied and operating energy use will be different for all houses, depending on volume of water used.

In order to investigate the relative performance of water supply systems and the impact of the system selection on the life-cycle performance, houses with 4 different floor areas (94, 146, 173 and 194 square meters) which would represent more recent and larger houses were considered. The 1980s house was omitted from the analysis because it was similar to the 1970s house in terms of floor area. The present study compares reticulated supply to a concrete rain tank system (capacity 25 m^3) with a level of consumption comparable with the volume of water available with different house sizes and therefore roof areas. In terms of the rain tank systems, the difference between the 4 houses would be the volume of water collected from the roof and the electricity usage for pumping different water volumes. Life-cycle energy, CO_2 emissions and cost were established for the 4 houses with alternative water supply systems.

Although the use of life-cycle analysis can facilitate the selection of the water supply system with the least environmental impact, decisions by individual home owners are governed by the cost implications of such choices. Australian research on the use of rain tanks and other low-impact systems for residential developments has identified the perceived higher cost as an impediment to the wider up-take of these systems [10]. Hence, both systems were analysed for life-cycle cost for the four house sizes. Current electricity prices charged by Mercury Energy for residential customers are divided into 2 components – line charges and unit charges. Based on the standard all inclusive price plan, the unit charge is 14.93 cents/kWh and the line charge is 78.92 cents/day [20]. Line charges common to all electricity uses in the house have been disregarded. GST is also excluded from all costs. Life-cycle cost was calculated in real cost terms (inflation excluded) using the current prices for water (by Metrowater in Auckland), electricity (Mercury Energy in Auckland) and materials (rain tanks, rain harvesting systems, water pumps, etc.) at a discount rate of 5% and constant prices. Life-cycle cost thus calculated represents the present value of the total amount that would be required to be set aside today to maintain water supply to the average house in Auckland over the analysis period.

2.2 Overall Performance of the Average House

2.2.1 Embodied Energy

In addition to influencing the volume of rain water that may be collected off the roof, floor area also influences the energy embodied in the building and the space heating energy requirement. Construction materials and methods used in older houses are different from those used currently (e.g., use of timber floor boards instead of particle boards, timber framed windows instead of aluminium framed windows, etc.). Since this analysis is considering the impacts on future developments it has been assumed that all houses are of the common light-weight timber framed construction used in New Zealand. The specifications adopted are as follows:

- particle board floor on raised softwood framing, double-sided foil insulation drooped over floor frame as insulation;
- softwood framed walls with 94 mm of glass fibre insulation within framework, plasterboard internal lining with paint finish, fibre cement external cladding;
- pitched softwood truss roof with corrugated metal cladding, flat ceiling lined with plasterboard, roof-ceiling space insulated with 95 mm glass fibre, and
- aluminium framed windows with single clear glazing.

Due to the large glazing areas used, the generic BIAC house is susceptible to overheating in summer and high heat loss during winter. Hence, in keeping with the requirements of NZS 4218:1996 [21], the window areas of larger houses have been limited to 30% of the external wall area. The aspect ratio of the BIAC house has been retained for larger houses for a meaningful comparison. The physical properties of the common house were assumed to be as shown in Table 2 to facilitate the analysis of embodied energy of the houses. It was also assumed that the nature of electrical and plumbing installations would be similar for all houses although wiring and roof guttering were increased accordingly.

Physical properties of common NZ house					
	Floor area (m^2)	Overall dimensions (m)	External wall area (m^2)	Internal wall area (m^2)	Window area (m^2)
BIAC house	94	6.7 x 14	93	211	30
1970s house	146	8.6 x 17	115	264	35
1990s house	173	9 x 19.2	127	286	38
2000 house	194	9.7 x 20	133	304	40

Table 2. Physical properties of common New Zealand house

2.2.2 Space Heating Energy

Space heating energy requirement, which depend partly on the external temperatures, also varies with the heating regime, the internal temperature to be maintained, and the orientation of the building. Two heating regimes were modelled using Annual Loss Factor (ALF3) thermal simulation software [22] to represent

- families with young children and those who work from home – all day heating (7 to 23 hrs), and
- families with both adults working away from home – morning and evening heating (7 to 9 and 17 to 23 hrs).

An internal temperature of 18^oC was selected in keeping with the World Health Organisation recommendations. It is reasonable to assume that the main living areas would have a north orientation if site conditions are conducive, and therefore houses were modelled accordingly.

2.2.3 Water Heating Energy

Although electricity use rises in the winter part of the year due to the use of energy for space heating this is partly attributable to the hot water system, given the lower temperature of incoming cold water. Research suggests more electricity is used in an Auckland house for water heating (28%) than for space heating (17%) [23]. Although research [24-25] has identified that household composition (such as the number of younger children, the number of female teenagers) affects the amount of water used, these factors have not been considered in this study due to practical difficulties. The hot water system consumes energy to heat water and maintain the storage temperature (due to standing losses) and to replace the hot water that has been used (consumed energy). A considerable amount of heat is lost through the cylinder wall and distribution pipes. The higher the difference between the temperature of the hot water and the surrounding air the greater the losses. Standing losses from the typical hot water system have been estimated to be about 27-34% of the total energy consumption [23]. However, these standing losses predominantly depend on the physical nature of the water heating system such as the cylinder size, insulation, location, etc., and could therefore be expected to be similar for all houses irrespective of the volume of water used. On average, energy use for the hot water system is estimated to be 4000 kWh/annum, of which 1050 kWh/annum is for the standing losses [26]. Previous research [26] estimated the actual hot water use in an average house to be 73 m^3/year, which is only 19% of the current water use. If estimated based on the above energy use data for the hot water system, the actual volume of hot water would be only 56 m^3/year, which is only 14% of the total water use. Although the standing losses that are a result of the physical nature of the hot water system would also depend on the volume and frequency of hot water use, and the actual temperature of hot water in the cylinder, which may be affected by a reduction in total water use, these would have to be established experimentally under various reduced water usage scenarios. Since the volume of water that can be collected using rain tanks in all houses, except those built after the year 2000, is less than 50% of the current water use, it would be reasonable to assume that all houses would use the maximum volume of water that is collected and therefore the energy use for hot water would also vary among all the houses as total volume collected varied. It is assumed here that the energy use for hot water would be proportionate to the total volume of water used in the house.

Operating requirements such as furniture, lighting, cooking and appliances would be similar for all houses and therefore were not included.

3. RESULTS AND DISCUSSION

3.1 Water Supply System

Life-cycle energy use by the two water supply systems (reticulated and concrete rain tank) over the useful life of the houses was calculated for the four houses and is as shown in Fig. 1. In terms of the life-cycle energy contribution, reticulated supply is 30% lower than rain harvesting systems with concrete tanks for the smaller BIAC house but similar for the 1970s house. However, for the larger 1990s and 2000 houses, rain harvesting with concrete tank is 13% and 18% respectively lower than reticulated supply in terms of life-cycle energy.

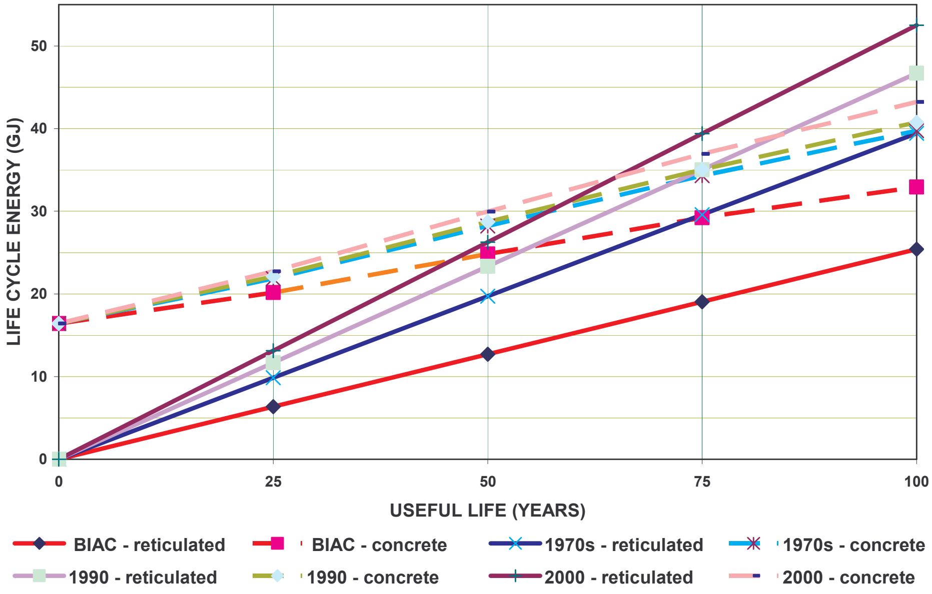

Fig 1. Life-cycle energy of alternative water supply systems

Life-cycle carbon dioxide emissions of water supply systems for the four houses follow a pattern similar to life-cycle energy. Carbon dioxide emissions due to reticulated supply are 55% lower than from rain harvesting with concrete tank for the BIAC house, but are only slightly better, with only 2% lower emissions, for the 1970s house. For the larger 1990s and 2000 houses that use a higher volume of water, a rain harvesting system with a concrete rain tank is 12% and 21% respectively lower in emissions compared with a reticulated supply. Life-cycle carbon dioxide emissions for four houses with reticulated and concrete rain tank systems are as shown in Fig. 2. In New Zealand, only 26% of electricity is currently produced from thermal sources such as coal, gas and oil, with 64% of electricity being produced using hydro-power [27]. Energy-related environmental impacts therefore tend to be very low in New Zealand compared with most countries. However, almost all the cheap and easy hydroelectric sites have already been developed, and it appears all new power stations are thermal, and future demand for electricity will therefore lead to higher emissions than the current values used for this analysis.

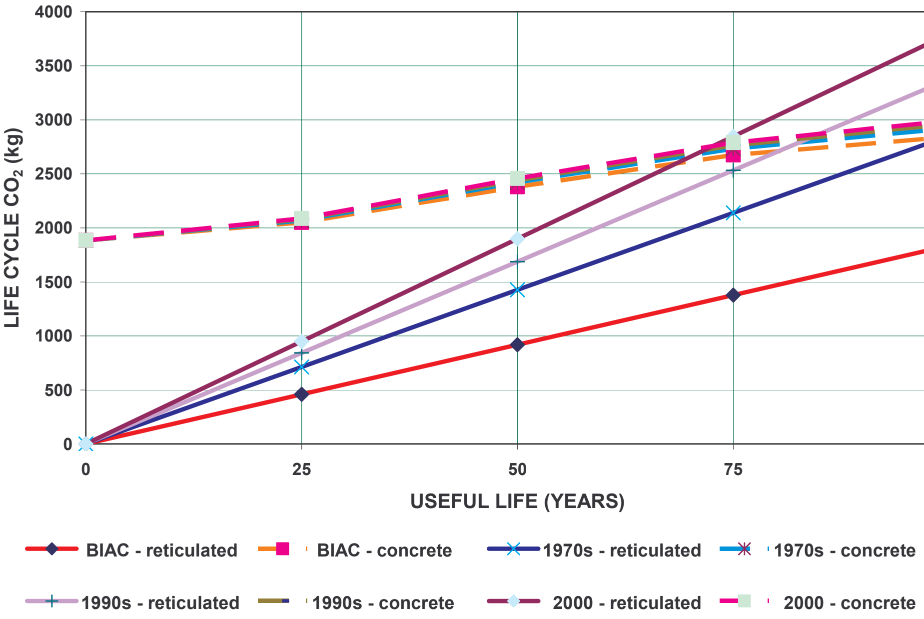

Fig 2. Life-cycle CO_2 emissions of alternative water supply systems

The life-cycle cost of water supply systems for the four houses are as shown in Fig. 3. In terms of initial cost the reticulated system is 61% cheaper than the concrete rain tank system. However, when annual charges for the reticulated supply system and the cost of water are considered over the lifetime, the concrete rain tank system is 8%, 25%, 32% and 36% respectively cheaper for the BIAC, 1970s, 1990s and 2000 houses than using a reticulated supply at a level of consumption comparable with that of the rain tank system. Cost of the two supply systems becomes similar by the end of the 7th, 8th, 10th and 15th years respectively for the BIAC, 1970s, 1990s and 2000 houses. However, being a pure economic evaluation these costs represent only the real cost to the home owner. Those external costs due to development activities (such as the loss of land due to a particular development, traffic congestion, noise pollution, etc.) that are generally borne by society have not been included in the above costs.

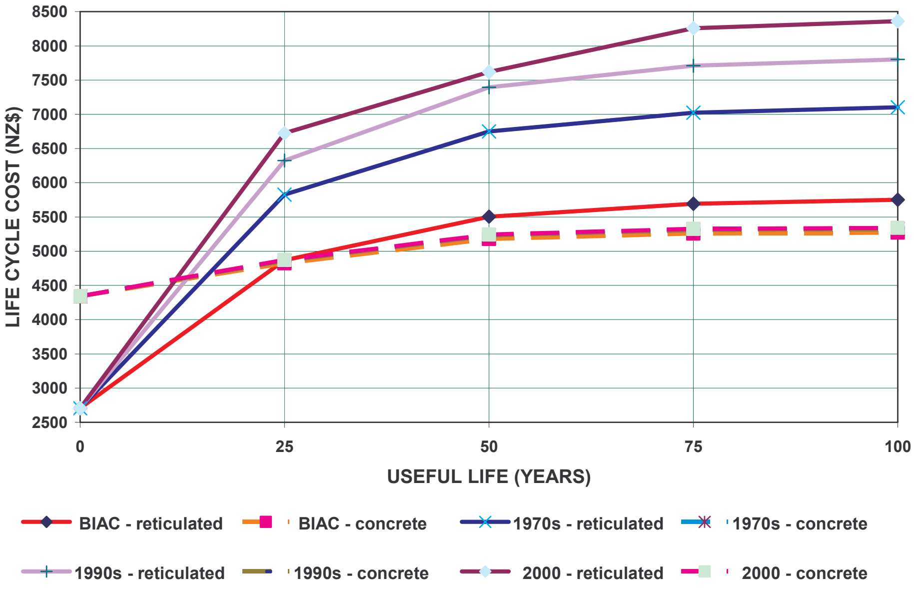

Fig 3. Life-cycle cost of alternative water supply systems

The above results suggest that for individual houses with a floor area of 146 m^2 or less the use of a reticulated supply with a level of consumption similar to what could be collected off the roof would be the best option in terms of environmental performance. For larger houses the use of a concrete rain tank system would be better in terms of both life-cycle energy and CO_2 emissions. However, irrespective of the volume of water used, rain tank systems are cheaper than the reticulated supply with annual charges.

3.2 Water Supply System in Overall Performance of Average House

The rest of this paper examines the impact of the use of different water supply systems on the overall performance of average New Zealand houses in Auckland under two usage patterns – working from home and working away from home. Although it could be argued that the embodied energy of houses would remain constant irrespective of the usage pattern, operating energy, especially the space heating energy requirement, would vary. Although water use could also be expected to rise with the working from home scenario compared with working away from home, this has been neglected. Life-cycle energy composition by end use can be summarised as shown in Table 3. This shows that the life-cycle energy use by the water supply system is only 1% of the total life-cycle energy use for both space heating schedules employed and the water supply system selected. (Even with the plastic rain tank system, which was not included in the study and has the highest life-cycle energy use, the life-cycle energy use by the water supply system is only 3-4% of the total life-cycle energy of the house.) In comparison, space heating energy use is 39-45% of the total life-cycle energy with the working away from home scenario and 44-48% with the working from home scenario for the various house sizes considered. Hence the impact of the water supply system on the life-cycle performance of the New Zealand house is negligible in terms of life-cycle energy.

Life-cycle energy composition by end use				
	BIAC	**1970s**	**1990s**	**2000**
House construction	15-17%	14-15%	16-17%	16-17%
Space heating	39-44%	43-47%	44-47%	44-48%
Hot water	40-43%	37-40%	36-38%	35-37%
Water supply	1%	1%	1%	1%

Table 3. Life-cycle energy composition of a common New Zealand house by end use (with the two space heating regimes and water supply systems)

Life-cycle CO_2 emissions composition by end use is summarised in Table 4 below. According to this, life-cycle CO_2 emissions caused by the construction and maintenance of the house contribute 39-61% of emissions, while the CO_2 emissions due to space heating and water heating contribute 18-34% and 18-26% of the total respectively, depending on the space heating schedule used and the water supply system selected. However, the CO_2 contribution from the water supply system is insignificant, at a maximum of 5% of the total emissions. The impact of the water supply system in the life-cycle performance of New Zealand house is therefore negligible in terms of life-cycle CO_2 emissions.

Life-cycle CO_2 composition by end use				
	BIAC	**1970s**	**1990s**	**2000**
House construction	57-61%	56-60%	39-43%	39-43%
Space heating	18-21%	20-23%	29-33%	29-34%
Hot water	19-20%	18-19%	24-26%	24-26%
Water supply	0.2-3%	0.3-4%	0.4 -5%	0.4 -5%

Table 4. Life-cycle CO_2 composition of common New Zealand house by end use (with the two space heating regimes and water supply systems)

Life-cycle cost composition of the 4 houses by the end-use category is shown in Table 5. The use of discounted cash flows over the life-cycle for evaluation of commodities such as cars, computers, etc., is a well-established economic practice. However, as has already been highlighted [28-30], when applied to buildings that have a very long life time compared with other commodities, these evaluations tend to focus on the initial cost of the building and operating and maintenance requirements tend to become insignificant. The life-cycle cost composition of this analysis confirms the views expressed in those studies as the initial construction cost is the single most dominant component, contributing 81-85% of the life-cycle cost. The life-cycle cost of water supply systems is only 4-6% depending on the system and the space heating schedule selected.

Life-cycle cost composition by end use				
	BIAC	**1970s**	**1990s**	**2000**
House construction	81-84%	82-84%	82-85%	82-85%
Space heating	5-6%	6-7%	6-7%	6-7%
Hot water	6%	5%	5%	5%
Water supply	5-7%	4-6%	4-6%	4-5%

Table 5. Life-cycle cost of common New Zealand house by end use category (with the two space heating regimes and water supply systems)

The above analysis suggests that in energy, carbon emissions and cost terms the impact of the water supply system is insignificant in the total performance of the house. The above analysis did not consider the other operating energy uses such as lighting, cooking and appliance use in the house, which could further reduce the relative impact of the water supply system. Results suggest it may be more beneficial for individual houses to reduce the space heating and water heating energy uses in order to the improve the environmental performance.

4. CONCLUSIONS

The current level of water consumption cannot be sustained with rain tanks in Auckland. Reducing the consumption by at least 50% through employing technical measures could improve the life-cycle performance of residential water supply in New Zealand. Once the consumption is reduced to a level that can be supplied by a rain tank for that particular house, the use of a rain harvesting system with a concrete rain tank would be the cheapest option irrespective of the house size. Depending on consumption (house size), savings could be up to 40% of the life-cycle cost of continued use of a reticulated supply.

Rain harvesting systems may not be practical in current medium-density developments due to lack of site area. However, for smaller houses with a floor area of up to 150 m^2, a 50% reduction in the current water consumption alone could be sufficient to gain life-cycle performance similar to or better than the use of rain harvesting with a concrete tank. For new developments with larger houses if sufficient land area is available, use of rain harvesting systems with a concrete rain tank could provide a cheaper service with less life-cycle impact.

However, the impact of water supply system is negligible in the total performance of the houses. For a home owner with limited resources it may therefore be more worthwhile to invest in better insulation to reduce the space heating and water heating energy required than in a rain harvesting system (based purely on environmental performance).

5. FURTHER RESEARCH

This study concentrated on individual houses in Auckland. However, the number of apartments in new constructions in Auckland is on the rise. These apartments would have to rely on the mains water supply. Research is necessary to establish environmental implications of water supply to such medium- and high-density developments.

6. ACKNOWLEDGEMENTS

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