A Simulation, optimization and economic analysis of solar standalone reverse cycle air conditioning system for typical Australian homes

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Abstract:

The rising penetration of vapor compression air conditioning systems in Australian dwellings has raised the peak power demand. Consequently, the electrical infrastructure requires significant, costly upgrades that is invariably passed on to all end-users. Electricity network charges account for about half the cost of an average household electricity bill, causing electricity prices to reach some of the highest levels in the developed world. Standalone solar air conditioning systems offer a radical demand side energy management solution, but have drawn criticism due to the initial high capital investment of the required components. This paper combines simulations and optimization techniques to correctly size an inverter-driven reverse cycle vapor compression air conditioner, with photovoltaic panels and battery bank to form a cost effective standalone solar air conditioning system, for a typical Australian two-story house, in three vastly different Australian climate zones. TRNSYS is used to configure these components and perform dynamic simulations, whilst GenOpt is used to carry out the optimization. Probability in yearly hours loss of load expectation is used for sizing and system life cycle cost is used for the economic assessment. It has been found that the life cycle cost of most optimized complete component configurations is AU$ 49,160 in Brisbane, AU$ 80,085 in Adelaide, and AU$ 114,906 in Melbourne. The cost of the standalone photovoltaic system alone was higher than that of an air conditioner powered by grid electricity, and the payback period exceed 20 years in the three locations. The levelized cost of electricity for the photovoltaic systems to power the air conditioner is 2.45 in Brisbane, 1.5 in Adelaide, and 1.48 AU$/kWh in Melbourne respectively which is far higher than current fixed tariff.

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Introduction:

Space heating and cooling in Australia account for about 40% of total residential energy consumption [1]. Increased market-penetration of air conditioning (AC) systems, the majority of which is now reverse cycle, has caused increases in both the overall and peak electricity demand. Peak demand occurs for short periods of time, about 1% every year, and requires large capacity infrastructure to accommodate the critical demand [2]. The projected increase in the number and size of dwellings together with comfort expectations will dictate the need for continually upgrading supply capacity with costs invariably flowing on to all end-users. It has been estimated that an AC with 2 kW electrical demand, costing the purchaser AU$1000, needs about 6000 AU$ in infrastructure costs to supply the power [3]. Currently, in typical Australian households power bills, around 45% of the charge is attributed to network augmentation [4]. Grid electricity price rises are also unfair due to cross subsidization, all householders pay higher prices whether they run high capacity AC or not. A growing market-penetration of grid-connected photovoltaic (PV) systems is further distorting the picture. Due to the time mismatch between PV peak power output at mid-day and householders peak demand in the evening, photovoltaic system owners reduce their overall energy consumption during non-peak demand,

but still place their demand on the grid during peak periods; further impacting on unfair electricity charge beside the price rise [5].
Electrical storage can play a vital role here because it can shift and mitigate the peak demand thus reducing stresses on the grid. PV systems and battery storage can be optimized to the level of offering standalone capacity, providing the entire power requirement for running an AC. Such a configuration is a radical solution to meet the price rises associated with AC peak demands, and eliminating unfair cross subsidies to large AC and PV system owners. Previous studies in this topic mostly focused on solar assisted AC systems, fewer studies focused on standalone reverse cycle heat pumps, arguing that the inconvenience associated with the large capital investment forms an obstacle to their widespread acceptance [6-8]. This study focuses on the techno-economic optimization of components used to form a standalone solar AC system for typical Australian single family house.

Climate zone and building model:

Due to the wide variety of climatic conditions across Australia, it is difficult to propose a typical AC and evaluate its economic-footprint Australia wide. Hence, three locations with vastly different climatic conditions are selected: Adelaide, Brisbane and Melbourne. Each location has respective typical weather data that is used by the National Housing Energy Rating Scheme (NatHERS) that predicts a house's annual heating and cooling load.
House construction and types also vary from region to region, however, for the purpose of this research, a house model that represents a typical Australian house [9] was used for each climate zone. This model is a detached, two-story house with a conditioned floor area of 180m^2 and meets the current Australian building code requirement of 6 stars, as judged by NatHERS. This implies that the house requires a maximum annual heating and cooling load of 43, 96 and 114MJ/m^2, for Brisbane, Adelaide, and Melbourne, respectively [10]. Note that slight adjustments to the building fabric were required in some cases to achieve the 6 stars rating.

Standalone system components specification:

The system's main components are:

1. Inverter-driven reverse cycle ducted vapor compression AC with nominal coefficient of performance of 3.5. The compressor is assumed to be capacity controlled via a variable frequency (and hence speed) drive.
2. Monocrystalline PV panels, with a nominal conversion efficiency of 16 %, are selected, and are tilted at angles equal to the site latitude, i.e. 27° in Brisbane, 35° in Adelaide and 37.8° in Melbourne.
3. Lithium-ion battery, with an assumed discharge efficiency of 90% and maximum allowable depth of discharge of 80%.
4. Other components used include an inverter, a maximum power point tracker and a charge controller. The charger is set to meet the demand before charging the battery.

Technical and economic criteria:

In this study, a probability approach is used to size both the AC capacity required, to meet the building thermal comfort load, and the solar standalone PV system for powering the AC. The economic criterion, used to evaluate the feasibility of the deployment, is the life cycle cost for a 20 years period. All cash flow is discounted back to the grid present value using 2.2% inflation rate and 7% real discount rate. The economic assessment is also supplemented by the payback period and the levelized cost of electricity.

Simulation and optimization algorithm:

To find the optimal cost-effective component combination for a system in each climate, the system capacity is optimized via the use of the main component sizes as design variables: i.e. AC and PV panels (kW), battery storage (kWh), while the life cycle cost (AU$) minimization is set as an optimization objective. The annual loss of load expectation (hours) in both space heating and cooling, and electricity required to operate the AC are set as an optimization constraints. To carry out the optimization, TRNSYS coupled with GenOpt software and Hybrid algorithm is used to find a component configuration with a minimized life-cycle cost [11] .

Economic parameters:

Table (1) shows the average price of the system components, which were taken from several online retail pricelist from suppliers based mostly in Australia.

Table (1) parameters used to calculate the life cycle costs, quoted in AU$.

Component	**Initial cost**	**Installation**	**Cost reduction**	**Maintenance**	**Life years**
Photovoltaic panel (kW)	1900/kW	1200/kW	0	0.3% of purchase cost	25
Battery bank (kWh)	1100/kWh	6% of initial cost	50% by 2035 [12]	0	10
Inverter, charger, and maximum power point tracker	(508.9*kW+ 885.76)+925	0	0	0	10
Air conditioner and variable speed drive (kW)	(324.42*kW+ 1500)+(135.6 *kW+93)	2500	16%	0	15

The payback period is determined by the grid electricity avoiding, and by a Federal government PV installation subsidy. The latter is based on the market price for each small-scale technology certificate (STC), which is equivalent to the amount of energy (MWh) generated over the PV system life time or 15 years period. One STC is worth about AU$35, which equates to an installation refund in Brisbane of AU$622, whilst AU$725 is refunded in both Adelaide and Melbourne. The cost of grid electricity assumed to be AU$0.34/kWh in Brisbane, AU$0.35/kWh in Adelaide and AU$0.33/kWh in Melbourne [13].

Results and Discussion:

There are many different configurations of components that achieve the same loss of load probability. Table (2) shows the system configuration / size for each location that corresponded to the minimum life cycle cost, whilst meeting the building space conditioning loss of load probability of 5% and electricity loss of load probably (i.e. that required to operate the AC) of 0.2%. The large capacity of the PV panels seen for Melbourne are required to operate the AC in winter when there is the largest space heating load, whilst the battery for the same location is largest to provide the load and avoid discharging the battery beyond 80%. Both the required PV and battery bank capacities are smaller for Adelaide as the space heating load in winter is smaller than that for Melbourne. Brisbane is in a tropical climate zone and requires a smaller thermal load and hence AC. The majority of Brisbane's loads are cooling that is needed in summer when the days are sunnier, which results in the need for a smaller PV system and battery storage capacity.

Table (2) size of optimized component configuration and life-cycle costs (LCC).

Location	AC (kW)	PV (kW)	Battery (kWh)	LCC (no rebate) AU$	LCC (rebate) AU$
Brisbane	5	2	19.5	50,404	49,160
Adelaide	10.5	8.9	25.4	86,615	80,085
Melbourne	9	15	39	125,789	114,906

Table (2) also shows the life-cycle costs with and without the STC rebate, i.e. the larger the PV capacity, the greater the reduction of PV system cost, however, overall system investment required is still large, especially in Melbourne. Figure (2) breaks down the overall life cycle cost (including the rebate) to its various costs for each climate zone. In each case, the cost of the battery forms the majority of the system cost, due to its high initial cost and the need to be replaced every 10 years.

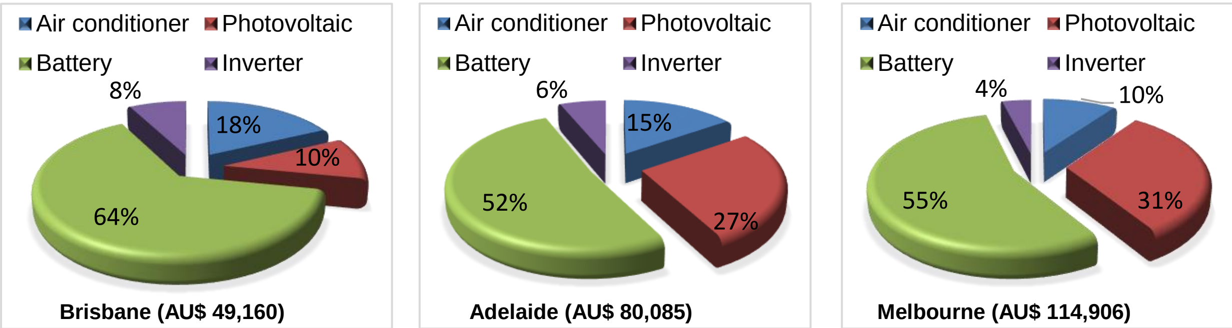

Figure (2) entire system life-cycle cost break down (with rebate)

In order to decide on whether the required investment in running the reverse cycle, air-conditioner off-grid, is justifiable or not, the cost of the standalone PV subsystem (without AC cost and with rebate) may be compared with an aggregated discounted running costs of grid electricity during 20 years. Such an assessment is shown in figure (3) which clearly showing that the financial input for the life of the standalone PV subsystem is higher than the aggregated purchase cost of electricity by 91%, 86% and 86% in Brisbane, Adelaide, and in Melbourne, respectively. Hence, using the standalone PV system is unjustifiable economically. For rural locations where the substation capacity is limited, connecting new householders to the grid may require augmenting the grid-capacity which involves a cost-penalty with an average estimate of 3885 AU$ per kW [14]. Deciding whether to invest in the standalone PV system or pay augmentation charges equal to the maximum electrical capacity required to run the AC is also shown in figure (3). After multiplying the augmentation charge by the maximum capacity required when running the AC, plus the running cost over 20 years, it seems even with such augmentation charge; the standalone PV system is still more expensive.

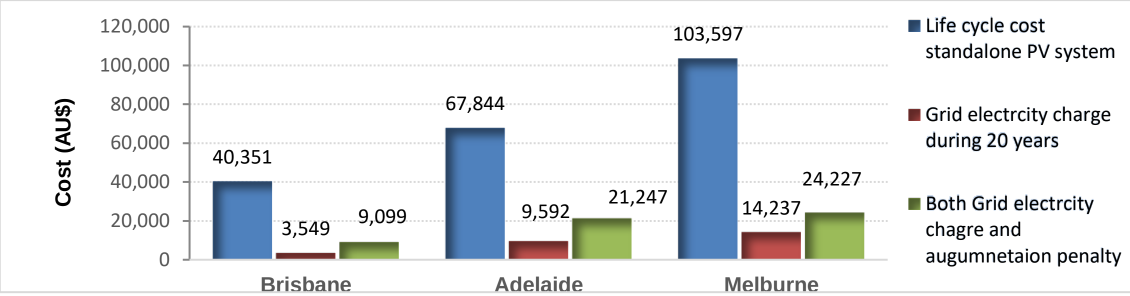

Figure (3) comparing the life cycle cost of the standalone solar PV subsystem (with rebate) with grid electricity power and augmentation charge

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Despite the large life-cycle cost, the standalone system can generate power for zero cost over 20 years, and therefore may still be viable if it can repay itself in less than 20 years. Unfortunately, figure (4) shows the years required to recover the estimated life cycle cost exceeded the 20 year study period in the three locations which makes the investment not attractive further. As the cost of the battery is already projected to be halved by 2035, and the economic costs remain a big barrier, a government incentive is required for the battery component, to make deploying the system feasible.

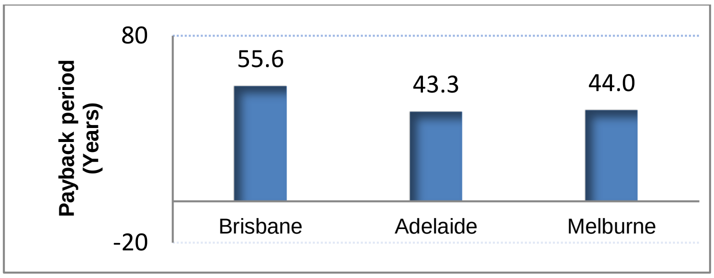

Figure (4) standalone solar PV system life cycle cost payback period.

The levelized costs of electricity can be used to compare and predict to what levels the price of grid electricity may rise to make investment in the standalone PV systems competitive. From figure (5), it seems the levelized cost of power produced from the PV system is higher than the grid electricity, particularly for Brisbane. Clearly, if grid electricity costs escalated in each given climate to the determined levelized cost of electricity, then the proposed optimized standalone PV system configuration becomes an economically viable alternative. As a standalone system, part of electricity generated by the PV system will be dumped when the battery is fully charged and the AC is not operating. In an alternative scenario, instead of off-grid system, if PV system dumped power feed for tariff to the grid, i.e. through smart system, investment in the same PV system configuration then may become justifiable or even profitable.

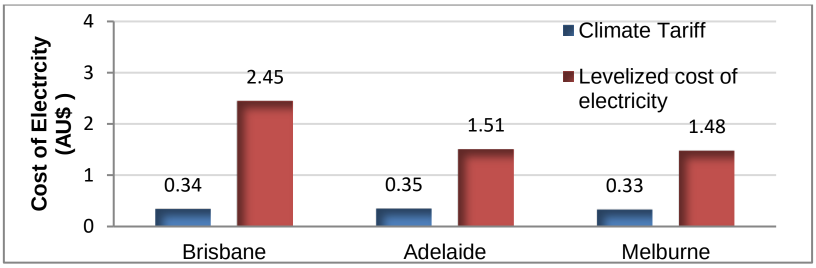

Figure (5) comparing levelized cost of electricity produced from the PV system with the climate zone tariffs

In view of the high cost of the expensive battery bank, it may be better to use a reverse cycle air-water heat pump integrated with a thermal storage capacity. A tradeoff between the thermal storage size, the heat pump and the battery capacity could facilitate a lower life cycle cost standalone solar power heat pump.

Conclusions:

In this paper, TRSNSY simulation is used to technically and economically optimize standalone reverse cycle AC systems for a typical detached two story house in three locations in Australia. The optimal components are sized for each climate. The results reveal that the life cycle cost of the standalone PV system even after factoring in current Australian government rebate for PV types in Brisbane is AU$ 49,160, in Adelaide is AU$ 80,085, and AU$ 114,906 in Melbourne. In none of the three climates, was the life cycle cost of the system comparable to purchasing electricity from the grid. The payback period was more than the 20 years study period, which is not attractive due to its unprofitability. The levelized cost of electricity for the standalone PV system needed to power the AC in AU$/kWh is 2.45 in Brisbane, 1.5 in Adelaide, and 1.48 in Melbourne, which all are more than double that of the grid electricity. Unless there are substantial changes in the performance/costs attributed to the major components and the electricity tariffs, the stand alone systems appear to be uneconomical despite their positive impact on the environment and on peak demand.

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