An energy-autonomous home in Melbourne – myth or reality?

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Abstract: Energy-autonomous buildings are possible. Completely energy self-sufficient houses can be found, for example, in Europe. If it is possible to cover the entire energy demand of a household from only renewable energy generated on site in a central European climate, what is required in a temperate climate, typical of southern Australia? This paper describes an investigation to broadly assess the technical, practical and financial feasibility of energy-autonomy for a hypothetical suburban house in Melbourne, Victoria. The findings firstly demonstrate the importance of reducing energy demand by using passive solar building strategies and energy efficient appliances to reduce demand to a reasonable level. The paper then discusses four scenarios and combinations of technologies to meet this reduced demand. The three scenarios which give energy autonomy increase the capital cost of a typical house by between 15% and 33%, and there would be insufficient roof area to accommodate the solar technologies required in two of the scenarios investigated. It is therefore concluded that while the goal of energy autonomy is technically feasible, it is not likely to be financially or practically acceptable. A fourth scenario of an energy-exporting house was also investigated and is shown to be a much more attractive option.

Keywords: *Energy autonomy, Housing, Melbourne, Conservation, Solar Technologies*

1. Introduction

Globally there is a long tradition in energy-autonomous housing. Examples include the Vale home built in 1974 [1] and more recently, the Solar House at Freiburg built in 1992 [2]. If energy-autonomous buildings can be realized in Europe, what does it take for residential housing in the temperate climate of southern Australia to be energy-autonomous? This paper explores the potential for an energy-autonomous home in the suburbs of Melbourne. The purpose is to broadly assess the available renewable energy (RE) technologies in terms of their likely cost and physical requirements in order to determine whether energy-autonomy is feasible and worthwhile. The current energy consumption of a hypothetical household has been analysed. The assumptions made to reduce this demand using accepted conservation strategies are then described. Various approaches to meet the remaining energy demand from renewable sources have then been assessed.

2. Residential energy consumption in Victoria

Residential energy consumption can be divided into five end-use groups (Fig. 1). Space heating accounts for 44.3 GJ per household per year or 58% of the total energy demand. Electrical appliances and water heaters are the next two major energy consumers, accounting for 20% and 18% of usage respectively. Energy used for cooking and space cooling is only 3% and 1% respectively, despite the large increase in the penetration of air conditioning since 1990 [3].

3. Energy conservation

Reducing the demand for energy for heating and cooling through energy conservation measures is crucial for an energy-autonomous building. Melbourne has a mild, temperate climate with cool winters and mean minimum temperatures of approximately 7° C. The summers are mild-to-hot with mean maximum temperatures of approximately 24°C from December until February. Peak temperatures, however, can exceed 40°C on occasions. The average daily horizontal solar radiation levels in winter and summer are 2.0 and 6.4 kWh m^{-2} respectively. Proper passive design is essential to moderate internal temperatures within a dwelling to minimise the need for conditioning. In this study, it has been assumed that accepted passive design practices in terms of: house orientation and aspect ratio; magnitude of north-facing glazing; thermal mass and insulation; living room and bedroom location; provision for cross ventilation; summer shading; and reduced infiltration have all been followed. Minimum energy performance requirements for new homes in Victoria currently require an energy rating of 5-stars. This rating equates to using 165 $MJ.m^{-2}$ annually for heating and cooling the home. However, sections of the building industry are already demonstrating that much more efficient homes can be constructed. One commercial builder of mass housing has unveiled a 9-star home, which has a predicted energy consumption of 21.9 $MJ.m^{-2}$. This practice should mean that the heating and cooling demand can be reduced substantially. In this study, it has been assumed that heating demand can be reduced by almost 90% and that cooling can be achieved without air conditioning. For a 220 m^2 home, the energy consumption will therefore be 4818 MJ per annum (1338 kWh).

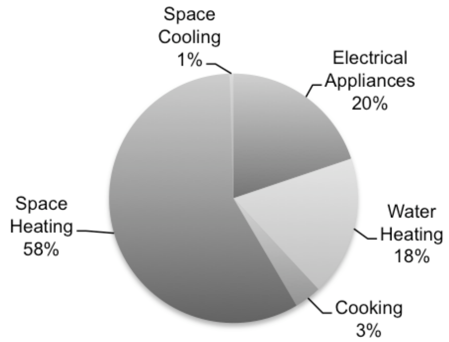

Fig. 1. Residential energy consumption by end use in Victoria (source: adapted from [3])

The average electricity demand of Victorian households in 2008 was 5,824 kWh per year or 16 kWh per day [3]. The electricity consumption of several families (three or four persons), who have made a conscious decision to reduce their energy use, shows that a daily use of 5 kWh is easily achievable without abandoning a modern and comfortable lifestyle [4][5]. Typical strategies to achieve this reduction include: choosing energy efficient appliances; reducing the size of the appliances e.g. the refrigerator to be appropriate to the demand; eliminating standby energy consumption (alone equal to about 10% of the total electricity use); and installing more efficient lighting. According to [6], most homes could reduce their energy use for lighting by 50 per cent or more by using more efficient technologies. In this study, it has been assumed that most or all of these strategies have been used to reduce annual electricity requirements to 1825 kWh i.e. 5 kWh per day.

In Victoria, 74% of household uses a gas cook top and 60% use an electric oven [3]. In an energy-autonomous home powered by RE, gas would not be used. The production of gas from biomass is an unrealistic proposition for a normal suburban household and therefore it has been assumed that electricity will be used for cooking using a combination of electric and microwave ovens, and an induction cook top. An induction cook top is about twice as efficient as a gas cook top [7]. In this study, a modest 5% reduction in energy required for cooking has been assumed because of the uncertainty of the usage patterns of the three cooking technologies to be employed.

The daily hot water usage of an average Australian household is about 193 litres i.e. 76 litres per person [8]; 57% of the hot water is used for showering, 11% for clothes washing and 32% for washing dishes and general household cleaning. High efficiency shower heads can reduce water usage in the shower to 7 litres per minute. Cold water clothes washing can reduce this hot water requirement by at least half. Although improvements in hot water system efficiency could produce further savings in the hot water energy use, this study has assumed that energy consumption for hot water will be achieved by a reduction in hot water usage alone and this will cut the demand down to 50 litres per day per person. Table 2 shows a summary of the current average and reduced annual energy demand for various tasks for a Victorian household.

Table 2: Current and reduced annual energy demand for a Victorian household [3]

	Average household consumption (kWh)	Reduced demand (kWh)
Electrical appliances	4,207	1,825
Water heating	3,851	2,460
Cooking	740	700
Space heating	12,292	1,338
Space cooling	109	0
Total	21,199	6,323

4. Renewable energy technologies

A wide range of technologies are available to harness RE sources. These technologies include solar photovoltaic and thermal systems, hydro, wave or tidal energy systems, wind turbines, biomass burners and digesters, and heat pumps. However, many of these systems are unsuitable either for a single residential dwelling or the RE sources are unavailable in an urban location. Micro-hydro, wave and tidal systems obviously cannot be employed in an urban area like Melbourne. Although wind turbine systems have been developed for rooftop installation in urban areas, wind energy technology is considered unsuitable for Melbourne [9].

Biomass burners in the form of woodstoves are currently used to heat Melbourne homes but their popularity is declining in preference to natural gas. It is predicted that residential energy supplied by wood will decline from 21% in 1990 to 8% by 2020 [3]. In Europe, high efficiency stoves burning pellets made from wood waste are used on a wide scale and encouraged. Although pellet stoves are still relatively new in Australia, pellets from plantation forests are set to become easily available in coming years in Australia. Whether pellet-burning stoves will reverse the preference for gas space heating is uncertain and therefore this technology is not considered in this study. Individual biogas digesters are also not considered because of the need for a reliable supply of feedstock, which is unrealistic for a suburban residence. Solar (electric and thermal) systems and heat pumps using geothermal energy are therefore considered to be the most suitable RE technologies for an energy-autonomous house in a Melbourne suburb and are discussed in more detail below.

4.1. Space heating

There two options for solar heating systems. One system is water-based i.e. hydronic, using radiators or coils in a concrete slab. A system capable of heating a 232 m^2 house would need eight 12-tube evacuated collectors and a 1200 litre storage tank [10]. The cost of the solar components of a hydronic system is estimated to be approximately A$19,000. However, the system would also provide domestic hot water, which would therefore reduce the cost by about A$5,000. The other system is air-based and would consist of a solar air heater, fan and thermal storage. In the 1970s and 1980s, rockbeds or piles were the preferred thermal storage medium [11]. However, solar air heating systems have declined in popularity and few systems have been installed in recent times and were therefore not considered in this study.

A ground-source heat pump uses the year-round relatively-constant temperature of the earth at 2-3 m below the surface. In Melbourne, this is approximately 15°C. A heat pump uses the energy in the ground to heat the house in winter. In summer, the process can be reversed for cooling by transferring the heat from the building to the ground, using it as a heat sink. In the case of a well-designed house, cooling should not be required. The pipe heat exchanger system, containing water or refrigerant, can be installed either vertically or horizontally. Vertical pipes require boreholes of 30 to 120 metre in depth. A horizontal system requires more space, but it is cheaper to install the pipes at depths of 1-2 m. In addition to space conditioning, ground-source heat pumps can also be used for hot water production. Their main disadvantage is the higher first cost for the excavation work compared to conventional HVAC technologies. In this study, it is assumed that the pipe heat exchanger is installed vertically because of the space restriction of a small urban garden and that the installed price is approximately twice the price of the heat pump alone [12].

4.2. Hot water production

A 30-tube evacuated tube system with a 315 litre storage tank and electric booster has a recommended retail price of approximately A$6500 [13]. In Melbourne, a correctly-sized domestic solar water heating system is generally estimated to contribute about 60-65% of a household's hot water demand. In order to achieve a higher solar fraction and therefore greater energy autonomy, a larger area would be required.

4.3. Electricity generation and storage

Depending on the type of RE system, the electricity generation will vary depending on the daily and seasonal conditions. Compared to a grid-interactive system which uses the main electricity grid as backup, a stand-alone power supply has to provide the entire energy demand either from the generation system directly or from a storage system. This means that the system has to be larger to meet peak loads, and therefore will be oversized at other times. Stand-alone photovoltaic systems in particular require energy storage to enable the energy generated during the sunshine hours to be available for later use. The most common storage system in Australia for stand-alone systems is a large capacity battery bank.

Fuel cells, like batteries, are electro-chemical power sources but, unlike batteries which store energy, fuel cells transform energy, the primary fuel source being hydrogen. Hydrogen can be produced from water by electrolysis with low emissions, if the electricity used for the process is generated by a RE technology such as a photovoltaic array or wind turbine. Such a system could provide electricity on demand and therefore offers the potential to overcome the intermittence of RE sources. The system will require an RE electricity supply, an electrolyser, compressor, purification system, storage cylinders and a fuel cell. The feasibility of a similar system in Australia has been investigated [14] and although the load requirement was ten times greater, some of their findings are relevant to this study. The PV system was the least cost of any combination investigated, and the electrolyser represented about half of the system costs, which was over A$300,000. One manufacturer has sold its first 4 kW RE fuel cell systems and the price of these is approximately A$57,000 [15].

5. Methodology

The various RE technologies considered have been sized and their cost estimated using on-line calculators. To simplify sizing, various assumptions have been made. The energy demand for water heating, cooking and general electricity is assumed to be independent of ambient conditions. Because of the solar passive design features and energy conservation measures, space heating is required now only in the three main winter months i.e. June, July and August. Energy demand is assumed to be equally spread across these three months. Fig. 2 shows the energy demand for the proposed autonomous house throughout the year.

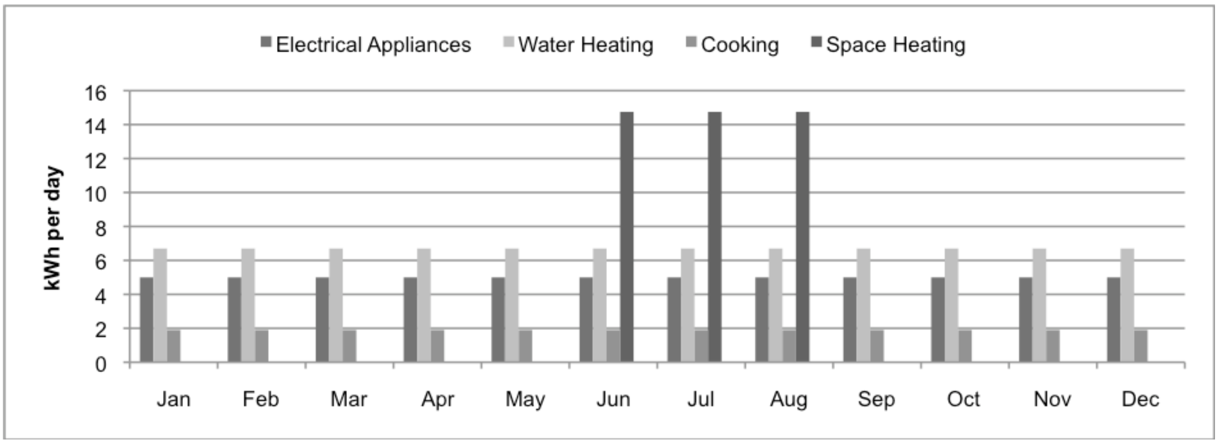

Fig. 2: Daily energy demand (kWh) throughout the year

6. Scenarios

Using different combinations of RE systems, three scenarios to provide the required energy to the autonomous house have been analysed. A fourth scenario using RE technologies in combination with conventional energy systems has also been included for comparison (Table 3). In each case, the house is a detached dwelling with a floor area of 220 m^2 and is occupied by three people. The assumed energy requirements for space heating, hot water and cooking are the 'reduced demands' shown in Table 2 and, depending on the technologies, the demand for electricity will increase above the requirements just for electrical appliances. In Scenario 1, 2525 kWh is required and spread evenly throughout the year. In Scenario 2, an additional 14.9 kWh per day are required in the winter months from the fuel cell. In Scenario 3, the heat pump will require electricity to provide hot water for both washing and space heating. Operating continuously in the winter months, it will therefore require an additional 5.3 kWh per day, assuming a COP of 4. In Scenario 4, only 1825 kWh is required because natural gas is used for cooking.

7. Results and discussion

In Scenario 1, a 17 m^2 evacuated tube array would provide both the space heating and water heating demand, although the system will be greatly oversized for the non-winter months. The photovoltaic system is sized to provide sufficient energy for the daily use in the winter months. A 6.6 kW system with a 1515 Ah battery bank to provide five days of backup is required to provide the electricity for cooking and appliance use [16].

Table 3: Scenarios of RE systems for energy-autonomous and grid-connected houses

End use	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Space Heating	Solar hot water	Hydrogen fuel cell	Ground source heat pump	Solar hot water
Hot Water	Solar hot water	Solar hot water + fuel cell waste heat	Ground source heat pump	Solar hot water + gas booster
Cooking	Photovoltaics	Fuel cell - cooktop Photovoltaics - oven	Photovoltaics	Natural gas
Appliances	Photovoltaics	Photovoltaics	Photovoltaics	Photovoltaics
Energy Storage	Batteries	Hydrogen in storage cylinders	Batteries	Grid-connected

In Scenario 2 the output from the photovoltaic system can be used both directly and indirectly to meet the various energy demands. Electrical appliance use and oven cooking can be met directly. The heating system and the cook top use the PV electricity indirectly in form of electrolysis-produced hydrogen. For space heating the hydrogen is fed to a fuel cell. The cook top is powered by hydrogen gas. Assuming a combined efficiency of 0.74 for the electrolyzer and purifier [14] and a fuel cell hydrogen-electricity conversion efficiency of 0.5, Scenario 2 has an annual electricity demand of 6181 kWh. However, the PV array size required is smaller than Scenario 1. If the electricity generated from the solar panels is insufficient in the winter months, the household can draw from the excess hydrogen energy stored over the summer, thus obviating the need for battery storage and an overly-large PV array size designed to produce the daily requirements in winter. The 4.2 kW system requires an area of approximately 34 m^2 [16][17]. The solar thermal system in this scenario provides 70 per cent of the hot water demand. It consists of a collector area of 5 m^2 with evacuated tubes and a storage tank of 315 litres. When the solar hot water production is insufficient, the waste heat from the fuel cell can be used as a back-up system.

In Scenario 3, a 2.1 kW ground-source heat pump (A$12,000 installed) provides the household with domestic hot water and space heating; a total of 21.28 kWh per day during the winter months. Assuming a COP of 4, this means that 5.32 kWh per day must be generated by the PV array in addition to that required to provide energy for the appliances and cooking. An 11.4 kW system is therefore required. In Scenario 4, the space heating demand is covered by a solar thermal heating system, as in Scenario 1. The photovoltaic system is sized to cover the annual electricity demand, rather than the daily load. A 1.5 kW solar system would generate 2,132 kWh over the year providing an excess of 307 kWh [16]. Natural gas is used for cooking and also to back up the solar hot water system with a solar fraction of 0.65, thus using another 1,561 kWh in total. A 2.5 kW photovoltaic system with an annual output of 3,553 kWh would make the household a net energy-exporter.

8. Feasibility Assessment

Table 4 shows the estimated area requirements and cost for each scenario. The median price of a house in Melbourne in mid-2010 was approximately A$560,000 and a typical house of the size assumed would have a north-facing roof of approximately 50 m^2. In terms of the physical feasibility, Scenarios 1 and 3 require a larger roof area than is available and are therefore not practical unless alternative unobstructed north-facing areas are available. The data in Table 4 also indicates that a fully energy-autonomous house would add between 15% and 33 % to the median price (Scenarios 1-3). However, a net-energy exporting house would only increase the price by 6%. It is acknowledged that the solar system costs are from one supplier only and lower prices may be available. In addition, the costs used do not include government rebates, which would also reduce the price, but only by approximately 10%. Reducing the number of days of battery storage would also reduce capital costs. The purpose of this exercise, however, is to achieve an order-of-magnitude assessment rather than detailed costing.

Table 4: Additional costs and roof area requirements for an energy-autonomous house

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Area (m^2)	SHD/HWS - 17	HWS - 5	PV (11.4 kW) - 88	SHD/HWS - 17
	PV (6.6kW) - 48	PV (4.5 kW) - 34		PV (2.5kW) - 19
	Total = ~ 65	Total = ~ 39	Total = ~ 88	Total ~ 36
Cost (A$k)	SHD/HWS ~ 19	HWS ~ 6.5	HP ~ 12	SHD/HWS ~ 19
	PV(6.6kW) ~ 100	PV(4.5kW) ~ 22	PV(11.4kW) ~ 174	PV(2.5kW) ~ 15
		H_2 ~ 57+		
	Total = ~119	Total = ~86	Total = ~186	Total = ~ 34

9. Conclusions

The purpose of this study was to broadly assess the technical, practical and financial feasibility of an energy-autonomous house in Melbourne. It is concluded that the energy-autonomous home in Melbourne is technically possible. With reduced demand, RE technologies are capable of providing a household's complete energy needs, but energy autonomy can only be achieved by installing over-sized systems, the output from which is not used much of the time. This means that very large and expensive systems are required, which are likely to be unacceptable to most homeowners. It is therefore concluded that the goal of energy-autonomy in a suburban Melbourne house is currently not worth pursuing. The alternative option of a low-energy house, which exports electricity produced from renewable sources to the grid offers many benefits in comparison to the autonomous version. Electricity storage systems are not necessary and the energy generating systems can be smaller and cheaper because seasonal differences can be balanced out by the grid. Furthermore, any excess energy produced in summer is not wasted but supplied to other grid users.

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