Development of an Approach to Compare the 'Value' of Electrical and Thermal Output from a Domestic PV/Thermal System

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Abstract

When considering the design of a PV/Thermal system, it is essential to determine the ratio of the values of the electrical and thermal output from the system. Otherwise there is no rational approach for optimising such a system, as there will be no single output to optimise. This paper focuses on methods that can be employed to develop a ratio between electrical and thermal output from a domestic style PV/Thermal system. Methods discussed include thermodynamic analysis using exergy; market analysis for both an open market and a renewable energy market; and environmental analysis using avoided greenhouse gas emissions. Ratios are developed for each method based on real data. An example is given comparing a PV/Thermal system that uses amorphous silicon cells with one that uses crystalline silicon cells. Levelised energy cost is plotted against the energy value ratio to show that there is a critical electrical-to-thermal energy value ratio below which a collector with a-Si cells is more cost effective than one with c-Si cells.

1. INTRODUCTION

It is a common misconception that a Joule of energy in the form of heat and a Joule of energy in the form of electricity are equally valuable. Electrical energy and thermal energy are not equally *useful*. The concept of usefulness of energy can be described roughly using examples, or a precise definition can be adopted using the thermodynamic concept of *exergy*. Electricity is often described as a 'high-grade' form of energy, perhaps because it is 'extracted from' or 'processed from' lower-grade steam at a power plant. We are familiar with the fact that conventional power plants have certain energy conversion efficiencies, say around 40%, and therefore electricity that comes out of a power plant is clearly more precious than the thermal energy that goes in. However, if the thermal energy is in the form of domestic hot water for washing and cleaning, then the link between the value of the hot water and the value of the electricity is less clear.

It would be desirable for policy makers and energy providers to understand the distinction between electrical and thermal energy. Renewable energy subsidy schemes *should* provide different subsidies for electricity and hot water generation to recognize the value of the energy produced – but often this is not the case. For example, the recently legislated "Mandatory Renewable Energy Target" in Australia allows a unit of energy as solar hot water to be counted as equal value to a unit of renewable electricity, without recognition that the electricity is inherently thermodynamically and technically harder to produce.

The Combined Heat and Power Solar System, or CHAPS system, at the Australian National University, is a 25x concentration parabolic trough system that combines photovoltaic cells to produce electricity with thermal energy absorption to produce hot water. The first CHAPS prototype is a domestic style system, suitable for hot water and electricity generation for a home. Future CHAPS systems will be larger single-axis tracking CHAPS systems installed on the roofs of commercial and light industrial buildings, and will contribute to building heating, cooling and power requirements. The development of the CHAPS system is preceded by PV trough technology development at the A.N.U. since the mid-1990s, culminating in the commissioning of a 20kW PV trough array at Rockingham in the year 2000 (Blakers, 2001).

When considering the design of a PV/Thermal collector, it is necessary to determine the ratio of the values of the electrical and thermal output from the system. Otherwise there is no rational approach to optimising such a system, as there will be no single output to optimise. This paper discusses different methods of valuing thermal and electrical output from a PV/Thermal collector, with a focus on domestic sized PV/Thermal systems, where the thermal energy is stored for use as domestic hot water.

2. THERMODYNAMIC VALUE

2.1. Energy

The first law of thermodynamics tells us that work and heat are both forms of energy. Thus a simplistic first law approach is to consider them to be of equal value. Various studies of PV/Thermal collectors have used this simple energy approach to express the combined efficiency of the electrical and thermal output (Sharan and Kandpal, 1992, Hegazy, 2000, Sopian et al., 1996 and 1997). To improve on this, one method that has been proposed is to use an energy efficiency ratio derived from conventional power plants (Huang *et al.*, 2001). The so-called *primary-energy saving* technique defines a primary-energy saving efficiency E_f as:

$$E_f = \frac{\eta_e}{\eta_{power}} + \eta_{th} \tag{1}$$

where η_e is the PV conversion efficiency, η_{power} is the conversion efficiency of a conventional thermal power plant (around 0.4), and η_{th} is the thermal efficiency of the PV/Thermal system.

However this technique does not consider the temperature or the pressure of the thermal output from the PV/Thermal system. Power stations use high-pressure steam suitable for driving turbines, which would not be generated by PV/Thermal collectors due to the fact that increasing the temperature of PV cells results in decreasing efficiency. It is self-evident that low temperature hot water from a PV/Thermal system is not as thermodynamically useful as high temperature steam from a coal-fired boiler.

2.2. Energy

The second law of thermodynamics addresses the fundamental limits that apply in the efficiency of conversion of heat to work. The predictions and formulations of the second law all follow from the simple observation that heat flows naturally from hot to cold objects but never the other way. Since work (e.g. electricity) can always be done on systems no matter how hot they are, it has a status equivalent to heat flow from a body of infinite temperature. The second law leads to a quantification of the "relative value" of different energy streams via Exergy analysis. Exergy (sometimes called Availability) is defined as the maximum theoretical useful work obtainable from a system as it returns to equilibrium with the environment. (see for example Bejan e*t al* (1996) and Moran and Shapiro (1998)). For a control volume, the rate of delivery of exergy from a flow ($\Delta\dot{A}_{21}$) if there is a single inlet and single exit denoted by 1 and 2, respectively, is given by:

$$\Delta\dot{A}_{21} = \dot{m}\left(h_2 - h_1 - T_0(s_2 - s_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \tag{2}$$

where $\dot{m}$ is the mass flow, h and s are specific enthalpy and entropy respectively, T_0 the environmental temperature, V the fluid velocity, z the height of the inlet or outlet, and g the acceleration due to gravity. The energy delivered to the control volume by the same flow ($\Delta\dot{E}_{21}$) is:

$$\Delta\dot{E}_{21} = \dot{m}(h_2 - h_1) \tag{3}$$

Table 1 below summarises the energetic and exergetic value of the energy flows for the typical conditions of a PV/T system.

Table 1. Exergetic comparison of electrical and thermal output

Energy stream	Energy	Exergy equation	Exergy	Energy/Exergy ratio
Electrical	1000 W	$\Delta\dot{A}_{electrical} = \Delta\dot{E}_{electrical}$	1000 W	1
Thermal $p = 500kPa$ $T_1 = T_0 = 25°C$ $T_2 = 65°C$ $\dot{m} = 5.98kg/s$	1000 W	$\Delta\dot{A}_{thermal} = \dot{m}(h_2 - h_1 - T_0(s_2 - s_1))$ $h_1 = 105 kJ/kg$ $h_2 = 272\ kJ/kg$ $s_1 = 0.366\ kJ/kg.K$ $s_2 = 0.893\ kJ/kg.K$	61.5 W	16.3

For this example, the ratio of electrical-to-thermal exergy is 16.3. Various studies have used exergetic efficiency to make a direct comparison between electrical and thermal output from a PV/Thermal collector (Takashima et al., 1994, Fujisawa and Tani, 1997). However, the significance of an exergy comparison is not clear if electrical or mechanical work is not the only desired output from the system, such as when the thermal output is hot water used directly for showers and washing.

3. MARKET VALUE

3.1. Open Market Approach

A pure thermodynamic comparison does not take into account the financial realities of energy generating systems. Another way of comparing the value of different forms of energy is to develop a ratio based on market value. The price of electricity is reasonably straightforward to determine, as the lowest price offered by the retailers to deliver electricity to the consumer. It is more difficult to attach a price to thermal energy based on market value, as usually it is not thermal energy that is delivered to the consumer, but energy in the form of electricity or gas. This is then converted to thermal energy in the form of hot water, and stored in a tank or circulated around the house for heating. The main exception is district heating, where thermal energy is delivered directly to customers through hot water or steam in pipes.

The price of the thermal energy must therefore incorporate the cost of a hot water tank with its electric elements or gas burners. Even heat from a district heating system has an additional installation cost, as a heat exchanger is required to extract heat from the primary hot water loop. Thermal storage systems have heat losses during the day, which increase the cost of the hot water delivered. Gas boosted storage systems are not perfectly efficient, further increasing the cost of hot water delivered.

The cost of a gas or electric hot water system can be expressed as a levelised cost in \$/kWh by applying discounted cash flow methods. The net present value (NPV) is equal to the difference between the present value of the net cash flows generated by a project and the initial cash outlay. This can be expressed as:

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{C_t}{(1 + k\Delta t)^r} - C_0 \tag{4}$$

where C_0 is the capital cost, C_t is the net cash flow generated at time t, n the life of the project, k the discount rate and Δt the compounding interval[1]. The levelised energy cost for a system is the unit price of energy output that would result in the system having a zero NPV over its lifetime. Table 2 sets out an example of cost calculations for gas and electric hot water services.

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[1] The NPV equation is often presented with the Δt omitted because it is assumed to be one year, but this is not strictly correct.

Table 2: Example of thermal energy cost calculations.

	Unit	**a) Gas HWS Standard**	**b) Gas HWS High efficiency**	**c) Electric HWS Continuous**	**d) Electric HWS Off peak**
Capital cost of HWS	$	836	1076	640	941
Installation cost	$	200	200	200	200
Hot water energy demand	kWh/year	3490	3490	3490	3490
Energy consumed	kWh/year	6500	4730	4640	4760
Life of HWS	Years	15	15	15	15
Inflation rate	%	3.0	3.0	3.0	3.0
Discount rate	%	7.82	7.82	7.82	7.82
Levelised cost of HWS	$/kWh	0.028	0.035	0.023	0.031
Primary energy price	$/kWh	0.034	0.034	0.109	0.055
Effective energy cost	$/kWh	0.064	0.046	0.145	0.075
Cost of plant	$/kWh	0.028	0.035	0.023	0.031
Total cost of hot water	**$/kWh**	**0.092**	**0.081**	**0.168**	**0.105**
Cost data is in Y2001 Australian Dollars					

Capital cost and installation prices come from Rheem (Feb, 2001). Hot water demand was taken from Australian Standards AS4234-1994, based on a large domestic system based in Canberra. Energy consumption was calculated using the simulation software TRNSYS (Klein, 1976a, 1976b), with gas burner efficiency and thermostat settings also based on Australian Standards. 50mm insulation was assumed for the electric offpeak and high efficiency gas tanks, and 25mm for standard tanks. System lifetimes were estimated, based on a typical warranty period of 10 years, and data from a survey of the United States by ASHRAE Technical Committee TC 1.8 (Akalin, 1978). The discount rate is a nominal rate based on the variable loans rate for personal mortgages with the major Australian banks. Both gas and electricity energy prices are from the Australian Gas Association (2000), adjusted to 2001 dollars, with off-peak rates assumed to be half normal rates. Operation and maintenance costs were not included for the sake of simplicity, system availability was assumed to be 100%, and a HWS was assumed to have no residual value at the end of its lifetime.

The example in Table 2 shows that the true cost of thermal energy (i.e. the hot water delivered to the customer) is significantly more than the cost of the primary energy source. As well as the calculated annual plant cost, the cost of thermal losses, and gas boiler inefficiencies significantly contribute to the overall total cost of the hot water. To develop a ratio between electrical and thermal energy cost, it is reasonable to assume the lowest cost option for the thermal energy (option b above). Dividing the standard tariff for electricity by this value yields an electrical-to-thermal value ratio of 1.33.

3.2. Renewable Energy Market Approach

The market that a PV/Thermal system operates in is not an open market. Most countries have policy measures designed to promote the use of renewable energy. Some of the more common policy instruments are buy back schemes, capital subsidies, tax exemptions, competitive bidding procedures for a specified market share, and renewable energy targets (International Energy Agency, 1998). The impact of these schemes is the creation of a separate market for renewable energy. In some cases the market can be further subdivided by generation type (eg. solar, wind, biomass, etc) as certain renewable energy policies are selective about what generation types are eligible. It is possible to develop levelised energy costs for both electrical and thermal energy from renewable sources using the discounted cash flow method.

Grid-connected photovoltaics levelised energy cost

PV modules prices offered online by six U.S. suppliers were surveyed in April 2001, with the results shown in Figure 1 below.

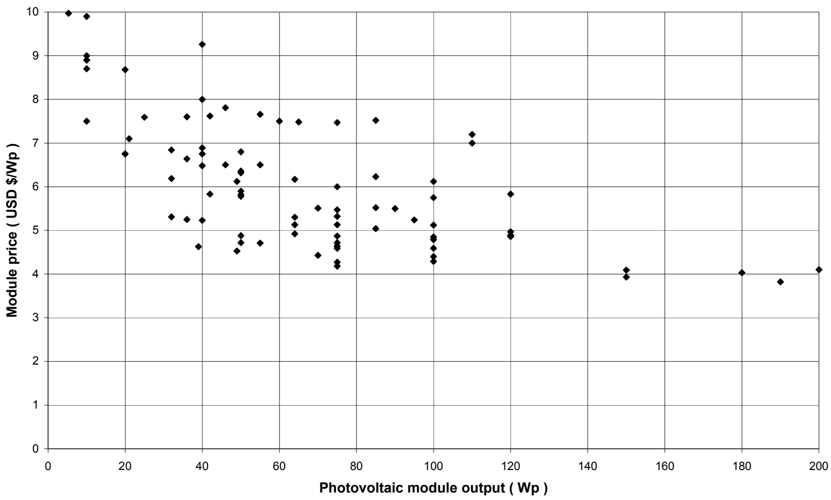

Figure 1: Photovoltaic module prices surveyed in the U.S. April 2001

Table 3 shows a levelised cost calculation for a grid connected PV system in the U.S. representing an 'average cost' system. The levelised cost is calculated only once, as all parameters except module cost are assumed to be the same for each system. A levelised energy cost of $0.367 is calculated for the PV system.

Table 3: Levelised energy cost calculations for a grid-connected residential photovoltaic system

Item	Unit	Value
d.c. PV module efficiency	%	14.0%
Inverter efficiency	%	90%
Factor accounting for non-standard rating conditions	%	90%
a.c. System efficiency	%	11.3%
dc power PV module cost	USD/Wp	$5.36
Power-related BOS	USD/Wp	$1.22
Area-related BOS	USD/m^2	$138
System Total	USD/m^2	$1059
Yearly insolation	KWh/m^2	1990
Yearly ac electricity produced	KWh/m^2	226
Energy inflation	%	3.0%
System Lifetime	Years	20
Discount Rate	%	7.82%
Levelised Energy Cost	USD/kWh	$0.367

Year	Cashflow (USD)	Sum of Present Value (USD)
0	-1059	
1	85	-980
2	88	-905
3	90	-833
4	93	-764
5	96	-698
6	99	-635
7	102	-575
8	105	-518
9	108	-463
10	111	-411
11	114	-361
12	118	-313
13	121	-267
14	125	-224
15	129	-182
16	133	-142
17	137	-104
18	141	-68
19	145	-33
20	149	0

The PV module price of $5.36/Wp was used, which is the mean price for modules larger than 40W from those surveyed. Note that a 'low end' price of $4.50/Wp would give a LEC of $0.325. Balance-of-system costs, cell and inverter efficiency were taken from year 2000 estimates by the DOE (DeMeo and Galdo, 1997). The DOE also suggest an additional efficiency factor of 0.9 to account from operation away from standard rating conditions. PV module efficiency was estimated for crystalline silicon cells, however the LEC is not sensitive to this figure. Canberra weather data for a typical year was used, assuming modules face north and are tilted at the latitude angle of 35.3°. It is assumed that the cost of energy will increase each year by 3%. The nominal savings for each year were estimated by inflating the base savings by this value. The 3% inflation value is an estimate based on projected electricity price increases in the United States (DeMeo and Galdo, 1997). The system lifetime of 20 years is commonly used as a realistic value for PV. Other financial assumptions are the same as for the previous example.

Solar hot water levelised energy cost

Table 4 shows a specific example of a levelised energy cost calculation for a solar hot water heater.

Table 4: Example of levelised energy cost calculation for a solar hot water system

Item	Unit	Value
Manufacturer		SunEarth
Collector area	m^2	3.47
Volume of tank	L	303
Yearly insolation	kWh/m^2	1990
Hot water energy demand	kWh	3517
Tank auxiliary energy used	kWh	1660
Solar energy used	kWh	1857
Cost of solar HWS including installation	USD	$2240
Volume of equiv. conventional HWS	L	156
Cost of equivalent conventional HWS	USD	$530
Cost of solar component of solar HWS	USD	$1710
Energy Inflation	%	3.0%
System lifetime	Years	20
Discount Rate	%	7.82%
Levelised energy cost	USD/kWh	$0.072

Year	Cashflow (USD)	Sum of Present Value (USD)
0	-1714	
1	138	-1587
2	142	-1464
3	146	-1348
4	151	-1236
5	155	-1130
6	160	-1028
7	165	-931
8	170	-838
9	175	-749
10	180	-665
11	185	-584
12	191	-506
13	197	-432
14	202	-362
15	209	-294
16	215	-230
17	221	-169
18	228	-110
19	235	-54
20	242	0

Solar HWS prices are full system prices, and include collectors, tanks, fittings and a provision for installation. Solar collectors surveyed come from four major U.S. manufacturers (SunEarth, Heliodyne, ACR Solar, and AET) with prices from five retailers. Data is from the first half of the year 2001. System performance was simulated using TRNSYS. Collector performance parameters come from an independent directory compiled by the Solar Rating and Certification Corporation (2001) in the U.S. Mass flow was assumed to be 10ml/s for each $1m^2$ of collector area. A hot water demand profile was used, based on an energy draw profile set out in the Australian Standards AS4234-1994. The magnitude of the demand was adjusted depending on the size of the tank. Canberra weather data was as used, as above for the PV systems. The TRNSYS model used simple differential temperature control, a Type 1 collector, a Type 140 tank with 10 thermal zones, a thermostat set to 60°C, and a 3.6kW auxiliary heating element, in the second and third zone from the top of the tank respectively. The over-temperature cutoff for the controller was set to 95°C. The base UA-value was 2.27 W/K for a 300L tank, and this was adjusted according to tank size. The price of a conventional HWS was deducted from each solar HWS such that net capital cost is a 'solar only' cost. The conventional HWS has a volume based on 0.75 times the daily hot water demand, as recommended by the European Committee for Standardization (1997). The price of the conventional HW system was interpolated from Y2001 price data from the two large U.S. manufacturers, Marathon and Bradford White. The lifetime of 20 years for the solar HW systems was based on advice from the SRCC, assuming specific components with shorter expected service life such as pumps, controls, and mixing valves are replaced as necessary during the system life. However, such maintenance costs are excluded for the sake of simplicity, and other financial assumptions are as previously.

Figure 2 shows the levelised energy cost calculated for each of these solar hot water system, using the same method as outlined in Table 4. In contrast to the PV case, LEC is calculated for each individual solar HW system, as each system has different parameters such as collector area, efficiency, tank size, etc.

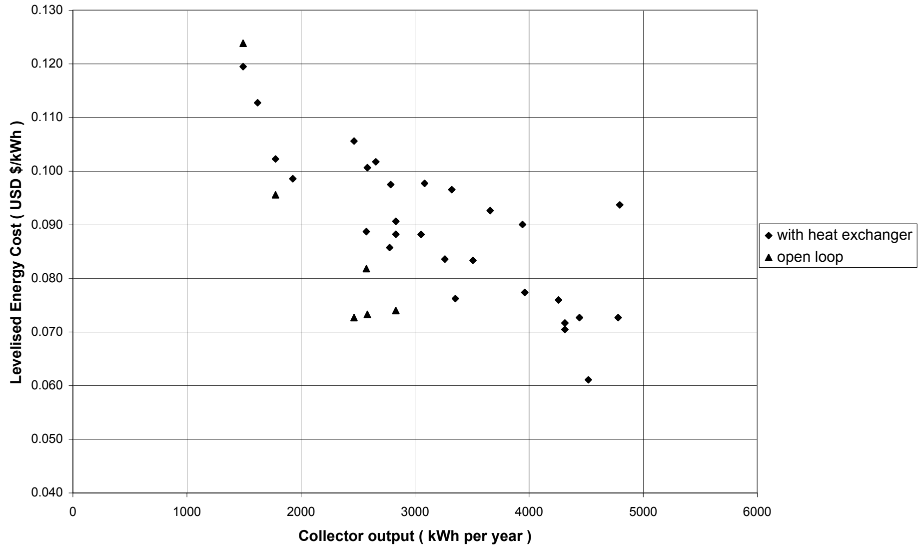

Figure 2: Levelised energy cost of hot water from a variety of solar hot water systems

The mean value of levelised energy cost of USD $0.087 is used to represent the 'average cost' of energy for the solar hot water systems surveyed. A 'low end' levelised energy cost might be closer to $0.075. The levelised cost calculations above give a ratio between electrical to thermal value from renewable sources of 4.24.

This ratio of 4.24 favours electrical energy far more than the ratio of 1.33 developed in Section 3.1 An optimisation of a PV/Thermal system using this ratio would therefore treat the electricity from the system as 4.24 times more valuable than the hot water output. Note that when 'low end' prices for both the PV system and the SHWS are used, this ratio does not change significantly, and has a value of 4.33 for the data surveyed.

4. ENVIRONMENTAL COST

One of the main drivers of renewable energy is its use as a means of reducing greenhouse gas (GHG) emissions associated with energy generation from fossil fuels. It is conceivable that the reduction of greenhouse gas emissions may become linked to strong enough financial incentives, such as carbon taxes and carbon credits, that their reduction will become a key design criterion. In this case, optimisation of a PV/Thermal system on a greenhouse gas savings basis would be important, and a ratio between the thermal and electrical output would need to be used based on greenhouse gas emissions.

The simplest way to calculate such a ratio is to look at emissions avoided by the use of the PV/Thermal system.

$$\begin{bmatrix}\text{Ratio of electrical to}\\ \text{thermal value}\end{bmatrix} = \frac{\text{Avoided CO}_2\text{ by PV electricity generated}}{\text{Avoided CO}_2\text{ by solar hot water generated}} \tag{5}$$

Assuming that emissions due to the PV electricity and the solar hot water are zero, this ratio simply becomes:

$$\begin{bmatrix}\text{Ratio of electrical to}\\ \text{thermal value}\end{bmatrix} = \frac{\text{Emissions due to conventional electricity}}{\text{Emissions due to conventional HWS}} \tag{6}$$

If GHG emissions are important, then it is assumed that installing a new solar HWS would be instead of a new gas HWS rather than a new electrical HWS. Natural gas in Australia has an average carbon dioxide emission factor of 183.2g-CO_2 per kWh of gas (Australian Gas Association, 2001). A hot water system with a high efficiency burner will have conversion efficiency around 85% (Australian Standard AS4234-1994), resulting in carbon dioxide emission levels of 215.6g-CO_2 per kW of hot water. Emissions due to electricity vary according to the fuel source used for generation, and vary substantially between different regions. For example, in Australia in 1999, emissions were 1467g-CO_2/kWh in Victoria, due to the extensive use of brown coal; 701g-CO_2/kWh in the Northern Territory, which uses mainly natural gas; and only 1g-CO_2/kWh in Tasmania due to almost total use of hydro power (George Wilkenfeld and Associates, 2000). On average, emissions were 1034g-CO_2/kWh for electricity delivered. Using this average value, the ratio of electrical to thermal avoided CO_2 emissions is 4.8.

Another way to make a comparison on an environmental basis between electrical and thermal output from PV/Thermal collector is to consider the life cycle GHG emissions. Life cycle GHG emissions include the emissions that originate from processes used to make a product, as well as embodied emissions from the materials from which the product is manufactured. Using this methodology, emissions attributed to renewable energy are not zero. Instead, emissions for thermal energy in the form of hot water take into account the life cycle emissions of the solar hot water system, and include the embodied emissions of the tank, collector and other components, and the emissions produced in its manufacture. Similarly, life cycle emissions for a domestic PV system include emissions from all materials and fabrication steps (eg. MG-Si production, wafer production, cell manufacture, and panel fabrication), plus emissions due to the BOS components.

Following on from Eq. 6, the following expression will give the ratio of electrical to thermal CO_2 emissions based on a life cycle analysis:

$$\begin{bmatrix}\text{Ratio of electrical to}\\ \text{thermal value}\end{bmatrix} = \frac{\begin{bmatrix}\text{life cycle emissions}\\ \text{of conventional electricity}\end{bmatrix} - \begin{bmatrix}\text{life cycle emissions of}\\ \text{PV electricity}\end{bmatrix}}{\begin{bmatrix}\text{life cycle emissions of}\\ \text{conventional hot water}\end{bmatrix} - \begin{bmatrix}\text{life cycle emissions of}\\ \text{solar hot water}\end{bmatrix}} \tag{7}$$

Using life-cycle GHG emission intensities for conventional electricity generation methods (Dones and Frischknecht, 1998), the average life-cycle greenhouse gas emission in Australia was calculated as 1042 g-CO_2/kWh based on the current fuel mix for electricity generation (Electricity Supply Association of Australia, 2001). Embodied energy requirements for manufacturing a 3kWp rooftop PV installation were calculated by Dones and Frischknecht (1989) for Swiss conditions. Their results were adjusted for Australian emissions intensity and Canberra insolation to give lifetime embodied energy values of 118 g-CO_2/kW and 201 g-CO_2/kWh for monocrystalline and polycrystalline PV respectively.

Life-cycle emissions for solar and conventional hot water systems in Australia were included in a study by Crawford (2000), which uses a hybrid process/input-output methodology. Using embodied emissions results from Crawford, life-cycle emissions were derived as 119 g-CO_2/kWh and 230 g-CO_2/kWh for solar and conventional hot water heaters respectively. These results are substituted into Eq. 7 to give a ratio of 8.32 or 7.58 when mSi or pSi cells are used respectively.

The ratio is noticeably higher than when embodied emissions are not included, and favours renewable electricity generation to a greater extent. The reason is that the embodied emissions associated with a solar hot water system are high relative to the alternative, a conventional gas hot water system.

5. COMPARISON

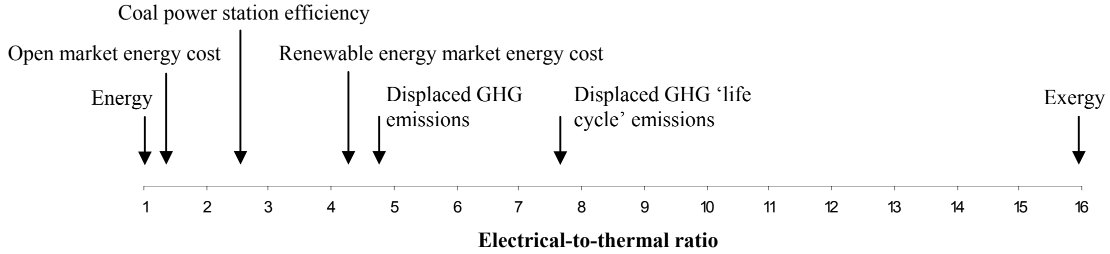

Figure 3: Summary of sample electrical-to-thermal ratios developed in this paper.

As Figure 3 demonstrates, the range of energy value ratios that could be used varies widely, from a lower value of 1, which could be used if the energy of the electricity and hot water was considered equally useful, to an upper value of 16, which could be used if the hot water output was to be used to produce electrical or mechanical work. It is suggested that the renewable energy market method provides the most realistic ratio for a PV/Thermal system as it is a renewable energy system. However this method is also most subject to variability, due to continued improvements in manufacturing technology leading to rapid price reductions, particularly for PV modules. Energy value ratios based on open market energy cost would make sense if there were absolutely no subsidies available for renewable energy. Energy value ratios based on displaced GHG emissions favour electricity even more than the other methods, due mainly to Australia's GHG intensive electricity production. These ratios will vary substantially according to the fuel mix for electricity production in the particular location.

The conclusion is that there is no simple answer for determining what energy value ratio should be used, rather the ratio should be a parameter selected for the circumstance applicable to a particular installation. The methodologies presented are intended to show how to work out the energy value ratio and provide guidance about what methodology to use for a particular application.

Establishing an energy value ratio allows 'thermoeconomic' optimisation to be carried out on systems with two outputs in terms of 'equivalent electrical LEC'. Equivalent electrical energy is obtained by dividing the total thermal energy by the energy value ratio, and adding it to the total electrical energy.

6. EXAMPLE RESULTS USING RATIO METHOD – CRYSTALLINE VERSUS AMORPHOUS SILICON SOLAR CELLS

The importance of knowing the relative value of thermal and electrical output can be shown by example. A question that has interested PV/Thermal researchers in recent times is whether or not amorphous silicon (a-Si) solar cells would be better than crystalline silicon (c-Si) solar cells for flat plate PV/Thermal applications. The main advantage of a-Si cells is a lower temperature coefficient of ≈-0.1%/K compared to –0.4%/K for c-Si (Bücher, 1995), which means lower PV efficiency reduction as the temperature of the cells increases. It has been suggested that a-Si cells may even have a slightly positive temperature coefficient for their 'stable' efficiency, due to a reduction in the Staebler-Wronski degradation when a-Si cells are operated at higher temperatures over the long term (Hof et al., 1996). The main disadvantage of a-Si cells is that they start at a lower efficiency, and therefore the cost the other PV/Thermal system components (thermal collector, tank, etc) is higher relative to the electrical output for a given area of collector. Typical stable module efficiency for a-Si cells is about 6% (Guha, 1996), whereas around 14% efficiency could be expected for commercially available c-Si modules in the same price range.

Table 5 shows how levelised energy cost is calculated for a domestic style PV/Thermal system. Energy results are based on a 4m^2 PV/Thermal collector located in Canberra, and are calculated using the same TRNSYS model as for the solar hot water system above, but with a Type 262 detailed PV/T collector model (Coventry et al., 2001) instead of a Type 1 flat plate collector model. It is assumed the cells have an absorptance of 0.9, and emissivity of 0.3 (LESO-PB/EPFL et al., 2000) and are attached to the collector plate with conductive tape. A glass cover with a 30mm air gap protects the cells. As above, photovoltaic module costs are $5.36/Wp for c-Si modules, and the same cost is assumed for a-Si modules. Remaining system costs are based on one of the solar hot water systems surveyed that has a 4m^2 collector, 300L tank, and a LEC for hot water of $0.088, which is slightly above the average of those surveyed. BOS costs for the PV are absorbed by the hot water collector cost.

Figure 4 compares a PV/Thermal system with a-Si and c-Si cells using the method above for a range of energy value ratios, and shows that a-Si cells would be preferable to c-Si cells when the energy value ratio is below about 4.5 for a flat plate PV/Thermal domestic system. This example demonstrates that understanding what ratio should be used in the particular location and economic environment impacts fundamentally on the optimum design of the system.

Table 5: Sample calculation of LEC for a c-Si PV/Thermal system

Item	Unit	Value
Collector area	m^2	4
Volume of tank	L	300
Cell efficiency	%	14%
Temperature coefficient	%/K	-0.4
Yearly insolation	kWh/m^2	1990
Electrical energy collected	kWh	912
Useful electrical output	kWh	821
Hot water energy demand	kWh	3483
Tank auxiliary energy used	kWh	1717
Thermal solar energy used	kWh	1766
Cost of collectors without cells	USD	$1040
Cost of cells	USD/Wp	$5.36
Power cost	USD/Wp	$1.22
Tank cost	USD	$1765
Installation cost	USD	$300
Cost of equivalent conventional HWS	USD	$530
Total system cost	USD	$6258
Energy value ratio		5
Equivalent electrical energy collected	KWh	1174
Energy Inflation	%	3.0%
System lifetime	Years	20
Discount Rate	%	7.82%
Levelised equivalent electrical energy cost	USD/kWh	$0.42

Year	Savings (USD)	Sum of Present Value (USD)
0	-6258	
1	503	-5791
2	518	-5345
3	534	-4919
4	550	-4512
5	566	-4124
6	583	-3752
7	601	-3398
8	619	-3059
9	638	-2735
10	657	-2426
11	676	-2130
12	697	-1848
13	718	-1578
14	739	-1321
15	761	-1075
16	784	-840
17	808	-615
18	832	-401
19	857	-196
20	882	0

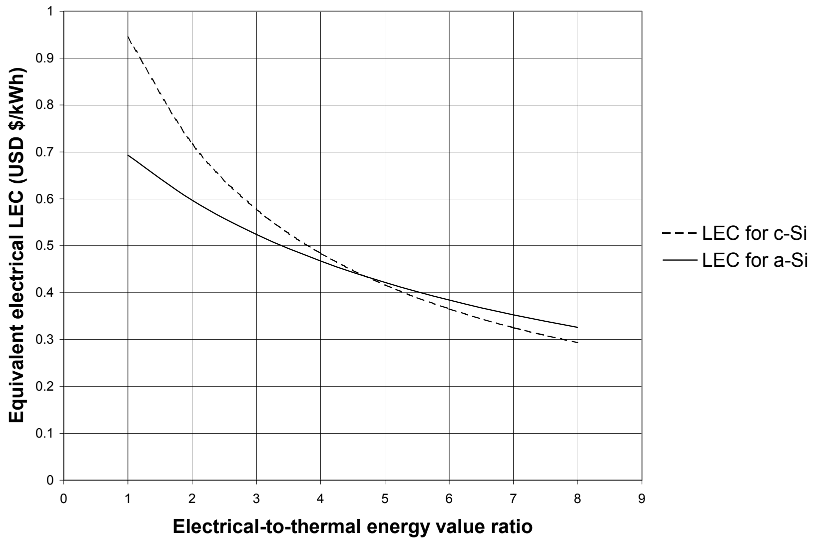

Figure 4: A comparison of the equivalent electrical LEC obtained by a PV/Thermal system using a-Si and c-Si solar cells for a range of electrical-to-thermal energy value ratios.

7. CONCLUSION

A ratio between the value of electricity and hot water allows a rational approach to PV/Thermal system design. A range of ratios have been developed that compare the value of electrical and thermal output for a domestic style system. It is suggested that a PV/Thermal system should use a ratio based on a renewable energy market approach unless there are strong environmental or economical reasons not to.

It has also been shown by example that the ratio chosen can have an important impact on the optimum design of a PV/Thermal concentrator system. For the example PV/Thermal system shown, amorphous silicon cells would result in a lower levelised energy cost than crystalline silicon cells if the energy value ratio is below 4.5, but a higher levelised energy cost above this value.

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