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Evaluating the economic parity of solar for industrial process heat

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ABSTRACT

Industrial process heat (IPH) uses nearly three-quarters of U.S. manufacturing sector fuel energy, with most of IPH powered by fossil fuel combustion. Appreciably reducing industrial CO_2 emissions will necessarily involve addressing IPH demand. Solar photovoltaics (PV) have contributed to the changing fuel mix of electricity generation in the United States, but on-site use of solar energy in the manufacturing sector remains insignificant. To understand the economic feasibility of IPH fuel switching, we develop an open-source process parity framework to identify conditions when solar process heat technologies can reach cost parity with an incumbent fossil fuel combustion technology. Building a case study that reflects common IPH demands and applicable solar technologies across several locations in the United States, we generalize the relationship between key parameters of solar resource, investment and fuel prices. We evaluate the use of solar thermal (ST) and PV connected electric boilers to partially substitute natural gas boilers in a brewery. Cost parity is not achieved in any analysis location for current solar system costs and fuel prices. Los Angeles County is most likely to achieve cost parity due to the higher fuel prices compared to other counties.

Introduction

The industrial sector represents a significant portion of energy use in the United States. Of the roughly 106 exajoules (EJ) of national energy use in 2019, industry accounted for 33% or 35 EJ [1]. The manufacturing subsector comprises 81% of industrial energy use, with the remaining use in the agriculture, construction, and mining subsectors [2]. The majority of energy used in manufacturing is used to provide industrial process heat (IPH): in 2014, energy use for IPH in the United States was nearly 11.5 EJ, or 74% of manufacturing fuel use [3]. The overwhelming majority—90%—of IPH is provided by fossil fuel combustion [4] and, as a result, greenhouse gas (GHG) emissions from onsite combustion for IPH in 2014 were 548.9 million metric tons carbon dioxide equivalent ($MMTCO_2eq$), or 52% of total combustion emissions for manufacturing [3].

Reducing GHG emissions associated with IPH can be accomplished by strategies that include implementing energy efficiency measures, switching to a lower-carbon energy carrier, carbon capture and sequestering the carbon in commercial products, or combinations thereof. These strategies are likely to involve investment in new capital equipment that must meet the economic criteria of companies or their business units. Low natural gas prices in the United States act as a barrier to investment in lower-carbon technologies under these investment criteria. We note that the continued growth in domestic natural gas production contributed in 2019 to a three-year low price [5].

Solar heat for industrial processes (SHIP) is one set of renewable thermal technologies available to reduce emissions related to IPH demand. SHIP converts solar energy to industrial heat using solar thermal (ST), PV assisted electrotechnologies, or hybrid systems. Although the applications of IPH span a large temperature range, from processes that use hot water to processes that melt steel, in 2014 two thirds of IPH demand in the United States was for process temperatures of or below 300°C [6]. Many exiting SHIP systems are designed to meet demands between 60°C to 250°C, while some ST systems, such as power tower (central receiver) systems, can provide temperatures of 600°C or higher [4]. PV-assisted electrotechnologies can provide heat in the same temperature range as ST systems and beyond. In addition, the module price of PV systems has dropped to 0.30–0.47USD/W in 2018 due to a highly competitive and oversupplied environment. The decrease in PV module prices is projected to continue as cumulative production rate

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Acronym or Term: Description (unit)

CHP	Combined Heat and Power
DNI	Direct Normal Irradiance (kWh/m^2/year)
DSGLF	Direct Steam Generation Linear Fresnel
DSIRE	Database of State Incentives for Renewables & Efficiency®
EB	Electric Boiler
EJ	Exajoules
FP	Current fuel price (USD/m^3)
GHG	Greenhouse Gas
HTF	Heat Transfer Fluid
IEA	International Energy Agency
IPH	Industrial Process Heat
IRR	Internal Rate of Return
LCOH	Levelized Cost of Heat
LR	Load ratio is the ratio of the design heat sink power of the solar system divided by peak hourly heat demand of the process
MACRS	Modified Accelerated Cost Recovery System
MMTCO$_2$eq	Million Metric Tons Carbon Dioxide Equivalents
NAICS	North American Industrial Classification System
O&M	Operations and Maintenance (USD)
Parity Fuel Price	Fuel price that results in process parity with the combustion, conventional heat technology (USD/ m^3)
Parity Investment Price	Overnight capital cost of the SHIP technology system that results in process parity with the combustion, conventional heat technology (USD/m$^2_{ap}$ or USD/kW)
Process Heat Load Shape	The hourly heat demand normalized to peak load (kWh/hr)
Process Parity	When the LCOH of a SHIP technology system (can include conventional heat) is equivalent to the LCOH of a combustion, conventional heat technology.
PTC	Parabolic Trough Collector
PTCTES	Parabolic Trough Collector with Thermal Energy Storage
PV	Solar Photovoltaic
PVEB	Solar Photovoltaic Electric Boiler
RMSE	Root Mean Square Error
SAM	System Advisor Model
SF	Solar Fraction
SHIP	Solar Heat for Industrial Processes
SREC	Solar Renewable Energy Credit
ST	Solar Thermal
SU	Solar utilization is defined as the annual percentage of solar energy delivered at the heat sink used as process heat
TES	Thermal Energy Storage
USD	United States Dollar
WACC	Weighted Average Cost of Capital

increases [7]. An analysis of 164 manufacturing facilities currently operating SHIP systems showed that total investment cost per installed thermal power mostly ranged between 300 and 800 USD2014/kWth for non-concentrating collectors and 800–1300 USD2014/kWth for concentrating collectors [4]. Of the manufacturing firms that operate SHIP systems in the United States, their total investment costs have ranged from tens of thousands to a few million USD [4].

The investment cost of SHIP systems is a significant factor in decision making for manufacturing facilities. Investments costs vary by SHIP technology, system size, and the presence of energy storage. Various literature sources that evaluate the cost of ST systems at different locations have been consulted to assess determinants of SHIP process parity, or the point at which the LCOH of a SHIP system is equivalent to the LCOH of a combustion heat technology. As summarized in Table 1, these sources focus on parity analysis and do not represent an exhaustive review of SHIP systems and their costs; additional sources are included in the supplementary information.

The objectives of this paper are to develop a framework to estimate the fuel prices and solar investment costs necessary to reach parity under multitude of scenarios and to investigate whether non-energy benefits significantly impact the parity between solar and conventional technologies. We illustrate the framework by applying it in a case study of a typical medium-size brewery that partially substitutes natural gas used for steam boilers with a SHIP system. This case study is selected based on the following criteria: (1) relatively large potential for solar replacement; (2) wide geographic distribution of facilities in the U.S.; (3) numerous facilities; and (4) data availability. The conditions to reach parity will be discussed for different locations. A sensitivity analysis has been conducted to explore the variance in LCOH values based on changes to input parameters.

Methods and assumptions

Process parity framework

We define process parity as the condition where the LCOH of a SHIP technology is equal to the LCOH of a combustion technology, based on assumptions of investment costs, O&M costs and other factors. The open-source process parity framework is developed to identify conditions when solar process heat technologies can reach parity with an incumbent combustion technology (https://github.com/NREL/Solar-for-Industry-Process-Heat). Moreover, we define parity investment price and parity fuel price as the solar system cost and price of fuel used by the combustion technology that results in process parity respectively.

The three major components of the process parity framework are technology models, LCOH models, and a process parity model. The technology models capture the technology specific parameters, such as technology costs and performance, used in the LCOH models. The LCOH model uses the technology model parameters and LCOH parameters to calculate the LCOH. Lastly, the process parity model changes components of the LCOH model to identify process parity, determine payback periods, and produce sensitivity analyses for different scenarios. All the components of the process parity framework and additional details of the methods and assumptions are presented in the supplementary information.

LCOH model

LCOH is a metric used to compare the cost of producing heat between different technologies in a consistent way. A modified LCOH equation sourced from IEA Task 54 is defined below in Eq. (1) where I_0 is the initial investment cost, S_0 are initial subsidies, C_t is the annualized cost, TR is the tax rate, DEP_t is the depreciation at year t, RV is the residual value, r is the discount rate, E_t is the energy delivered to the process

Table 1
Summary of literature on SHIP parity.

Authors	Industry	Location	Solar Technology	Main Factors Affecting Economic Performance
ST parity analysis with natural gas/fuel oil				
Sing et al. (2020) [8]	Milk processing industry	Malaysia	Solar collector	Collector price, collector efficiency, and discount rate
De Leon and Galione (2019) [9]	Industrial sector	Uruguay	Parabolic trough collector (PTC) and linear Fresnel technology (LFT)	Plant location, tax exemption, and size of the plant
Kurup and Turchi (2019) [10]	Brewery	California	Concentrating solar power (CSP)	Project life, federal tax rate and the solar field cost (150–200 USD/m^2)
Mouaky et al. (2019) [11]	Experiment	Semi-arid environment	Parabolic trough collector (PTC)	Solar field cost (<288 USD/m^2) and soiling[1]
Li et al. (2017) [12]	Dairy	Australia	Concentrated ST collector integrated with latent heat thermal energy storage (LHTES)	Integrated collector storage (ICS) (cost +20%, thermal output −10%)
Gabbrielli et al. (2014) [13]	Laundry, dairy, industrial sector	Various	concentrating Fresnel collectors (CSLFC)	A specific cost under 205/USDm^2 and direct normal irradiance (DNI) larger than 1900 kWh/m^2/year
Lemos et al. (2019) [14]	Dairy	Brazil	Flat plate collector (FPC), evacuated tube collector (ETC), and PTC	Cannot compete with natural gas in almost all cases
ST parity analysis with PV assisted heat pumps (1 shift/day and 5 days/week working schedule for heat pumps)				
Meyers et al. (2017) [15]	Industrial sector	Various	Solar thermal plants	ST plants < 263USD/m^2 in low irradiation locations, such as Copenhagen, and < 551USD/m^2 in high irradiation locations, such as Chile or North Africa
PV/T system parity analysis				
Riggs et al. (2017) [16]		United States	Dish concentrator PV/T	Electricity generation and price. LCOH = −0.014USD/kWh (Hawaii), and 0.0123USD/kWh (California)

[1] Soling means dust, dirt and particle accumulation on the surfaces of solar concentrations, panels or receivers.

and T is the period of analysis [17].

$$LCOH = \frac{I_0 - S_0 + \sum_{t=1}^{T} \frac{C_t(1-TR) - DEP_t \times TR}{(1+r)^t} - \frac{RV}{(1+r)^T}}{\sum_{t=1}^{T} \frac{E_t \times (1-TR)}{(1+r)^t}} \tag{1}$$

We modified the original IEA equation by reducing E_t by the tax rate TR to account for the taxation of energy production. However, this change will not affect LCOH parity between different energy systems. The LCOH is calculated in real cash values with the discount rate estimated by the weighted average cost of capital (WACC), a weighted average of debt and equity costs, and is used as an estimate of the discount rate e.g., [17,18]. A WACC of 6.4% is used as the discount rate for this analysis [19,20] The discount rate is assumed to remain constant over time which may not reflect a changing WACC due to changing market conditions. The LCOH equation assumes the 100% equity case without any debt financing structures.

Non-energy factors

There are several non-energy factors that play a role when combustion IPH equipment is replaced with SHIP, including change of in-plant and outside-plant land area, elimination of operating permit fees, reduction of operation and maintenance (O&M) costs, reduced labor costs, elimination of fuel handling costs, noise abatement, reduced air emissions, reduced water use, and reduced process controls costs [21–24]. The non-energy factors implemented in the process parity framework are limited to those for which data are available or reasonable engineering assumptions could be made: emissions-related costs, permit related costs, land area reduction estimations, and specific technology benefits. We note that our discussions with industry representatives indicate that although non-financial criteria do play a role in investment evaluation, they may not be directly integrated with the decision-making process.

Simulation overview

The primary focus of this paper is to investigate the process parity for the installation of a solar process heat system integrated in parallel with a single central boiler at a facility. The simulation seeks to answer when a facility could economically substitute its fuel consumption by solar heat. The simulation does not include detailed plant-level heat integration and control strategies. Rather, the goal is to understand the impact of location specific parameters such as incentives, solar resources, fuel prices, emission costs, taxes, etc. on economic parity. The highest level of detail on the process integration side is represented by the hourly facility steam demand determined using representative load shapes developed by McMillan et al.[6]. for industries in the U.S., and facility electricity consumption load shapes. The major steps in the simulation

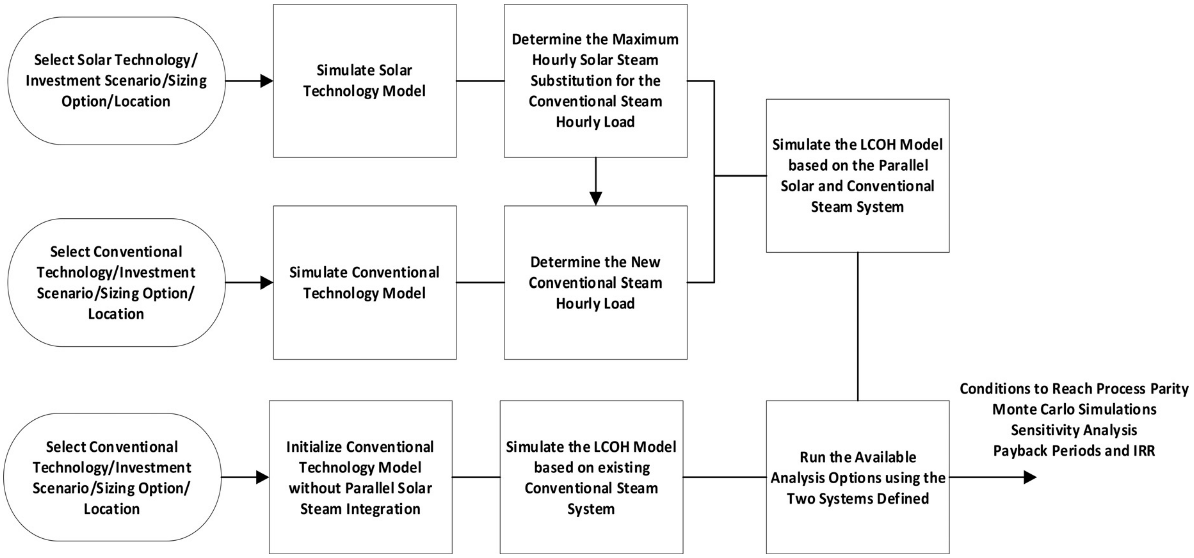


Fig. 1. Major steps in the simulation to determine process parity for selected technologies.

are described below in Fig. 1. The following subsections will describe each major step in the simulation.

Technology packages and sizing

Conventional fossil-fuel combustion technologies. The conventional technologies available for the analysis are steam boilers, and combined heat and power (CHP); however, the case study considers only a natural gas boiler. The natural gas boiler model is either operated alone or alongside a SHIP system. A single central steam boiler is selected to meet the facility steam demand to simplify the analysis and avoid nuances with addressing steam loads by rotating between multiple boilers and backup boilers. In addition, hot water demands are met by heat exchange with steam at 100% efficiency. Because we consider a single steam boiler at the facility before solar process heat integration, the boiler is sized to the peak steam load of the total process steam and hot water demand. The boiler efficiency is described by a part load efficiency curve [25]. Part load efficiencies below 25% are not included in the model as we assume the minimum operating part load for the boiler is 0.25 [25]. We assume the boiler operates continuously and when there is no process demand the boiler operates at minimum load or hot standby to avoid thermal stress due to cold starts [26].

Solar technologies. The solar technologies available for this analysis are PTC with and without TES, DSGLF, and a fixed-open rack PV system. All technology models are developed in SAM, an open-source and freely available tool developed to provide detailed hourly energy modeling for a variety of renewable energy technologies [27]. The reference system design is sized to deliver 1 MWth at the process or at the heat exchanger. We assume constant values for system parameters normalized to system size, which is necessary to extend the analysis of the selected solar technologies for installations smaller and greater than 1 MWth. In other words, the heat generation of a 2 MWth solar system is exactly two times the generation of a 1 MWth solar system. The solar field size is left as a simulation choice in the analysis.

PV-assisted electric boiler. An electric steam boiler technology model is coupled to a PV technology model from SAM or using PV assisted by the grid. When there is not sufficient electricity to meet steam demand in the PV-coupling case, the natural gas boiler is used. In the PV-coupled with grid assistance case, grid electricity is purchased using the location-specific electricity charge and demand rates when PV electricity is insufficient. Grid-assisted systems are implemented in complete replacement situations where the capacity factor of the PV is significantly below the facility capacity factor. In the PV only case, the electric boiler is sized to the peak AC power output of the PV system. In the PV grid-assisted case, the electric boiler is sized to meet the total facility steam demand as there is no auxiliary gas boiler.

Table 2
Efficiency of solar heat to steam.

System	PTC	PTCTES	DSGLF	PVEB
Efficiency to Steam	0.85 [28]	0.85 [28]	1	0.99 [29]

Technology model simulation

Simulating the relevant technology packages consists of three steps:

1 Determining solar heat and fuel at each hour for the system
2 Sizing of the technology (described in prior section)
3 Determining all capital and operating costs (solar field, emission-related, fuel cost, etc.) and deflating it to USD 2019.

The steam heat load (kWh/hr) is determined by the facility load shape. The total annual energy consumption (steam and hot water or fuel) (kWh) for a reference system described in the case study sections is distributed across the load shape to determine the hourly energy consumption of the process. For the conventional system without solar heat, this load is met by a single conventional steam boiler.

For the systems with parallel solar heat integration, at each hour the maximum possible amount of solar heat is dispatched up to the hourly heat demand. Excess solar heat is assumed to be wasted and unused to ensure the constant oil return temperature used by SAM. We define hot standby mode as the minimum possible operating load defined by the turndown ratio. For steam systems, the turndown ratio is 4 and for process heat systems the turndown ratio is 5. Thus, at any given hour with steam demand, the solar system can only substitute up to 75% and 80% of the heat demand for steam and heat systems, respectively. The conversion of the heat transfer fluid in the solar systems to the end-use is described by a constant efficiency, summarized in Table 2.

The capital and fixed operating cost assumptions are presented below in Table 3. Each component is cost deflated using the Producer Price Index (PPI) or the Chemical Engineering (CE) Index. Since we are considering the installation of a ST system for an existing facility, we assume that there are no capital-related expenses and that the conventional heat system is fully depreciated (Table 4).

Table 3
Key financial and technical parameters for brewery case study SHIP technologies [30–37].

Description	PTC	PTCTES	DSGLF	PV	EB	Depreciated Boiler
Capital Cost	270 USD2018 /m^2 $_{ap}$	270 USD2018 /m^2 $_{ap}$	205 USD2018 /m$^2_{ap}$	1520 USD2018/kW	61.02 USD2017/kW	0
O&M Cost	14.7 USD2010/kW	18.6 USD2010/kW	18.6 USD2010/kW	16 USD2018/kW	1% of capital costs	32 USD2019/kW

Table 4
Summary of LCOH model inputs.

Description of Brewery Characteristic	Assumption
Annual Production Volume	250,000 hl
Total Heat Demand	11,800 MWth
Operating Hour Schedules	Low: 4698 h, Average: 5922 h, High: 6923 h
Analysis Period	20 years
Depreciation Schedule	5-year MACRS for solar-based energy systems. 20 year straight-line for boiler.
Nominal Discount Rate	0.064
Electricity Prices	Zip code specific utility rate structures
Emission Related Costs	State-specific cost structures
Escalation Rates	Fuel: state-specific Electricity: 0.0125 O&M: 0.02
Fuel Price	State specific
Subsidies	Investment tax credit and state/utility specific subsidies
Other costs	State-specific permitting costs to construct, operate, and modify boilers

Table 5
Regression results for parity investment and fuel prices.

	PTC Parity Investment Price	DSGLF Parity Investment Price		PTC Parity Fuel Price	DSGLF Parity Fuel Price
α_0	−90.2	102	β_0	0.895	0.797
α_1 (LR)	−751	−1782	β_1 (LR)	10.3	14.8
α_2 (DNI)	0.0520	−0.0515	β_2 (DNI)	−0.0032	−0.0033
α_3 (FP)	753	1262			
R^2	0.97	0.98	R^2	0.84	0.87
RMSE (Train)	12.1	27.2	RMSE (Train)	0.055	0.060
RMSE (Test)	12.3	26.6	RMSE (Test)	0.052	0.058

LCOH model simulation

The LCOH for each solar and conventional technology system is calculated using the equation defined in the LCOH model section. The LCOH model inputs for the case study are described in Table 4. The annual production volume and total annual heat and electricity demand is determined from the reference system described in the supplementary information. The heat load shapes are based on a dataset that relates the annual heat usage by temperature for a facility by the number of employees and other factors [6].

Locations are defined on a U.S. county basis. The parameters that vary by location include the solar technology weather file, emission costs, labor burden rates, incentives, boiler permit costs, fuel prices, land prices, electricity rate structures, etc. The analysis locations are selected based on the five breweries with the greatest annual heat consumption in the U.S. [6]. The analysis length is based on typical lifetimes for the technologies in the systems [38,39]. The discount rate selection is described in the LCOH model section. The electricity prices are selected using the Utility Rate Database for the zip code of the analysis locations.

Process parity calculation

The point of process parity is determined by adjusting LCOH parameters in the conventional and solar-based systems until the LCOH is equivalent between the two systems. Three process parity approaches are considered in this analysis:

1. Adjust the ST plant overnight capital cost (USD/m^2) in the solar-based system until the LCOH is equivalent to the conventional system.
2. Adjust the fuel price for both the solar-based system (integrated in parallel with the existing conventional technology) and the conventional system until the LCOHs are equivalent.
3. Adjust the fuel price for the conventional system until the LCOH is equivalent with a ST system that completely replaces the conventional system (PV technologies with grid assistance)

A generic root finding algorithm is used to identify the parameter value (fuel price or ST plant overnight capital cost) to reach parity. This calculation is repeated for different ST sizes to generate the investment and fuel parity curves found in the results sections.

Brewery case study description

Beer brewing is a subset of the beverages industry (NAICS code 3121), which in the United States in 2014 used approximately 91 PJ of energy, or 0.5% of total manufacturing fuel use [40]. Process heat demand is almost exclusively provided by natural gas-fired boilers and accounts for 42% of total beverage industry energy use [40]. Natural gas combustion for process heat generated the equivalent of 1.9 million metric tons CO_2. As of 2018 there were 3890 breweries in the United States, with at least one in every state, the District of Columbia, and Puerto Rico [41].

The main investment scenario considered for solar process heat in the brewery industry is the partial substitution of natural gas consumed to meet steam and hot water demands by solar heat. We recognize that other investment scenarios, such as construction of a new, greenfield facility, may use different financial criteria. Specifically, we assume a brewery is evaluating the installation of a solar technology to be operated in parallel with the existing gas boiler. The existing boiler is assumed to be fully depreciated, based on the observation that boilers above 10.55 GJ/hour are typically fully depreciated based on their boiler age [42]. The existing boiler is assumed to fire natural gas, as natural gas is the largest fuel category for boilers in the U.S. beverage in-

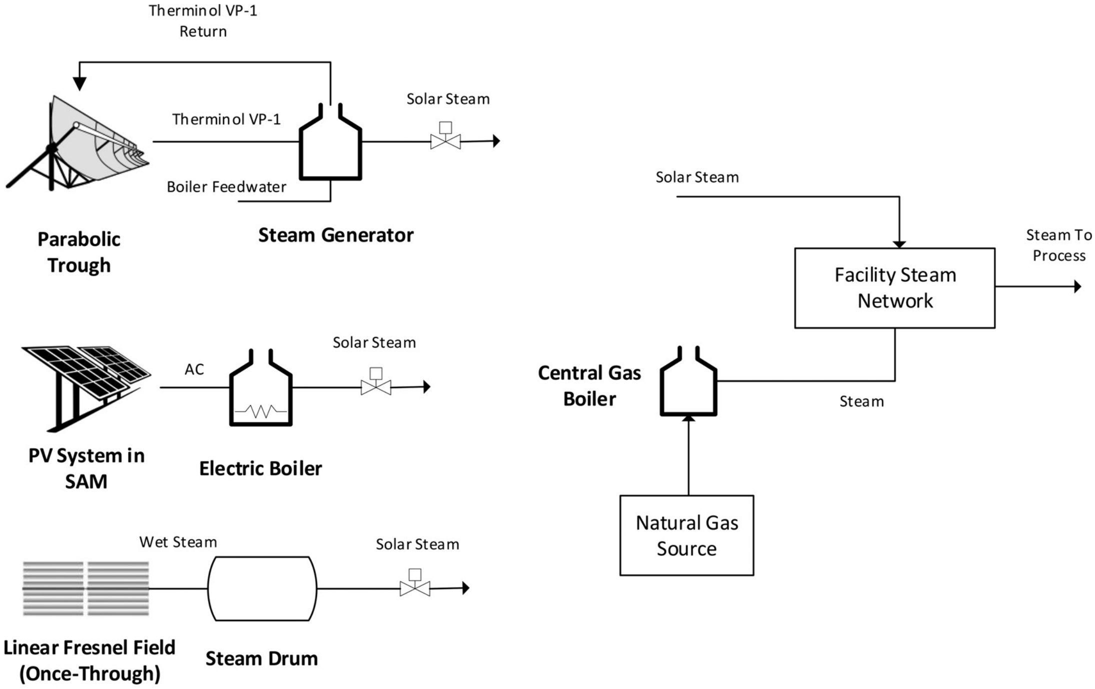
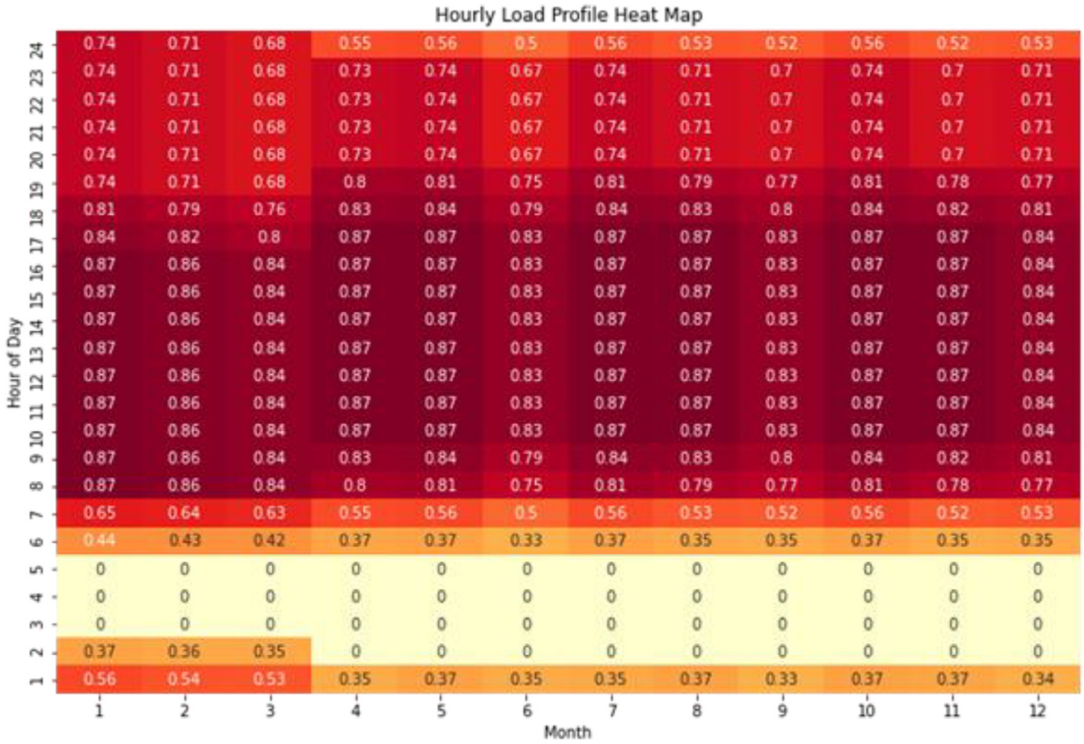


Fig. 2. Solar heat integration schemes and existing natural gas boiler for the brewery case study. The PTC scheme assumes heat transfer between feedwater and steam in a HEX. The PVEB scheme assumes an EB assisted by a PV array. The DSGLF scheme assumes direct stream generation.



Hour of Day	1	2	3	4	5	6	7	8	9	10	11	12
24	0.74	0.71	0.68	0.55	0.56	0.5	0.56	0.53	0.52	0.56	0.52	0.53
23	0.74	0.71	0.68	0.73	0.74	0.67	0.74	0.71	0.7	0.74	0.7	0.71
22	0.74	0.71	0.68	0.73	0.74	0.67	0.74	0.71	0.7	0.74	0.7	0.71
21	0.74	0.71	0.68	0.73	0.74	0.67	0.74	0.71	0.7	0.74	0.7	0.71
20	0.74	0.71	0.68	0.73	0.74	0.67	0.74	0.71	0.7	0.74	0.7	0.71
19	0.74	0.71	0.68	0.8	0.81	0.75	0.81	0.79	0.77	0.81	0.78	0.77
18	0.81	0.79	0.76	0.83	0.84	0.79	0.84	0.83	0.8	0.84	0.82	0.81
17	0.84	0.82	0.8	0.87	0.87	0.83	0.87	0.87	0.83	0.87	0.87	0.84
16	0.87	0.86	0.84	0.87	0.87	0.83	0.87	0.87	0.83	0.87	0.87	0.84
15	0.87	0.86	0.84	0.87	0.87	0.83	0.87	0.87	0.83	0.87	0.87	0.84
14	0.87	0.86	0.84	0.87	0.87	0.83	0.87	0.87	0.83	0.87	0.87	0.84
13	0.87	0.86	0.84	0.87	0.87	0.83	0.87	0.87	0.83	0.87	0.87	0.84
12	0.87	0.86	0.84	0.87	0.87	0.83	0.87	0.87	0.83	0.87	0.87	0.84
11	0.87	0.86	0.84	0.87	0.87	0.83	0.87	0.87	0.83	0.87	0.87	0.84
10	0.87	0.86	0.84	0.87	0.87	0.83	0.87	0.87	0.83	0.87	0.87	0.84
9	0.87	0.86	0.84	0.83	0.84	0.79	0.84	0.83	0.8	0.84	0.82	0.81
8	0.87	0.86	0.84	0.8	0.81	0.75	0.81	0.79	0.77	0.81	0.78	0.77
7	0.65	0.64	0.63	0.55	0.56	0.5	0.56	0.53	0.52	0.56	0.52	0.53
6	0.44	0.43	0.42	0.37	0.37	0.33	0.37	0.35	0.35	0.37	0.35	0.35
5	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
2	0.37	0.36	0.35	0	0	0	0	0	0	0	0	0
1	0.56	0.54	0.53	0.35	0.37	0.35	0.35	0.37	0.33	0.37	0.37	0.34

Fig. 3. Average hourly heat load normalized to peak demand for each month of 2014.

dustry [40]. The solar options considered for breweries are direct steam generation linear Fresnel (DSGLF), PTC, PTC with 6 h thermal energy storage (PTCTES), and PVEB. The integration scheme for the brewery case study is shown below in Fig. 2.

Variation in brewery operating schedules are implemented using low, average and high operating hour heat and load shapes for conventional boilers. An average operating hour load shape is shown in Fig. 3. Load shapes represent the hourly heat or electricity consumption normalized by annual peak consumption. Development of the boiler load shapes is described in [6].

We assume that the PV system is coupled to the electric boiler via an AC connection. The inverter modeling is included with the SAM technology package. We assume that excess PV electricity generation can only be used to mitigate the cost of purchasing electricity at the brewery

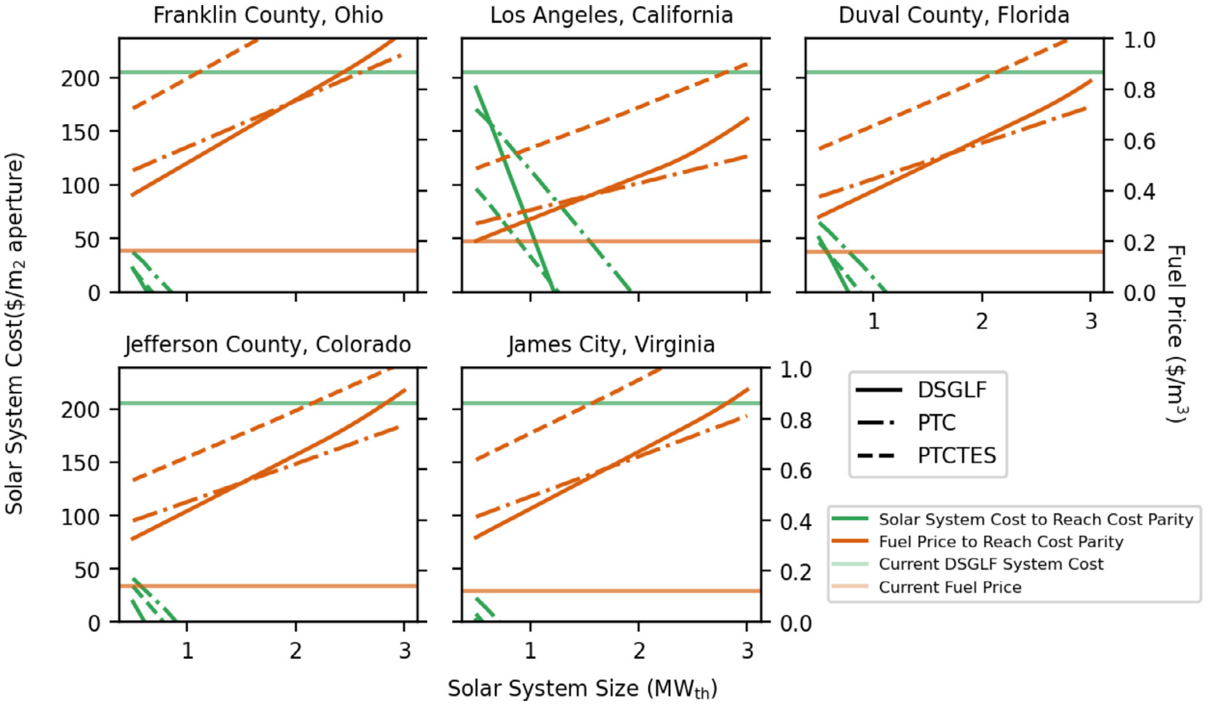


Fig. 4. Investment and fuel price curves to reach parity with the existing boiler system for each technology in each location as a function of solar system size at the heat exchanger (MWth).

and that grid electricity cannot be used to assist the PV system. Consequently, we also assume that electricity cannot be sold to the grid or be processed as SRECs. This assumption is made because this analysis considers the production of electricity for process heat only rather than a hybrid process heat and electricity business model.

Process parity results

Parity fuel and investment prices

We explore two conditions for process parity (i.e., equivalent LCOH) between SHIP and conventional IPH systems based on the brewery case study: changing the fuel price or solar system investment price. Cost parity is not achieved in any analysis location for current solar system costs and fuel prices, as shown in Fig. 4. Los Angeles County is most likely to achieve cost parity due to the higher fuel prices compared to other counties. Based on our analysis, however, it is uneconomical for beer breweries operating an existing central gas boiler to integrate a SHIP to reduce their overall process heating costs. The performance of the PTCTES system is poor because our current implementation in SAM currently does not optimize for the assumed load profiles.

Fig. 5 presents PVEB results, which are less economically favorable than the ST technologies. Again, a brewery in Los Angeles County is closest to reaching fuel and investment parity. James City is least favorable (investment cost parity does not appear in the figure), given its relatively low solar resource and fuel price.

To explore the effects of solar system size and fuel price in more detail, payback periods for Franklin County, Ohio are plotted in Fig. 6. The caveat of using payback period as an investment metric is that it does not account for changes in annual savings beyond the payback period. Payback periods of less than five years are not possible for assumed all fuel price and system size combinations.

Generalized process parity results

Multiple linear regression analysis is performed based on the brewery case study for the investment parity as a function of load ratio, DNI, and current fuel price; fuel price parity is generalized as a function of LR and DNI. The variables in the regression models are selected to represent the significant capital and operating cost components of the LCOH. Investment parity is represented by Eq. (2) and fuel parity by Eq. (3). For fuel parity, the operating costs cannot be addressed by fuel prices because the fuel parity price is the output of the model. Instead, the fuel consumption should be used to represent the operating costs. The solar fraction is not included due to the nontrivial task of estimating the solar fraction for a prospective solar installation at a facility and the interdependence between load ratio/DNI and solar fraction.

$$I_{parity}\left(USD/m^{2}{}_{ap}\right) = \alpha_0 + \alpha_1 * LR + \alpha_2 * DNI + \alpha_3 * FP \tag{2}$$

$$FP_{parity}\left(USD/m^{3}\right) = \beta_0 + \beta_1 * LR + \beta_2 * DNI \tag{3}$$

The data used to fit the regression models is obtained by running the LCOH and parity simulations across a 1000 county subset of the approximately 3000 U.S. counties for different solar installation sizes. This set of counties represents a DNI of between 1450 and 2740 kWh/m^2 /year [43] and natural gas prices of 0.07 to 0.28 USD/m^3 [44]. Load ratios are randomly selected between 0.16 and 0.48 which represents solar installations of 1 to 3 MW$_{th}$ at the heat sink for the brewery load shape. Average RMSEs for the training set, which is used to fit the regression models [45], are reported using four-fold cross validation with a train test split ratio of 0.3. The average value of the model parameters across four folds is used to evaluate the RMSE and R^2 for the test data. Parameter p-values are determined to evaluate whether they are significant with respect to the investment and fuel price parity.

The multiple linear regression is only performed for DSGLF and PTC systems for two reasons: the PTCTES system's thermal storage dispatch is not optimized and there currently does not exist an automated way of selecting the best electricity rate structure for a location for electrified technologies. We do not consider solar investment costs in the fuel price parity regression equation as solar investment cost baselines generally do not vary significantly between locations in the U.S. [32]. Other LCOH parameters excluding the ones defined in Eqs. (2) and 3 may vary by location. However, we do not expect these parameters to contribute

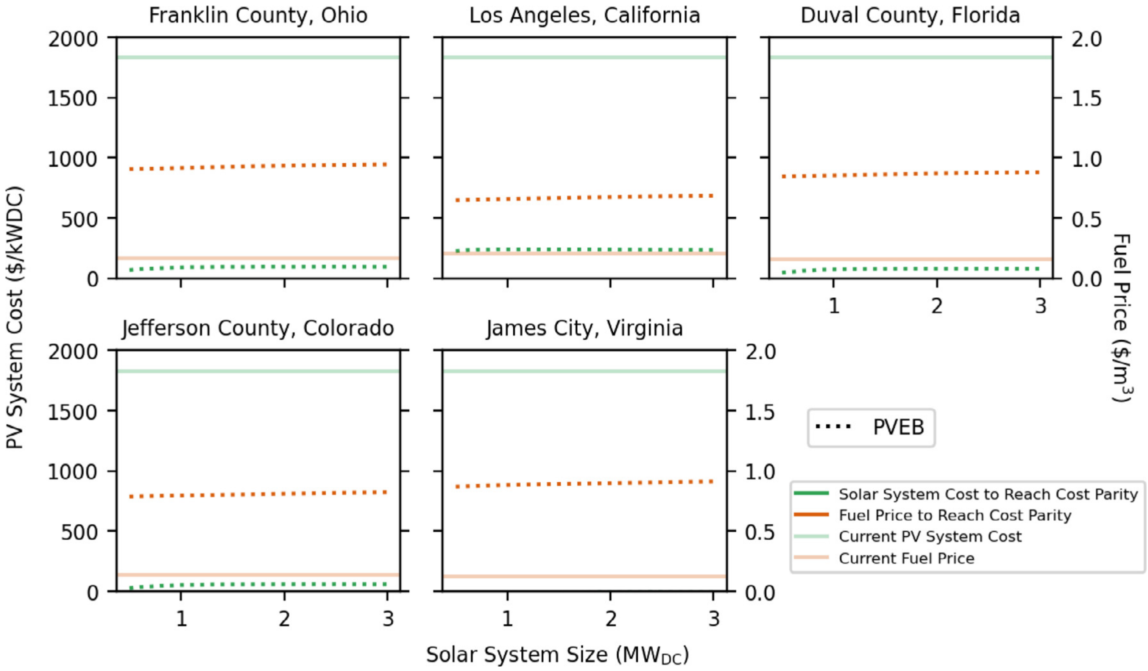
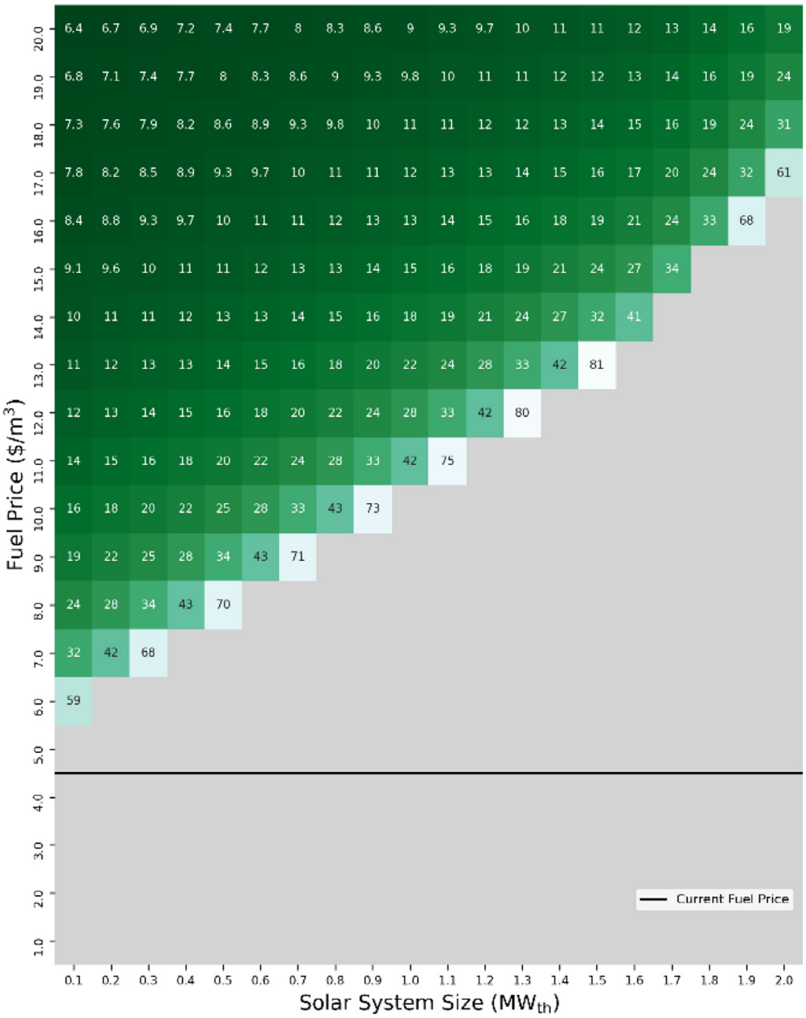


Fig. 5. Investment and fuel price curves to reach parity for PV-electric boiler (PVEB) without grid-assistance integrated in parallel with the existing gas boiler in each location as a function of solar system size at the heat exchanger (MW$_{DC}$).



Fuel Price ($/m³) \ Solar System Size (MW$_{th}$)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
20.0	6.4	6.7	6.9	7.2	7.4	7.7	8	8.3	8.6	9	9.3	9.7	10	11	11	12	13	14	16	19
19.0	6.8	7.1	7.4	7.7	8	8.3	8.6	9	9.3	9.8	10	11	11	12	12	13	14	16	19	24
18.0	7.3	7.6	7.9	8.2	8.6	8.9	9.3	9.8	10	11	11	12	12	13	14	15	16	19	24	31
17.0	7.8	8.2	8.5	8.9	9.3	9.7	10	11	11	12	13	13	14	15	16	17	20	24	32	61
16.0	8.4	8.8	9.3	9.7	10	11	11	12	13	13	14	15	16	18	19	21	24	33	68	
15.0	9.1	9.6	10	11	11	12	13	13	14	15	16	18	19	21	24	27	34			
14.0	10	11	11	12	13	13	14	15	16	18	19	21	24	27	32	41				
13.0	11	12	13	13	14	15	16	18	20	22	24	28	33	42	81					
12.0	12	13	14	15	16	18	20	22	24	28	33	42	80							
11.0	14	15	16	18	20	22	24	28	33	42	75									
10.0	16	18	20	22	25	28	33	43	73											
9.0	19	22	25	28	34	43	71													
8.0	24	28	34	43	70															
7.0	32	42	68																	
6.0	59																			
5.0																				
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Fig. 6. Effect of solar system size and fuel price on the payback period in Franklin County, Ohio.

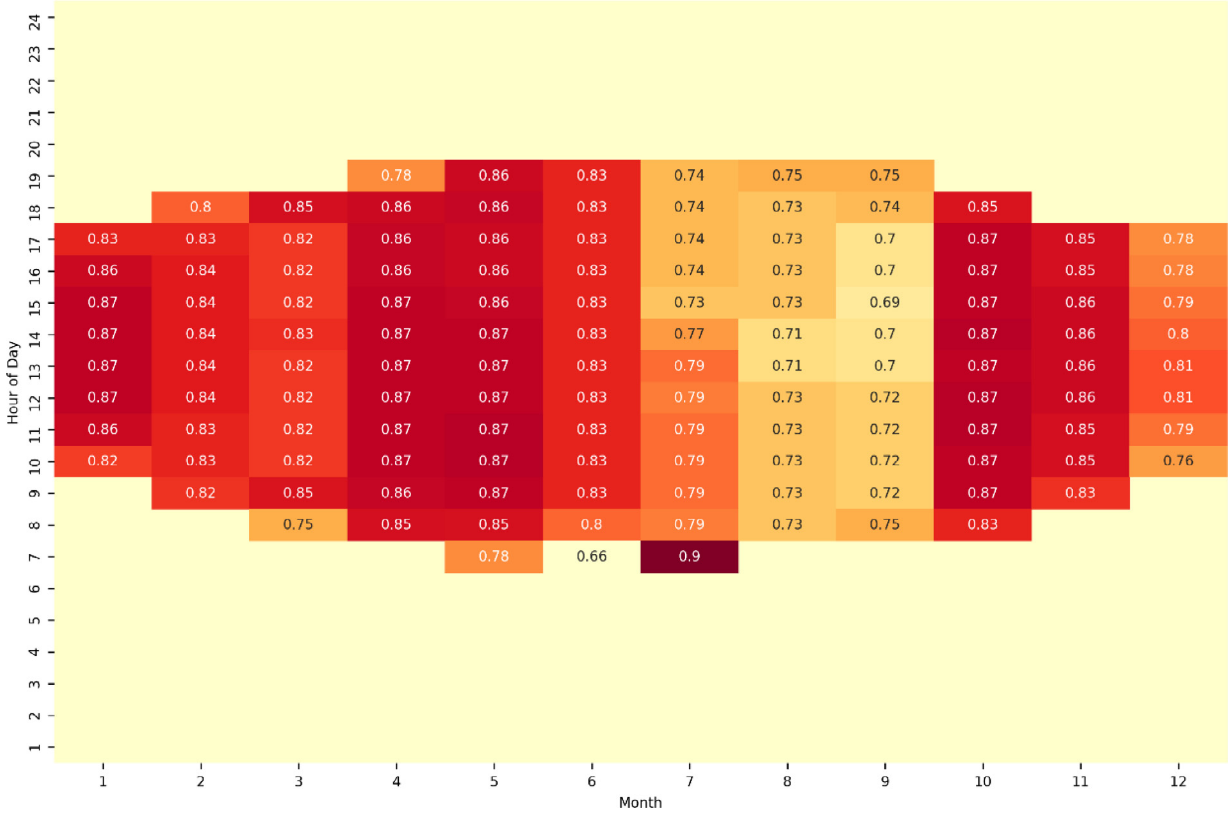

Fig. 7. Solar utilization for a 1 MWth DSGLF installation in Los Angeles, California by hour of day and month. Values for utilization outside of daylight hours are equal to zero and are not shown.

significantly to the LCOH as there is not significant sensitivity to these parameters as shown in the sensitivity analysis, found in the supplementary information.

Results of the regression analysis are shown below in Table 5. The parameter p-values were all less than 0.0001, indicating that the parity fuel and investment prices are significantly dependent on the equation parameters. The agreement of the training RMSEs imply that the model is not significantly overfit or underfit.

The parity fuel price regression analysis did not produce a good fit because operating costs are not captured due to the exclusion of solar fraction. If one chooses to consider adding solar fraction (SF) and its interaction terms with LR and DNI, the regression models R^2 and RMSE is improved to approximately 0.97 and 0.7 respectively in both cases using the equation below. However, as mentioned previously, the calculation of solar fraction for a prospective solar heat integration is nontrivial.

$$\begin{aligned} FP_{parity} &= \beta_0 + \beta_1 * LR + \beta_2 * DNI + \beta_3 * SF \\ &\quad + \beta_4 * SF * DNI + \beta_5 * SF * LR \end{aligned} \tag{4}$$

Discussion

Process parity of ship systems

Annual SHIP costs must be lower than conventional system costs regardless of SHIP investment price for parity to be reached. Brewery fuel costs were identified as a key parameter that could be used to estimate whether process parity could be achieved. The annualized cost of producing steam is the main hurdle to achieving widespread parity with natural gas boilers. For many locations with larger system sizes, solar thermal installations above 1 MWth cannot achieve parity with conventional systems solely by reductions in solar investment costs, such as a ST capital cost reduction projection of 25% [46]. This is due to the higher operating costs of the hybrid solar system compared to the gas boiler in those locations. To reach parity the hybrid system must have lower combined operating and fuel costs compared to a natural gas boiler. One potential method to effectively increase the price of using natural gas is to implement a carbon price. Carbon prices of 50 to 100 USD/ton in 2030 may be necessary to achieve Paris Agreement climate goals [47].

One issue that warrants additional discussion is the potential for energy storage. The relatively low solar utilization at higher system sizes and the low solar fractions point towards storage as a potential system improvement. The solar utilization heat map for a 1 MWth DSGLF system without thermal storage in Los Angeles County is presented as Fig. 7. The figure shows there is a significant amount of energy available for storage (up to 35% of generation) in the summer months. However, the available energy for storage drops significantly in the winter months. Although there is high solar utilization in the winter months, most of the steam demand is unmet. While storage can potentially meet evening loads in the summer months due to excess generation during the day, it is unlikely that storage will be sufficient to meeting evening loads in the winter months. Thus, whether storage will reduce the LCOH of the system is a complex analysis that depends on the solar system size, storage size, the process demand load shape and the economics of each component. Identifying suitable and economically viable sizes of storage for different solar system sizes and load shapes are left to future work.

Conclusions

A process parity framework, underpinned by unit cost models for DSGLF, PTC, PTC TES, PVEB, and conventional boilers, is developed to identify the barriers for cost parity between SHIP and a conventional IPH technology. The resulting analysis showed that process parity currently does not exist for the replacement of conventional IPH loads with SHIP for a typical brewery in the U.S., primarily due to the current low natural gas prices. Additional limitations to process parity include availability of low-cost grid or PV electricity, SHIP capital costs, and the lack of solar generation during cloudy periods and overnight.

Additional research

The process parity framework is an initial approach for understanding the technoeconomic components of cost parity between SHIP and conventional IPH technologies. Additional research is needed to refine the framework components. This includes further validation of model unit costs and operating load shapes against installed SHIP systems. Additional research is needed to improve the resolution of current models to the facility level, including land, fuel, and electricity prices, available land area, and the integration of process level information (e.g., hourly process temperature requirements).

The process parity framework can also be expanded to address the barriers identified in this paper. Further research on available cost-effective storage options and optimal storage sizing is critical to achieve higher solar fractions and widespread process parity. Future work could include upgrading solar thermal systems in SAM to include a heat target dispatch algorithm and running the updated models for every U.S. county. Cost optimal theoretical process load shapes for flexible plant operations is another research area that can potentially reduce LCOH and reduce the amount of storage required. Research on the impact of utility rate structures on electrified IPH systems is critical to identifying steps that utilities can make to help electrified systems reach widespread parity.

Further analysis can also be conducted for different investment scenarios such as greenfield and line extensions. Although these investments are considered riskier compared to replacement investments, identifying how parity can be achieved is an important step in reducing the aversion to high-capacity SHIP installations. An important related area for significant further research is the development and understanding of new business models of valuing and delivering heat as a service. This emerging field is being implemented with the use of Energy Service Contracts (ESCOs) or heat contracts [48]. These provide the end-user with a stable heat price and shift the responsibilities for maintenance and operation of the SHIP to the service provider.

Declaration of Competing Interest

None.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.seja.2021.100011.

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