ISES
International
Solar Energy Society

Conference Proceedings

EuroSun 2016
Palma de Mallorca (Spain), 11 – 14 October 2016

Solar Process Heat Potential in California, USA

Parthiv Kurup[1], **Craig S. Turchi**[1] **and Guangdong Zhu**[1]

[1] National Renewable Energy Laboratory (NREL), Golden, Colorado (USA)

Abstract

The cost for solar industrial process heat (SIPH) is quantified by defining the levelized cost of heat (LCOH). The state of California, in the United States offers a favorable environment for SIPH given its excellent insolation, industrial gas prices typically higher than the national average, and policies promoting solar-thermal deployment. Given historically low gas prices, competing with natural gas remains the primary challenge to deployment. However, this study finds that the solar LCOH from Concentrating Solar Power (CSP) collectors for many regions in California is expected to be lower than the LCOH from natural gas, using a representative installed solar hardware price and the average price for industrial natural gas in California. Lastly, modifications are in progress to the parabolic trough and Direct Steam Generation (DSG) trough and Linear Fresnel models within NREL's System Advisor Model (SAM) to allow users to more easily predict performance for these industrial heat and steam-generation applications.

Keywords: *solar industrial process heat, SIPH, IPH, parabolic trough, CSP, LCOH, California*

---

1. Introduction

In 1977 the International Energy Agency (IEA) established the Solar Heating and Cooling (SHC) program to create an environment for the development and progression of SHC (IEA, 2016). An EU-led collaborative project between the SHC program and the SolarPACES program known as Task 49/Task IV was created specifically to establish and help meet the potential of solar Industrial Process Heat (SIPH) (IEA, 2016; SolarPACES, 2016a). (Note that the IEA uses the acronym "SHIP" for solar heat for industrial processes. The term "industrial process heat" is recognized in the United States, and this paper will refer to these applications as solar IPH or "SIPH"). Much of the initial work in the IEA program dealt with the potential of nonconcentrating, flat-plate collectors. Flat-plate solar collectors are common in many countries, including the United States, where the overwhelming majority is applied to domestic home heating or water heating for swimming pools (SHIP, 2016). While these are excellent applications for low-temperature collectors, this paper deals with the growing interest in the deployment of concentrating parabolic trough collector technologies that can achieve temperatures needed within the industrial sector.

Thermal energy and steam are ubiquitous needs in industrial processes. From the extraction of raw materials to food processing, heat is a vital part of the processing and manufacturing sectors. In the 1970s and 1980s there was great interest in collection of solar-thermal energy for buildings and IPH applications (Kutscher et al., 1982). Despite significant effort, very few projects came to fruition, mainly due to high solar collector costs and an associated inability to effectively compete with natural gas (Carwile and Hewitt, 1994). In recent years, the improvement and proliferation of solar collectors for electricity generation and the development of sophisticated solar collector modeling tools has regenerated interest in solar process heat applications.

Despite great potential, the worldwide adoption of concentrating collectors for SIPH generation is modest. For example, as of Sept. 2016, of the 191 SIPH plants listed in the "IEA SHIP Plants" database, only 25 involve concentrating collectors of either parabolic trough or Linear Fresnel technologies (SHIP, 2016). The

doi:10.18086/eurosun.2016.02.07 Available at http://proceedings.ises.org

25 SIPH plants in operation are for industries such as food and dairy production (e.g., heat for sterilization of milk) (SHIP, 2016). Due to the excellent solar resource conditions in the United States (especially in the Southwest) and the ubiquitous need for IPH, the United States has a sizeable opportunity for greater deployment of concentrating solar-thermal collectors with the associated benefits of increased solar jobs and lower carbon emissions. For example, within the industrial sector in the United States the estimated consumption of energy for heat for applications such as washing, sterilization, and preheating was approximately 24,000 trillion Btu (TBtu, or 7,000 TWh_{th}) in 2014 (EPA, 2016). Depending on the specific industry in question, between 35% and 50% of the total energy consumption can be for IPH applications (EIA, 2013).

Linear-focus collectors, such as parabolic troughs and Linear Fresnel reflectors, can reach temperatures up to about 550°C (SolarPACES, 2016b). For solar hardware developers, expansion into IPH offers access to new markets for already well developed CSP collector technologies. For policy makers and businesses concerned about greenhouse gas emissions, solar-thermal energy is a potential valuable substitute for natural gas used for process heat in the industrial sector. This paper evaluates the installed cost of a modern parabolic trough collector and re-examines the potential for solar-thermal technologies to supply IPH in light of the demonstrated reductions in technology cost. The state of California is used as a prime example of where this application may grow in the United States.

2. Current Cost Of Parabolic trough Collectors

NREL recently completed a cost analysis of two different state-of-the-art parabolic trough solar collector assemblies (SCAs) (Kurup and Turchi, 2015a). The effort first developed a bill of materials (BOM) for the subject designs based on published literature and discussion with the system developers. A key tool in the analysis was a suite of software tools called Design for Manufacture and Assembly (DFMA). The DFMA software package is used industry-wide and has two parts: Design for Manufacture and Design for Assembly (Boothroyd Dewhurst, 2016). The DFMA tool has detailed databases and allows the user to calculate a primary manufacturing cost for each component and then assemble it within the overall product/assembly. Design for Manufacture was used for the majority of the components within the BOMs to model the SCA as if it were to be manufactured in commercial quantities. As such, the material, manufacturing processes, key dimensions, and machining steps were estimated.

A SCA is built of a string of trough modules controlled by a single drive and represents the smallest unit of a functional parabolic trough solar field. The DFMA methodology was applied to the trough structural assembly, i.e., frame, foundation and pylons. The cost of specialty components such as receiver tubes, drive systems, and glass mirror panels were based on quotes from representative suppliers.

Of the two trough modules examined—SkyFuel's SkyTrough and FLABEG's Ultimate Trough—the former is more amenable to deployment in small solar fields due to its smaller size and ability to be fabricated onsite without a specialized assembly jig or facility. These are important factors for SIPH, which is expected to use much smaller solar fields than systems for electric power generation. It is important to note, that the SkyFuel SkyTrough has already been used for solar heat addition to the overall process at the Stillwater hybrid solar-geothermal plant and is considered suitable for SIPH applications (NREL, 2016; Wendt et al., 2015).

The key subsystems for the SkyTrough module and SCA analysis were the receivers, receiver supports, mirror panels, parabolic ribs, space frame, torque plates, drives and control, drive pylon and regular pylons, and the foundations. The main subsystem categories for NREL's SkyTrough BOM and analysis are seen in Figure 1. The SkyTrough SCA consists of 8 modules and has a total length of 115 m and aperture width of 6 m. Details on the SkyTrough SCA can been viewed in the default *CSP Physical Trough* model within NREL's free System Advisor Model (SAM, https://sam.nrel.gov/), version 2016 release.

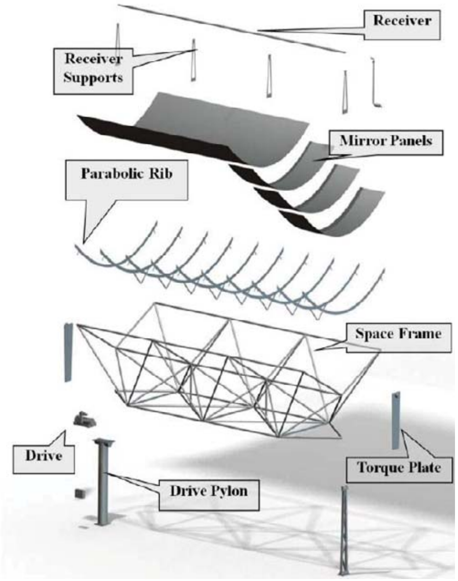

Fig. 1: Main components of the SkyTrough module and picture of regular pylon. (Illustration from SkyFuel)

Within each subsystem NREL estimated dimensions and costs using manufacturing analysis for the subsystems (including the manufacture of the drive and nondrive support pylons). Construction activities were estimated for the digging and placement of the foundations.

Each subsystem was broken down into the specific components that would make up a module and an individual SCA. From that point the BOM and the manufacturing, assembly, and installation analysis per SCA followed. Other troughs have been used for SIPH, e.g., Abengoa Solar's PT1 (California Energy Commission, 2010). Unlike the PT1 which uses silvered glass mirrors, the SkyTrough uses a polymer-film reflector. The vendor's quoted prices were used for capturing the cost of this component.

The NREL analysis on the manufacturing, assembly, installation equipment, and construction activities assumed a production volume of 1500 SCAs. The Installed Cost/m^2, as seen in Figure 2 for 1500 SCAs was found to be \$170/m^2. Hence, the assumption is made that a central manufacturing factory is making sufficient parts for 1500 SCAs per year, for combined SIPH or CSP applications, while the number of SCAs assembled on-site varies with project size. Given the thermal capacity of a SkyTrough SCA is about 2.2 SCAs/MW$_{th}$, and assuming a SIPH project size of 5 MW$_{th}$, 100 SCAs would represent about nine projects per year. For comparison, only two of the 25 concentrating solar projects in the SIPH database are ~5 MW$_{th}$ (SHIP, 2016).

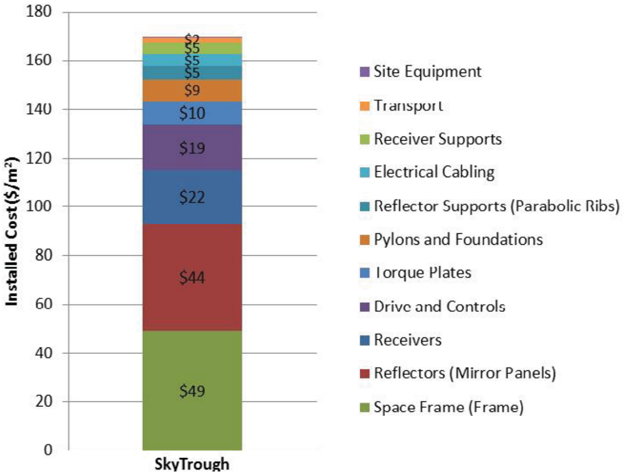

Fig. 2: Installed cost for the SkyTrough assuming 1500 SCAs. Total installed cost is estimated at \$170/m2. (Kurup and Turchi, 2015a)

3. Overall IPH Usage in the United States

In the present paper we have highlighted the results from a specific “top-down” methodology and analysis approach that first examined the regional solar resource potential and the thermal energy demand characteristics of potential user industries (Kurup and Turchi, 2015b). The work focused on specific industries that have the largest thermal energy requirements in the appropriate temperature range for concentrating solar collectors. This method provides an initial, high-level assessment of the SIPH potential (which was then focused on California). Full details of the methodology and its development are outside the scope of this paper. Understanding the conventional energy source (e.g., natural gas, waste heat, or electricity) is also examined to assess the economic potential.

The U.S. Manufacturing Energy Consumption Survey (MECS) is a national sample survey that collects information on the U.S. manufacturing establishment, their energy-related building characteristics, and their energy consumption and expenditures (EIA, 2010a). Based on MECS data, the U.S. manufacturing sector has three primary energy sources: fuel, steam generation, and electricity generation. Considering the direct and indirect (e.g., onsite steam production) use of all energy sources, process energy consumed approximately 10,000 TBtu (as in Figure 3). This represents approximately 42% of the total primary energy consumption in the U.S. manufacturing sector. (Note 1 TBtu ≈ 0.3 $\mathrm{TWh_{th}}$.) From Figure 3, the importance of process heating within process energy as a whole is clear. For 2010, the MECS industries utilized 7,204 TBtu/yr (2,100 $\mathrm{TWh_{th}}$/yr) for process heat—or approximately 29% of the total primary energy in the U.S. manufacturing sector.

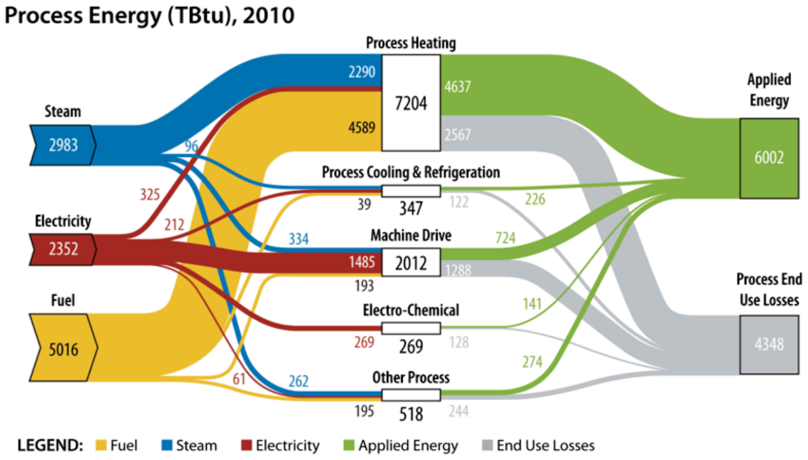

Fig 3: Sankey diagram of process energy flow in U.S. manufacturing sector in 2010 (EERE, 2016). Values are shown in trillion BTU

Figure 4 shows the fully compiled MECS 2010 end-use subcategories for natural gas, which is the fuel most often used for process heating, conventional boiler use, and combined heat and power (CHP) or cogeneration. In contrast, electricity is most commonly used for direct machine drive with some use in process heating. Data indicates that natural gas replacement is the biggest opportunity for SIPH. Situations where electricity can be offset will be rare although they may present favorable economics.

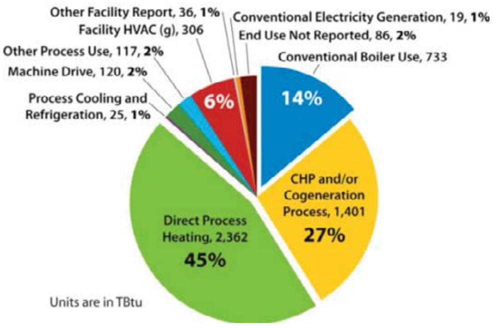

Fig. 4: 2010 United States MECS overall natural gas breakdown by end use (EIA, 2010b)

The U.S. industrial and manufacturing sectors are the largest consumers of natural gas and electricity for process heat either directly or indirectly through steam production via a conventional boiler (EIA, 2010b; Fox et al., 2011). A representation of the potential U.S. IPH market size for steam is provided in Figure 5, which depicts annual steam consumption for the manufacturing sectors of Food, Paper, Petroleum and Coal Products, Chemical and Primary Metal Manufacturing – the five sectors that have the greatest usage of natural gas. The total consumption in the range between 100ºC and 260°C amounts to about 1700 TWh_{th}/yr. To put this in perspective, the 64 MW_e Nevada Solar One CSP plant produces about 0.35 TWh_{th}/yr so the thermal energy potential depicted in Figure 5 represents the equivalent of about 4,800 such plants if all the sites were suitable for SIPH. All the sectors listed in Figure 5 utilize steam in temperature ranges suitable for solar generation; however, the food industry presents a particularly appealing target. As noted previously, the food sector has been the application of choice for many international SIPH plants.

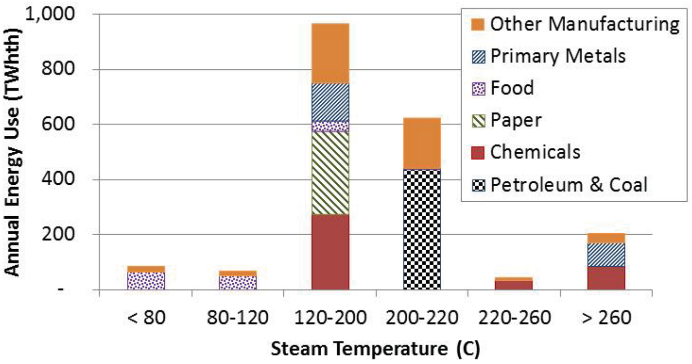

Fig. 5: IPH annual energy use for steam generation for the industries utilizing the greatest amount of natural gas (Fox et al., 2011)

4. Focus on California Industrial Natural Gas and Solar Potential

4.1 Industrial Natural Gas consumption in California

A 2014 California Energy Commission (CEC) study listed natural gas consumption for industries in California (Schrupp, 2013), and according to the MECS 2010 data, the food industry in the United States consumed approximately 59% of its total natural gas consumption for applications of direct process heating and conventional boiler use (EIA, 2010b). Assuming this percentage holds for the food industry in California, it can be estimated that about 10 TWh_{th}/yr were consumed for direct process heating and conventional boiler use in the state in 2014 (Schrupp, 2013), which is the thermal equivalent of about 30 solar fields as big as Nevada Solar One (NSO).

This methodology was continued across all MECS sectors listed in Table 1 below. Table 1 shows the GWh_{th} used by the MECS industries identified as the biggest consumers of steam at less than 260°C in California (i.e. for Food, Paper, Petroleum and Coal Products, Chemical and Primary Metal Manufacturing). The CEC concluded industries in California such as food processing, chemicals, petroleum, and primary metals manufacturing "represent prime areas of opportunity for reducing natural gas use" (Schrupp, 2013).

Tab. 1: Estimated natural gas consumption for direct process heating and boiler use in California for select MECS industries

MECS sector with North American Industry Classification System code	Natural Gas Consumption for Process Heating (GWh_{th}/year)
Food Manufacturing (311)	10,200
Paper Manufacturing (322)	1,244
Petroleum and Coal Products Manufacturing (324)	31,211
Chemical Manufacturing (325)	3,526
Primary Metal Manufacturing (331)	2,134
	48,100

4.2 Solar Industrial Process Heat Potential in California: A look at the Food Industry

In the present paper as mentioned, the results from a specific energy analysis are presented (Kurup and Turchi, 2015b). The full method and derivation of the results is outside the scope of this paper. When the Direct Normal Irradiance (DNI) resource and available land area at a 10-km by 10-km resolution are looked across California, the estimated Technical Thermal Energy Potential for California from using parabolic troughs was 23,000 TWh_{th}/year (Kurup and Turchi, 2015b). As can be seen, the Technical Thermal Energy Potential of California at ~23,000 TWh_{th}/year is orders of magnitude beyond the demand of 48 TWh_{th}/year shown in Table 1.

An objective for this paper is to highlight specific industries known for high use of natural gas or electricity for IPH to their local solar thermal energy potential. For this study, the Food industry and sample sub-industries in California were considered prime candidates. These include the MECS food sub-industries of animal-food manufacturing, breweries, dairy product manufacturing, and fruit and vegetable producers. To highlight that the thermal demand of these industries can be theoretically met with the SIPH potential found for California, maps have been created overlaying the location of the industries in California and the estimated Technical Thermal Energy Potential. Figure 6 shows the co-locations of known animal-food processing plants, breweries, and dairy products along with the Technical Thermal Energy Potential by county in California. These 3 sub-industries were selected as they were considered representative of the Food industry of California.

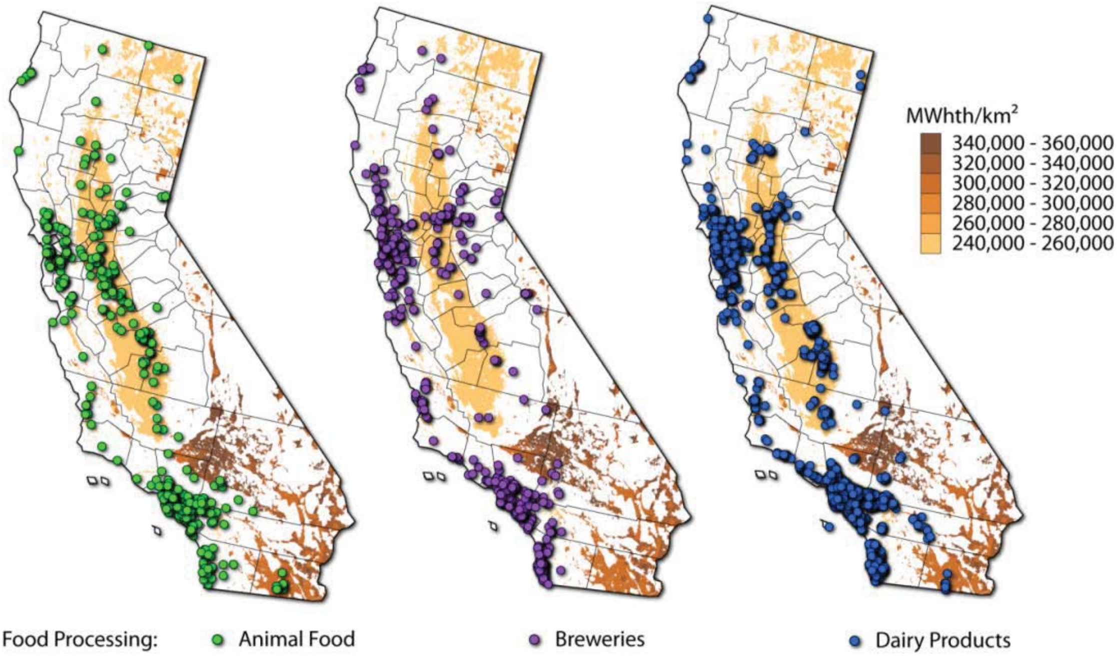

Fig. 6: Locations of animal-food manufacturing, breweries, and dairy products plants across California along with annual solar Technical Thermal Energy Potential (MWhth/km^2/year) (Kurup and Turchi, 2015b)

Figure 7 zooms in on Fresno, California and shows the locations of the animal-food manufacturing, breweries, dairy product manufacturing, and fruit and vegetable producers overlaid with the solar thermal energy supply. Developed city areas and other exclusion zones are shown in white. While the majority of sites are within the Fresno city limits, there are clusters of specific industries that could potentially benefit from SIPH plants. As can be seen, clusters A, B, and C of fruit and vegetable manufacturing plants potentially have available land for solar developers to install SIPH facilities and provide heat to augment steam production processes. Clusters of multiple users near a potential SIPH plant site increase the likelihood of favorable economics.

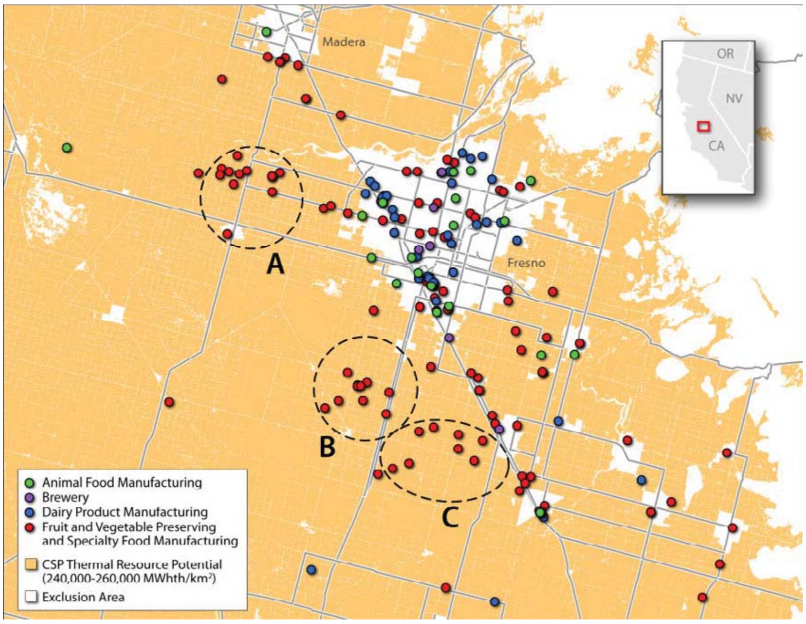

Fig. 7: Close-up of Fresno, CA showing the solar thermal generation potential and potential user industries. (Kurup and Turchi, 2015b)

4.3 Selection Of Heat Transfer Fluid (HTF) For SIPH

Different solar thermal collectors have different temperature capabilities (IRENA, 2012). Table 2 lists different temperature ranges and the likely solar collectors and HTFs to supply IPH at those conditions.

Tab. 2: Temperature regions and recommended HTFs for SIPH

Temperature Range	Solar Collector Type	HTF of Choice
< 80°C	Flat plate Non-tracking compound parabolic Solar pond	Water
80 to 200°C	Parabolic trough Linear Fresnel	Water/steam
200 to 300°C	Parabolic trough Linear Fresnel	Mineral oil or steam
300 to 400°C	Parabolic trough Linear Fresnel	Synthetic oil
400 to 550°C	Parabolic trough Linear Fresnel	Steam or Molten salt

Temperatures below about 80 °C can be achieved with non-tracking, non-concentrating devices such as solar ponds and flat-plate collectors to supply hot water, swimming pool heating, or space heating. While such applications are excellent matches for solar energy, the development and deployment of these systems are outside the scope of this study, which is dedicated to concentrating solar collectors.

At the other end of the spectrum, temperatures above about 550 °C exceed the limit of linear-concentrating systems and require the use of point-focus systems such as parabolic dishes and central receivers. These units most often deploy molten salt or high-pressure steam as the HTF, although some designs have been tested with air.

The region of interest for the present study is the realm of temperatures that can be achieved with tracking, linear-focus concentrating collectors. These collectors have a proven track record, utilize simple one-axis tracking, and can be deployed in a modular fashion by adding additional collector length. The optics of linear-focus systems can achieve temperatures up to about 550°C. However, as one moves to higher temperatures, the requirements for the HTF and the receiver become more restrictive, which generally means more expensive hardware and fluids are required. Per Figure 5, it is anticipated that the majority of SIPH applications will target temperatures below about 220 °C.

4.4 Estimated Cost of Solar Thermal Heat

The levelized cost of heat (LCOH) is a convenient metric for estimating lifetime cost of a solar collector system for process heat applications. LCOH is defined analogously to LCOE, which conventionally refers to levelized cost of electric energy. In its simplest form, LCOH is defined as:

$$LCOH = \frac{(TIPC) * (FCR) + (Annual\ O\&M)}{Annual\ thermal\ generation} \qquad \text{(eq. 1)}$$

where TIPC is the Total installed project cost, FCR is the fixed charge rate, and annual O&M includes both fixed and variable operating costs. The FCR depends on a range of financial parameters that can have a significant influence on LCOH. NREL's SAM model includes various ways of estimating LCOE. The latest release includes a procedure for estimating and using the FCR method that is used in this study. Additional details on SAM's LCOE options can be found in the SAM Help Menu (NREL, 2015).

Figure 8 shows the LCOH for a range of installed solar costs and three different solar resource levels that are representative of California. For an installed solar field cost of about $160/m^2, solar thermal energy is competitive with natural gas (i.e., has a lower LCOH) at its 2015 average California price of $6.35/MMBtu (EIA, 2016) in California where DNI > 6 kWh/m^2/day. DNI > 6 kWh/m^2/day corresponds to all shaded regions shown in Figure 6. Note that Figure 8 shows the installed solar field cost and the assumed total project cost based on a multiplier for balance of plant and indirect costs. Total installed project cost includes solar field, site preparation, heat transfer fluid piping, heat exchanger, and other project costs. Added to these direct costs is a 7% contingency and 25% indirect costs. Like LCOE, the LCOH is sensitive to the financial assumptions. In this scenario the fixed charge rate is set at 0.101, which corresponds to a weighted average cost of capital of 6.2%.

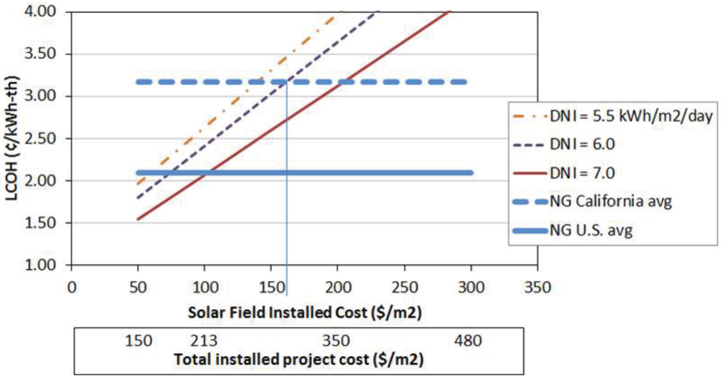

Fig. 8: Estimated LCOH for different solar resource and solar field costs compared with two natural gas (NG) prices from 2015. Total installed project cost includes solar field, site preparation, HTF piping, heat exchanger, and other project costs. No solar incentives are included. Gas costs include $200/kW burner cost and 80% efficiency. Based on FCR = 0.101, WACC = 6.2% (updated from Kurup and Turchi, 2015b)

The data suggests that economic SIPH applications can be found in California at existing solar hardware costs and market gas prices, with incentives in the marketplace further expanding the range of feasible projects. For example, the California Solar Initiative–Thermal Incentive Program offers industrial sites up to $800,000 to set up an SIPH plant for the displacement of natural gas (CPUC, 2016). Solar technology developers estimate that under this program, even with the relatively low gas prices of today, payback period on these projects could be less than three years. In summary, project viability will be strongly dependent on the specific solar project costs—including any incentives—and the specific gas pricing contract in place. The deployment of a few successful pilot projects would be expected to spur further utilization of SIPH with a concomitant decrease in project development costs.

5. Modifications to SAM to Facilitate SIPH

The solar-thermal models in SAM were developed to estimate the performance and cost of electric power generation. The first stage of the modeling is estimating the solar resource and the efficiency of the solar collectors. Operation of the system, however, is dependent on the demands of the integrated steam-Rankine power cycle. For users whose concern is thermal energy production, not electricity, there is no easy way to avoid interference from the power cycle constraints. In 2015 NREL showed that retention of the power cycle caused a 6% underestimation of performance from what should have transpired had the model been freed of the power cycle constraints (Turchi and Neises, 2015). This was after making changes to the SAM input values to minimize cycle impacts. In the absence of those changes, the underestimation was at least 14%.

NREL are currently modifying the SAM code to create a model set that does not require a power block and is suitable for SIPH modelling. The technologies chosen currently include: Parabolic trough with oil/water as the HTF; Direct Steam Generation (DSG) trough; and DSG Linear Fresnel. These changes are being applied exclusively to the *Physical Trough* and *Linear Fresnel* models within SAM, as these are the technologies expected to be most useful for SIPH applications. Initial validations of the new SAM code have been undertaken, with further testing and iteration expected.

6. Conclusions and next steps

Recent advances in parabolic trough design and manufacturing has led to reduced cost per square meter of aperture area. Analysis of the SkyTrough—a design that is suited for use in relatively small SIPH applications—predicts that the installed solar field cost can be as low as $\$170/m^2$. Collector designs that are tailored for efficient construction and deployment at small plant capacities are essential for viable SIPH systems. Inclusion of balance of system and indirect costs brings this total to about $\$350/m^2$ (Kurup and Turchi, 2015b).

An examination of solar resource and natural gas use for IPH in California indicates a Technical Thermal Energy Potential that far exceeds the appreciable demand in the state and highlights the food and dairy sectors as good candidates for early adoption of SIPH systems.

Three general application temperatures between 80°C and 400°C are defined for linear concentrating collectors based mainly on the preferred HTF. The low-temperature region of 80-200°C is best suited for use of water or steam, the intermediate region of 200-300°C can utilize DSG or mineral oils, and the high-temperature region of 300-400°C must use DSG or more costly synthetic oils. It is noted that the industrial demand for steam is dominated by temperatures in the range of 120 to 220°C; thus, the best SIPH market target is believed to be systems using pressurized water or steam in the range of 120 to 220°C.

California offers a favorable environment for SIPH given its good insolation, gas prices typically higher than the U.S. national average, and policies promoting solar-thermal deployment. Given historically low gas prices, competing with natural gas remains the primary challenge to deployment. However, this study finds that the solar LCOH for many regions in California is lower than the LCOH from natural gas, using a representative installed solar hardware price and the average price for industrial natural gas in California. The economic case for SIPH only improves as gas prices climb or if a price is leveed on carbon emissions.

Lastly, modifications underway to the *Physical Trough* and *Linear Fresnel* models within SAM which will allow users to more easily predict performance for these industrial heat and steam-generation applications. These changes will remove the requirement of having a steam-Rankine power cycle in the SAM model and allow users to design for steam as the final product. These modeling options are expected to debut in the parabolic trough and Linear Fresnel models in SAM 2017.

7. Acknowledgments

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 w. Funding was provided by the Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Program. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

8. References

Boothroyd Dewhurst Inc., 2016. DFA: Product Simplification and DFM: Concurrent Costing. http://www.dfma.com/software/dfma.htm , accessed September 19.

California Energy Commission, 2010. Industrial Process Steam Generation Using Parabolic trough Solar Collection. CEC-500-2011-040. California Energy Commission, Sacramento.

California Public Utilities Commission (CPUC), 2016. California Solar Initiative Thermal Program Handbook. California Public Utilities Commission, San Francisco. http://www.gosolarcalifornia.ca.gov/documents/CSI-Thermal_Handbook.pdf, accessed Sept. 19 2016.

Carwile, C., Hewitt, R., 1994. Barriers to Solar Process Heat Projects: Fifteen Highly Promising (But Cancelled) Projects. NREL/TP-472-7295. National Renewable Energy Laboratory, Golden, Colorado.

Environmental Protection Agency (EPA), 2016. Renewable Industrial Process Heat. https://www.epa.gov/rhc/renewable-industrial-process-heat, updated May 5 2016, accessed Sept. 19 2016.

Fox, D.B., Sutter, D., Tester, J.W., 2011. The thermal spectrum of low-temperature energy use in the United States. Energy Environ. Sci. 4, 3731–3740.

International Energy Association (IEA), 2016. Solar Heating and Cooling Programme. http://www.iea-shc.org/, accessed Sept. 19 2016.

International Renewable Energy Agency (IRENA), 2012. Concentrating Solar Power. Renewable Energy Technologies: Cost Analysis Series. International Renewable Energy Agency, Abu Dhabi.

Kurup, P., Turchi, C.S., 2015a. Parabolic trough Collector Cost Update for the System Advisor Model (SAM). NREL/TP-6A20-65228. National Renewable Energy Laboratory, Golden, Colorado.

Kurup, P., Turchi, C.S., 2015b. Initial Investigation into the Potential of CSP Industrial Process Heat for the Southwest United States. NREL/TP-6A20-64709. National Renewable Energy Laboratory, Golden, Colorado.

Kutscher, C.F., Davenport, R.L., Dougherty, D.A., Gee, R.C., Masterson, P.M., May, E.K., 1982. Design Approaches for Solar Industrial Process Heat Systems. SERI/TR-253-1356. Solar Energy Research Institute, Golden, Colorado.

NREL, 2015. System Advisor Model (SAM) release version 2015-06-30, LCOE calculator financial model. https://sam.nrel.gov/, accessed Sept. 19 2016.

NREL, 2016. Stillwater Geosolar Hybrid Plant. http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=4279, accessed September 19.

Schrupp, L., 2013. The Natural Gas Research, Development and Demonstration Program. CEC-500-2013-014. California Energy Commission, Sacramento.

Solar Heat for Industrial Processes (SHIP), 2016. SHIP Plants - Locations - United States. http://ship-plants.info/solar-thermal-plants, accessed September 19.

SolarPACES, 2016a. Task IV: Solar Heat in Industrial Processes. http://www.solarpaces.org/tasks/task-iv-solar-heat-integration-in-industrial-processes, accessed September 19.

SolarPACES, 2016b. CSP – How it Works. http://www.solarpaces.org/csp-technology, accessed September 19.

Turchi, C.S., Neises, T., 2015. Parabolic trough Solar-Thermal Output Model Decoupled from SAM Power Block Assumptions. National Renewable Energy Laboratory, Golden, Colorado.

U.S. DOE Office of Energy Efficiency & Renewable Energy (EERE), 2016. Sankey Diagram of Process Energy Flow in U.S. Manufacturing Sector. http://www.energy.gov/eere/amo/static-sankey-diagram-process-energy-us-manufacturing-sector, accessed September 19.

U.S. Energy Information Administration (EIA), 2010a. 2010 MECS Survey Data. http://www.eia.gov/consumption/manufacturing/data/2010/, accessed Sept. 19 2016.

U.S. Energy Information Administration (EIA), 2010b. Table 5.4 End Uses of Fuel Consumption, 2010. http://www.eia.gov/consumption/manufacturing/data/2010/pdf/Table5_4.pdf, accessed Sept. 19 2016.

U.S. Energy Information Administration (EIA), 2013. Table 5.1 By Mfg. Industry with Net Electricity (physical units). http://www.eia.gov/consumption/manufacturing/data/2010/pdf/Table5_1.pdf, released March 2013, accessed Sept. 19 2016.

U.S. Energy Information Administration (EIA), 2016. Natural Gas Prices. http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_SCA_a.htm, modified August 31 2016, accessed September 19.

Wendt et al., 2015. Stillwater Hybrid Geo-Solar Power Plant Optimization Analyses. Proceedings of the Geothermal Resources Council 2015 Annual Meeting, 20-23 September 2015, Reno, Nevada pp. 891-900.