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Solar Energy for Industrial Rooftops: An Economic and Environmental Optimization

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Abstract

Industrial applications present a largely undeveloped market for solar technologies, especially heat applications in the medium temperature range. At present, the vast majority of industrial process heat demand is met by natural gas, but several solar technologies are available which could potentially displace a meaningful fraction of the gas used in this application. The flat rooftops of factories can support solar thermal (ST) collectors, photovoltaic (PV) collectors, or a mix of both. However, determining the best solar mix is not straight-forward due to the number of parameters involved. To address this challenge, this paper conducts a multi-pronged optimization for several metrics in several characteristic locations around the world to maximize solar performance and minimize the system cost and environmental impacts. The environmental impacts considered here include the embodied energy and embodied greenhouse gas emission during the solar technology manufacturing process. Annual optimizations were conducted for each location using TRNSYS and Genopt. A particle swarm optimization (PSO) method was used in all optimizations to find the global optima of the stochastic trends. Thus, monocrystalline PV and linear Fresnel solar thermal collectors were compared via an hour-by-hour optimization of various objective functions was performed in—Sydney, Australia; Andir, China; and Prescott, USA. The objective functions were the embodied energy payback time, embodied greenhouse gas emission payback time, system performance, levelized cost of energy, and a single function that combines these indicators. Our results indicate that in locations where the direct normal irradiation is high, the optimum ST fraction increases. In Andir, China, Sydney, Australia, and Prescott, USA the resulting system performance indicated that ST system should occupy (50, 30, and 53) % of the available area, respectively. However, in the same locations using embodied energy, greenhouse gas emission and the economic indicators, the optimum ST area to available space ratio is (100, 70, and 100) %, (45, 0, and 90) %, and (19, 0, and 100) %, respectively. A sensitivity analysis of the solar technologies cost variation, interest rate, natural gas, and subsidies was also conducted. Although these variables are significant for the absolute LCOE and system feasibility, it was found that the optimum solar mix is impacted by the interest rate or subsidies and the natural gas price has only a marginal impact on the optimum solar mix. Overall, we believe this study provides guidance on how to compare different solar technologies based on critical indicators.

Nomenclature

EE	Embodied energy	$CO2_{eq}$	Equivalent carbon dioxide
PBT	Payback time	NG	Natural gas
ST	Solar thermal collector	LT	Lifetime
PV	photovoltaic panel	LCC	Life cycle cost
SF	Solar fraction/ contribution	LCOE	Levelized cost of energy
GHG_e	Greenhouse gas emission	CT	Carbon tax
$EGHG_e$	Embodied greenhouse gas emission	ETS	Emission trading scheme

HRSG	Heat recovery steam generator	$	US dollar
BOS	Balance of system	**Subscript**	
PSO	Particle swarm optimization	el	Electrical
GHI	Global horizontal irradiation	th	Thermal
DNI	Direct normal incident	e	Emission
i	Discount rate	eq	Equivalent

1. Introduction

Research and development efforts have largely been aimed at extracting the maximum possible useful energy per unit area from solar technologies by improving the solar-to-electric efficiency of photovoltaic panels (PV), boosting the output and the temperature range of solar thermal collectors (ST), and generally reducing the total installed cost per unit of energy output. Moreover, following the Paris agreement in 2015, it was decided that carbon emissions should be mitigated, with countries choosing a mix of regulations, imposing direct carbon taxes, or implementing emission trading schemes (ETS) (Jayaraman and Kanitkar 2016) – all of which benefit solar collectors.

While residential solar (PV and ST) and large-scale solar farms (PV and concentrating ST) have seen a lot of success in recent years, the authors suggest that manufacturing industries will also adopt solar technologies in the near future. In particular, industrial process heat applications consume a lot of primary energy globally – 85 EJ/year, where 30% of this energy comes from natural gas (Philibert 2017). This demand could potentially be offset by solar collectors installed on factory rooftops. Solar thermal collectors seem a natural choice for this since they can directly generate the high (thermodynamic) quality heat required, but the electricity derived from photovoltaic modules could just as easily be converted to heat. Thus, solar technology choice is not clear for industry and there is a continuous competition between solar technologies. Choosing between these technologies depends on the system performance, the local solar resource, the environmental impact, and the system cost. Although these systems are considered clean in their usage stage, they are not without environmental impact during their whole lifetime (Ardente et al. 2015).

Solar collectors aim to optimize the solar output per unit area. Some designs have coupled PV with ST – in so-called photovoltaic thermal collectors (PVT), but most of the commercial designs are only suitable for low-temperature applications. Therefore, some recent PV/ST hybrid designs have been proposed which heat at a higher temperature, typically utilizing concentrated light (e.g. the CPVT design proposed by (Joshi and Dhoble 2018)). Beam-splitting PVT designs have uncoupled the technologies to produce high temperatures heat output, and improve the PV efficiency by filtering the solar irradiation to select the best radiation wavelength that matches with the PV spectrum (Crisostomo et al. 2015). Other studies propose new designs for thermal collectors that can produce high-temperature heat and be easily installed on factories rooftops (Li et al. 2017). However, all of the proposed new designs are not mature yet, and hence, side by side PV/ ST configuration may present a promising solution. (Mousa and Taylor 2017) have compared the performance of several PV/ ST configurations for an industrial application using resistance heating to convert electricity to heat and found that a side by side PV-ST configuration can provide better performance than using PV or ST alone in some locations. The co-authors (Mousa and Taylor 2018) have also compared various PV/ ST configurations using solar assisted heat pumps to convert electricity to heat with a specific coefficient of performance (COP) and found that the side by side PV/ ST can produce a high energy output compared to PV and ST. However, these comparisons cover only one aspect of the study. Other crucial factors affect the selection of the best technology such as the technology cost and life-cycle environmental impacts.

Serval studies have assessed the life cycle impact of solar photovoltaics (Fthenakis and Kim 2011; de Wild-Scholten 2013), solar thermal collectors (Battisti and Corrado 2005; Kylili et al. 2018), and

PVT collectors (Raman and Tiwari 2008; Agrawal and Tiwari 2010). Moreover, the life cycle impact of these technologies has been compared on many occasions (Carnevale, Lombardi, and Zanchi 2014) (Michael and Selvarasan 2017). Solar technologies cost has been assessed in several studies such as (Jakhrani et al. 2012; Gavagnin et al. 2017), were technologies cost varies between locations depending on many factors such as the technology price, installation and maintenance cost and balance of system components costs. There is no study that optimizes the side by side PV/ ST mix based on their performance, economic and environmental impact for rooftops industrial applications.

In this paper, a life cycle objective function that combines the system cost embodied greenhouse gas emission and embodied energy along with the solar technology performance (solar contribution) will be optimized using TRNSYS and Genopt software to find the best mix of solar technologies on a factory rooftop. This optimization will be performed in several locations, three good solar resource locations — Sydney, Australia, Andir, China, and Prescott, US. These locations have been selected to reflect different irradiation and direct normal incident (DNI). Monocrystalline PV and linear Fresnel solar thermal collectors will be compared in this study. These technologies were chosen because they can be easily installed over rooftops. Additionally, monocrystalline PV is the most efficient among all solar PV alternatives and Fresnel thermal collectors can supply medium temperature heat at high efficiency.

2. Solar System

2.1. System design

A sterilization industrial application that requires steam at 134 °C was investigated. Constant load requirements were used, with the total matching the demand provided by a manufacturer (Bany Mousa and Taylor 2016). The total annual steam demand is 624 tonnes and the required steam enthalpy is 2,745 kJ/kg, which is equivalent to an annual thermal load of 1,668 GJ. In this system, the solar thermal collectors with an outlet heat transfer fluid temperature of 180 °C feed a heat recovery steam generator (HRSG) which is coupled with a preheater that can recover the fluid which goes to the storage tank at 105.5 °C. The annual performance of this low-temperature steam application has been modeled and validated in TRNSYS (Bany Mousa and Taylor 2016; Mousa and Taylor 2018). It was found that the load profile has a slight effect on the annual performance due to the large heat transfer fluid flow rate. Therefore, to accelerate the simulations and minimize the optimization consumed time, a constant steam average flow rate has been used to simulate the load annual demand

The HRSG inlet fluid temperature was maintained at 180 °C. therefore, a gas - boosted auxiliary heater is added to boost the temperature up during the low irradiation time or supply the load if there is no solar irradiation. If the tank temperature exceeds the required temperature, the normal temperature fluid is added to cool the heat transfer fluid temperature down to 180 °C. Fig 1 shows the side by side solar system configuration schematic diagram in TRNSYS (TRNSYS types are shown in the diagram). Both solar photovoltaics and solar thermal collectors are used to supply the industrial load simultaneously; the PV system is heating the storage tank through a heat pump (presented by a thermal heating device and equation) that converts the generated electricity into heat with 1.5 COP (Mousa and Taylor 2018), however, the thermal collector heats the tank directly as it generates heat. A differential controller is added between the thermal collector and the tank, and another controller is added between the solar assisted heat pump and the tank to ensure that the tank content does not boil or flow back if there is no solar irradiation.

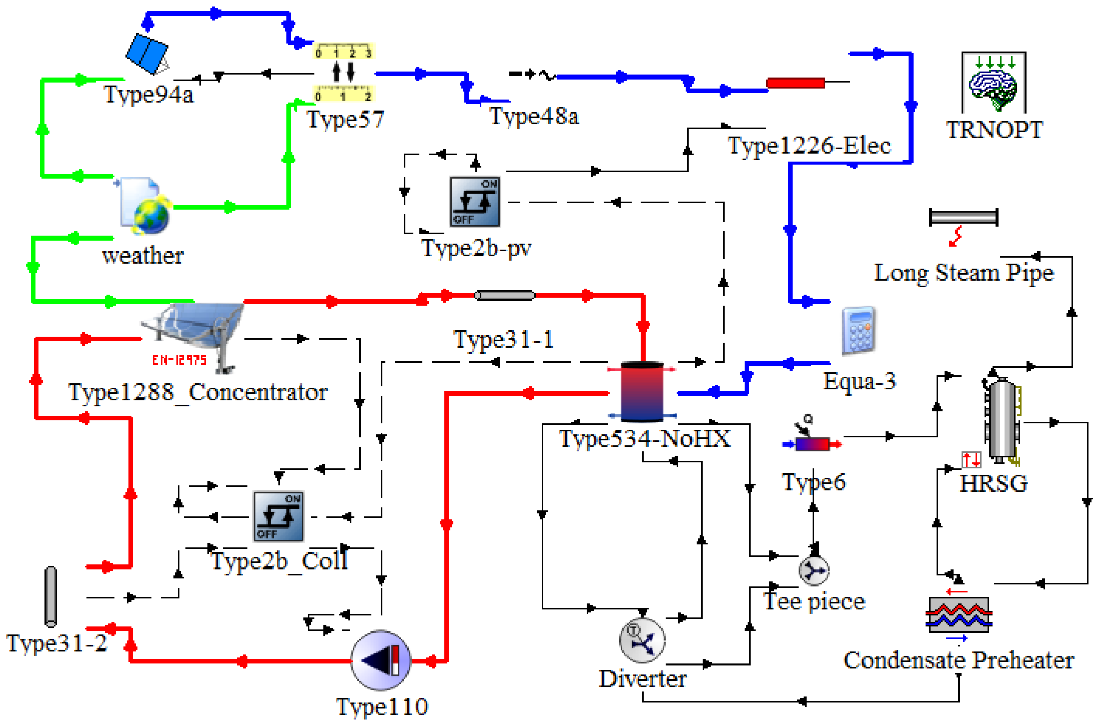

Fig 1. Industrial system schematic diagram in TRNSYS

2.2. Solar technologies cost

PV module prices have dropped rapidly during the last decade. However, these prices vary between locations as the module price, balance of system (BOS) and installation costs vary. This variation is due to the regional differences such as domestic support policy, manufacturing price, and labor cost (IRENA (2018)). Installed PV average prices in various locations have been used in this study. PV costs vary between residential (<10 kW), commercial (<500 kW) and utility (>500 kW) sectors. Our industrial application reflects a small commercial sector (<100 kW application), therefore, the estimated costs of PV technology between residential and commercial sector from (IRENA (2018)) has been used. The PV estimated cost includes the installation cost in each location.

Fresnel collector estimated capital cost for a mass production (x1,000) is \$560/m^2 (Shirazi et al. 2016), and for a mass production (x10,000) is \$ 345/m^2 aperture (retrieved from the manufacturer cost assessment). Installation costs have been assumed to be 50% of the capital cost in the US, thus installation costs in other locations have been scaled to the US installation percentage based on the 2016 average income in each country to the US 2016 average income (see equation 1). Operational and maintenance cost in each country is deemed to be constant every year. It can be expressed as a fraction of the capital cost. PV panels outperform ST collectors economically in all locations using the estimated mass production (x1000) collector cost, and hence the mass production (x10,000) ST collector cost is used in this study followed by a comprehensive ST/PV cost ratio impact on the optimum ST/ PV distribution ratio.

$$\text{Installation cost ratio} = (\text{Installation \% in the US}) \left(\frac{\text{Country monthly average income}}{\text{US monthly average income}}\right) \quad (1)$$

Table 1 summarises the linear Fresnel collector and PV panels estimated prices including capital cost and installation in several locations (IRENA (2018)). STP280S-20 monocrystalline PV module which has 17.2% efficiency has been used in this study, therefore, the prices have been converted to a unit of aperture area (\$/m^2) based on its efficiency.

Table 1. Solar technologies estimated costs (including Installation)

Location	Installation capital cost ratio [%]	ST including Installation ($/m^2)	PV panels with installation			
			$/W (IRENA (2018))	$/m^2	LCOE $/kWh$_{el}$ (IRENA (2018))	
					Residential	**Commercial**
China	**7.26**	**370**	**1.168**	**201**	**0.1059**	**0.084**
Australia	**43.89**	**496**	**1.567**	**270**	**0.1026**	**--**
US	**50**	**518**	**2.678**	**461**	**0.1545**	**0.112**

2.3. Natural gas price

As the used auxiliary heater relies on natural gas as a conventional source of energy, it is noteworthy to look at the development of the natural gas price during the past two decades. Natural gas prices are volatile; they do not have a clear trend with high fluctuations over the time and hence the average natural gas price for 20 years before 2016 have been used in this study. Fig 2 shows the natural gas prices at the hub for several markets worldwide (Global British Petroleum 2017). The average gas price for all these markets was around 5.86 $/GJ. In all markets, the average gas prices varied by (-77 to 120) %, through this period. The end user retail prices are higher than the market price by up to 35% due to the tax and levy costs (i.e. euro countries tax and levy cost markup) (Eurostat statistics explained 2018). The final user natural gas price is higher due to insurance and the third-party profit margin. Therefore, it is assumed that the average end user retail price for industrial customers is 50% higher than the market price (i.e. 8.8 $/GJ). This is used as a base natural gas price for all studied scenarios followed by a sensitivity analysis for the market average natural gas prices due to its variation by (-77 to 120) %, that is (2.02 - 19.35) $/GJ industrial customer natural gas cost.

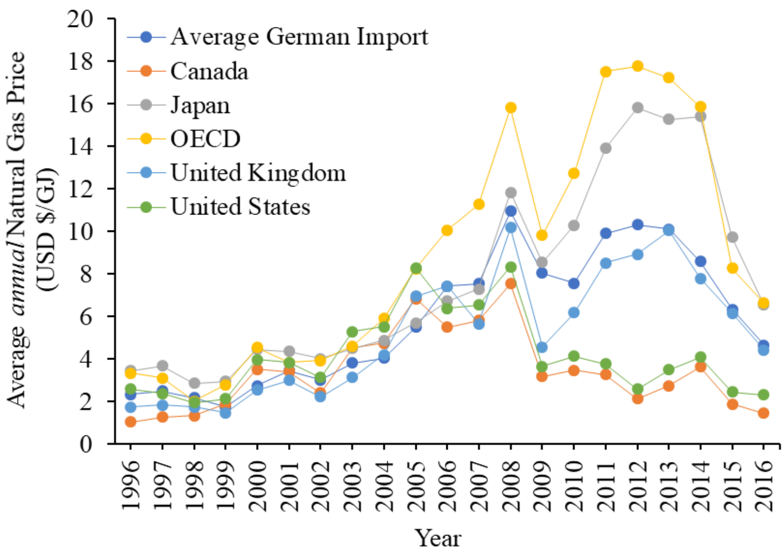

Fig 2. Global average annual Natural gas price variation

2.4. Interest rate and subsidies

This analysis assumes that a company would likely do a rooftop solar installation with near 100% debt financing since it could be considered as an improvement/renovation of their building/factory. This could be most easily rolled into a long-term building loan at a relatively low cost of finance. In this case, the interest rate provides a good approximation of the discount rate. Therefore, average lending interest rates of several indicative countries are shown in Table 2 for a short time frame of 5 years (2012-2017) (The World Bank 2018). Locations with high lending interest rates are not promising for solar technologies in general since the levelized cost is very sensitive to the cost of financing.

On the other hand, subsidies can help to reduce the effect of interest rates, they can either be imposed on the capital cost as a lump sum or annually over a specific timeline, or over the course of the system lifetime – assumed to be 30 years (i.e. 1/30th of the subsidies each year).

Table 2. Average interest rates for several countries with interest variation

Location	Average interest rate	Minimum interest rate	Maximum interest rate
China	5.1	4.4	6
Australia	5.9	5.2	7
US	3.3	3.2	3.5

2.5. Greenhouse gas emission and carbon cost

Embodied greenhouse gas emission of the used solar thermal collector and the solar photovoltaic panel of this system have been assessed and analyzed in detail by the co-authors in the selected locations (in a separate study - not published yet). The average embodied energy was assumed the same across the countries, it is found that the ST and PV primary embodied energy was 2.62 and 2.66 GJ_{th}/m^2 - aperture area respectively. All carbon tax and ETS values have been derived from (World Bank and Ecofys 2018) unless otherwise mentioned. Table 3 shows the embodied emissions factors for each of the proposed solar technologies in all selected countries along with the carbon tax implemented in each of the compared countries.

Table 3. Environmental impacts of solar technologies

Location	ST- Embodied GHG_e (kg/m^2 aperture)	PV- Embodied GHG_e (kg/m^2 aperture)	CT or ETS ($/tonne) (World Bank and Ecofys 2018)	Natural gas emission kg_{CO2eq}/GJ_{th}
China	803	556	9 [Beijing ETS]	61.84
Australia	892	595	17.95 (Australian Government Clean Energy Regulator 2015)	69.72
US	539	461	15.10	66.74

3. Methodology

The particle swarm optimization (PSO) method is one of the most popular algorithms used in the simulation-based optimizations (Askarzadeh 2017). PSO with an inertia weighting algorithm was used in this study because it is available and easily implemented with Genopt library (which can link with TRNSYS). The design variables are the storage tank volume, heat transfer fluid flow rate, solar photovoltaic area, and solar thermal collector area. After running the algorithm, the optimum storage volume and flow rate were identified and henceforth, the objective function result was plotted at these design specifications.

The objective function is the life cycle cost levelized cost of energy (LCC_{LCOE}) that combines the embodied energy cost, embodied emission (GHG_e) cost and the installed solar system cost. The embodied energy (EE) is multiplied by the average natural gas (NG) price to find the embodied energy cost, GHG_e is multiplied by the carbon tax (CT), and the system cost is multiplied by the estimated installed technology cost. The optimization results of the combined objective function along with each of the sub-objectives are shown in the results section. The following equations are used to find the optimum PV/ ST mix based on the EE PBT, GHG_e PBT, LCOE, and the combined objectives LCOE (LCC_{LCOE}).

$$EE = 2.62\, ST_{area} + 2.66\, PV_{area}$$

$$SF = \frac{Load\ (GJ_{th}) - Aux(GJ_{th})}{Load\ (GJ_{th})}$$ (Bany Mousa and Taylor 2016)

$$EE\ PBT = \frac{EE(GJ_{th})}{SF * Load\ (GJ_{th}/year)}$$

$$EGHG_e = PV_{CO2_{eq}}\left(\frac{kgCO2_{eq}}{m^2}\right) * PV_{area} + ST\left(\frac{kgCO2_{eq}}{m^2}\right) * ST_{area}$$

$$GHG_e PBT = \frac{Embodied\ GHG_e(kgCO2_{eq})}{SF * Load\ (GJ_{th}/year) * NG_e[\frac{kgCo2_{eq}}{GJ_{th}}]}$$

$$System\ Cost = PV_{area} Cost_{PV} + ST_{area} * Cost_{ST}$$

$$LCOE = \frac{System\ cost}{\sum_{t=1}^{LT} SF * Load\ (GJ_{th})/(1+i)^t}$$ (Starke et al. 2018)

$$LCC = EE(GJ_{th}) * NG\left(\frac{\$}{GJ_{th}}\right) + EGHG_e(KgCo2_{eq}) * CT\left(\frac{\$}{KgCO2_{eq}}\right) + system\ Cost\ (\$)$$

$$LCC_{LCOE}(\$/(kWh_{th}) = \frac{LCC}{\sum_{t=1}^{LT} 0.0036 * SF * Load\ (GJ_{th})/(1+i)^t}$$

4. Results and discussion

Fig. 3 shows the performance impact on the optimum solar technology's mix. The optimum performance mix tends towards using more ST collectors in the high beam irradiation locations. In Sydney/ Australia, Andir China and Prescott/ US, the GHI (in kWh/m^2) and DNI (%) were (1608, 53.2), (1906, 66.3), (1964, 75), respectively. Therefore, the location irradiation intensity and beam content are the major factors that affect the PV versus ST selection. System performance shows that ST system must occupy 50%, 30% and 53 % in Andir, Sydney, and Prescott respectively.

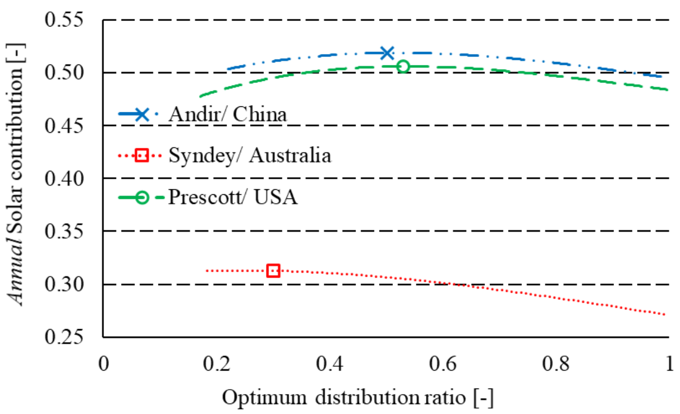

Fig. 3 Optimum solar technology mix in various locations based on the performance objective function

The embodied energy function optimization shows that in most cases the ST collector outperforms PV due to the lower embodied energy (see Fig. 4). However, in terms of the embodied greenhouse gas emission, there is a trade-off depending on the technology's embodied emission, and local resource emission factors. Regarding the embodied energy, a 100% ST is recommended in Andir/China and Prescott/ US while in Sydney/Australia, 70% ST is recommended. Based on the greenhouse gas emissions payback time, in Andir/ China and Prescott/ US, the ST collector to the total available area optimum mix is 45% and 90%, respectively, while PV is the clear winner in Sydney/ Australia.

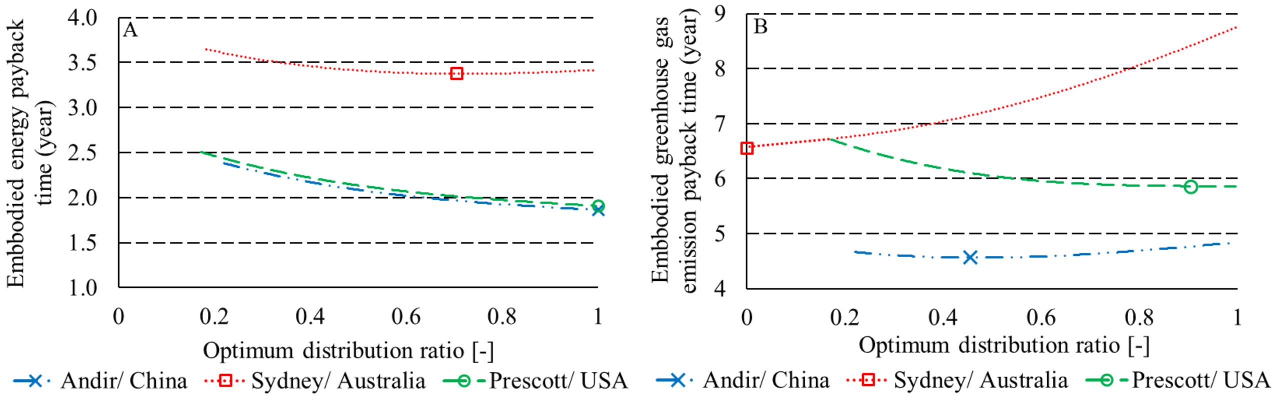

Fig. 4 Optimum solar technology mix in various locations based on the embodied objective functions: (A) Embodied energy function; (B) Embodied emission function

Of course, the cost of technology is the crucial factor that determines the true viability of these systems. Fig. 5 shows the optimum mix of solar technologies based on cost functions. Although the capital cost of an ST system installed in Prescott/ US is higher than a PV system, 100% ST is recommended due to its higher performance (e.g. point 'o' in Fig. 5 A). In Andire/ China and Sydney/ Australia, PV outperforms ST due to the high ST to PV cost ratio (e.g. points 'x' and '□' in Fig. 5 A). Fig. 5 B shows the combined life-cycle cost function in each of the selected locations. From this plot, it is clear that in Prescott/ US and Sydney/ Australia, the combined objective has the same results as the single LCOE function. However, since levelized cost engages other factors such as the performance, embodied energy and embodied emission have a slight impact on the optimum technologies mix in Andir/ China, an 81% ST to 19% PV mix is recommended in Andir/ China.

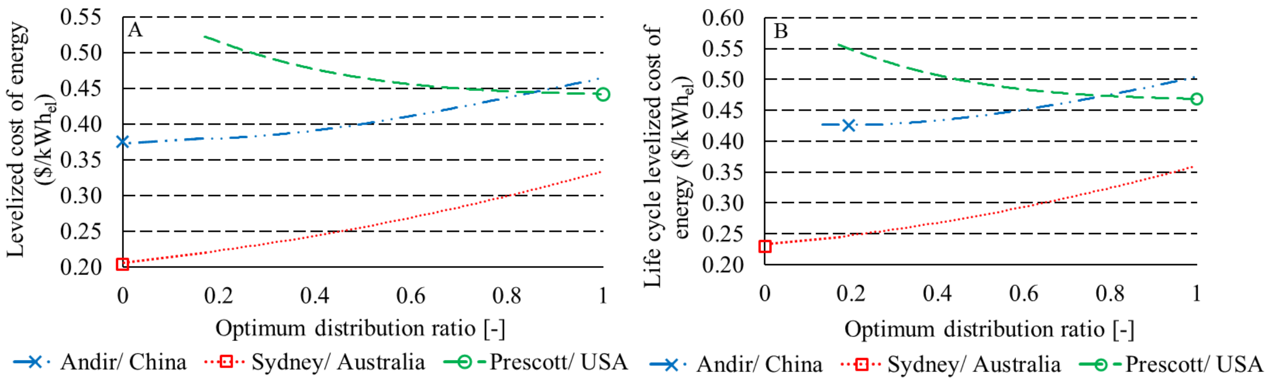

Fig. 5 Optimum solar technology mix in various locations based on cost functions: (A) Levelized cost of energy; (B) Life cycle levelized cost of energy

The calculated LCOE ($/kWh$_{th}$) can be converted to $/kWh$_{el}$ using the electricity to thermal conversion factor (COP of 1.5 for this industrial application), it is found that the optimized LCOE values in each location are in the range of (IRENA (2018)) estimated prices (see Table 1). The optimization results show that the cost function has the largest effect on the combined cost function. Therefore, several ST to PV cost ratios has been studied to see the effect of the technology cost variation on the optimum solar mix. Fig 6 shows the relation between the ST and PV technologies cost to the optimum solar mix which minimizes the combined cost function. The side by side system configuration presents a feasible solution if the solar technologies cost ratio is in the range of 0.9 to 1.3 in Australia/ Sydney. Similarly, the side by side configuration is feasible in China/ Andir and US/ Prescott if the cost ratio is between (1.2 to 2).

A sensitivity analysis for the interest rate, natural gas price variation, and subsidies from sections 2.3 and 2.4 are used to see how they affect the optimum solar mix based on the combined cost function. A Base case that has 50% optimum solar mix is used in this analysis (see Fig 6). Increasing the interest rate does not affect the optimum solar mix because it has the same effect on both solar technologies costs. However, natural gas price variation affects the embodied energy cost in the combined cost function and hence it is expected that natural gas price would influence the optimum solar mix. Using the minimum and maximum values for natural gas price shows that the optimum mix varies between (47.5 to 54) %, (48.5 to 53) % and (47 to 58) % in Sydney, Prescott, and Andir respectively. On the other hand, the optimum mix is insensitive to the subsidies because implementing any subsidy scheme will not change the solar technologies cost ratio, however, subsidies, interest rate, and natural gas price affect the absolute LCOE.

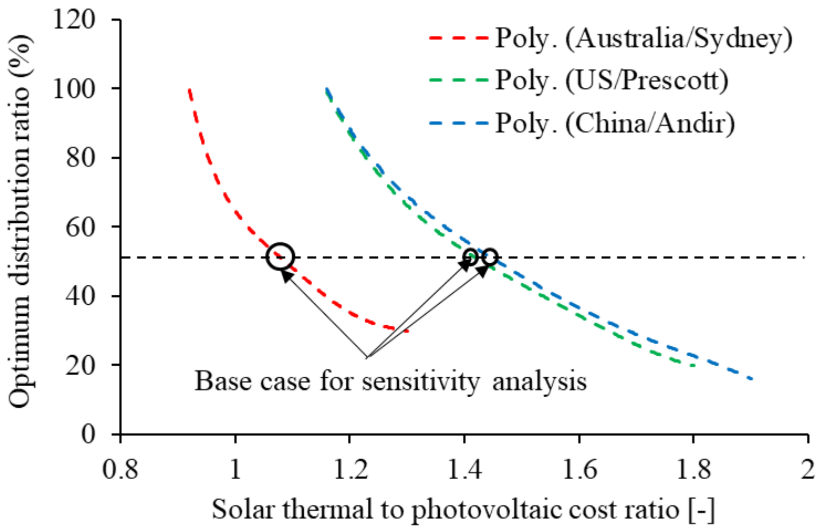

Fig 6. Solar technologies cost ratio impact on the optimum solar mix in various locations

Locations where global solar irradiation and beam irradiation such as China/ Andir and US/ Prescott are promising for solar thermal collectors, however, in locations where the DNI is lower such as Australia/ Sydney, PV has more chance to succeed.

The impact of the side-by-side system can be determined by comparing the natural gas usage reduction and greenhouse gas emission mitigation for the installed solar technologies for the industrial sector. For example, in Prescott/ US (Arizona) the solar fraction using PV or ST alone is less than 48.4% compared to 53 % using the side by side PV/ ST system. This corresponds to a 9.5% improvement for using the proper technology mix. To take this a step further, in 2016, natural gas consumption in Arizona was 392 PJ, with the industrial sector consuming 6 % of the state's natural gas (SWEEP 2017). Estimating that ~17.8 % of this goes to medium temperature industrial process heat applications as the global average (IRENA (2015)) (Mekhilef, Saidur, and Safari 2011) — e.g. 4.2 PJ of natural gas consumption for industrial process heat. In Arizona, based on the US average, it is estimated that 0.64 % of the solar sources are used for industrial heating (IEA (2017)) (U.S. Energy Information Administration 2018), and hence they are potentially displacing 26.8 TJ of natural gas in Arizona. Therefore, assuming that the solar resources of Prescott represent the whole of Arizona and that industry in the state - applying the side by side configuration on the installed solar technologies for this application, the optimum technology mix shown in this study would provide a means to offset 2.55 TJ more natural gas consumption than PV or ST alone. This reduction in natural gas consumption corresponds to 170 tonnes of $CO2_{eq}$ mitigation in Arizona according to the natural gas emission factor in the US (see Table 3). The similar offset is possible in many locations around the world. While a detailed analysis of more locations (including the rest of the state of Arizona) is outside the scope of this work, but there is significant potential for optimization as solar technologies are adopted in industrial process heat applications.

Conclusion

This study provides a comparison between potential solar thermal and PV technologies for providing medium temperature heat to factories by installing solar collectors on their rooftops. The analysis used several objective functions and a simplified combined life-cycle cost function. It shows that a *mixture* of PV and ST technologies in a side by side configuration can optimize the economic and environmental objectives. Our results indicate that there is a trade-off between the various objectives. In locations where the direct normal irradiation is high, the total useful energy output of solar thermal collector is higher, whereas, lower direct normal irradiation locations are better for PV technology, however, this is only one aspect of the comparison. To perform a comprehensive comparison, embodied energy, cost, and environmental impact were also considered. Our methodology relies on simulation-based optimizations using TRNSYS and a Genopt PSO algorithm. The resulting embodied energy and emissions results were converted to cost using a constant fuel and carbon tax price in each location. A sensitivity analysis of interest rate, natural gas price, subsidies and technologies cost revealed that the optimum ST/ PV mix is insensitive to interest rate and subsidies, but the optimum solar mix ratio is highly dependent on the technology cost. It was found that the natural gas price affects the embodied energy cost in the combined cost function and hence natural gas price variation has a slight effect on the optimum solar mix. Nevertheless, all these factors: interest rate, subsidies, natural gas, and technology cost have a significant effect on the absolute LCOE value and system feasibility indeed. The significance of this new configuration can be expressed in the form of natural gas savings and greenhouse gas emission mitigation relative to implementing a single technology. In Arizona alone, up to 170 tonnes, CO_{2eq} reduction is possible using the optimum side by side configuration.

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