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THE LIFE CYCLE COST OF STANDALONE SOLAR AIR-WATER HEAT PUMPS FOR AUSTRALIAN HOMES

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Abstract:

To combat increasing electricity prices due to the high operating costs of conventional reverse cycle air-air-heat pumps (RC-AA-HP), they can be powered by standalone PV systems as a radical demand side energy management solution. However, the heavy power consumption of their compressors necessitates very large and expensive standalone photovoltaic (PV) systems. Alternatively, reversible air-water heat pumps (RC-AW-HP) are integrated with thermal storage units, hence with downsized capacity RC-AW-HP but large thermal storage, the building thermal load can be handled equally. The resultant benefits of standalone PV powered RC-AW-HP, is the potential to need smaller, hence, less costly battery storage. One issue associated with using a standalone PV system is the excess power generated. However, the excess power can be utilized to power domestic heat pump water heater (D-HP-WH) which has a different load profile. Previous researches have not focused on such a system configuration, this study focuses on the techno-economic feasibility of a highly optimized component configuration for such a system to meet the entire all-year round space conditioning and domestic hot water demands of a typical Australian house in three vastly different Australian climatic conditions. The entire system is modelled and simulated in TRNSYS and coupled with GenOpt to carry out the optimization. The lifecycle cost assessment on the most optimized component configuration for 0.2% annual hours loss of load probability in generated electricity, reveal that the twenty years life cycle cost is AU$ 76,917 in Brisbane, AU$ 88,539 in Adelaide and AU$ 120,454 in Melbourne. These life cycle costs are higher than case of conventional RC-AA-HP and D-HP-WH run by grid electricity, consequently, powering RC-AW-HPs with standalone PV system is currently not cost competitive with powering them with grid electricity.

Keywords: *solar air-conditioning systems, heat pumps, photovoltaic, standalone*

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1. Introduction

An increase in the market-penetration of RC-AA-HP is the main cause behind the rise not only in total usage of, but also in peak electricity demand. In Australia, peak air-conditioning (AC) demand occurs for short periods of time, i.e. only around 40 hours every year (Productivity commission, 2013). However, the entire electricity infrastructure should have sufficient capacity to handle any peak demand. Handling growing residential AC peak electricity demands requires ongoing upgrades in electricity infrastructure (Johnston, 2006). This has resulted in a rapid increase in electricity prices in several countries. In the case of Australia, prices have increased rapidly since 2007 (Carbon and Energy Market, 2012), and almost 50% of the rise was attributed to recouped investments in network infrastructure upgrades. To reduce such ongoing costly investment, a residential demand side energy management solution is necessary. Residential grid-connected photovoltaic (PV) systems lack potential for reducing peak air conditioning demands due to a time mismatch between midday peak PV generated power and residential evening air-conditioning peak demands. Utilizing standalone PV systems to power AC may offer radical demand side solutions. However, a large capacity battery is needed to buffer sufficient energy required to support the operation of large capacity of RC-AA-HP compressors during non-sunshine hours. As per current market status, battery banks, despite dramatic cost reduction are still prohibitively expensive, standalone PV to power RC-AA-HP is deemed economically unfeasible (Dan, et al. 2013; Gupta, 2011). Alternatively, RC-AW-HP is integrated with thermal storage, which allow meeting building peak demand with a downsized compressor capacity (Ehyaei et al., 2010; International Energy Agency and Energy Technology Systems Analysis Programme, 2013; Rismanchi et al., 2013). Trade-offs between the capacity of the PV array size, the battery bank, the heat pump and the thermal storage volume facilitate configurations that reduce the system life cycle cost. A drawback of standalone PV systems is what to do with excess power (Walid et al., 2011), practically, with the poor load factor of residential AC in Australia. But, that excess power can be utilised to operate doemstic heat pump water

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heater (D-HP-WH). A resultant benefit is that little oversizing is required, but the system still meets the entire 12 month thermal demand of the building. Previous studies have mostly focused on solar assisted AC, i.e.; less attention has been given to the economics of standalone AC, particularly in such configurations for combined space conditioning and domestic water heating. This study focus on optimizing the size of such system component configuration, with the aim of minimizing the system life cycle cost. The system will be sized for the thermal demands of typical Australian houses in, three vastly differnt Australian climate zones.

2. Building and system specifications

Since space conditioning, domestic hot water demand, and availability of solar radiation are all influenced by the climatic conditions of the site, the size and cost of the system will be site dependent. Thus, the system will be sized for the three different Australian climatic conditions selected: Brisbane, Adelaide, and Melbourne. To make research findings applicable to typical Australian homes, the space conditioning demand for a typical, detached, two story single family houses with 180 m^2 conditioned area was determined (Wong, 2013). In regard to the thermal fabric of the house, it was constructed of brick-veneer and insulated to meet the minimum Australian mandatory building thermal energy efficiency requirement of 6 stars energy rating criteria. According to that rating, the minimum annual thermal energy required to maintain the house thermally comfortable should not exceeds 43 MJ/m^2 in Brisbane, 96 in Adelaide, and 114 in Melbourne (Nation Wide house energy rating scheme, 2012). The domestic hot water demand is taken from the demand pattern provided in Australian standard AS/NZS 4234:2008 for evaluating energy consumption of hot water systems (Australian/New Zealand Standard, 2008).

The standalone heat pump is constructed from a PV and thermal subsystem, see figure (1). The PV subsystem, which includes the PV panels, lithium ion battery bank, and the DC-AC inverter, provides all the power required to run the thermal subsystem. The PV is monocrystalline with a conversion efficiency of 16%; the battery is lithium ion allowing a discharge depth limited to 80% of its available capacity. The inverter is sized according to the peak-power required by the load. The charge controller logic is set to prioritizing meeting the demand, then charging the battery. The PV panel is oriented due north and tilted with angle equal to the local latitude.

The thermal subsystem includes two sub-subsystems. One sub-subsystem is a RC-AW-HP which maintains the temperature of the water inside a stratified water storage tank below 10^{o}C in summer and above 45^{o}C in winter. The RC-AW-HP has nominal coefficient of performance of 3.2 in cooling mode and 4 in heating mode. But the performance at part load condition adjusted by with the normalized performance data for one of market available RC-AW-HP brand using its online published technical data. Two pumps are used to circulate the water; one in the heat pump-thermal storage loop activated with RC-AW-HP, one in the thermal storage-air handler unit loop activated with the air handler unit fan whenever there is a space conditioning demanded. A variable speed fan is used to control the flow of air supplied to the house through a ducted system set to control and maintain zones at setting temperatures suggested by (Nationwide house energy rating scheme, 2012). The maximum flow of the supplied air is limited to 8 air-changes per hour, and the parasitic power of the fan and pumps is scaled with the RC-AW-HP capacity. The thermal storage unit is assumed to be sensible stratified water tank that heats/cools the air when water circulates through the air-handler unit. The tank is simulated with 20 nodes, and the insulation level around the storage tank set to R2.7 (0.37 $W/m^2.k$) (AIRAH, 2013). The storage function changes from chilled buffer storage in summer to hot buffer storage in winter and the inlet and outlet ports location was optimized concurrently with the season.

The other sub-subsystem is a heat pump water heater, used to maintain the temperature of the water inside an insulated tank at 60^{o}C to prepare sanitary hot water sufficient for four persons in a house. The heat pump performance data is normalised from the manufacturer's published catalogue data for four heat pump capacities.

Figure (1) shows the components and configuration of the system

3. Methodology

3.1 Evaluation criteria

Technical criteria was used to correctly size the system component to adequately meet the three building thermal loads; space heating in winter, space cooling in summer, and water heating all year around. For standalone systems, matching energy demand and available energy capacity should be viewed not only in terms of the daily or yearly energy required but also in terms of demand time. Hence, the annual hour's loss of load probability is used for sizing both the thermal and the electrical subsystems. The criteria are based on the number of hours throughout the year when the demand exceeded the system's available capacity. The current system is sized for the following annual hours loss of load probability targets: the RC-AW-HP is sized for 5% of the space thermal conditioning demand, the D-HP-WH for no more than 1% of the domestic hot water demand, and standalone photovoltaic subsystem for 0.2% of the electricity demand of both heat pumps.

The optimization was performed using component sizes as design variables, life cycle cost as objective and standalone as constraints. For speed and accuracy, Hybrid algorithm is chosen for finding the optimal component size.

The economic criterion used is a life cycle cost for twenty years. All cash flow related to the system is discounted back using real discount rates. The life of components is adjusted to the study period by replacing or reselling at salvage value equal to the remaining life of the component.

3.2 TRNSYS project model:

TRNSYS 17 (TRaNsient SYstem Simulation Program) (Klein, 2012) is used to build a complete project model that represents the standalone solar PV subsystem, RC-AW-HP, and D-HP-WH in separated subproject models. Project components include those from the TRNSYS standard library, TESS (Thermal Energy System Specialists) library and three more components developed by the researcher. The project model is coupled with GenOpt optimization (Wetter, 2011) developed at Lawrence Berkeley National Laboratory for minimization of a cost function.

3.3 Economic parameters

Table (1) below lists parameters that feed into the economic model, all of which are gathered by the researchers from online retail price lists and suppliers based mainly in Australia.

Table (1) details related to price of components that feed to the economic model (C refer to component specific capaicty).

Component	Initial cost		Installation	Cost reduction	Maintenance	Life years
Photovoltaic panel (kW)	1900/C	(C in kW)	1200/kW	0	0.03% of purchase cost	25
Battery bank (kWh)	1100/C	(C in kWh)	6% of purchase cost	50% by 2035	0	10
Inverter, charger, and maximum power point tracker	(508.9*C+ 885.76)+925	(C in kW)	0	0	0	10
Reverse cycle air-water heat pump	581.6+447.6*C	(C in kW)	$AU 2500	16% by 2035	5% of purchase cost	15
Heat pump water heater	5.3538*C+ 819.9	(C in m^3)	$AU 500	16% by 2035	5% of purchase cost	15
Pump	269+239.6 *C	(C in kg/s)	$AU100 per pump	0	0	15
Storage tank	680*C + 720	(C in m^3)	$AU100	0	0	15
Air-handler unit	35.95*C+680.69	(C in kW)	0	0	0	20

The financial parameters used in the economic model are a 2.2% inflation rate and a 7% nominal discount rate. Also, the Australian government subsidies installing PV and D-HP-WH under a Small-scale Renewable Energy Scheme, offering a rebate called the small scale renewable energy technology certificate (STC)

(Clean Energy Regulator). With this rebate, householders can receive a discount based on the number of STCs that the system is eligible for. Market prices for STCs fluctuate, but currently stand at around AU$ 35 per STC. The number of STCs that a system may attract depends on its size and the geographical location where it is to be installed. For PV systems, each 1 kW is eligible for a cash- back equal to AU$ 622 in Brisbane, and AU$ 725 in both Adelaide and Melbourne. For the D-HP-WH, the number of STCs depends on both the manufacturer and size of the tank. But D-HP-WH which can displace highest energy should be eligible for AU$ 1484 (i.e. 42.2 STC) in both Adelaide and Brisbane, and AU$ 1621 (i.e. 46.3 STC) in Melbourne. These rebates are deduced from the life cycle cost after the optimization.

4. Results and discussion:

6.1 Technical optimization:

System optimization was carried out to reduce the system life cycle cost by varying components sizes but maintaining the above mentioned targeted reliability in annual hours loss of load probability constraints. To guarantee the accuracy of optimal results, each optimization was repeated six times with a different preliminary component size estimated for each of the above stated climate zones. Each optimized configuration was obtained after more than 500 year rounds simulations with 7.5 minute time step. Table (2) lists the components size yields from an optimization which configured the most minimized life cycle cost system. The discrepancy between different component sizes appropriate for each climate is strongly linked with the amount of highest thermal load, the amount of highest heat pumps electrical energy demand, the season when these demands occur, and at what time of day, and how long it continued. For the current research targeted reliability, if the system's available capacity fits the building yearly load profile and the climatic pattern of the site, then it should be practically applicable when it is sized to operate as a standalone system.

Table (2) shows the optimal size of each RC-AW-HP, for each climate zone. In Brisbane, despite the minor space conditioning demand for sensible cooling and heating, compared to Adelaide, a relatively very large thermal storage, i.e. 7.4 m^3, and a large capacity RC-AW-HP, i.e. 3 kW, was needed compared to that anticipated. For Brisbane, this is due to the need to remove the high humidity which dictates maintaining a larger quantity of water chilled at and below 10^oC. Apparently, during the night, less electrical energy is consumed by the RC-AW-HP when using large chilled water storage; instead, the second pump operates more in circulating the vast ready chilled water. This expains why a smaller battery (20 kWh) is needed in Brisbane, compared to those required in both Adelaide and Melbourne. In Brisbane, concurrency of summer high solar intensity with a high cooling load enables the PV system to amply generate the required power to run the heat pumps and recharge the battery.

Table (2) optimized size of components forming the minimized life cycle cost of the standalone system.

	Battery (kWh)	RC-AW_HP (kW)	Photovolatic (kW_p)	Thermal storage (m^3)	D_HP_WH (m^3)
Brsibane	20	3	9	7.4	0.27
Adelaide	28	2	9	7.8	0.34
Melbourne	44.5	5	12	3	0.34

Contrary to Brisbane, in Melbourne the peak space conditioning demand occurs in winter, and lasts for several successive days, the significant part of it occurring at night. When compared to Adelaide, relatively larger capacity RC-AW-HP, i.e. 5 kW, was needed to charge heat in a smaller volume thermal storage, i.e. 3 m^3. Obviously, maintaining a smaller volume of heated water and using a more powerful RC-AW-HP demands less electrical energy than in the case of using downsized RC-AW-HP and a large volume hot storage. Also, when compared to Adelaide and Brisbane, the capacity of the PV panel is larger, i.e. 12 kW_p, since it generates less electrical energy under days with overcast skies. Inevitably, a considerably larger battery bank capacity, i.e. 44.5 kWh, was also required to avoid power interruption during the day and guarantee continuous night operation.

Table (2) shows that for Adelaide, the optimized configuration requires smaller RC-AW-HP, i.e. 2kW, and large thermal storage, i.e. 8 m^3, than the other two climates. This is due to a high peak sensible cooling demand and significant heating load. On account of the noticeable variation between electrical and thermal storage sizes in hot and cold climates; it can be concluded that using large chilled water storages for space cooling in summer considerably reduces the required battery capacity for the same annual loss of load probability. Unlikely, using hot storage for space heating not have that considerable potential to reduce the minimum required battery capacity.

The capacity of the configured PV panel, i.e. 9-12 kW_p, may look a little large for residential buildings, but the system configuration is standalone with a superior degree of reliability, less than 5 hours per year the electricity demand is not met. Should more annual hour's electrical loss of load portability be tolerated, the size and cost of the electrical parts of the system will reduce substantially, but then the system need to be assisted by mains-grid electricity.

In terms of sizing the D-HP-WH, the size that was found to be suitable for Brisbane was a 270 litre tank and heating rate of 75 litres per hour, while those suitable for Adelaide and Melbourne were 340 litre tanks and heating rates of 75 litres per hour. The power that was needed to operate the heat pump was added to the power required to run the RC-AW-HP during the optimization. The daily D-HP-WH power pattern is similar throughout the year, but higher in winter than in summer. Adding the D-HP-WH power profile caused the PV subsystem to be a slightly oversized, but significant amount of the PV dumped power was usefully utilized by the D-HP-WH.

It is important to emphasize that these configurations do not represent those with the best fit technical configuration for the building load, nor for the selected climate zones. They represent configurations that with a given component cost and target constraints, lead to obtaining the component configurations that have minimized life cycle cost systems. Should the system to be sized for other climates, by loading the applicable load profile, or other cost or constraints targets, the project model can be used to determine the optimized standalone system's components configuration.

6.2 Economic evaluation:

The twenty years life cycle cost of the most optimized component size configuration presented in table (2) was found to be AU$ 83,907 in Brisbane, AU$ 96,814 in Adelaide and AU$ 130,782 in Melbourne. Depending on the size of the PV panel and the climate, when government rebates in the form of STCs are added to both the PV panel and the D-HP-WH, the life cycle cost reduces in Brisbane to AU$ 76,917 , in Adelaide to AU$ 88,539 and in Melbourne to AU$ 120,454. If the system life cycle cost break down to the life cycle cost of main forming components then it becomes obvious which component costs dictate the cost of the system.

Figure (2) shows in each of the three climate zones, the greatest cost is associated with the battery, followed by the PV panels, followed by the thermal storage unit. If the percentage of investment attributed to the battery and the thermal storage are cross-correlated and compared for the three climate zones, it becomes evident that, when the percentage cost of thermal storage is higher, the percentage cost attributed to the battery is less. Since the price of the cubic meter of thermal storage is less than the price of each kWh battery capacity it replaces, with larger thermal storage the life cycle cost of the system must in all probability decrease correspondingly. To be more specific, in space cooling dominated climates, large chilled water storage can reduce the minimum capacity of a battery required for settling standalone solar PV powered RC-AW-HP.

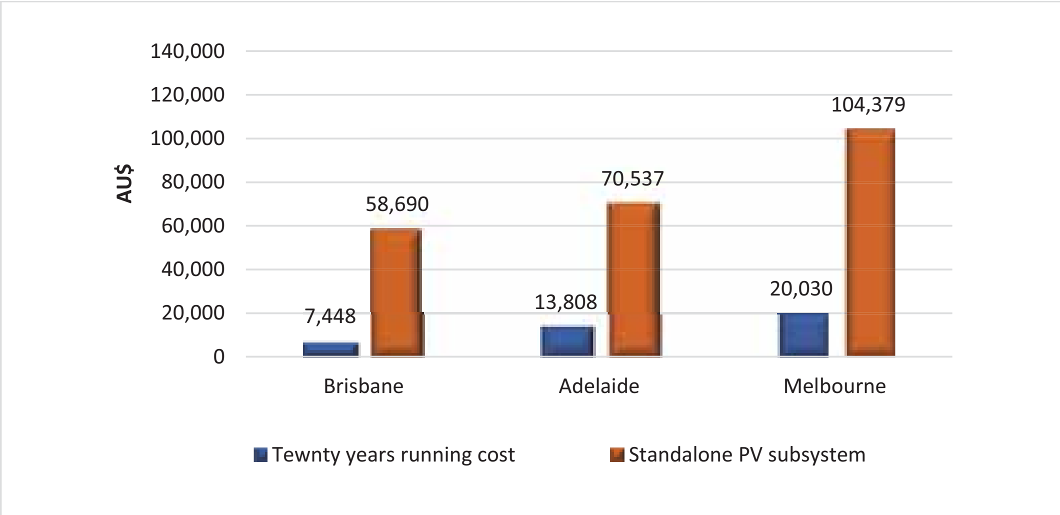
Figure (2) the life cycle cost break down to main forming components in the three climates

6.3 Competitiveness with conventional system:

To investigate how such standalone PV powered RC-AW-HP and D-HP-WH is cost competitive in comparsion with powering them by grid electricity, the life cycle cost of the PV subsystem is compared with the twenty years running cost of the conventional RC-AA-HP and D-HP-WH if electricity is purchase from the grid. The comparison is shown in figure (3). Clearly, the investment required in the reliable standalone PV system is enormously higher than purchasing the power from the grid for running the conventional systems in the three climate zones. Hence, the economic potential of space conditioning houses with RC-

AW-HP off-grid is weak in comparsion with current component costs and electricity charges. Unless in case of remote dwellings where costly investment in constructing new or extending electricity network infrastructure is needed to sustain powering conventional AC. Adding these infrastructure costs to the running cost can influenec individual householders to select the presented standalone PV powered heat pumps instead of paying for infrastucture network extensions.

Figure (3) comparing the twenty years running cost and standalone PV subsystem life cycle cost in the three climates



5. Conclusion:

In this study, a TRNSYS 17 project model is used to optimize the configuration of components forming the standalone PV subsystem powering RC-AW-HP and D-HP-WH for the thermal demand of typical Australian house in three vastly different Australian climatic zones. The life cycle cost of most optimized configuration of these systems with rebate was found to be AU$ 76,917 in Brisbane, AU$ 88,539 in Adelaide and in Melbourne AU$ 120,454. It has been found that chilled water storage can contribute to reducing the capacity of the battery, consequently, the overall standalone system cost. Whether investment in such a system is cost competitive with purchasing electricity from the grid to power conventional RC-AA-HP and D-HP-WH in residences; the life cycle cost of the standalone PV subsystem is compared with a 20 year discounted electricity cost needed to power conventional RC-AA-HP and D-HP-WH. The results demonstrate that purchasing electricity from the grid to run these conventional options costs much less than investing in a standalone PV subsystem. Indeed, unless the tariff increase considerably, or, the cost of batteries decrease significantly, or the householder is faced with heavy investment in electricity infrastructure charges, it is currently uneconomic to invest in a standalone PV driven air to water heat pump systems.

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