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The future of low carbon industrial process heat: A comparison between solar thermal and heat pumps

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ABSTRACT

Low carbon heat generation is now a major concern for many industries to achieve sustainability targets, however, it is not always clear which renewable or low carbon process heat technology is the most economical. This article develops a techno-economic assessment methodology to compare the cost effectiveness of solar thermal and electricity powered vapor compression heat pumps for process heat generation. Using key investment and performance indicators, it clearly elucidates the lower cost renewable or low carbon heat technology under most conditions found in low temperature industries. The analysis also calculates the maximum turn-key specific investment, inclusive of all material, labor, and financial costs, for solar thermal to remain financially competitive against heat pumps, serving as a target for the solar thermal industry. The methodology, which is independent of plant size, process temperature, and technology, reveals key results when applied to three cities in Europe of varying solar irradiation and current electricity costs. In Seville, the maximum turn-key specific solar investment is typically greater than 500 €/m^2_{ap}, meaning that solar thermal will most likely provide lower cost heat than heat pumps. The case for Stockholm is the opposite, with the maximum investment being primarily less than 300 €/m^2_{ap}, a challenging turn-key solar plant investment target that leads to the superiority of heat pumps in this region. There is a wide range (230–1000 €/m^2_{ap}) of maximum turn-key solar thermal investment figures for a central German location (Würzburg), indicating that either technology could be selected, but this is highly dependent on the process and other boundary conditions. Therefore, at any time now or in the future, the developed methodology can flexibly compare solar thermal and heat pumps so that the lower cost process heat technology can quickly be selected, while also providing a plant investment target for the solar thermal industry.

1. Introduction

As industries begin to reduce their carbon footprints in accordance with corporate, national, and international goals, renewable and low carbon heat will replace current fossil fuel options. However, it is often unclear what the most economical technology measures are. To help industries with their investment decisions, this article develops a robust methodology to determine which technology can produce low temperature process heat at a relatively lower cost: solar thermal (ST) or a vapor compression heat pump (HP) powered with grid electricity.

General economic assessments for renewable energy have been frequently published, with some studies focused specifically on renewable heat for industrial processes and their calculated heat costs and investment payback time (Silva et al., 2014; Lima et al., 2015; Ommen et al., 2015; Sharma et al., 2018). However, few studies have comparatively assessed ST and HP. A national study of renewable and low carbon energy options for Australian industrial gas users shows multiple levelized cost of heat (*LCOH*) scenarios of various process temperatures against natural gas (Lovegrove et al., 2015). These results indicate that solar process heat at 200 °C is less expensive when natural gas costs > 36 €/MWh, and at 100 °C, when natural gas costs > 12 €/MWh, at a site with an annual irradiation of 1850 kWh/m^{2}a. Turn-key ST plant investments are estimated to be between 350 and 1000 €/kW_p or 500 and 1400 €/m^2_{ap} (assuming 0.7 kW_p/m^2_{ap}, a standard conversion adopted from the International Energy Agency – Solar Heating and Cooling research community) for flat plate and vacuum tube collectors. In the same study (Lovegrove et al., 2015), electrically driven vapor compression HPs are economically competitive when producing heat at 100 °C against a natural gas cost > 24 €/MWh, though this is highly dependent upon Coefficient of Performance, electricity cost, and operational hours. A similar report details renewable and low carbon energy integration in industry, focusing on ST, HP, and biomass (Taibi

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Nomenclature

Abbreviations

CO_2e	carbon dioxide equivalent emissions
EU	European Union
HP	heat pump
IEA	International Energy Agency
MC	Monte Carlo simulation
PV	photovoltaic
ST	solar thermal

Symbols

COP	coefficient of performance, kW_{th}/kW_{el}
C_{el}	electricity cost, €/MWh_{el} or €/kWh_{el}
	inflation of electricity costs, %
DR	discount rate, %
e_{sol}^{PV}	specific annual PV yield, $kWh_{el}/kW_{p,el}$
η_{COP}	heat pump efficiency
ε_{gen}	validation error, €/m^2_{ap}
$F'_{ST,HP}$	correction factor for practical load cases (ST vs HP)
F_1	parameter of $F'_{ST,HP}$ correction factor
F_2	parameter of $F'_{ST,HP}$ correction factor
FLH	full load hours, h/a
I	specific plant investment, €/m^2_{ap}, €/kW_{th}, €/$W_{p,el}$
ICR	investment cost ratio, (€/m^2_{ap})/(€/MWh)
$LCOE$	levelized cost of energy/electricity, €/kWh_{el}
$LCOH$	levelized cost of heat, €/kWh
OM	operation and maintenance, %
q_{sol}^{ST}	solar thermal plant specific yield, kWh/m^2_{ap}
Q	thermal energy, kWh_{th}
$RMSE$	root-mean-square error, normalized, %
SD	degradation rate, %
ST_{elec}	electrical used by solar thermal, kWh_{el}
$\theta_{0,1,2,3,4,5}$	model coefficients
T_{amb}	ambient temperature, °C
$T_{P,flow}$	process load flow temperature, °C
T_{sink}	heat sink temperature for the heat pump, °C
T_{source}	heat sink source temperature for the heat pump, °C
$UA_{storage}$	heat losses for the thermal storage, W/K
W	work (electric), kWh_{el}

Scripts

ap	aperture
el	electrical
gen	generalized calculation of term
HP,ideal	ideal operational case of a heat pump
local	local calculation of term
market	market conditions of term
sol	generated solar energy
th	thermal
val	validation set of term

et al., 2012). The calculated "break even" price for an installed ST plant against other fuel stocks varies between 200 and 300 €/kW_{th} for low (1200 kWh/m^2) and high (2000 kWh/m^2) solar irradiation locations respectively, or 140–210 €/m^2_{ap} when assuming a 0.7 kW/m^2_{ap} conversion. The authors state that HP will compete with ST as a low carbon heat technology but they do not directly compare the two technologies to determine under which conditions one would produce heat at a lower cost than the other. An assessment of subsidies and costs in the European Union (EU) energy sector, undertaken by Ecofys (2014), shows that when ST is coupled with a gas boiler, it is typically less expensive than an air source HP, though in the domestic, not the industrial, sector. A wide reaching study by IRENA (2015) compiles the renewable energy options for industry by 2030, predicting that ST generated heat (< 150 °C) could cost anywhere between 30 and 90 €/MWh, and HP generated heat anywhere between 20 and 50 €/MWh. While this study provides an indirect technology comparison, its results allow limited flexibility in ST specific yield, technology cost, electricity cost, and HP operation time, with the latter set to a very optimistic 7000 h. The ongoing ENPRO project, led by AEE INTEC, takes this assessment one step further, providing support for energy audits, renewable heat integration, and techno-economic analysis of both ST and HP (Wilk et al., 2017) in the industrial sector. Pérez-Aparicio et al. (2016) develop a comparison methodology between ST and a photovoltaic (PV) powered HP, similar to the work of Meyers et al; Meyers et al. (2016; 2018). While the methodology from Pérez-Aparicio et al. (2016) is applied to a handful of sites around the world, it only assesses a HP at a fixed performance and process temperature at 60 °C, serving as a preheater to achieve 200 °C with PV electrical resistance heating. In addition, the results do not allow for flexibility in future technology costs and are not supported by energetic simulations. Neyer et al. (2018) use their developed assessment tool to compare a PV powered air-water heat pump against a solar thermal system for domestic needs in Madrid, indicating a slight economic advantage for the former but did not address potential application for industrial process heat demand.

Previous economic assessments have generally focused on comparing current process heat technology, i.e. fossil fuel boilers, with a potentially lower cost renewable or low carbon heat technology, ST or HP. In the coming years, the question will shift from "Can renewable or low carbon process heat be less expensive than fossil fuel heat?" to "Which renewable or low carbon heat technology is better suited to achieve the industry's carbon reduction or sustainability goals?" In this light, this article's main objective is to develop a robust methodology coupled with an exemplary case study in Europe that determines which renewable or low carbon process heat technology, ST or HP, can produce heat at a relatively lower cost, taking into account various financial and industrial process conditions.

2. Methodology

This section develops a methodology to assess which renewable or low carbon process heat technology, ST or HP, can produce lower cost heat under primary boundary conditions. In Section 2.1 the main influencing parameters of both ST and HP are presented. Section 2.2 describes the techno-economic comparison methodology, using said parameters. Section 2.3 uses the methodology to create assessment calculations to compare the two technologies under ideal and non-ideal conditions, leading to a universally applicable process for technology comparison, both now and in the future.

2.1. Primary boundary conditions

The energetic performance of ST and HP is subject to very specific industrial parameters that greatly influence each technology's ability to generate heat. Some, but not all, of these parameters include the industrial heat load profile and schedule, demanded temperature, and waste heat source. The type of technology selected, ranging between flat plate and compound parabolic concentrators for ST to various refrigerants, pumps, and pressure levels for HP, determines the potential thermal energy generation per year at a given cost. Due to the near