Opportunities for Solar Industrial Process Heat in the United States

Colin McMillan,[1] Carrie Schoeneberger,[2] Jingyi Zhang,[2] Parthiv Kurup,[1] Eric Masanet,[2] Robert Margolis,[1] Steven Meyers,[3] Mike Bannister,[1] Evan Rosenlieb,[1] and William Xi[1]

1 National Renewable Energy Laboratory
2 Northwestern University
3 Independent Contractor

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List of Acronyms and Abbreviations

ACEC	areas of critical environmental concern
BES	battery energy storage
BLM	Bureau of Land Management
Btu	British thermal units
CHP	combined heat and power
COP	coefficient of performance
CSP	concentrating solar power
DNI	direct normal irradiance
DOE	U.S. Department of Energy
DSG	direct steam generation
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
EU	European Union
FPC	flat plate collector
GCF	ground coverage factor
GHG	greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GHI	global horizontal irradiance
GW_p	gigawatt-peak
HTF	heat transfer fluid
IPH	industrial process heat
JSON	JavaScript Object Notation
kW_{el}	kilowatt-electrical
kWh	kilowatt-hours
$kWh_{p,PV}$	kilowatt-hours-peak photovoltaic
kWh_{th}	kilowatt-hours-thermal
kW_{th}	kilowatt- thermal
LF	linear Fresnel
MECS	Manufacturing Energy Consumption Survey
MMBtu	million Btu
MW_e	megawatt-electric
MW_{th}	megawatts-thermal
NAICS	North American Industry Classification System
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
PCM	phase change materials
PTC	parabolic trough collectors
PV	photovoltaics
PVHP	PV-connected ambient heat pumps
SAM	System Advisor Model
SIPH	solar industrial process heat
TBtu	trillion British thermal units
TES	thermal energy storage
TWh	terawatt-hours

UV	ultraviolet
WHRHP	waste heat recovery heat pump

Executive Summary

This report marks a renewed interest in evaluating the opportunities for solar technologies to meet industrial process heat (IPH) demand in the United States. The industrial sector has not typically received the same level of attention and rigor in energy analysis as other end-use sectors, even though the industrial sector accounts for nearly one-third of all U.S. primary energy use (EIA 2020). With the emergence of very low-cost solar photovoltaic (PV) technologies, it is important to develop data and analysis that enable decision makers and analysts to strategically explore how IPH demands could shift toward PV and other solar technologies over the coming decades. This report evaluates established solar thermal technologies, as well as PV-connected electrotechnologies for IPH applications; other renewable heat generation opportunities, such as biomass and geothermal, are excluded.

Today, the majority of IPH demands rely on combustion of fossil fuels. However, switching to an alternative source of renewable thermal energy, particularly when that energy is used in production processes, comes with more challenges than switching to an alternative source of electricity generation. These challenges include a wider range of process heating technologies, greater difficulty of storing heat and transporting heat over long distances, and process integration considerations. Process integration is particularly challenging due to factors such as the need for extensive process modification, the large number of heating loads and associated integration points, variety of heat transfer media, and the variation in process operation.

Fossil fuels account for about 87% of all manufacturing fuel use in the United States, which is essentially the same as four decades ago (EIA 1983; 2017). Our analysis of IPH shows substantial demand for temperatures below 300°C (572°F), much of which is demand for hot water and steam currently provided by fossil fuel combustion boilers. This range of process temperatures is well-aligned to non-concentrating and concentrating solar thermal technologies, as well as PV-connected electrotechnologies.

Our analysis examines the county-level opportunities for seven solar technology packages to meet U.S. IPH demand:

- Flat plate collectors (FPCs) with hot water storage
- Parabolic trough collectors (PTCs) with and without thermal storage
- Linear Fresnel (LF) direct steam generation (DSG) collectors without storage
- PV-connected electric boilers
- PV-connected ambient heat pumps with hot water storage
- PV-connected waste heat recovery heat pumps (WHRHP)
- PV-connected resistance heating.

We formally defined the opportunity for solar for IPH (SIPH) in terms of solar fraction: the portion of county-aggregated IPH demand that could have been met by solar generation at each hour in 2014. For every county in the continental United States, we considered the available land area, hourly solar resource, IPH temperatures, and hourly IPH demand. Although we developed for our analysis a greatly improved resolution of IPH demand and we provided a broad foundation for future analysis and research, we did not estimate opportunities at the level of individual facilities. Likewise, the opportunities we identified are purely technical; a separate

analysis was performed to examine the economic potential of several SIPH systems and will be published separately.

We estimate that in 2014 about 11.2 quadrillion British thermal units (Btu) of fuels were combusted to meet IPH demand in the United States, which is equivalent to 11% of United States total primary energy use and about 28% of all the energy used in the residential and commercial sectors combined. The most significant IPH demand—2.5 times the size of the next-largest industry—occurs in petroleum refining. All told, we estimate the six largest industries (Petroleum refineries, Paper (except newsprint) Mills, Paperboard Mills, Iron and Steel Manufacturing, Basic Chemical Products, and Ethyl Alcohol Manufacturing) constitute 50% of all IPH demand. Natural gas, waste gas (including petroleum refining fuel gas), and biomass (including black liquor from chemical pulping) constitute over 80% of combustion fuels used for IPH. About 35% of IPH demand is used in combined heat and power systems.

Figure ES-1 summarizes the opportunities for SIPH by individual solar technology, distinguished by color, by combining their spatial and temporal dimensions. Each technology is matched to relevant IPH demand by temperature, capacity, and other relevant technological parameters. Technologies in the top right of the chart meet their relevant IPH demand for a larger percentage of the year and for a greater number of counties. PTC technology, when combined with thermal energy storage (TES), not only has the largest opportunity in terms of distribution over geography and time, but also in terms of applicable IPH demands. PTC with TES represents the displacement of nearly 2,500 trillion Btus of combustion fuels, which corresponds to 137 million metric tons of CO_2, or about 15% of all industrial combustion CO_2 emissions. The figure also demonstrates how critical TES is to enable SIPH technologies, seen in the significant difference in the frequency and distribution of meeting IPH demands between the two cases of PTCs.[1]

[1] An interactive map of county results is available from https://nrel.carto.com/u/gds-member/builder/51943617-62eb-4241-8b30-c943fce85692/embed.

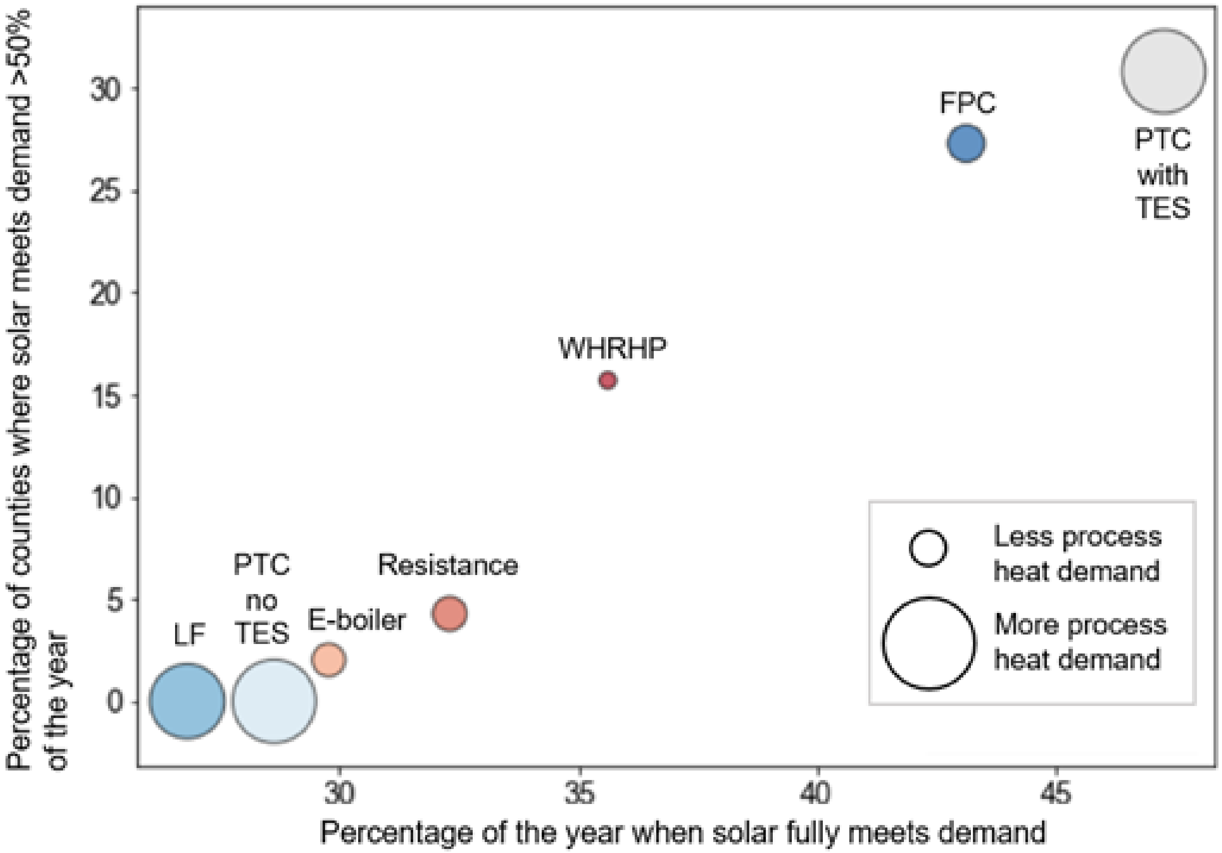

Figure ES-1. Comparison of SIPH technologies sized by summer peak IPH demand

Size of bubble corresponds to supplied process heat demands.

Color of bubble used to distinguish SIPH technology.

e-boiler = electric boiler
LF = linear Fresnel
PTC = parabolic trough collectors
TES = thermal energy storage
WHRHP = waste heat recovery heat pump

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1 Introduction

1.1 Revisiting Solar Industrial Process Heat

This report marks a renewed interest in evaluating the opportunities for solar technologies to meet industrial[2] process heat (IPH) demand in the U.S. manufacturing sector, returning to a topic that was last covered 40 years ago by Brown et al. (1980).[3] Not only has our ability to model the topic changed dramatically since then, but so, too, have the solar technologies and nature of the U.S. manufacturing sector. The purpose of the project reported here is to develop the first national analysis of the potential for solar technologies (PV, solar thermal, and hybrid approaches that produce electricity and/or heat) to power a wide range of manufacturing IPH end-uses. The project will add to a growing body of information that supports strategic decision making about this largely unexplored opportunity for solar energy expansion.

Industry has not typically received the same level of attention and rigor in energy analysis as other end-use sectors, even though the sector accounts for nearly one-third of all U.S. primary energy use (EIA 2020). This has created a blind spot in U.S. energy policy and research and development. Limiting factors for industrial analysis have included the heterogeneity and complexity of industrial processes and technologies as well as a lack of current, disaggregated, and consistent data sets on industrial energy use. In this analysis, we addressed both limitations by developing new levels of detail for the spatial, temporal, and energic characteristics of industrial energy use in the United States.

Two characteristics of the manufacturing sector that have changed very little in 40 years are the prevalence of fossil fuel use and the rarity of solar energy use for IPH in the United States. In 1980, fossil fuels accounted for about 87% of manufacturing fuel use (EIA 1983); in 2014, that figure was also about 87% (EIA 2017a). Overall, renewable sources provide just over 7% of U.S. industrial energy, but nearly 99% of this energy is from biomass (EIA 2017b). Nearly all this biomass is concentrated in the pulp-and-paper and food subsectors, where it is generally combusted in boilers to produce steam.

Following the dramatic increase of corporations' share of installed utility-scale photovoltaic (PV) generation in the United States since 2014 (Heeter, Cook, and Bird 2017), a new focus on expanding the options for renewable thermal energy has emerged (Renewable Thermal Collaborative 2017). However, switching to an alternative source of thermal energy, particularly when that energy is used in production processes, comes with more challenges than switching

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[2] Although we use the U.S. Energy Information Administration (EIA) convention for defining industry—agriculture, construction, manufacturing, and mining—we define IPH as the energy used by the manufacturing sector for conventional boilers, combined heat and power and cogeneration, and process heating equipment.
[3] Since at least 1970, the manufacturing sector has become less energy-intensive overall and structural changes have constituted about a third of this decrease in intensity (Belzer 2014; Boyd et al. 1987). These structural changes, as well as the changes that have occurred within industries, have implications for the opportunities for solar technologies. An industrial structure that relies less on very high temperature processes (such as iron and steel production) may be more amenable to solar technologies for process heat. As we detail in Section 2.1, we estimate that in 2014 about two-thirds of industrial process heat was for temperatures of or below 300°C, much of which was hot water and steam provided by boilers.

to an alternative source of electricity generation. These challenges include a wider range of process heating technologies, greater difficulty of storing heat and transporting heat over long distances, and process integration considerations. Process integration is particularly challenging due to factors such as the need for extensive process modification, the large number of heating loads and associated integration points, variety of heat transfer media, and the variation in process operation.

As part of its Manufacturing Energy Consumption Survey (MECS), the U.S. Energy Information Administration (EIA) asks manufacturers about their ability to switch to an alternative fuel within 30 days without extensive process modifications. The 2014 survey results indicate that unrealized fuel-switching opportunities could reduce natural gas use by 11%; the inability of equipment to use a different fuel was implicated in 78% of the unswitchable natural gas use (EIA 2017a).

Our analysis examines the opportunities for seven solar technology packages to meet U.S. IHP demand:

- Flat plate collectors (FPC) with hot water storage
- Parabolic trough collectors (PTC) with and without thermal energy storage
- Linear Fresnel (LF) direct steam generation (DSG) collectors without storage
- PV-connected electric boiler
- PV-connected ambient heat pumps (PVHP) with hot water storage
- PV-connected waste heat recovery heat pumps (WHRHP)
- PV-connected resistance heating.

Our inclusion of PV-connected electrotechnologies marks a departure from many existing studies of the potential of solar technologies to meet industrial heat demand, as reviewed in Section 1.5 and by Schoeneberger et al. (2020). To our knowledge, no on-site PV-connected electrotechnologies are currently in use for IPH applications.[4] Including PV-connected process heating electrotechnologies contributes to an expanding body of analysis on the opportunities to electrify the U.S. industrial sector (Mai et al. 2018; Electric Power Research Institute (EPRI) 2018); electrification in combination with a decarbonized grid has been identified as one pathway for reducing greenhouse gas (GHG) emissions in the industrial sector (Rissman et al. 2020; Rogelj et al. 2018; White House 2016).

Renewable energy could clearly play a significant role in decarbonizing industry. However, realizing that role would require a massive scale-up within a narrowing window of time for implementing emissions mitigation. With the emergence of very low-cost solar PV technologies, it is important to develop data and analysis that enable decision makers and analysts to explore strategically how IPH demands might shift toward renewable sources over the coming decades.

The audience for this analysis includes other industrial energy analysts; government organizations at the local, state, and national levels; manufacturing companies that are interested

[4] PV-connected induction heaters have been proposed and demonstrated at the lab scale (e.g., Singh and Khan [2016]). We exclude the use of battery energy storage (BES) to maintain a scope that is closer to existing solar IPH (SIPH) system configurations.

in exploring solar technologies for providing process heat, as well as companies developing and selling solar technologies.

The subsequent portions of Section 1 provide overviews of IPH demand, SIPH technologies and current applications, key barriers to SIPH, and the scope and general assumptions of our analysis. The remaining sections of the report detail the analysis used to estimate the opportunities for SIPH by county. In Section 2 we discuss estimation of annual county-level IPH demand and hourly load shapes, scoping of relevant electrotechnologies, and IPH unit process calculations. Section 3 details estimation of available land area by county, and selection and modeling of SIPH technologies. We discuss the calculation approach and results for SIPH opportunities in Section 4. These results are discussed in Section 5 and Section 6 provides conclusions and opportunities for additional research.

1.2 Overview of Industrial Process Heat

Industrial process heating is the transfer of heat to a material within a production process by convection, conduction, or radiation. Process heating technologies are typically categorized by fuel type: fuel-based technologies combust solid, liquid, or gaseous fuels to generate heat; steam-based technologies transfer heat from steam generated by combustion; electric technologies use electric currents or electromagnetic radiation to generate heat either directly within or indirectly transferred to the material being processed; and hybrid technologies use more than one fuel type (DOE 2016a; 2015a; Chindris and Sumper 2012).

The importance of process heat as an energy end-use and a source of emissions has garnered recent attention (e.g., Sandalow et al. 2019; Friedmann, Fan, and Tang 2019), as the paths to decarbonizing other end-uses, such as light-duty transportation and building heating and cooling loads, are understood as relatively straightforward (Davis et al. 2018). This attention to process heat has tended to focus on energy-intensive, high-temperature processes used in basic materials industries such as iron and steel, cement, and steam methane reforming. Iron and steel and cement are the two largest GHG-emitting industries from a global perspective, accounting for over half of global GHG emissions from industry (IEA 2020). Although these industries and other high-temperature processes present special challenges for alternative energy sources, it is important to remember that they are part of a spectrum of process heat demands that includes low-temperature demands. The analysis of geothermal direct use is one recent of focus on low temperature IPH applications in the United States (DOE 2019).

Although the difficulties of substituting high-temperature process heat are largely shared by basic materials industries regardless of their location, the process heat demands of individual countries will depend on the composition of industries and their technologies. Breakouts of IPH demand by temperature range are summarized in Table 1 by global average, for European Union (EU) members, and the United States. The most notable difference is the percentage of IPH demand for very high temperatures. In the United States the cement and iron and steel industries—both of which are energy-intensive industries with very high process temperature requirements—are smaller relative contributors to industrial energy use and emissions. The chemicals and pulp and paper industries, which have lower temperature IPH demands, are much more significant portions of manufacturing energy use in the United States.

Table 1. Comparison of IPH Demands by Temperature Range

Global (Solar Payback 2017)		EU (Naegler et al. 2015)		United States (this report)	
Temperature Range	Percentage of IPH Demand	Temperature Range	Percentage of IPH Demand	Temperature Range	Percentage of IPH Demand
< 150°C	30%	< 100°C	14%	< 100°C	33%
150°–400°C	22%	100–500°C	24%	100–500°C	44%
>400°C	9%	500–1,000°C	23%	500–1,000°C	13%
		> 1,000°C	39%	> 1,000°C	9%

Totals may not sum to 100% due to rounding.

Electricity used for IPH is included in the Global and EU estimates, but not in the United States estimates. Electricity used for IPH in the United States was 375 TBtu (110 TWh) in 2014 (EIA 2017a).

1.3 Overview of Solar Technologies for Industrial Process Heat

We focus our analysis of opportunities for solar IPH (SIPH) on three general types of solar technologies: non-concentrating collectors, concentrating collectors, and PV-connected electrotechnologies. This report is focused not on how PV can supply electricity to the grid for subsequent use to then provide IPH, but rather how solar energy can provide IPH on-site.[5] In this section, we summarize these technologies; a more complete review of available literature and detailed discussion is available in Schoeneberger et al. (2020).

Non-tracking collectors—which can be non-concentrating collectors, such as FPCs and evacuated tubes, or concentrating collectors, such as compound parabolic troughs—are the most common solar thermal technology for providing hot unpressurized water (REN21 2018). Each technology operates and reaches maximum efficiency over different temperature ranges. For FPCs, this range is typically 30°C–80°C, but recent collectors that use vacuum insulation can provide temperatures up to 100°C (REN21 2018). Selective coatings can push this temperature range even higher, and stagnant fluid temperatures have been shown to reach 200°C (Moss et al. 2018; Rockenbaugh et al. 2016; Sakhaei and Valipour 2019).

Directly using energy from concentrating solar thermal technologies for IPH applications is simpler than it is for electric power production because of the removal of the power block (Turchi et al. 2016). Removing the power block avoids the heat-to-electricity losses that occur when using concentrating solar power (CSP) to produce electricity. For industrial sites, however, the use of concentrating collectors for IPH has been rare in the United States (Schoeneberger et al. 2020). SIPH with the concentrating collectors designed for power generation applications can supply heat at temperatures exceeding 400°C (Kurup and Turchi 2015). The size of the SIPH solar field depends on the thermal energy demand and land availability for retrofit applications. Kurup and Turchi highlight specific SIPH collectors that can be installed on roofs or small areas

[5] A current application of solar power for IPH that is not within the scope of this report is PV grid electricity and the existing use of electrotechnologies for IPH, such as electric arc furnaces.

on the ground near an end user, unlike the larger scale common with CSP electricity generation projects that cannot be installed in such applications.

PTCs typically use a liquid-heat transfer fluid (HTF) in the solar field, and several companies produce troughs for SIPH applications. The most common and well understood use of PTCs is for SIPH; see Turchi et al. (2019) for a review of LF and parabolic trough systems.

Much of the IPH demand is for steam, either directly used in processes or indirectly where the steam adds heat to a system or process. Solar collectors can generate steam either in the solar field (i.e., DSG) or by using the more traditional approach where an HTF from the solar field transfers heat to a boiler through a heat exchanger. DSG decreases system complexity and, potentially, capital costs by removing the HTF and boiler.

The final category of SIPH of interest to this analysis is that of PV-connected electrotechnologies, including ambient heat pumps, WHRHPs, resistance heaters, and electric boilers. We discuss these technologies and their use in IPH applications in Appendix A. Heat pumps generate heat from ambient air, waste heat, water, or the ground by using electricity or gas, to raise the temperature for heating or to lower it for cooling. The heat pump cycle can be used for IPH applications such as dryers, boilers, process cooling towers, and refrigeration plants (Lazzarin 1995). Resistance heating produces heat by passing an electric current either through a resistor, which generates heat that is then transferred to the process, or to a conductor that directly increases the temperature of the material to be heated (DOE 2015b). Resistance heating can be used in a variety of IPH applications and across a wide range of temperatures and industries. Electric boilers are a subset of resistance heaters, and they use either electrodes or heating elements to produce hot water and steam.

1.4 Key Barriers for Solar Technologies

The low penetration of renewable energy overall in industry stems from several factors, including geographic separation of resources and demand, land-use constraints, high costs, and the risk of process disruption (Philibert 2017). Very energy-intensive manufacturing industries may also have characteristics—such as capital-intensive industry structures with long investment cycles and low innovation rates—that in general act as barriers to energy transitions (Wesseling et al. 2017).

Additional aspects of manufacturing facilities act as barriers for SIPH adoption. Thin margins and tight production schedules may lead to a reluctance to change and concerns about the length of downtime during installation of a SIPH system (Schoeneberger et al. 2020). Additionally, many SIPH systems are designed to supplement, not replace, combustion-based IPH equipment, which creates a hybrid system with additional complexity to be managed by facility operators. The low adoption of on-site SIPH systems in the United States means that most facilities are unfamiliar with their operation, maintenance, and repair, which may contribute to a sense of technological risk.

Even if production is scheduled for no more than one eight-hour shift per day, TES is likely required to maintain a higher solar fraction, balancing the daily variability of solar resources. Studies of the potential for load shifting and other demand side management strategies that change the timing, or the magnitude and timing of energy demand in manufacturing industries have so far focused on electricity use (e.g., Paulus and Borggrefe 2011; Pechmann et al. 2017). However, their results do provide some insight to the opportunities and barriers for IPH flexibility. Olsthoorn et al. (2015), for example, find that the most significant barriers to electricity load shifting are risk of production process disruption, risk of lower product quality, and disruption to operations.

1.5 Overview of Thermal Energy Storage

Solar energy is a variable resource, meaning its availability changes by time of day and season. This variability can create an imbalance between the supply of solar energy and IPH demand, over the same hourly and seasonal periods. Thermal energy storage (TES) is used to balance demand by storing energy when it is not needed and dispatching it when it is needed. TES is a key enabler of SIPH, particularly in cases where industries operate multiple shifts per day or have processes that operate continuously. Three of our selected technology packages—FPC, PV HP, and PTC —are modeled with TES included. In this section, we provide an overview of TES systems. In later sections (Section 4.3.1 and Section 5.2), we discuss the importance of TES and highlight its effects for enabling opportunities for SIPH.

The large fluctuations in the availability of solar energy are a significant challenge for its effective use and storage, which involves minimizing thermal losses and efficiently extracting stored energy (Lefebvre and Tezel 2017). TES systems are classified as sensible heat storage, latent heat storage, and thermochemical storage (Kuravi et al. 2013). Latent heat TES systems that use phase change materials (PCM) "are useful because of their ability to charge and discharge a large amount of heat from a small mass at constant temperature during a phase transformation like melting-solidification" (Gomez 2011, 1). Crespo et al. (2019) review latent TES technologies for process temperatures between 120°C and 400°C, which is a significant portion of our identified IPH demand. Hybrid adsorbents, adsorbents with salt impregnations, and adsorbents with alkaline additions are the materials with the best TES performance (Lefebvre and Tezel 2017). Adsorption processes are not currently economically competitive, but this could change soon with improvements to materials and system optimization (Lefebvre and Tezel 2017).

For electrotechnologies, energy can be stored either in a TES or in electrical form. The most common form of electrical energy storage is battery energy storage (BES). We have excluded BES from our analysis because the combination of PV-connected electrotechnologies with BES falls further outside of existing SIPH applications than only PV-connected electrotechnologies. BES, along with other energy storage options, is a critical part of the future analysis we discuss in Section 6.2. The analysis that supports our selection of electrotechnologies for IPH is detailed in Appendix A.

1.6 Existing Studies of Opportunities for Renewable Energy in Industry

As of 2019, 301 solar thermal systems that were larger than 50m^2 were installed for IPH around the world, and they collectively provided thermal capacity of 441 megawatts-thermal (MW$_{th}$) over a gross area of 905,000 m^2 (Weiss and Spörk-Dür 2020). The two largest systems—located in Oman and Chile—constitute nearly 75% (327.5 MW$_{th}$) of the installed thermal capacity. In the

United States today, about 22 MW_{th} of total installed power exists for SIPH applications (Schoeneberger et al. 2020).

The portion of solar energy generated on-site for use in the U.S. manufacturing sector remains extremely low[6].In 2014, the manufacturing sector purchased about 781 terawatt-hours (TWh) of electricity and generated about 134 TWh of electricity; noncombustable renewables[7] contributed 1.64 TWh, which is equivalent to about 1.2% of own generation (EIA 2017a).

Taibi et al. (2012) estimated that global renewable energy use in the manufacturing sector could quintuple by 2050, reaching 21% of fuel and nonfuel (feedstock) use. And the most recent estimate of the potential for renewable energy in global industry heat demand is 19% by 2030 (Saygin et al. 2015). As of 2018, however, global renewable energy use in the most energy-intensive industries was about 10%, most of which was biomass and waste (IEA 2019). The use of renewable energy technologies, along with energy storage and other enabling technologies, for achieving zero emissions by 2060 has been described for the iron and steel, cement, chemicals, and aluminum subsectors (IRENA 2020). Although the mix of emissions reduction measures varies by industry, the resulting share of renewable energy (including electricity and district heating from renewables) ranges from 29% for chemicals to 60% for aluminum.

As Schoeneberger et al. (2020) note, many other studies have estimated the technical potential of solar technologies to meet process heat demand at national and industry levels. However, we identified just three studies that incorporated parameters for process heat characteristics, process heat load profiles, solar irradiance, and available land or rooftop area (Quijera et al. 2014; Lauterbach et al. 2014; Quijera et al. 2011). These three studies all focus on single facilities in a particular industry. Studies of national potential (e.g., Vajen et al. (2012)] and Vannoni et al. (2008)]), generally estimate potential not by directly simulating generation of solar technologies, but by first identifying the portion of IPH demand that is relevant for solar thermal technologies based on temperature and then applying general estimates of available roof area and average solar fraction. Also, they typically do not use hourly heat demand data in their calculations. These studies have found technical potential in European countries of between 3% and 5% of industrial heat demand. Other national potential analyses for Spain (Lillo-Bravo et al. 2018), Mexico (Ramos et al. 2014), Argentina (Lillo et al. 2017), and Tunisia (Calderoni et al. 2012) do not incorporate details about process heat demand beyond general industry type and process temperature.

Conversely, Schweiger et al. (2000) simulated non-concentrating and concentrating collectors over five sites in Spain and Portugal to estimate annual energy yield (kWh/m^2) as a function of process heat temperature. Kalogirou (2003) simulated the annual solar yield of five collector types and estimated their annual solar contribution at different process heat temperature levels for relevant process heat demands in Cyprus. The authors estimated an annual solar contribution as much as 80% for lower temperature levels (i.e., 60°C and 90°C) and as high as 50% for the highest temperature level (240°C). Beath (2012) examined the alignment of Australia's

[7] Noncombustable renewables include solar, wind, hydropower, and geothermal generation. No further disaggregation is provided.

geographic distribution of solar resources and industrial energy use, including process temperature, but stopped short of simulating solar generation at the industrial sites.

1.7 Scope of the Analysis

The scope of our analysis is IPH demand from the manufacturing sector in the continental United States. The base year of our analysis is 2014, which is the latest year for which comprehensive energy statistics are available from MECS. We assume the matching of solar technologies and IPH demand shown in Figure 1 occurs on a county-aggregated level and not at the level of individual facilities. IPH demand is not spatially disaggregated beyond the county level, although some facility-level data are used in the estimation of energy use prior to aggregation at the county level. Operational characteristics, such as operating schedules and temperature, are not defined at the level of individual facilities. These characteristics may vary significantly between facilities for the same process. Likewise, solar resources and available land area are also aggregated at the county level, as described in Section 3. One implication of this spatial aggregation is that we do not consider in detail the area available for individual facilities and the heat transport from solar fields; this is an opportunity for future analysis and is discussed later in the report. We also do not consider available rooftop area.

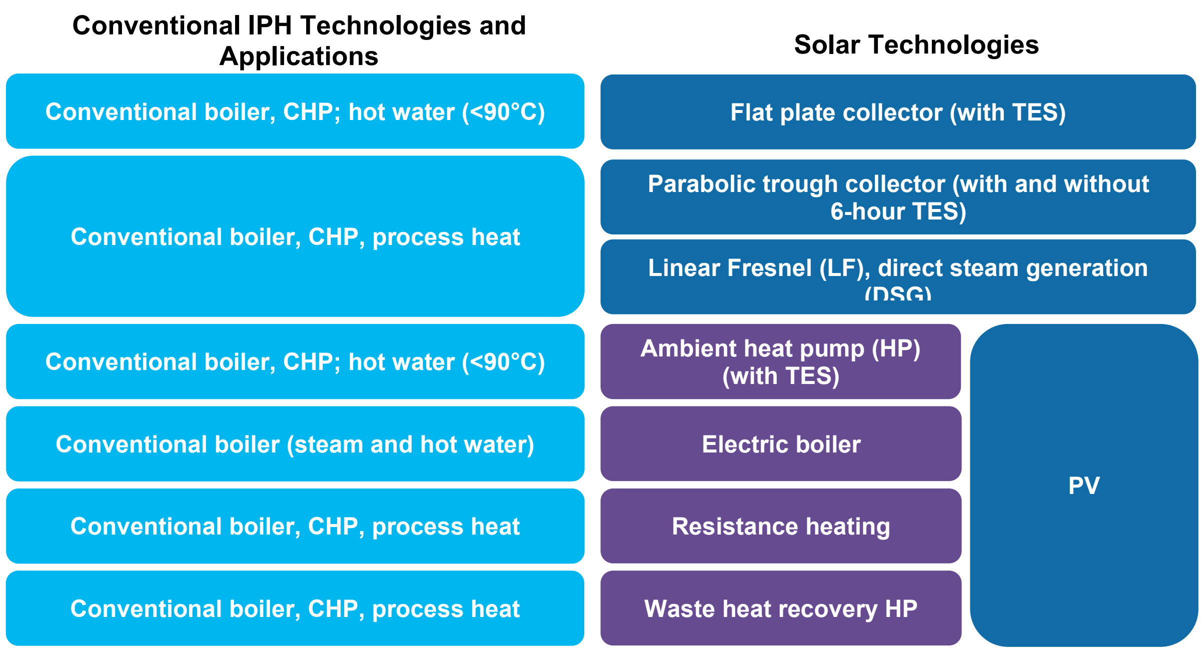

Figure 1. Applications of industrial process heat matched to relevant solar technologies

We define IPH to mean the use of combustion fuels in conventional boilers, combined heat and power (CHP)/cogeneration, and process heating equipment, as well as purchased steam[8], in the manufacturing sector. Our definition excludes heat use in other industrial sectors, such as grain

[8] Purchased steam is a relatively small portion of total manufacturing fuel use, contributing about 604 TBtu, or 4%, in 2014 ("Manufacturing Energy and Carbon Footprint Sector: All Manufacturing (NAICS 31-33)," U.S. Department of Energy (DOE), https://www.energy.gov/sites/prod/files/2019/06/f64/Manufacturing%20Energy%20Footprint-2014_Latest_compliant.pdf).

drying in agriculture, as well as the use of electricity for process heating. The overall scope of combustion energy and IPH demand is summarized in Table 2. We estimate a total combustion fuel use in 2014 of 12,600 trillion Btu (TBtu) (3,690 TWh). Of this, we estimate about 11,200 TBtu (3,280 TWh) could be allocated to an IPH end use. Disaggregating this amount into process temperatures yields an estimated IPH demand of 11,000 TBtu (3,220 TWh)[9], which is the basis for our analysis. As indicated in the table and discussed further in Appendix A, it was not possible to disaggregate the entirety of IPH demand by process temperature. This explains the difference between the second and third columns of Table 2.

After identifying IPH demands by end use and process temperatures, we undertake additional, unit-process level analysis to identify the demands by solar technology. For example, Table 2 shows that 99% of the CHP and/or cogeneration process demands and only 22% of the process heating demands were considered as potential opportunities for the PTC. The sum of matched demands across all end-uses for PTC represents 73% of total IPH demand. From those matched demands, we then estimate process energy using assumed efficiencies for boilers and other types of IPH equipment. The process for matching the appropriate subset of IPH demands and estimating process energy for each solar technology package is described in Section 2.4 and Appendix C.

[9] The Manufacturing Energy Consumption Survey (MECS) would be the most relevant basis for comparison with our energy estimates. However, MECS does not include process temperature information and a significant portion—nearly 40%—of 2014 manufacturing energy use is not disaggregated by end use ("2014 MECS Survey Data: Energy Consumed as a Fuel by End Use," EIA, https://www.eia.gov/consumption/manufacturing/data/2014/#r5). An alternative source that does disaggregate MECS data by end use estimates that 10,475 TBtu of combustion fuels were used in conventional boilers, CHP/cogeneration, and process heating ("Manufacturing Energy and Carbon Footprint Sector: All Manufacturing (NAICS 31-33)," DOE, https://www.energy.gov/sites/prod/files/2019/06/f64/Manufacturing%20Energy%20Footprint-2014_Latest_compliant.pdf).

Table 2. Scope of IPH Demand by Solar Technology

	IPH End Use			
	CHP and/or Cogeneration Process	**Conventional Boiler Use**	**Process Heating**	**Total**
Total Combustion Energy in 2014 in TBtu (in TWh)				**12,600 (3,690)**
Disaggregated by End Use	3,930 (1,150)	3,420 (1,000)	3,800 (1,110)	11,200 (3,280)
Disaggregated by Temperature	3,890 (1,140)	3,380 (990)	3,730 (1,090)	11,000 (3,220)
Percentage of IPH Demand in Scope by Solar Technology				
PTC	99%	100%	22%	73%
LF	91%	80%	0%	57%
PV + Resistance	9%	11%	73%	31%
Electric Boiler	0%	100%	0%	31%
FPC	46%	35%	0%	27%
PVHP	46%	35%	0%	27%
WHRHP[a]	2%	2%	1%	2%

[a] WHRHP percentage reflects relevant portion of waste heat from IPH demands.

The percentage of IPH demand in scope by solar technology is calculated by matching IPH demand to solar technology at the unit process level using process temperature, heat transfer medium, where applicable, solar technology capacity constraints.

2 Process Heat

2.1 County-Level Process Heat Demand

This analysis builds on energy estimates at the facility-level (McMillan et al. 2016; McMillan and Ruth 2019) and the county-level industry (McMillan and Narwade 2018). These earlier estimates were first developed with the goal of providing levels of spatial and operational detail that are missing from established sources of energy data, such as MECS (EIA 2017b) and the State Energy Data System (EIA 2017d). This additional level of detail enables process heat and other industrial energy demands to be more closely matched with local solar resources and the operating characteristics of solar technologies.

We discuss details of the updates in Appendix B, but, in general, we improved the use of facility-level data from the Environmental Protection Agency's (EPA's) Greenhouse Gas Reporting Program (GHGRP) by partitioning energy calculations based on emissions reporting method. This allowed the calculations to reflect fuel-level information, including higher heating values, reported to the EPA. Additional improvements were made to the capture of combustion unit information for categorizing energy by end-use category.

The most significant change was the expansion of the calculations to include process temperatures. This was accomplished by disaggregating energy data calculated by industry and process heat end-use category (i.e., process heating, conventional boiler, and CHP/cogeneration unit) to process energy and temperature using estimates developed by Brown, Hamel, and Hedman (1997). This disaggregation was a critical step in matching process heating demands to the appropriate solar and electric technologies. We undertook additional characterizations of these baseline data, such as separating hot water and steam demands from boilers, to identify the relevant demand more closely for different technologies, as described in Section 4.

Our analysis provides the highest resolution estimates of combustion fuel use for IPH demands in the United States, and it reveals an even greater contribution from demands at temperatures below 300°C than shown by McMillan and Ruth (2019) due to our inclusion of all manufacturing industries and not just the largest, most energy intensive industries. We estimate that of the roughly 11,000 TBtu of process heat demand in 2014, approximately 73% (8,010 TBtu) was below 300°C. This represents about one-third of total industrial primary energy use[10] and 11% of total primary energy use of the United States in 2014 (EIA 2020).

Figure 2 summarizes the total cumulative IPH demand by temperature, as well as by end use. The figure shows the significant portion of process heat demand at temperatures below 300°C, which is a result of the large contributions of hot water and steam demands from boilers. Industrial process heat demands just above 400°C are related to kilns, furnaces, and other related equipment that rely on the combustion of fuels to transfer heat directly or indirectly to a process.

[10] Our definition of industrial energy use also includes the agriculture, construction, and mining sectors.

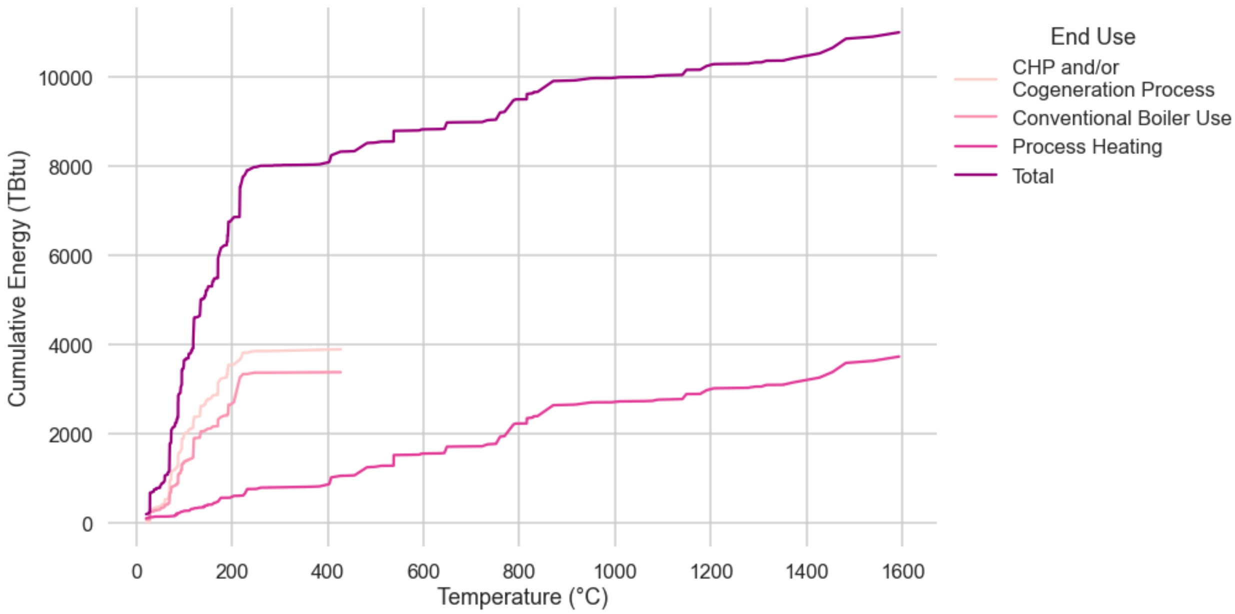

Figure 2. Cumulative industrial process heat demand by end-use category

The resolution of this data set allows us to examine many facets of IPH demand. We briefly explore demand in terms of temperature, end use, industry, and fuel type. Recognizing that additional insights could be gained from further analysis, we encourage readers to download the data set[11] and contribute to the open-source codebase used for the calculations[12].

As seen in Figure 3, most counties in the United States have some, albeit small, IPH demand. The counties with the largest IPH demand are concentrated in a few counties in Texas, Louisiana, California, and Indiana. The top five out of roughly 3,070 counties account for 12% of IPH demand, equivalent to the bottom 2,450 counties. These areas are generally home to clusters of energy-intensive industries, such as chemicals, petroleum refining, and, to a lesser extent, iron and steel. Counties within a north-south band that runs through Montana, North and South Dakota, and Kansas, have the least process heat energy. As will be shown, while solar radiation is very good in the U.S. Southwest, there is also significant potential in other states and counties where there is also significant process heat demand (e.g., Florida, Illinois, and Missouri). It is also important to note counties in northern states (e.g., Minnesota and Maine), which have very cold weather conditions and lower solar resources, also have larger IPH demands.

[11] "Manufacturing Thermal Energy Use in 2014," NREL Data Catalog, https://doi.org/10.7799/1570008.
[12] https://github.com/NREL/Solar-for-Industry-Process-Heat

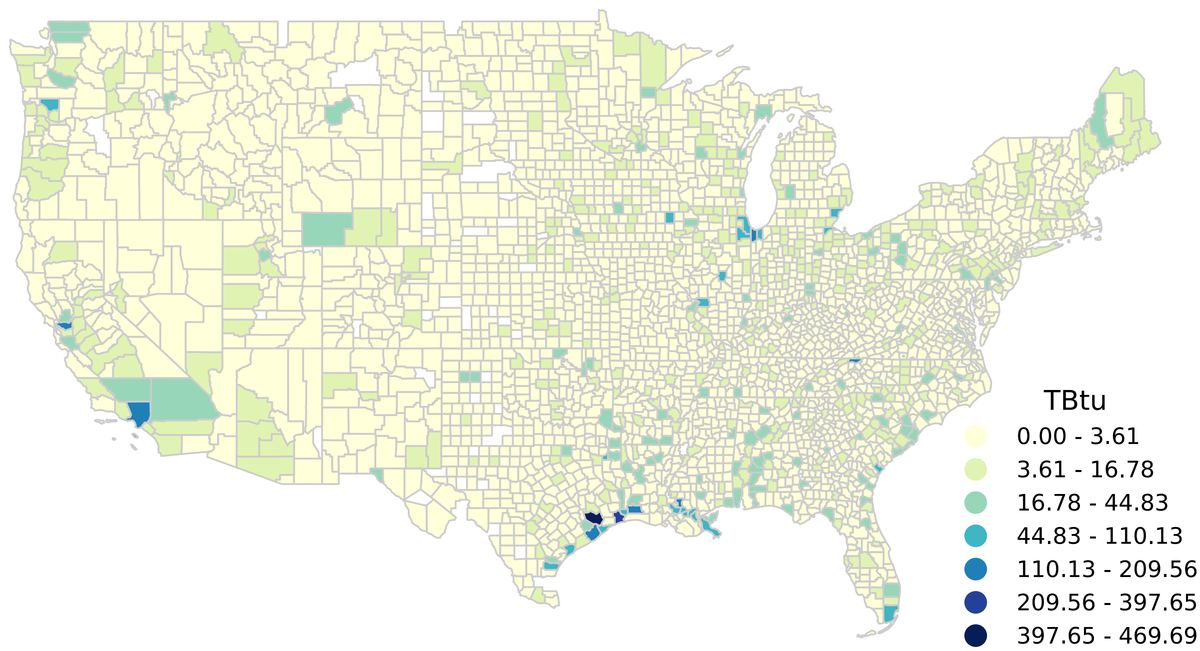

Figure 3 Geographic distribution of industrial process heat demand by county in 2014

Natural gas provided about 47% of industrial process heat demand in 2014. As shown in Figure 4, waste gas provided the second-largest portion of process heat demand, or 20% of total process heat demand. The large contribution of waste gas reflects the large process heat demands of petroleum refining, petrochemical manufacturing, and other chemicals industries, wherein fuel gas and byproducts of certain industrial processes are combusted as a fuel source. These gases include refinery gas from refinery distillation operations, fuel gas produced during propylene oxide and other organic chemicals manufacturing, as well as coke oven gas and blast furnace gas.

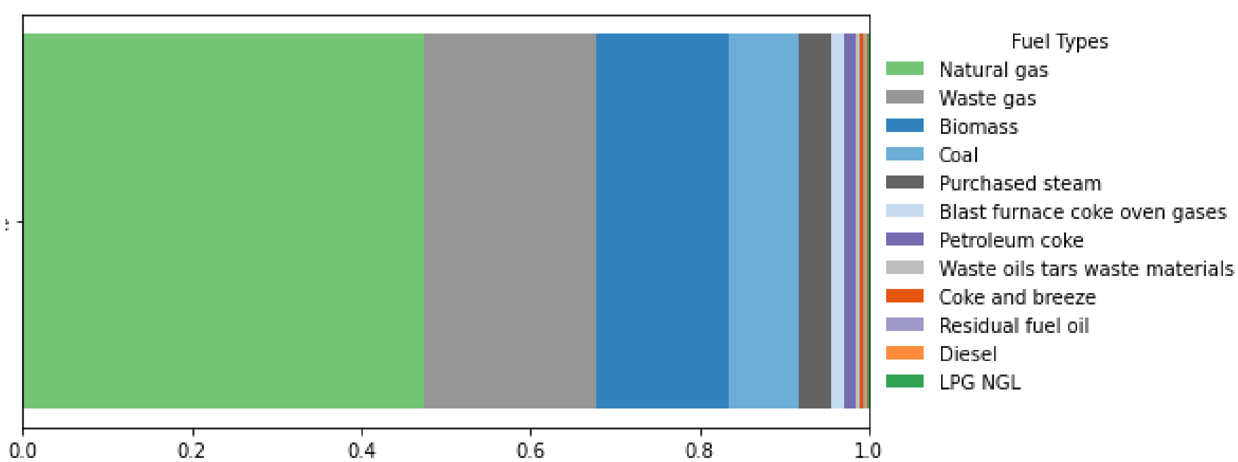

Figure 4. Fuel type mix of industrial process heat demand

Our analysis indicates that petroleum refining[13] was the largest source of process heat demand in 2014. That industry used over two times the energy for process heat as the next-largest industry, which was paper (except newsprint) mills. As shown in Table 3, the largest heat demands within petroleum refining occurred between 100°C and 300°C, which comprised about 63% of the industry's total process heat demand of 2,210 TBtu. We estimate that about 75% of IPH demand for paper (except newsprint) mills, paperboard mills, and pulp mills is for process temperatures below 100°C.

Table 3. Largest Users of Process Heat and their Largest Temperature Demands in 2014

NAICS[a]	Industry	Total Process Heat Demand (TBtu)	Temperature Range of Largest Process Heat Demand Temperature (°C)	Heat Demand within Temperature Range (TBtu)	Process Temperature Percentage of Industry Total Process Heat Demand
324110	Petroleum Refineries	2,210	100–300	1,380	63%
322121	Paper (except Newsprint) Mills	870	<100	643	74%
322130	Paperboard Mills	803	<100	608	76%
331110	Iron and Steel Manufacturing	601	>1,000	313	52%
325199	Basic Chemical Products	593	100–300	281	47%
325193	Ethyl Alcohol Manufacturing	526	100–300	202	38%
322110	Pulp Mills	489	<100	367	75%

[a] NAICS = North American Industry Classification System

2.2 Representative Heat Load Shapes

Along with process temperatures, operating schedules and load are also critical elements for matching solar technologies to IPH demand. These temporal aspects of IPH use are even less well-defined than temperature and geographic distribution. Schoeneberger et al. (2020) found that process heat load profiles were used in less than half of identified solar IPH case studies. We were unable to find any publicly available industrial load profile data sets that were suitable for our modeling efforts. So, we estimated representative heat load curves that are used to estimate demand by the North American Industry Classification System (NAICS) code, employment size class, and end-use category for every hour in 2014.[14] In this section, we briefly

[13] Although future projections are outside of the analysis scope, we note that petroleum refining and ethanol production could face large decreases in demand from transportation electrification.
[14] Representative load shapes are available from the NREL Data Catalog: https://doi.org/10.7799/1570008.

discuss two existing sources of load shape data before describing our process for estimating representative heat load shapes.

Existing publicly available load shape data include the Electric Power Research Institute's (EPRI) Load Shape Library, which includes representative electricity hourly load shapes for industrial end uses across North American Electric Reliability Corporation region (EPRI 2020). Separate load shapes in the Load Shape Library are defined for combinations of peak and off-peak season, peak and average weekday, and average weekend. Although these data cover the entire United States, they are not disaggregated by specific industry.

The EPA's Air Markets Program Data provides hourly heat load and steam load observations by combustion unit type for facilities that participate in EPA emissions trading programs (EPA 2020). Although this data source is very detailed, it is limited in its industry coverage. Only 22 NAICS codes are represented in the data. The reporting facilities are part of energy-intensive industries, such as pulp and paper, petroleum refining, and iron and steel manufacturing, and the reporting facilities are assumed to all be very large. That said, we found it useful to generalize load data from these facilities to use in our own estimates for large facilities that fall under the same energy-intensive NAICS codes.

Without a suitable existing data source to use, we developed a set of representative heat load shapes using a variety of data sources. Our goal was to capture the differences in hourly process heat demand by characterizing operating schedules based on industry, facility size, and seasonality. We did not consider the operating schedules of processes or of individual pieces of equipment. So, these load shapes should be thought of as representing aggregate process heat demand for an entire facility and not representing individual processes within a facility itself. These load shapes are then aggregated at the county level, which obscures the operational variation between facilities. We deem our load shape assumptions to be acceptable given the scope of capturing all manufacturing industries across all contiguous U.S. counties. We acknowledge the importance of future research that more accurately describes the temporal aspects of IPH demand and their variability (see Section 6.2). Our process for estimating representative load shapes is composed of four general components:

- **Operating Schedule:** We used average weekly operating hours published by quarter in 2014 by the U.S. Census Bureau (2018a) for 94 industry groups to develop a typical operating schedule specified by day type (i.e., weekday, Saturday, and Sunday) and quarter. We also used the census data standard error estimates to calculate operating schedule upper and lower bounds. These bounds were then used for sensitivity analysis of the opportunities for solar technologies to meet process heat demand.
- **Seasonality:** We tested for the presence of seasonal operation by comparing quarterly operating hour responses and their annual averages over time by industry. All industries were assumed to operate throughout 2014 at the annual average of their weekly operating hours. Operating hours were distinguished by quarter only when seasonality was identified.
- **Facility Size:** The Census Quarterly Survey of Capacity Utilization represents an aggregation of responses from establishments of different sizes. We assumed that, on average, smaller facilities in the same NAICS code would operate fewer hours every week than larger facilities. To test this assumption, we used annual operating hours and

facility employment size reported by participants in the U.S. Department of Energy (DOE) Industrial Assessment Center program (DOE 2020a) to test for statistically significant differences in annual operating hours by employment size class.[15] A special category of process heat load shapes was created for large industries that are also EPA GHGRP reporters using generalized load data from EPA's Air Markets Program Data.
- **Equipment Turndown:** We assumed a minimum load would be maintained in facilities during nonoperating hours to avoid equipment damage that might result from thermal shocks and other stresses caused by on/off cycling. We assumed a 4:1 turndown ratio for boiler heat load shapes (Babcock & Wilcox 2020; Cleaver-Brooks 2020a) and a 5:1 turndown ratio for process heating load shapes.

2.3 Electrotechnology Scoping and Technical Potential of Selected Electrotechnologies

Based on a thorough literature review, we identified fourteen different electrotechnologies that have applications to process heating within the U.S. manufacturing sector (EPRI 2012; Knoke and Tidball 2011; den Ouden et al. 2017; DOE 2008; CEATI, n.d.). These electrotechnologies are summarized in Table 4 (page 18). Industrial heat pumps and electric boilers have already seen substantial market uptake, and their application has potential to further increase (IETS 2013; Cleaver-Brooks 2020b). Other electrotechnologies listed in Table 4 also have growth potential due to advantages over conventional process heating technologies, such as rapid heating, faster start-up, no combustion gas, automatic control systems, lower maintenance costs, and higher production rates (Knoke and Tidball 2011). A detailed description of each electrotechnology listed in Table 3 is provided in Appendix A, whereas the applicable end uses for each electrotechnology are summarized in Table A-1. Due to time and resource limitations, in the current study it was necessary to down-select to a few electrotechnologies for deeper opportunity analysis at the county level. This selection was made based on three screening criteria:

- The technical potential for conventional fuel replacement in applicable process heating end uses at the U.S. national level
- Data availability for credible modeling
- Market growth outlook as shown in Table 4.

The scoring rubric for each criterion is further discussed in Appendix A.2. For each criterion, we assigned a weighting factor. The potential for conventional fuel replacement was deemed the most important criterion for this study, and it was therefore assigned a weighting of 2. Modeling feasibility, and market growth outlook were each assigned a weighting of 1. The overall score for each electrotechnology was calculated by summing the multiplication of the score given to each criterion and its weighting factor.

[15] Although small and medium-sized facilities are the focus of the Industrial Assessment Center program, the database does include a wide range of reported employee counts, with some facilities in the database having more than 500 employees.

Based on the results of the screening process in Table 3, we selected electric boilers, ambient heat pumps, resistance heating and melting technologies, and WHRHPs for detailed technical opportunity analysis. However, induction heating and melting, infrared processing, microwave heating and drying, radio frequency heating and drying, and direct arc melting also presented attractive options that could be considered in future studies. Ultraviolet curing, plasma processing, vacuum melting, laser processing, and ladle refining were all found to have more limited conventional fuel replacement potential at the U.S. national level compared to the selected options, and were therefore excluded from further consideration in this study. The technical potential of WHRHPs, electric boilers, and resistance heating are further discussed below. The technical potential of ambient heat pumps is discussed in Sections 3.3.3 and 4.3.6.

Table 4. Summary of Screening of Electrotechnologies

Electrotechnologies	Technical Potential for Conventional Fuel Replacement[a]	Weighted Score[b] of Technical Potential	Data Availability[c]	Weighted Score of Modeling Confidence	Market Growth Outlook[d]	Weighted Score of Market Growth Outlook	Overall Score
Electric boiler	3	6	3	3	3	3	**12**
Ambient heat pump	3	6	3	3	2	2	**11**
Resistance heating and melting	3	6	3	3	2	2	**11**
Waste recovery heat pumps	2	4	3	3	3	3	**10**
Induction heating and melting	2	4	3	3	3	3	**10**
Infrared processing	2	4	3	3	3	3	**10**
Microwave heating and drying	2	4	3	3	3	3	**10**
Radio-frequency heating and drying	2	4	3	3	3	3	**10**
Direct arc melting	2	2	3	3	3	3	**10**
UV (ultraviolet) curing	1	2	3	3	3	3	**8**
Plasma processing	1	2	3	3	2	2	**7**
Vacuum melting	1	2	2	2	3	3	**7**
Laser processing	1	2	3	3	2	2	**7**
Ladle refining	1	2	1	1	1	1	**4**

[a] Score rubric for technical potential for conventional fuel replacement: potential >= 500 TBtu/year, score = 3; 100 TBtu/year <= potential < 500 TBtu/year, score = 2; potential < 100 TBtu/year, score = 1

[b] Weighting factors: technical potential for conventional fuel replacement (2), data availability (1), and market growth rate (1)

[c] Score rubric for modeling confidence: case studies with sufficient technical information or mature engineering models, score = 3; case studies with limited technical information or preliminary models, score = 2; few/no technical case studies and no models, score =1

[d] Score rubric for market growth outlook: 5-year growth rate (from 2015 to 2020) >= 10%, score =3, 0% <= 5-year growth rate <10%, score =2; 5-year growth rate<0%, score =1 (EPRI 2016)

2.3.1 Electric Boilers

The technical potential of replacing conventional boilers with electric boilers was estimated to be about 916 TBtu of conventional fuel replacement. This estimate was based on the current fuel consumption of conventional boilers in different industries, an assumed boiler capacity distribution in each major industry, and the available capacities of electric boilers currently on the market. The conventional fuel consumption by conventional boilers in different industrial subsectors was obtained from the MECS data set (EIA 2014c; 2014a; 2014b; DOE 2014b), and the boiler capacity distribution in the United States was estimated from boiler population data in (Energy and Inc (2005) and (EPA 2012). The technical potential calculations were based on an assumed maximum electric boiler capacity of about 190 million Btu (MMBtu)/hour based on a review of electric boilers currently available on the market (Cleaver-Brooks 2020a; Electro Industries 2020; Bryan Boilers 2020b, 2020a; WilsherCo 2020; Vapor Power 2020c, 2020a, 2020b). The total fuel usage and technical potential of using electric boilers to replace conventional boilers is shown in Figure 5.Detailed technical potential calculation steps and results are in Appendix A.3.

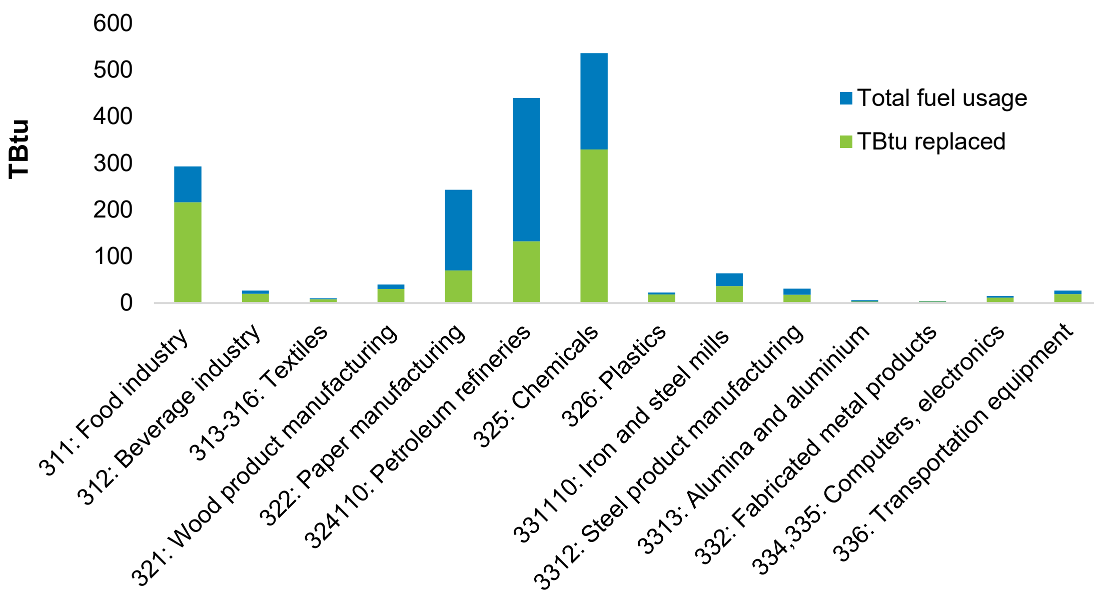

Figure 5. Total fuel use of conventional boilers and technical potential of using electric boilers to replace conventional boilers

The technical potential was estimated by multiplying the conventional fuel consumption of conventional boilers by a replacement ratio calculated from the assumed boiler capacity distribution in each subsector. As shown in Figure 5, the food subsector (NAICS 311), petroleum refinery industry (NAICS 324110), and chemicals subsector (NAICS 325) have higher technical potential, at 216 TBtu/year, 132 TBtu/year, and 329 TBtu/year respectively. In the food subsector, the high technical potential can be explained by the assumed boiler capacity distribution: 74% of conventional boilers can be replaced by electric boilers based on the assumed maximum electric boiler capacity of 190 MMBtu/hr. In the petroleum refinery industry, the total energy consumption by conventional boilers is relatively high (440 TBtu/year), and this is the main reason for the high technical potential, with a 30% replacement ratio. In the chemicals subsector, the high technical potential is a result of both high energy consumption of conventional boilers (536 TBtu/year) and a high replacement ratio (60%) associated with its assumed boiler capacity distribution.

Subsectors such as beverage (NAICS 312), textile (NAICS 313-316), wood product manufacturing (NAICS 321), plastics (NAICS 326), fabricated metal products (NAICS 332), computer and electronics (NAICS 334, 335), and transportation equipment (NAICS 336) have lower technical potential as shown in Figure 5. Although they have relatively high replacement ratios, the low technical potential is caused by the low overall conventional fuel consumption of conventional boilers in these subsectors at the U.S. national level. However, at the level of individual plants in these subsectors, electric boilers may still be attractive options for substantial conventional fuel replacement.

2.3.2 Waste Heat Recovery Heat Pumps (WHRHPs)

The technical potential of WHRHPs was estimated to be about 380 TBtu/year. To derive this estimate, we first identified the subsectors that generate the most waste heat and the unit processes within these subsectors that generate this waste heat. The waste heat source and heat sinks in different subsectors were identified from numerous case studies and technical reports. Waste heat loss fractions were calculated based on different temperature references, and percentages of waste heat not recovered were estimated from the report (Johnson, Choate, and Davidson 2008). Amounts of available waste heat were calculated from the heat contents of input fuels obtained from our estimated IPH demand,[16] assumed heat loss fractions, and assumed percentages of waste heat currently not recovered. Finally, the technical potential was calculated by multiplying waste heat by the coefficient of performance (COP) of the applicable heat pump technology. Details about the calculation strategy for WHRHPs are provided in Appendix A.4.

The technical potential of WHRHPs has been discussed by others (Johnson, Choate, and Davidson 2008; EPRI 2010; Thekdi and Nimbalkar 2015). The main differences between these studies and our study are that we (1) matched each heat source with an applicable heat sink within a given process system, wherein the size of the sink limited the recovery potential; and (2) considered the percentage of waste heat that has been already recovered in the technical potential estimation. Input work/heat refers to the heat pump operational energy requirements.

[16] "Manufacturing Thermal Energy Use in 2014," NREL, Last Updated September 27, 2019, https://doi.org/10.7799/1570008

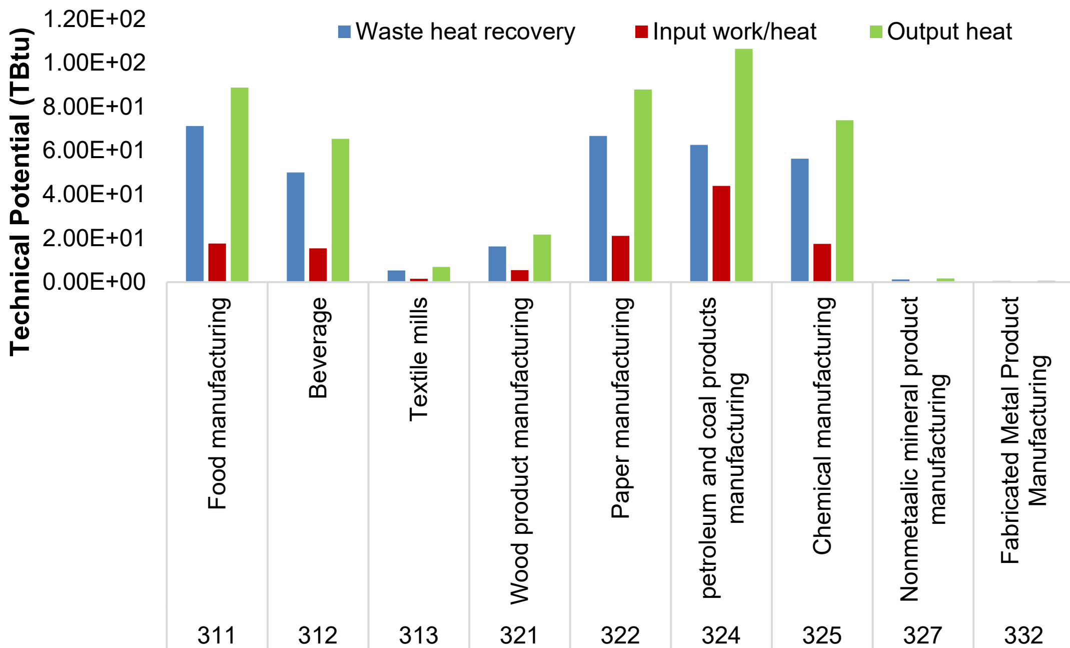

Figure 6. Estimated technical potentials of using waste heat recovery heat pumps (WHRHPs)

As shown in Figure 6, the food (NAICS 311), paper (NAICS 322), petroleum coal product (NAICS 324), and chemicals (NAICS 325) industrial subsectors have higher technical potentials for using WHRHPs. The blue color bars show waste heat that can be recovered in each subsector, and the green color bars represent the heat output from WHRHPs that is matched with a heat sink. Details about WHRHP types are provided in Appendix A.1.

2.3.3 Resistance Heating and Melting

The technical potential of resistance heating/melting was estimated to be about 1,834 TBtu. This potential was calculated from the total fuel use associated with each end use from our IPH demand estimates and the fraction of fuel usage in different unit processes that is technically replaceable by resistance heating (Brown et al. 1997). As shown in Figure 7, resistance heating has higher technical potential in the food, chemical manufacturing, nonmetallic mineral product manufacturing, and primary metal manufacturing subsectors. The detailed technical potential calculations and results are in Appendix A.

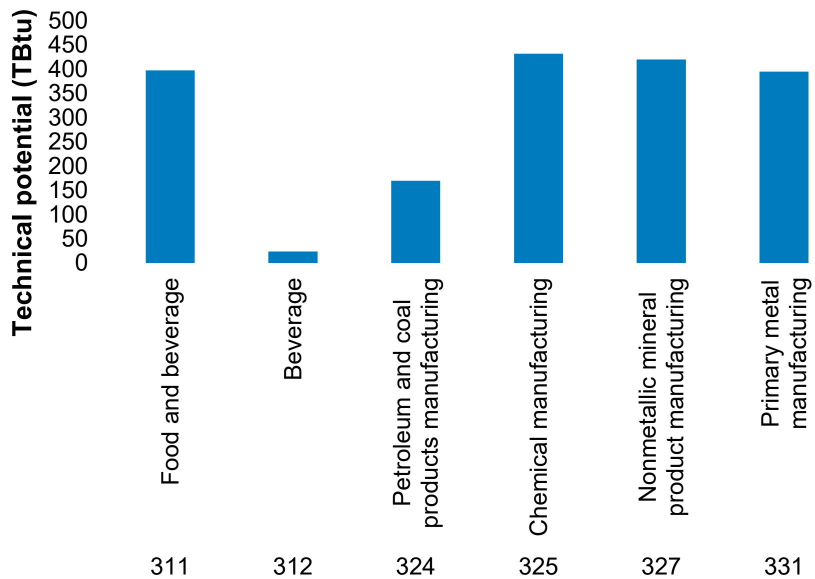

Figure 7. Estimated technical potentials of resistance heating/melting

2.4 Unit Process Calculations

Because heat demands vary by process temperature, fuel type, and hours of operation within subsectors, it is useful to characterize demand at the level of the unit process requiring heat. A unit process represents a single manufacturing system operation, such as pasteurization in food and beverages production or distillation in petroleum and chemicals production. An evaluation of process heat at this level is necessary when considering the integration of alternative heating technologies.

As described in Section 2.1, county-level heat demand is categorized by fuel use (energy content and fuel type), but the physical heat delivered to a unit process is often in the form of steam or hot water and contains less energy because of efficiency losses from the fuel combustion step. The process-level heat demand must be known to determine the opportunity for solar generated heat, so that energy requirements are compared at the same point Figure 8.

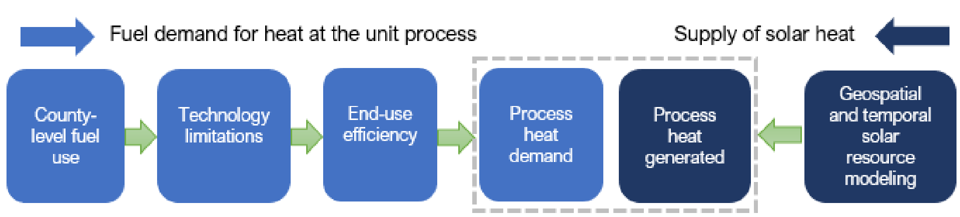

Figure 8. Process heat demands and process heat supply matching

For each solar technology group covered in this study, we calculated process-level heat demand from county-level fuel demand, considering the end uses relevant to the type of heat the solar technology provides as well as its technology limitations, such as achievable temperature range and potential within applicable industries. End uses are based on the MECS reporting structure and include conventional boilers, CHP, and process heating, the latter referring to direct, combustion-based heating. Figure 9 shows simple block diagrams of the three end uses.

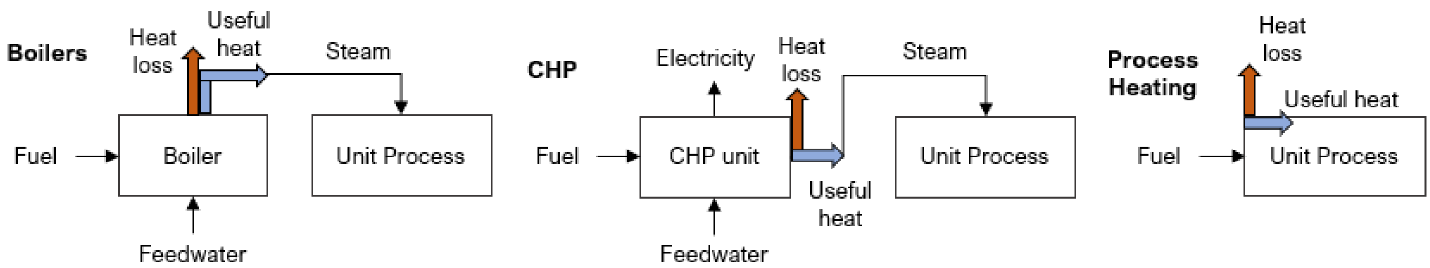

Figure 9. Block diagrams of the three end-use categories for IPH

With each end-use, there is an efficiency loss between the primary energy associated with the fuel and the useful heat energy used by the process. The thermal efficiency of boilers changes with fuel type: CHP units have both a thermal and electrical efficiency that depend on the prime-mover type of units, and direct process heating has heat losses in combustion. The calculations for end-use efficiency, as well as the filtering of county-level fuel demand to process-level heat demand, are described in Appendix C.

The integration of SIPH systems in existing manufacturing facilities is an important factor for determining their technical opportunity. To this end, we considered technology constraints for each solar technology package in our process demand calculations. The system descriptions of the solar technology packages and their generation potentials are discussed in Section 3, but the method for determining process heat demands of each is introduced here.

Solar thermal technologies provide heat in the form of hot water, steam, or HTFs, while solar PV provides electricity. In addition to the type of heat supplied, solar thermal and electric technologies differ in achievable temperature ranges, and the types of unit processes for which they are technically feasible. For example, an FPC is used in hot water heating and, therefore, would only be able to meet heat demands for industries and unit processes that require hot water. In another example, an electric resistance heater can theoretically supply low to very high temperature heat, but because of the commercial availability of the technology, it is limited to the unit processes for which commercially available or demonstrated technologies exist. This matching exercise between characteristics of solar generated heat and applicable heat demand provided a specific portion of process heat demand for each solar technology package. The full description of calculations is in Appendix C.

3 Solar Generation

3.1 Solar Resources and Land Availability

Solar resources are substantial across the United States. Both global horizontal irradiance (GHI), and direct normal irradiance (DNI) have wide variation, but they also range from “good to excellent” in different parts of the country (NREL 2019b). For GHI, the range in the United States is 1,000–2,500 kWh/m^2/year (NREL 2019b). Figure 10 shows the annualized daily mean map for the GHI for the contiguous United States, where the GHI is in the range of 1,350–2,500 kWh/m^2/year (NREL 2019b). As can be seen, there is ready availability of solar resource from which heat can be produced directly or from which electricity can be generated to then produce heat via direct current (DC) or alternating current (AC) technologies across the country.

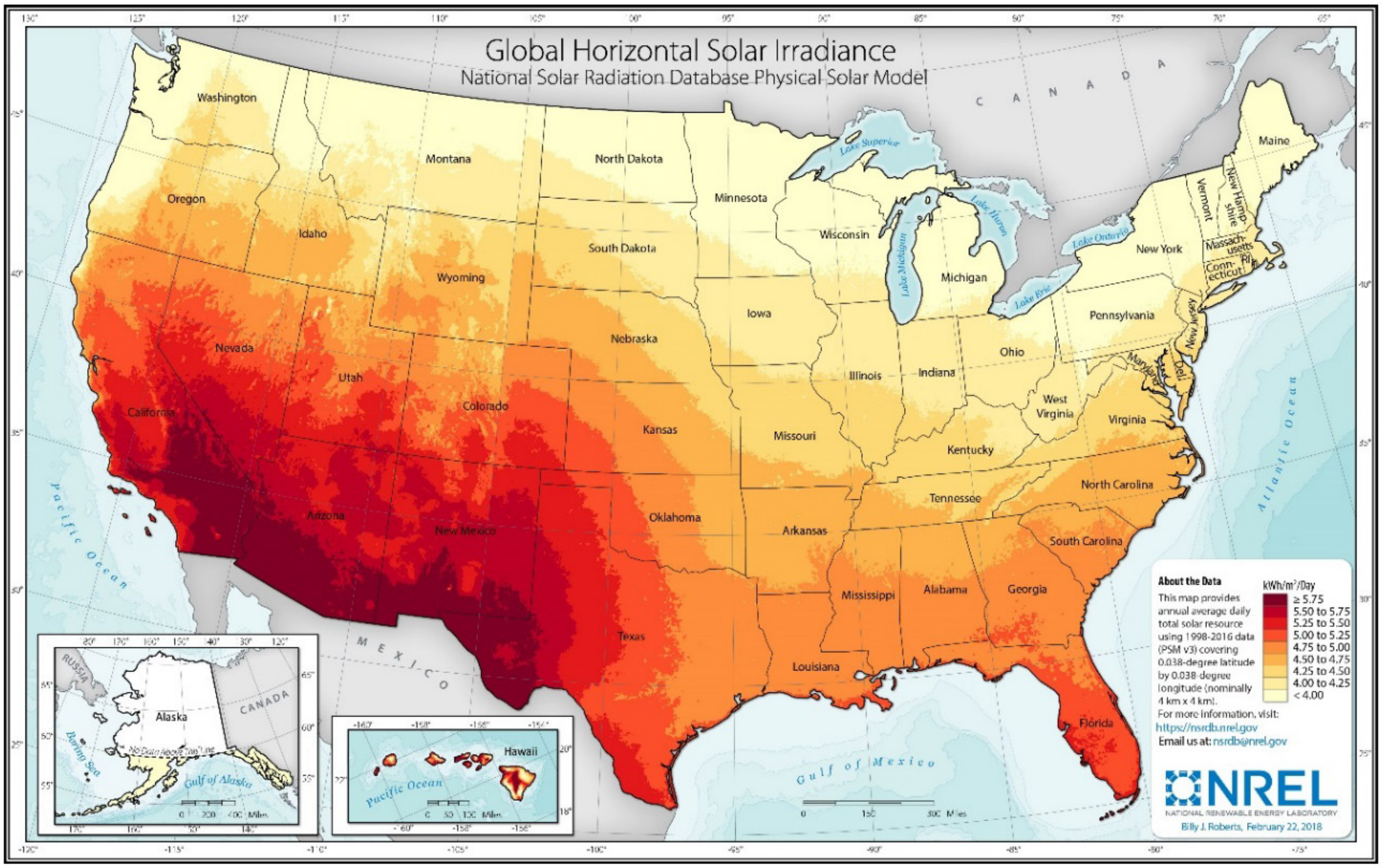

Figure 10. Map of the mean solar resource available to PV systems in the United States

Credit: Billy Roberts

Similarly, the DNI conditions across the United States can be considered some of the best in the world. Figure 11 shows the annualized daily mean map for the DNI for the contiguous United States, where the DNI is in the range of 1,450–2,740 kWh/m^2/year, based on a daily average of 4.0–7.5 kWh/m^2/day (NREL 2019a). As Figure 11 highlights, the Southwest has been found to be excellent for SIPH (Kurup and Turchi 2015). It is important to note that DNI requirements for heat production are lower for CSP-based process heat than they are for electricity generation.

For example, in most countries, for CSP for electricity generation to be typically economically feasible, DNI needs to be more than 2,000 kWh/m^2/year (IRENA 2012), which is more than 5.0 kWh/m^2/day. For process heat, 4.0 kWh/m^2/day or more is sufficient, which is approximately 1,500 kWh/m^2/year (IRENA 2012; Kurup et al. 2019). Sufficient resources then allow solar thermal technologies, especially high-temperature technologies such as CSP to provide heat across the country. This will be shown also in our results (Section 4.3).

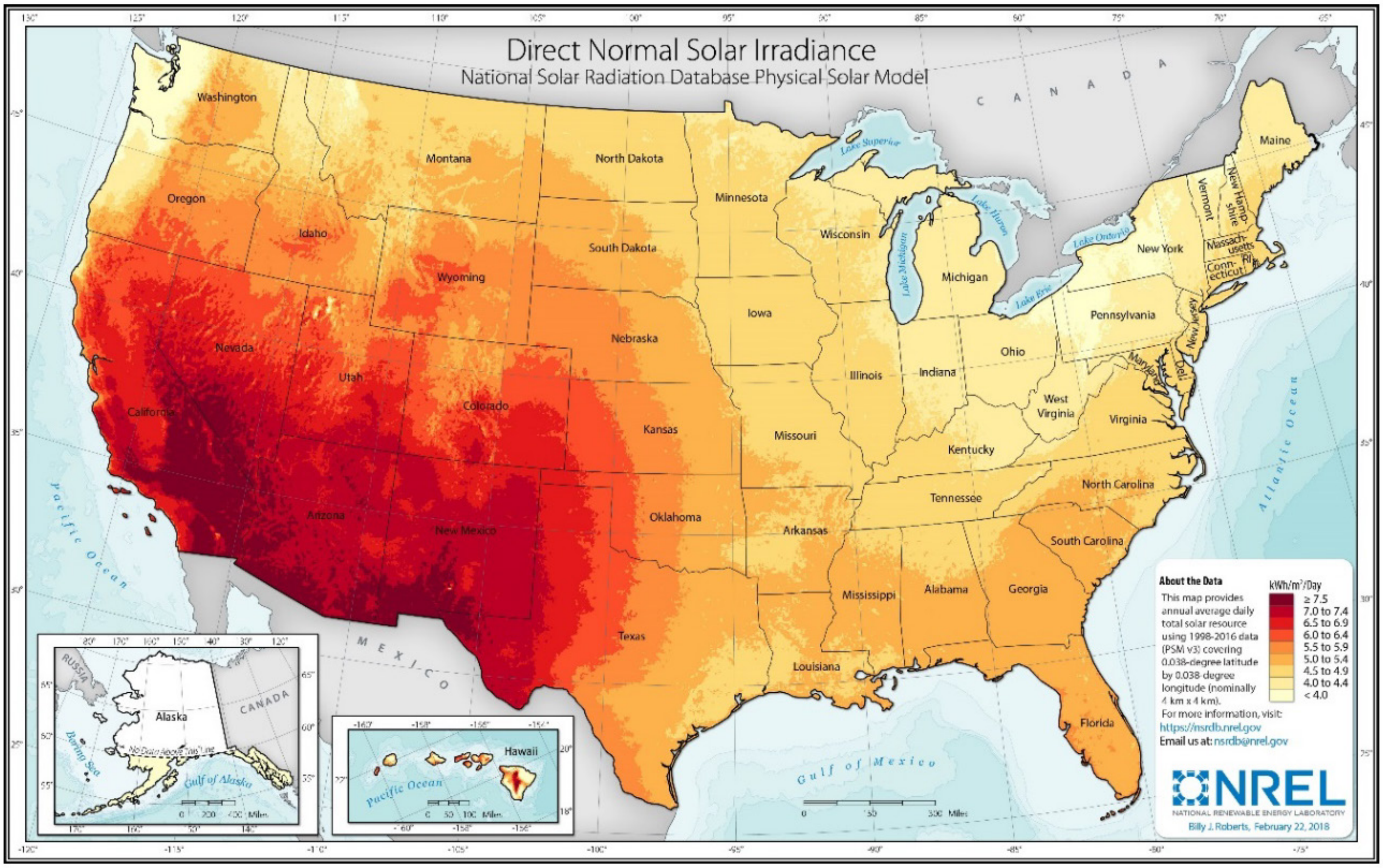

Figure 11. Map of mean solar resource available to CSP systems in the United States

Credit: Billy Roberts

Though there is significant land and solar resource in the United States, further refinement of the land available for this analysis is needed. To characterize the SIPH potential of a county, it is not enough to merely consider the solar resource available; it is also necessary to consider which areas within the county are unlikely to be able to support development of SIPH. Many land use and land policy criteria can make an area an impossible or highly unlikely location for SIPH development. For instance, federal law prohibits almost all development in certain areas of critical environmental concern and mountainous terrain contains slopes that are generally cost prohibitive or impossible for the installation of solar collectors. Attempting to understand the land that these restrictions may exclude from development is important not only because the excluded land may represent a large portion of the land in the county—the excluded land might also disproportionately be in areas of the country with good or poor resource potential.

To choose the proper criteria, we used the criteria used by Murphy et al. (2019) as a starting point. Theirs were developed based on development patterns in large-scale CSP systems. Unlike tower collector systems the PTCs and FPCs used for SIPH do not require large tracts of contiguous land, so the minimum contiguous area filter from the criteria is removed. Additionally, as the solar collectors involved are generally smaller and are less of a sightline nuisance, no additional buffers were placed around areas with development restrictions. However, SIPH systems also need to be close their accompanying industrial uses. Because of this, more-stringent assumptions for development restriction were used for areas of environmental concern and federal lands. The exclusion of built-up urban areas is also retained. Though there is potential for the development of SIPH within existing urban areas where industrial facilities are close to vacant land with the right zoning (or on available rooftops), SIPH development would require very high-resolution and accurate data on the locations of industrial facilities and vacant land within urban areas. Such data were outside the scope of this national-scale analysis, but an analysis of such availability could present a relevant extension of this work. For a full list of exclusions used, see Table 5.

Table 5. All Exclusion Criteria Used for the Analysis

Data Set	Criteria
Slope	slopes greater than 3% (for parabolic trough) or 5% (for PV or FPC)
Urban Areas	suburban areas
	urban areas
Land Cover	open water
	woody wetlands
	emergent herbaceous wetlands
	deciduous forest
	evergreen forest
	mixed forest
BLM ACEC	Bureau of Land Management areas of critical environmental concern
Federal Lands	national battlefield
	national conservation area
	national fish hatchery
	national monument
	national park
	national recreation area
	national scenic area
	national wilderness area
	national wildlife refuge
	wild and scenic river
	wildlife management area
	national forest

Data Set	Criteria
	national grassland
	U.S. Air Force Guard land
	U.S. Air Force land
	U.S. Army land
	U.S. Army Guard land
	U.S. Coast Guard land
	U.S. Marine Corps land
	U.S. Navy land
Airports	Airports
Protected Areas Database of the United States	Status 1: an area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a natural state within which disturbance events (of natural type, frequency, intensity, and legacy) are allowed to proceed without interference or are mimicked through management
	Status 2: an area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance.
National Conservation Easement Database	Status 1: managed for biodiversity: disturbance events proceed or are mimicked
	Status 2: managed for biodiversity: disturbance events suppressed

3.2 Solar Heat Technology Packages

As highlighted in Figure 1 (page 8), the chosen solar technologies have been solar thermal technologies (i.e., FPCs and CSP collectors) and electric heating (e.g., PV and resistive or heat pump technologies). For the solar thermal technologies, the heat can be provided either directly (as in the case for DSG) to the process or indirectly via an HTF (e.g., Therminol-VP1) to a process heat exchanger. Similarly, PV can also provide indirect or direct heating, depending on the technology connected to the electrical supply.

As of 2019, there were a reported and known of 817 SIPH systems across the world, with most being FPCs like glazed or evacuated tube collectors, followed by concentrating collectors (Epp and Krüger 2020). At present, no PV process heat systems are used in industry; however, because of the decreasing costs of PV, PV-based heat could be a low-cost IPH option dependent on the conditions (Meyers, Schmitt, and Vajen 2016). For SIPH applications, it has been found that a solar field that can generate approximately 1 MW_{th} for the process is suited for larger IPH applications such as breweries (Kurup and Turchi 2019). As has been found in prior research, when specific installed SIPH installations are considered (either FPCs or CSP collectors), most per site installations are below 1 MW_{th}. For example, Schoeneberger et al. (2020)

found that when the food products subsector, which has the most installations (~73 MWth of installed capacity and 120 sites[17]), is looked at globally, the average site solar field size is approximately 0.6 MW_{th} (Schoeneberger et al. 2020). Therefore, ~1 MW_{th} at the process has been found reasonable as the system size for the SIPH technology packages.

Different technology packages sized around delivering 1 MWth at the process (directly) or at the heat exchanger have been modeled using the System Advisor Model (SAM). SAM is a NREL open-source and freely available tool, developed to provide detailed hourly energy modeling for a variety of renewable energy technologies being deployed today, and for some technologies the techno-economic analysis. SAM has a long history of accurately modeling solar water heating (DiOrio et al. 2014; Freeman et al. 2018), and more recently CSP for SIPH applications (Kurup et al. 2017).

For the use of CSP technologies for heat generation rather than for electricity, the impacts of the powerblock have been removed and validated process heat modules are now available in downloads of the SAM (Kurup et al. 2017). Within SAM 2020, the ‘Parabolic Trough – Heat’ and the 'Linear Fresnel Direct Steam’ models are present (NREL 2020). Currently no electrical PV-based heat technologies are built as a specific technology option, but they can be simulated by creating a PV field for electricity and post-processing the heat generated. This has been done in this project. Future work may incorporate different CSP, different storage, or other direct heating technologies.

The TES options available in SAM’s Parabolic Trough models include sensible-heat storage using water (either unpressurized or pressurized), synthetic oil (e.g., Therminol VP-1, which is used in the CSP electricity industry), or molten salt (nitrate-based Solar Salt). Other liquids may be defined by the user by entering their relevant physical properties. In these cases, the solar field HTF is directly stored, i.e., the solar field HTF is the same as the TES fluid. NREL have investigated the modeling and results of the use and integration of PCM storage coupled to the SAM output of the DSG LF collector module, but this function is unavailable in the public release of SAM (Akar et al. 2020; Kurup et al. 2020), and is therefore excluded from this analysis. For this analysis, only water and oil TES options are used, as currently there are no molten salt or PCM based CSP SIPH solutions for industry. Though BES is becoming increasingly popular for commercial and utility-scale electricity generation, it is still absent from IPH applications. Therefore, storing any excess electricity from the PV generation is also excluded from this study, as it is not currently considered for IPH applications. Nor has any consideration been given in this study to the sale of excess PV-produced electricity to the utility grid, which would have an effect similar to on-site electrical energy storage.

Table 6 (page 30) highlights the technology packages used as the basis for this analysis. These can be modeled within SAM and then in the Renewable Energy Potential (reV) model, which is described in Section 3.3.3. It is important to note that the choices in Table 5 highlight a selection of technology packages with near-term suitability (Akar et al. 2020; Epp and Krüger 2020) and

[17] This total does not include 15 installations, which have a combined thermal capacity of 1.51 MWth (Gómez García 2020)

near-term low-cost potential[18] (Meyers, Schmitt, and Vajen 2016; 2017). These technology selections include solar water heating via a commercially utilized FPC with water storage, CSP parabolic troughs with and without oil storage, CSP DSG LF collectors, and PV DC. It is also important to mention that the PV DC system is sized to be approximately 1.2 MWth, which with a DC-to-AC inverter ratio of 1.2 would provide a 1-MW_e (megawatt-electric) system.

Finally, it is also important to note that the technology packages provide different temperatures and may not be well-suited for all industrial processes. For example, the solar water heating system in Table 6 is designed so that the exit temperature of the heated water is limited to 90°C. The CSP technology packages (trough technology, with and without storage) use Therminol VP-1 and have a maximum temperature of 393°C. The CSP LF DSG collector steam output is limited to 300°C. The PV technology package shown in the table (i.e., PV DC), is producing electricity. AC electricity is also produced, through an inverter ratio of 1.2. As highlighted in subsequent sections, some electrical technology packages utilize the DC electricity (e.g., for resistive heating) and AC electricity for renewable heat technologies (e.g., PV and HPs). The temperatures that each PV-based technology package can reach varies, but are in the range of 90°C–1,800°C.

[18] For example, PV providing electricity for renewable heat via resistance heaters and heat pumps based on the fuel and solar resource conditions.

Table 6. Technology Packages Used in SAM to Create the System Representations for the High Performance Computer Modeling

Technology Package	MW_{th} of Solar Field	MW_{th} at the Heat Exchanger	HTF	Volume of TES/Hours of Storage	Collector/Type	Total Land Area	Aperture Area/ Absorption Area (m^2)
Solar water heating-FPC	1.0	~1.27	Glycol	60 m^3	Heliodyne Gobi 410 001	~0.5 acres	2,014 m^2
CSP: oil trough, no TES	1.5	1.00	Therminol-VP-1	0	SkyFuel SkyTrough	~2 acres/ ~8,094 m^2	2,624 m^2
CSP: oil trough, 6 hours of TES	2.5	1.00	Therminol-VP-1	6 hours	SkyFuel SkyTrough	~4 acres/ ~16,187 m^2	5,248 m^2
CSP with DSG LF collector, no TES	1.2	1.00	Water/Steam mix	0	Novatec	~1 acre/ ~3,698 m^2	3,082 m^2
PV DC for connection to resistive heater[a]	1.2	NA	NA	NA	Standard module from PVWATTs Calculator with fixed open rack	In SAM output	In SAM output

[a] For PV AC, the same solar field is used, but 1 MWe is used as the system size.

3.3 Overview of Modeling

3.3.1 System Advisor Model

The SAM,[19] is a techno-economic computer model developed and is distributed by NREL that calculates performance and financial metrics of renewable energy projects (Freeman et al. 2018). Project developers, policymakers, equipment manufacturers, and researchers use graphs and tables of SAM results when evaluating financial, technology, and incentive options for renewable energy projects. SAM simulates the performance of PV, CSP, solar water heating, wind, geothermal, and biomass power systems, and it includes a basic generic model for comparisons with conventional or other types of systems.

For this analysis, we used SAM to determine solar plant energy production for the weather characteristics at a given location. Power plant configurations were developed in the SAM desktop application and saved as JavaScript Object Notation (JSON) files. SAM is typically used to determine outputs for one plant configuration at a given location at a time. Processing the multiple plant types and locations required additional modeling capabilities.

3.3.2 Renewable Energy Potential Model (reV)

The reV model[20] is a first-of-its-kind, detailed spatiotemporal modeling assessment tool that calculates renewable energy capacity, generation, and cost based on geospatial intersection with grid infrastructure and land-use characteristics. NREL developed the reV model to help utility planners, regional and national agencies, project and land developers, and researchers assess renewable energy resource potential. The reV model currently supports PV, CSP, and wind turbine technologies. It can model from a single site to an entire continent at temporal resolutions ranging from five minutes to hourly, spanning a single year or multiple decades. Coupled with SAM, the reV model's generation module estimates system performance based on user-defined parameters, including solar panel tilt angle, azimuth, inverter load ratio, efficiency, and others.

For this analysis, we used the reV model to automate the retrieval of atmospheric parameters from the National Solar Radiation Database (NSRDB)[21], execute the SAM models, and compile output data sets for all counties in the continental United States. The NSRDB[22] contains solar irradiance and other atmospheric data for a point grid spaced at roughly 4-km intervals across the country. The appropriate NSRDB site to use for each county was identified by locating the site nearest to the county center. County centers were determined from geospatial data downloaded from the U.S. Census (U.S. Census Bureau 2018b).[23]

Once the SAM configurations were saved as JSON files and appropriate NSRDB sites for each county were determined, we used reV to run SAM with the NSRDB solar irradiance for the selected NSRDB sites. Desired SAM output parameters were extracted from the model and

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[19] "System Advisor Model (SAM)," NREL, https://sam.nrel.gov.
[20] "reV: The Renewable Energy Potential Model," NREL, https://www.nrel.gov/gis/renewable-energy-potential.html
[21] "NSRDB: National Solar Radiation Database," NREL, https://nsrdb.nrel.gov.
[22] "NSRDB Data Viewer," NREL, https://maps.nrel.gov/nsrdb-viewer.
[23] The specific 2018 file titled "cb_2018_us_county_500k.zip" was used.

saved for later analysis. The combined reV and SAM modeling was performed on the Eagle high-performance computing system at NREL.[24]

3.3.3 PV and Ambient Heat Pump Model

The process to determine the thermal energy generation technical potential by combining PV and electrically driven vapor compression heat pumps is discussed in Appendix E. Models developed by Meyers et al. (2018b; 2018a) serve as the basis for evaluating the PVHP technology package. In short, the hourly PV-generated electricity is used to power a heat pump that "lifts" heat from ambient outdoor air into a process fluid (water) that is stored and subsequently used to heat a process load at its desired temperature. The county-specific hourly process and ambient temperatures are used to determine the electrical-to-thermal efficiency of the PVHP system and subsequently the hourly specific thermal yields, in kilowatt-hours-thermal (kWh_{th}) per kilowatt-hour-peak-PV ($kWh_{p,PV}$) installed. This metric is called the Specific PV+HP Yield, and it is used to size a solar PV plant that can meet both peak summer and winter average monthly process heat demand on a per county basis. Finally, the required land use needed to meet the process heat demand is quantified by incorporating row spacing to avoid shading throughout the year.

3.4 Process Integration of SIPH

We do not deal explicitly with integrating the solar technology packages within industrial facilities given their site-specific nature, which is outside our analysis scope. However, doing so is critical to realizing the opportunities for SIPH identified in this analysis and building off the foundation provided by this report. We discuss the need for increased analysis resolution in Section 6.2. Solar thermal technologies can be integrated at the supply level, where solar heat is generated and distributed via a heat transfer medium, and the process level, where solar heat is delivered directly to a process via a heat exchanger, dryer, evaporator, or steam injection (Ilyes Ben Hassin et al. 2015). The integration of PV-connected electrotechnologies can be similarly classified (e.g., electric boilers integrated at the supply level and resistance melters integrated at the process level). The challenges for SIPH integration include extensive modification of existing processes and integrated process technologies that are not designed for SIPH; solutions include combining solar collectors and industrial processes in a single unit and developing hybrid thermal systems (Brunner 2020).

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[24] "Eagle Computing System", NREL, https://www.nrel.gov/hpc/eagle-system.html.

4 Opportunities for Solar for Industrial Process Heat

4.1 Definition of the Opportunity for IPH and Solar Fraction

The opportunities for solar technologies to meet IPH demand evaluated in this analysis are similar to the frequently reported technical potential, which is defined as a renewable energy's generation potential given system, topographic, and land-use constraints, and system performance (Lopez et al. 2012). Figure 12 shows the progression from raw resource potential to technical potential. However, in this study, we extend our analysis beyond a singular calculation of technical potential by comparing it on an hourly scale to estimated process heating loads.

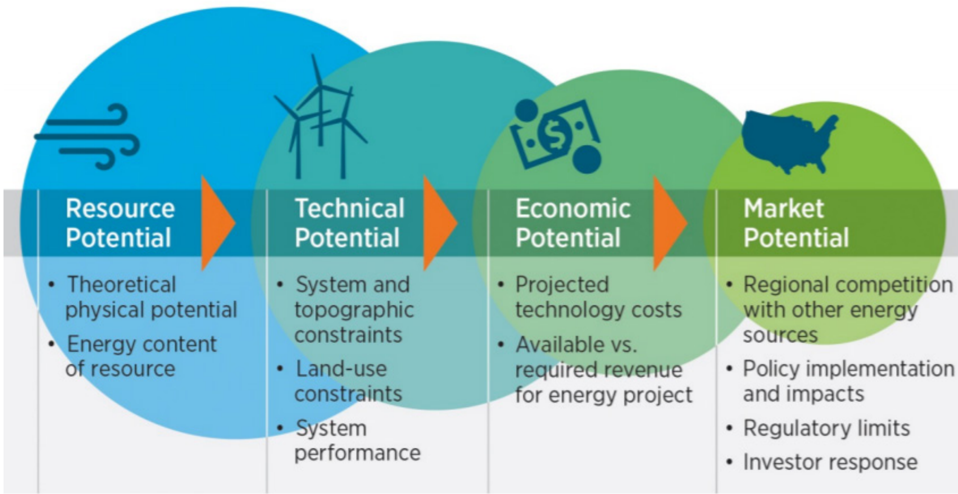

Figure 12. Levels of renewable energy potential

Source: (Lopez et al. 2012)

This comparison of solar heat potential and process heat demand leads to the calculation of a solar fraction, which is defined as the contribution of solar energy to the total load. The solar fraction is calculated for each technology package exclusively, for every county in the United States, and for every hour of the year. Using the solar fraction, we can describe the opportunity for SIPH technologies in terms of location, time of year, and industry.

Defining the potential for SIPH from a technical perspective is a necessary, but insufficient, condition for understanding the opportunities for their adoption. Recognizing the importance of economic considerations, we used the data and results of this study to develop a techno-economic analysis framework that estimates the point at which SIPH reaches a point of "process parity" with combustion heating systems based on the levelized cost of heat and other economic parameters. The results are not presented here, but a subsequent publication will apply this framework in case studies of steam generation and electric resistance heating.

4.2 Calculation Approach

4.2.1 Solar Scaling

The opportunity for a solar technology package to meet IPH demand is a function of its hourly generation, system footprint area, and available land area. As described in Section 3.2, each solar technology package is defined as a ~1-MW base system. These base systems are then scaled up to meet IPH demand based on either December or June generation sizing and are given the available land area for each county. Scaling the solar technology packages based on December generation when U.S. meteorological conditions are at their worst for efficient thermal energy generation (i.e., low solar irradiance and ambient temperatures) results in larger systems. This may lead to the case where more energy is produced in summer months than is required. This overgeneration is essentially wasted, negatively affecting the economics of the system and its potential for widespread adoption. Conversely, sizing the systems in June when irradiance and ambient temperatures are greater results in smaller system sizes and avoids the issues of overproduction, but also lower generation in the winter months.

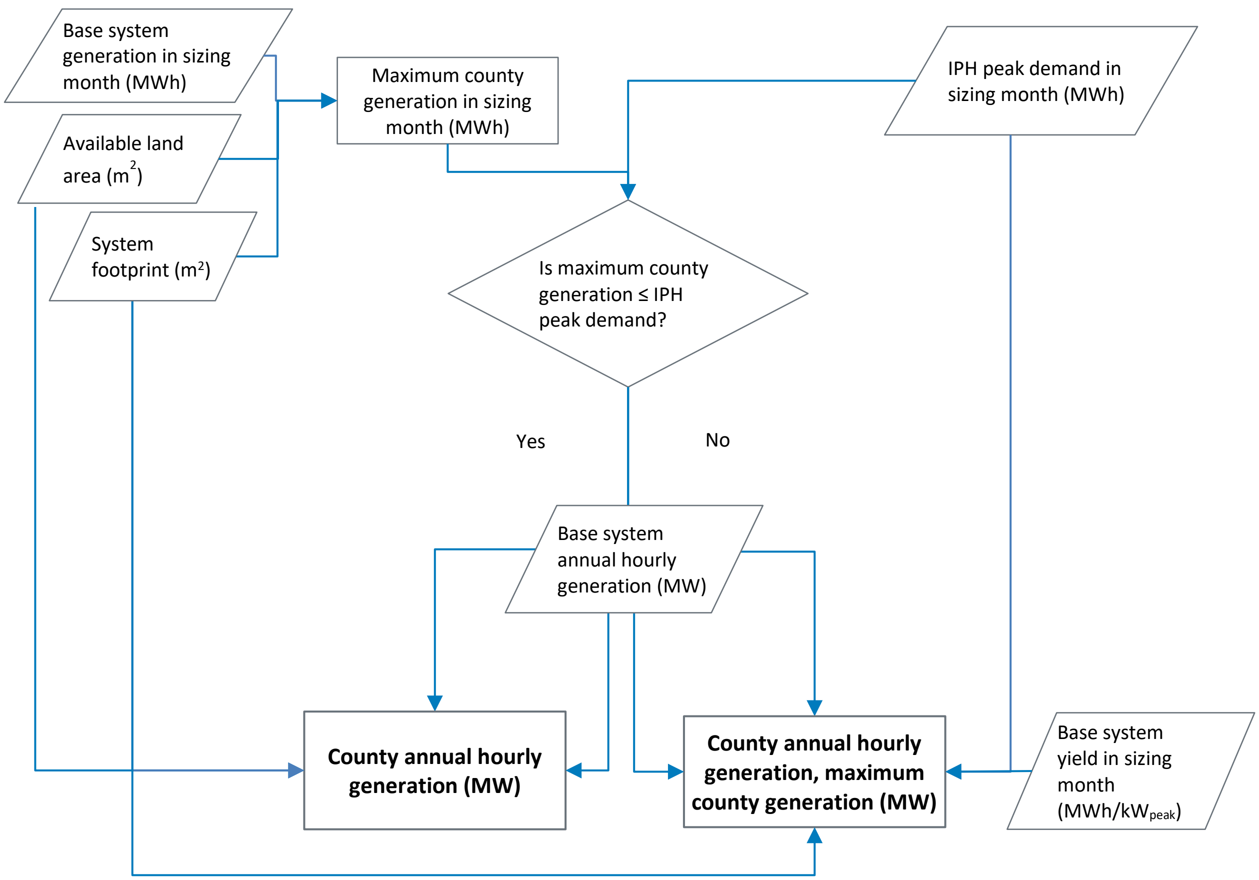

Figure 13. Process flow for scaling solar technology packages to IPH demand

4.3 Results

4.3.1 Electricity/CHP Considerations

For several cases in our analysis of SIPH systems because we do not consider electrical energy storage, we must account for externally supplied electricity and, thus, additional fuel. This requirement applies to the cases of PV + resistance heating and WHRHPs, and any replacement of heat from CHP units.

First, the utilization of PV with electrotechnologies would require a process shift from a combustion-based heating system to an electric system.[25] With a fully electric system expected to meet continuous operation schedules, external electricity would have to be supplied when solar is not available. This extra electricity would come from the grid or, in some cases, a facilities' own power plant. For the resistance heating and WHRHP cases, we accounted for additional electricity, and their resulting fuel requirements, for each county by using the EPA's eGRID database (EPA 2020). The calculations and results are described in Appendix F.

Second, the addition of SIPH systems that replace steam demand from CHP units would result in a reduction of onsite electric power generation. This effect would largely impact the system's efficiency and economics, although we do not address the latter. The impacts of a reduced load on CHP efficiency and electricity generation are discussed in Appendix A-6.

The different types of CHP systems can be classified by their prime movers: reciprocating internal combustion engines, combustion/gas turbines, boilers with steam turbines, microturbines, and fuel cells (Darrow et al. 2015). Of these five different prime mover types, combustion/gas turbines with steam generators and boilers with steam turbines account for the largest shares in the U.S. manufacturing sector (Darrow et al. 2015). Therefore, these two prime mover types were selected for investigation in this study. Specifically, we calculated reductions in both fuel inputs and electricity generation associated with replacing CHP steam with one of our considered solar packages based on assumed load-efficiency curves for different CHP unit types and capacities (Darrow et al. 2015; DOE 2016b; Bresolin et al. 2006; 2006). Detailed information is in Appendix A.6.

4.3.2 Opportunities for SIPH by County

A key factor of a solar technology's technical opportunity is its ability to provide the necessary heat load, reported here as the solar fraction. The following set of maps displays how often the solar fraction is greater than or equal to one, signifying that solar heat is fully meeting process heat demands. The maps, in Figure 14 and Figure 15, show the potential for solar heat technologies across the United States based on SIPH systems sized to meet peak load for the month of June. These figures capture the temporal and spatial aspects of SIPH opportunities; the total magnitude of opportunity by technology is discussed in Section 4.3.2 and Section 4.3.3.[26]

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[25] Electric boilers can be run in parallel with combustion-based boilers and do not apply here.

[26] An interactive map of county results is available at https://nrel.carto.com/u/gds-member/builder/51943617-62eb-4241-8b30-c943fce85692/embed.

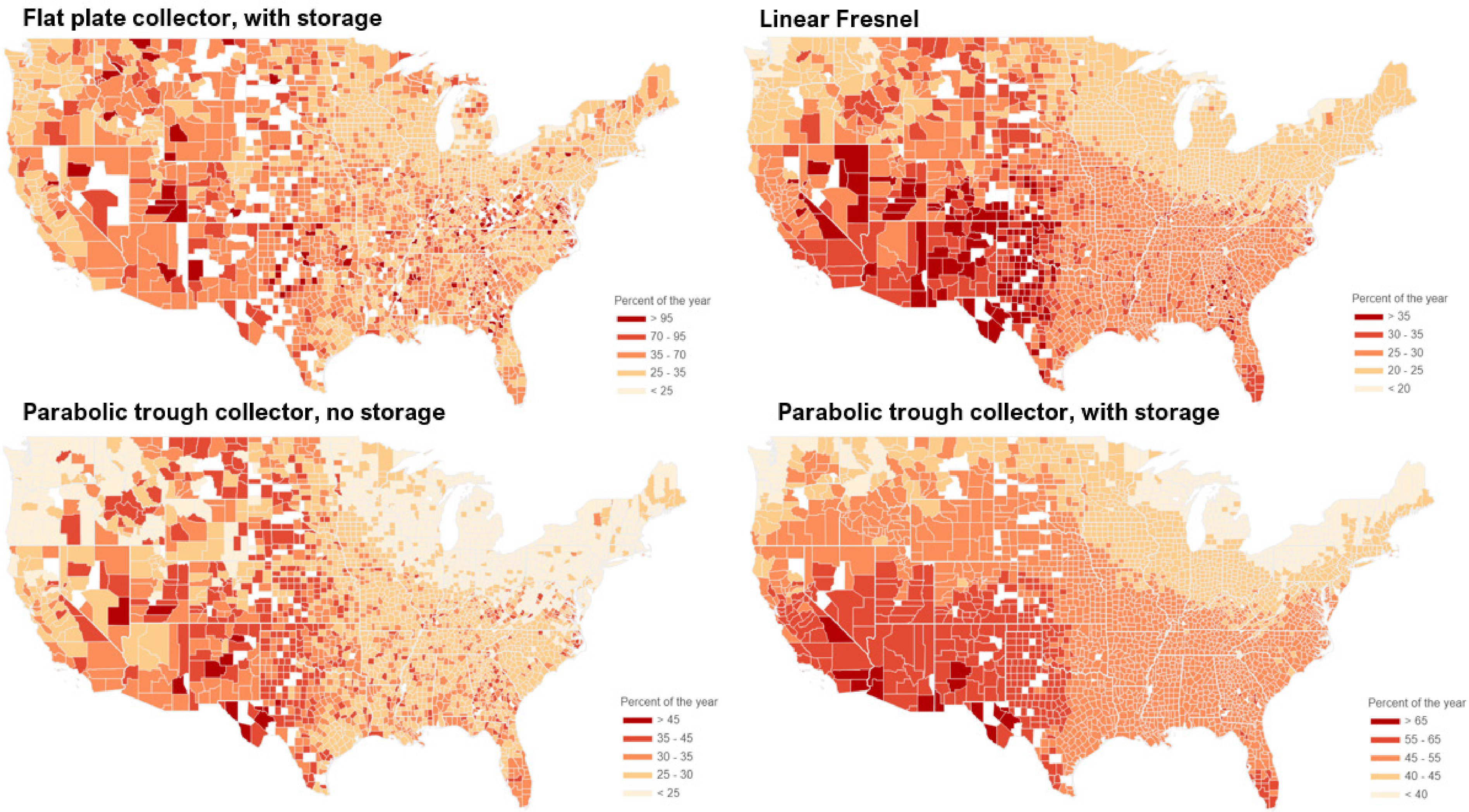

Figure 14. County-level maps showing the percentage of the year when solar heat is fully meeting process heat demand using solar thermal technologies (FPCs, LF DSG, PTC with TES, and PTC without TES) sized to peak summer demand

Figures are not meant to be compared due to differences in bin intervals. Counties colored white have no relevant IPH demand for the solar technology.

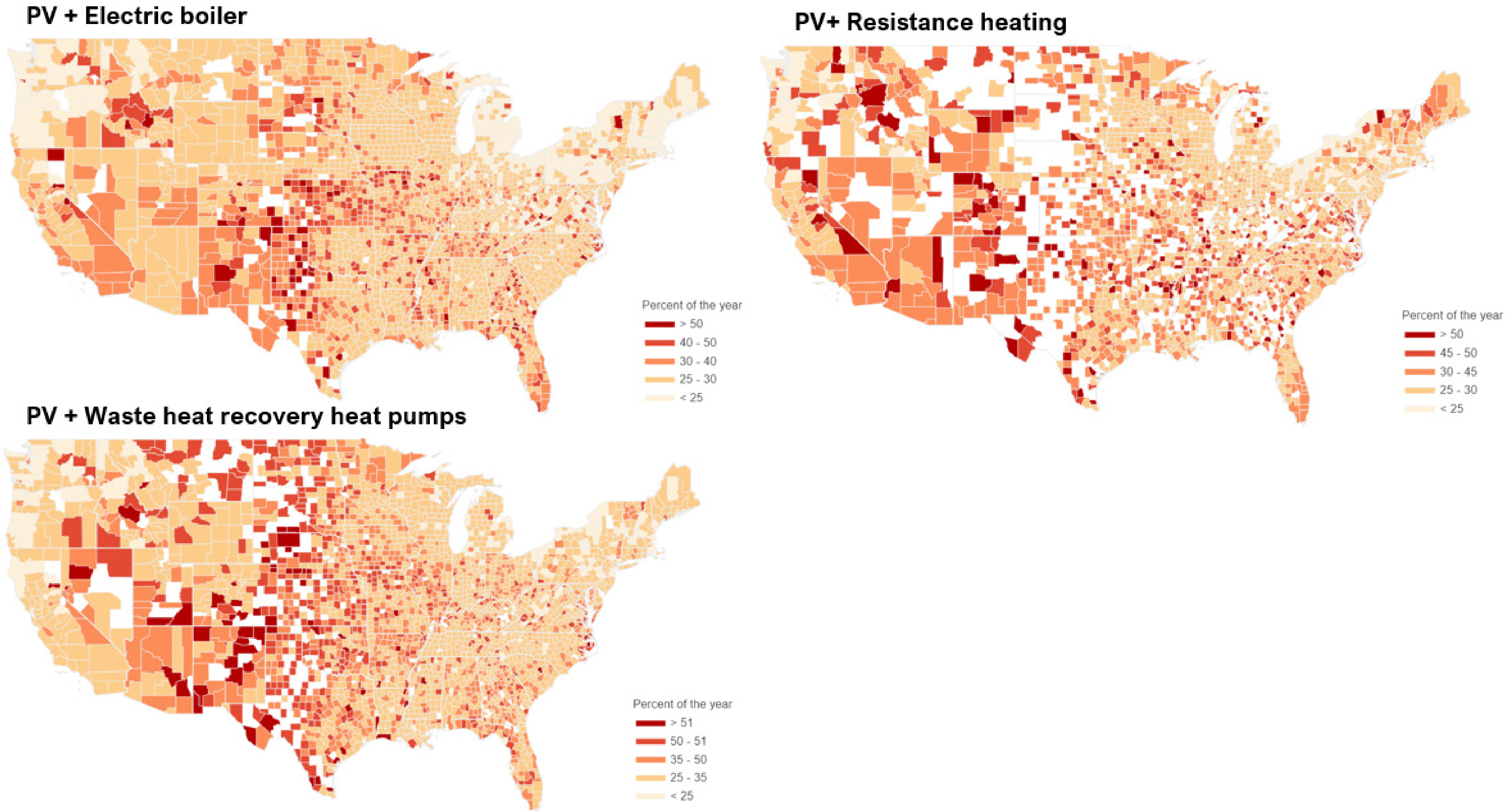

Figure 15. County-level maps showing the percentage of the year when solar heat is fully meeting demand using PV-based electrotechnologies (E-boiler, resistance heating and WHRHPs) sized to peak summer demand

Figures are not meant to be compared due to differences in choropleth bin intervals. Counties colored white have no relevant IPH demand for the solar technology.

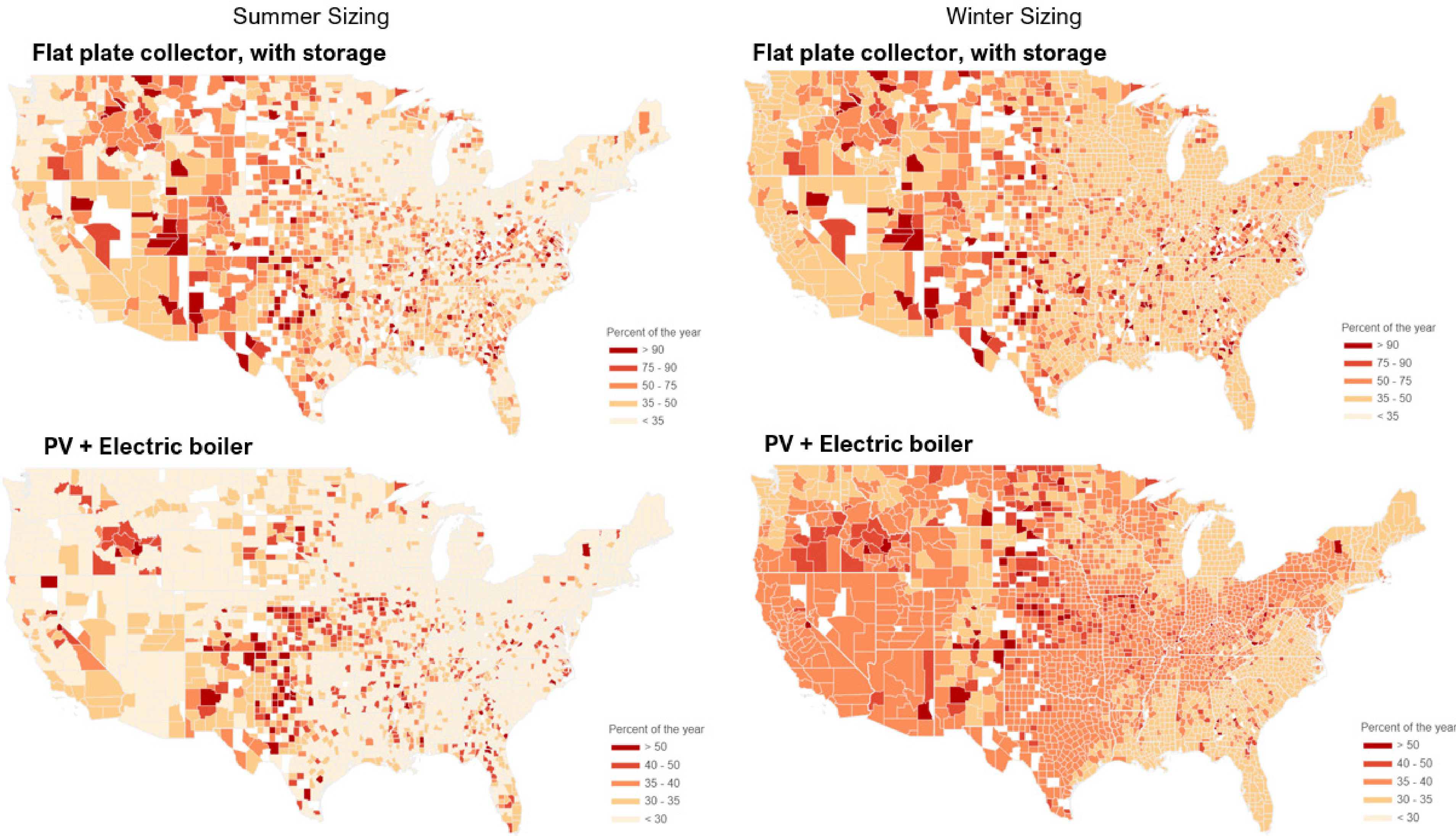

Figure 16. County-level maps showing percentage of the year when solar heat fully meets demand for the FPC and E-boiler cases, comparing summer and winter-sized solar systems

Figures are not meant to be compared due to differences in choropleth bin intervals. Counties colored white have no relevant IPH demand for the solar technology.

With the LF and PTC cases, regional variation is more pronounced than with the FPC or electrotechnology cases. This result is due to the technology limitations associated with these solar thermal technologies; the process heat demand matched to LF and PTC systems was limited by the maximum temperatures of heat the systems could provide, compared to required process temperatures. The supplied temperature of these solar thermal systems decreases in colder months, concurrent with the decrease in ambient temperature. The ability to meet heat demand for the entire year is reduced in northern parts of the country as a result.

Though the results in Figure 14 and Figure 15 are based on SIPH systems sized for summer; a system sized for winter accounts for decreased solar irradiance in parts of the country and is consequently larger, leading to high solar fractions more frequently throughout the year. A comparison of summer- and winter-sized systems for the FPC case is shown in Figure 16 (page 38). With winter sizing, solar can fully meet demand for more than half the year for 82% of counties, compared to 34% of counties with summer sizing. Although winter-sized systems present a higher technical opportunity, their larger size leads to increased costs, and further economic analysis would be needed to determine their suitability.

For all solar technology packages, winter-sized systems result in solar heat meeting demand more often, as seen in Figure 17. Among the different technologies, FPC has the highest frequency of meeting demand on average. Different storage assumptions were used in the PVHP modeling and, as a result, the results show the PVHP meeting IPH demands at all hours throughout the year.

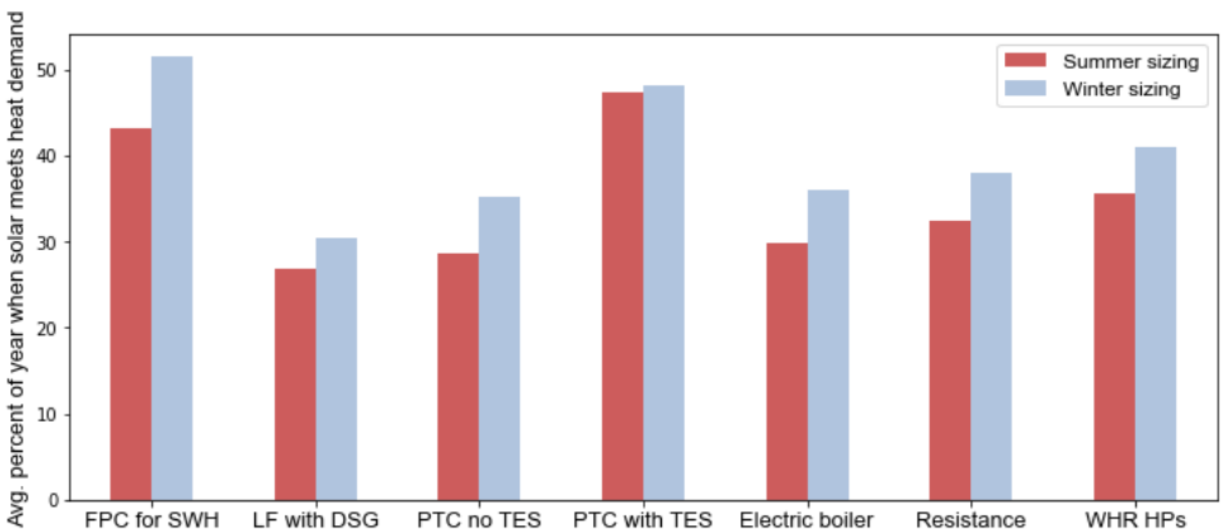

Figure 17. Average frequency (in percentage of the year) that solar heat fully meets demand

Figure 18 compares the solar technologies by combining the spatial and temporal dimensions of their technical opportunity. Technologies in the top right of the chart meet demand for a larger percentage of the year and for a greater number of counties. A noticeable difference between the two PTC cases demonstrates that the presence of TES is significant and largely impacts the frequency and distribution of meeting demand.

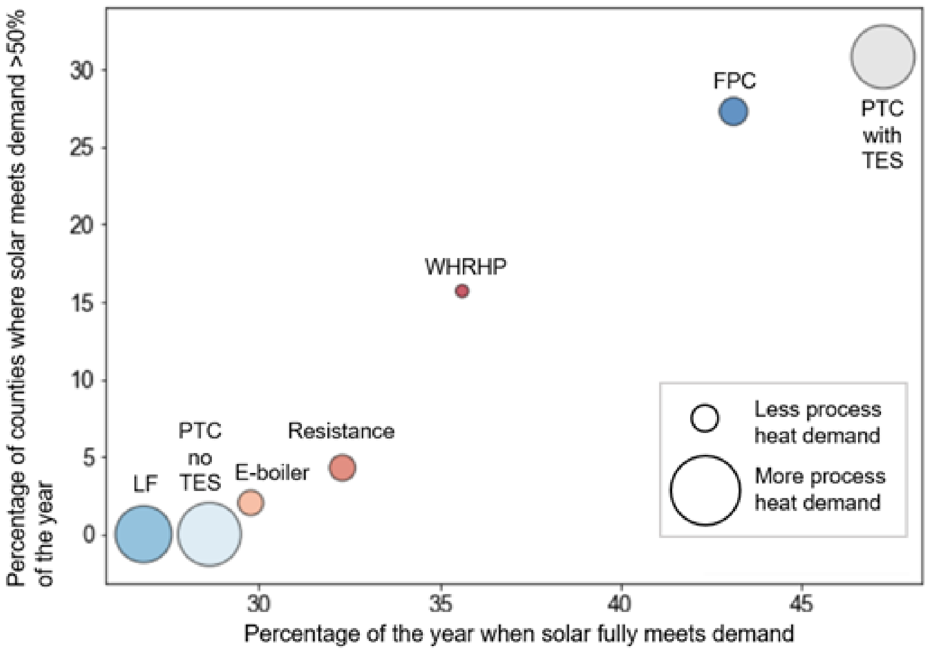

Figure 18. Comparison of SIPH technologies sized to summer peak IPH demand, with size of bubble corresponding to their supplied process heat demands

Color of bubbles is used to distinguish technologies.

E-boiler = electric boiler

To illustrate the effect of TES at a closer timescale, Figure 19 (page 41) displays a heat map of the solar fraction for the two PTC cases in Polk County, Iowa with 6 hours of storage. The heat map shows the hours of the day on the y-axis and the months of the year on the x-axis, with each internal square representing the solar fraction at a specific hour of the day averaged for each month; these values are displayed in the squares.

The significance of TES is apparent in Figure 19, as the solar fraction of PTC with TES is greater than one for 28% more of the time than PTC without it.

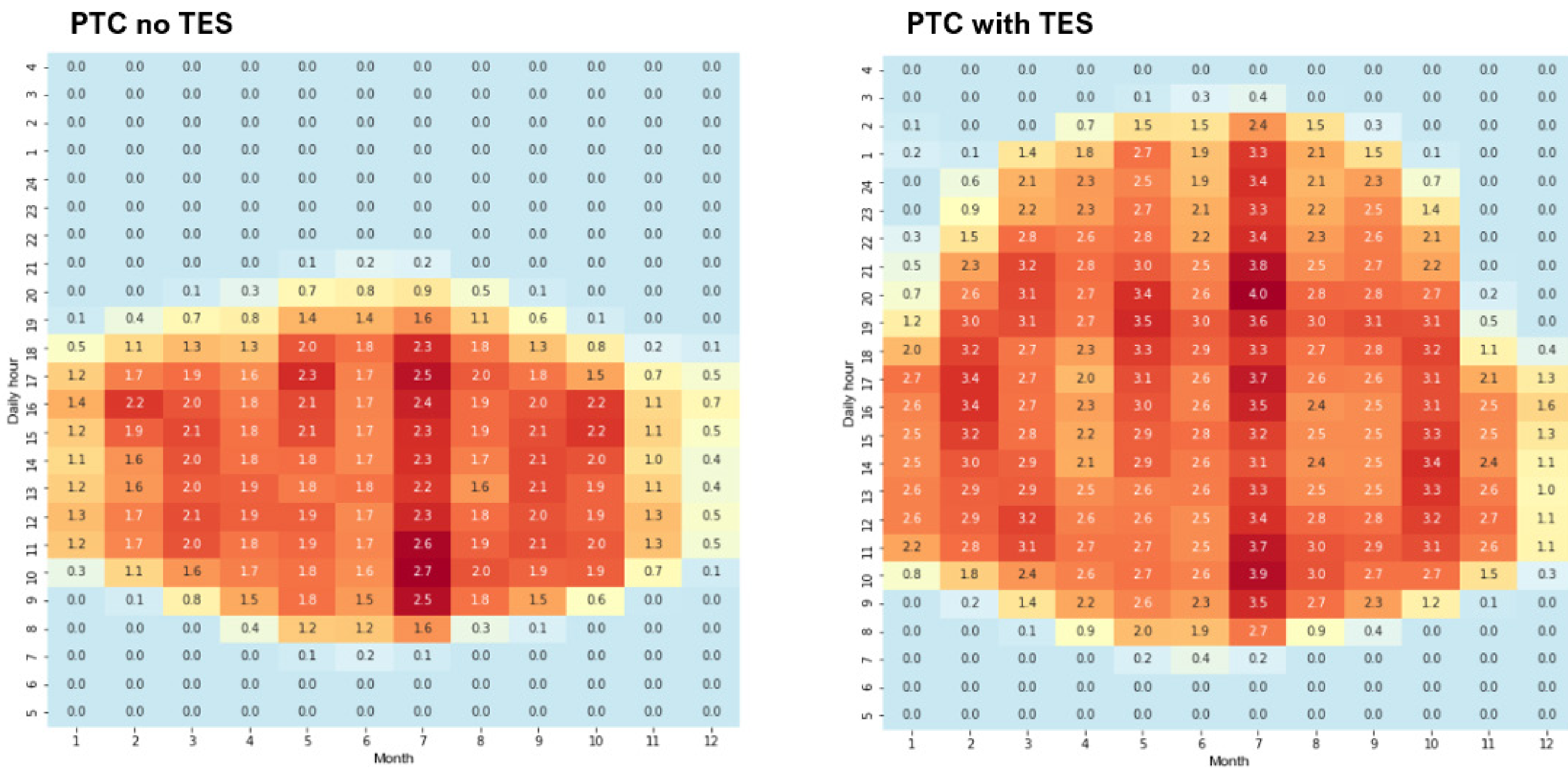

Figure 19. Heat maps of the two PTC cases showing the solar fraction for hour of the day and the month of year for Polk County, Iowa

4.3.3 Opportunities by Industrial Subsector

The technical opportunity of solar technologies can also be evaluated by its potential to supply heat within industrial subsectors. The solar heat potentials (Figure 20) represent the total amounts of heat these solar technologies can provide in a year based on a summation of their hourly solar fractions. The solar heat potentials are annual totals for several key subsectors.

The largest overall opportunity for SIPH occurs in the chemicals subsector, followed by the pulp and paper subsector. Both subsectors have large IPH demands that are met by CHP and conventional boilers; however, IPH demands below 100°C in the pulp and paper industry were characterized exclusively as steam, which explains the lack of opportunities for FPC, which were defined only for hot water IPH demands. The chemicals subsector is more diverse in terms of its use of hot water, however, and opportunities for FPC on the order of about 350 TBtu were identified.

Opportunities for PV+resistance heating of roughly the same magnitude occur in the metals, chemicals, food, and petroleum and coal products subsectors. As expected, opportunities for WHRHPs are the smallest, and they are concentrated in the pulp and paper, petroleum and coal products, and chemicals subsectors.

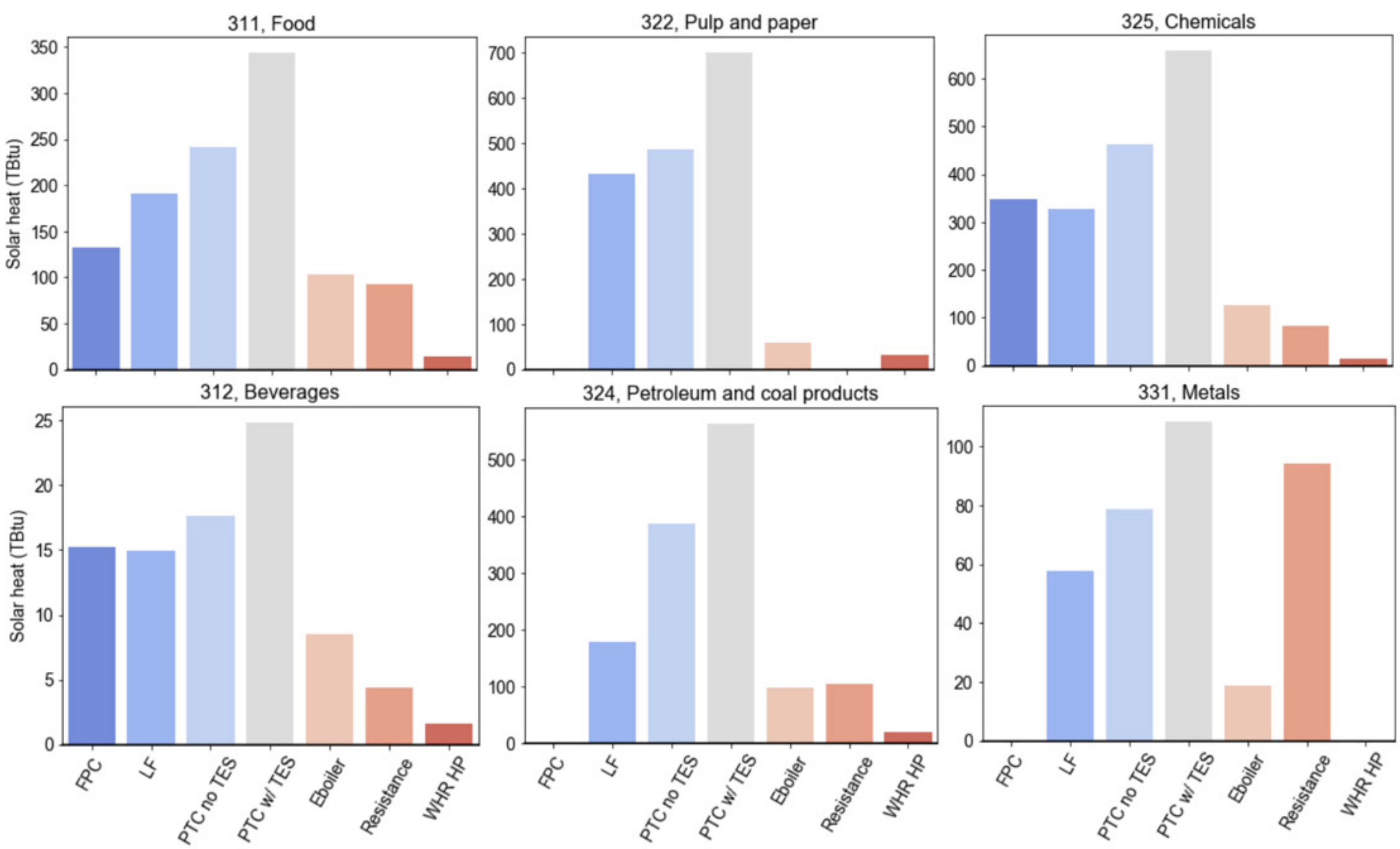

Figure 20. Annual solar heat potential (TBtu) for high-heat-demand subsectors

The solar heat potentials for all subsectors are shown in Appendix F, as is the total solar heat potentials as a fraction of demand for each technology package.

4.3.4 Fuel Savings

With the potential to meet heat demand during a substantial portion of the year, solar heat technologies can provide significant reductions in conventional fuel use, which can lead to avoided combustion emissions. The amounts of fuel savings were calculated based on hourly solar fractions for each county and by fuel type. Figure 21 shows the total annual fuel savings by fuel type for each technology package. Figure 22 and Figure 23 show the fuels displaced by month for solar thermal technology and electrotechnology packages, respectively, for summer peak IPH demand sizing.

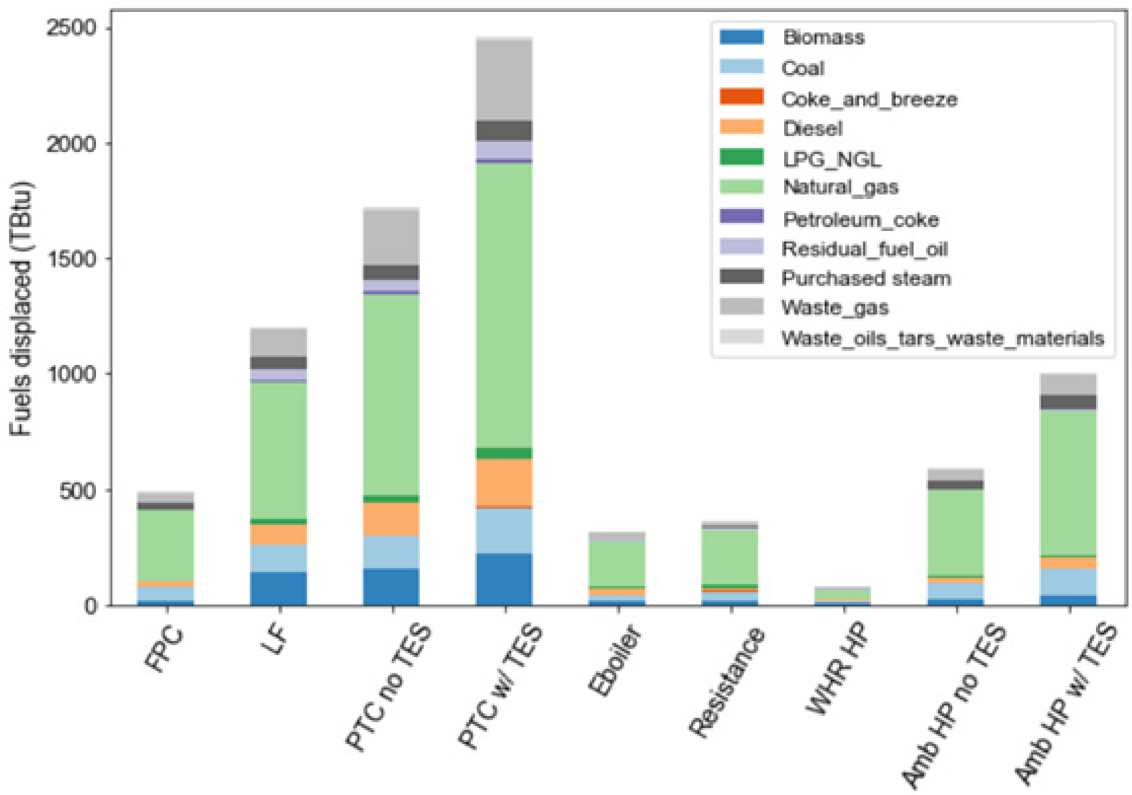

Figure 21. Total fuels displaced for each solar technology package (in TBtu/year)

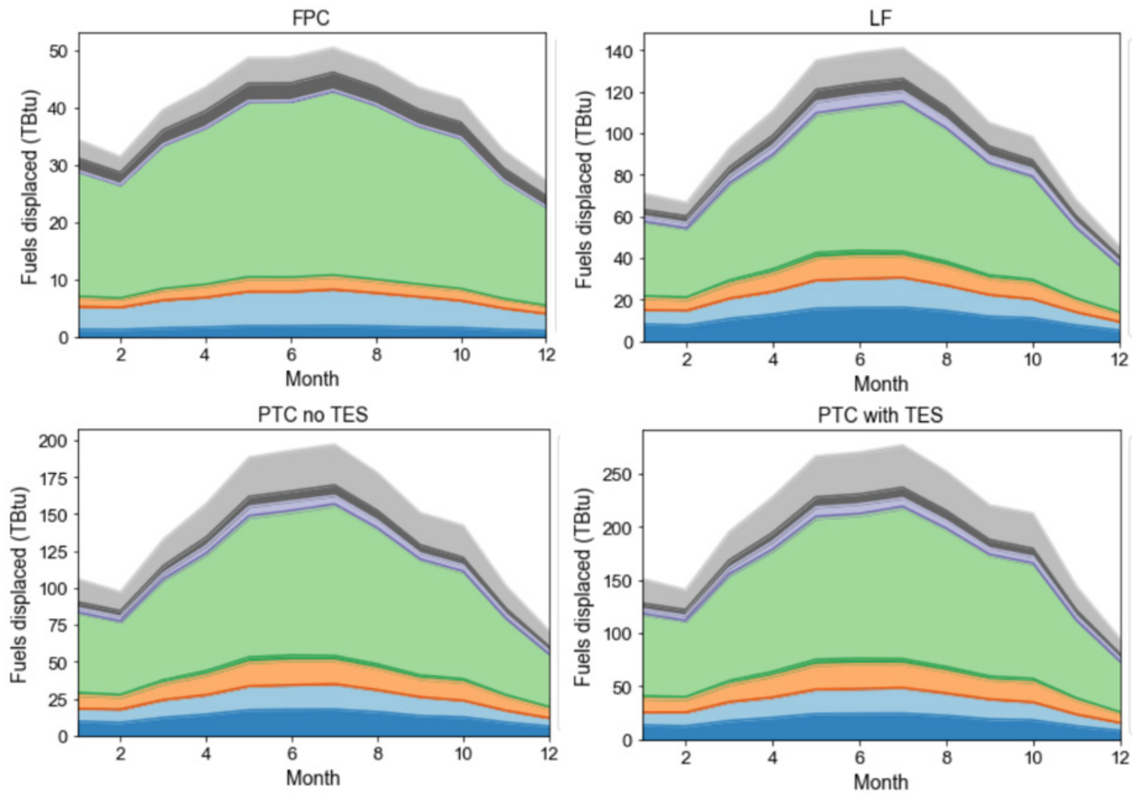

Figure 22. Monthly fuel displaced by solar thermal technologies (in TBtu/month)

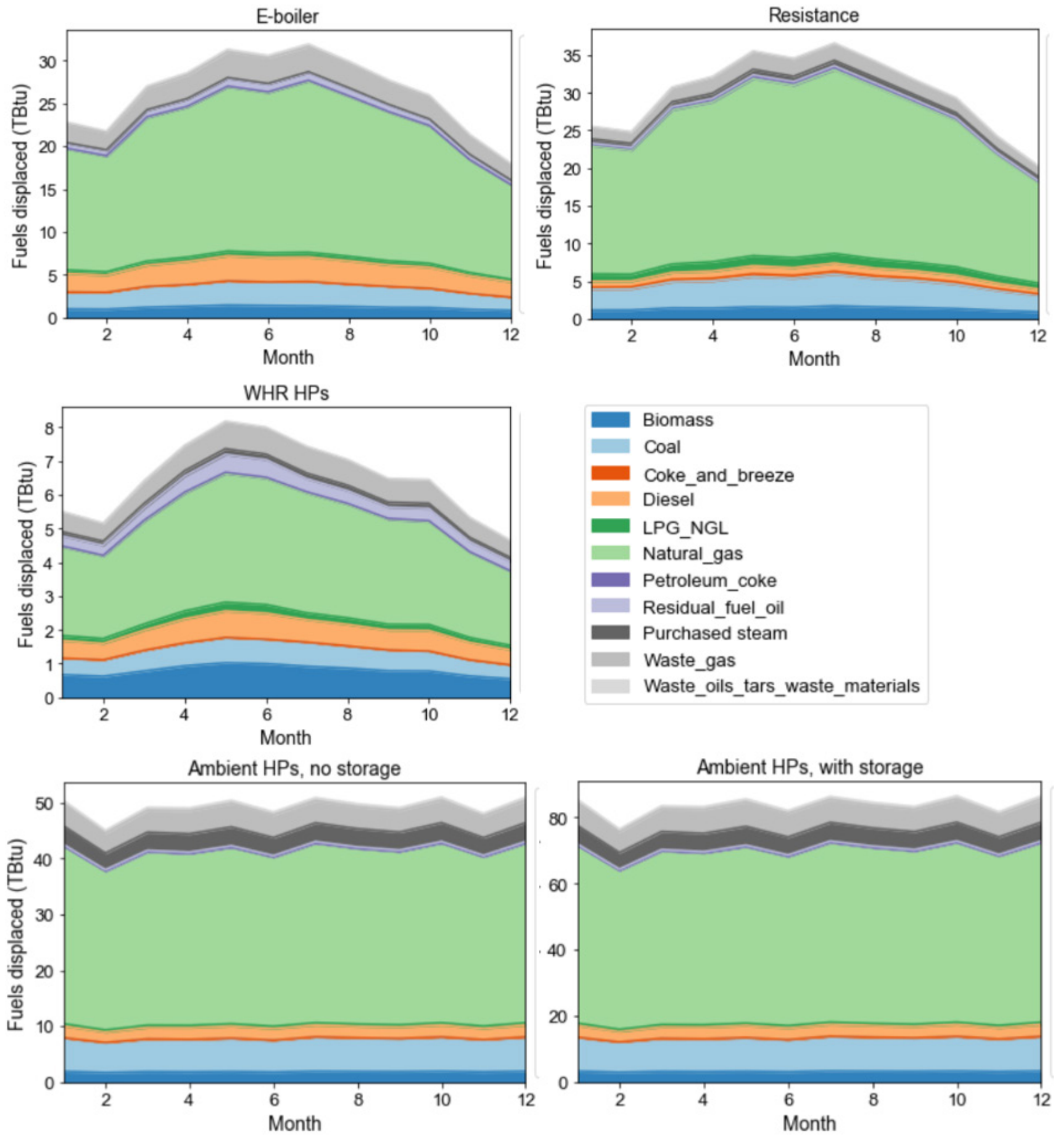

Figure 23. Monthly fuel displaced by electrotechnologies (in TBtu/month)

Across all technology packages, the predominant fuel that is replaced is natural gas, given its abundant use in U.S. process heating. There are also high potential savings with coal and diesel, and in some cases biomass. While coal and diesel are purchased fuels, biomass can be an in-plant byproduct within the forest product industries; therefore, finding another end use could present a practical challenge or potential opportunity for such facilities. In the summer months, the potential fuel savings are highest because solar irradiance is increased in more parts of the county, leading to greater frequencies of high solar fractions.

The total amount of carbon dioxide emissions avoided due to fuel savings for each solar technology is shown in Table 6. Carbon dioxide emissions were calculated based on fuel savings described previously and emissions factors taken from EPA data on stationary combustion (EPA 2018). The carbon dioxide emissions calculated for each fuel were summed and listed as totals for each technology. In 2014, U.S. carbon dioxide emissions from industrial fossil fuel combustion were about 891.6 million metric tons (EPA 2017). In relative terms the technology with the smallest potential, WHRHPs, represents an avoidance of about 0.5% of total industrial combustion emissions. The technology with the largest opportunity, PTC with TES, represents about 15% of total industrial combustion emissions of CO_2.

Table 7. Carbon Dioxide Emissions Avoided (million metric tons)

	FPC	LF DSG	PTC no TES	PTC w/ TES	E-boiler	Resistance	WHRHP
Summer sizing	26.6	70.3	95.8	136.4	18.3	20.9	4.7
Winter sizing	32.2	75.4	106.2	137.4	18.1	18.7	5.3

4.3.5 Land Use

The area of land required for each SIPH system was scaled to meet peak load during the months of June or December according to the description provided in Section 4.2.1, and the results of land use totaled and by county shown in Figure 24 and Figure 25. The total land use required ranges from 221 km^2 (0.2% of available land) for the FPC case to 5,463 km^2 (1.4% of available land) for the PTC with TES case, with summer sizing, and 521 km^2 (0.4% of available land) to 18,960 km^2 (2.9% of available land), respectively, with winter sizing (Appendix F.4). As a comparison, Connecticut, the third-smallest state by area, is 14,357 km^2.

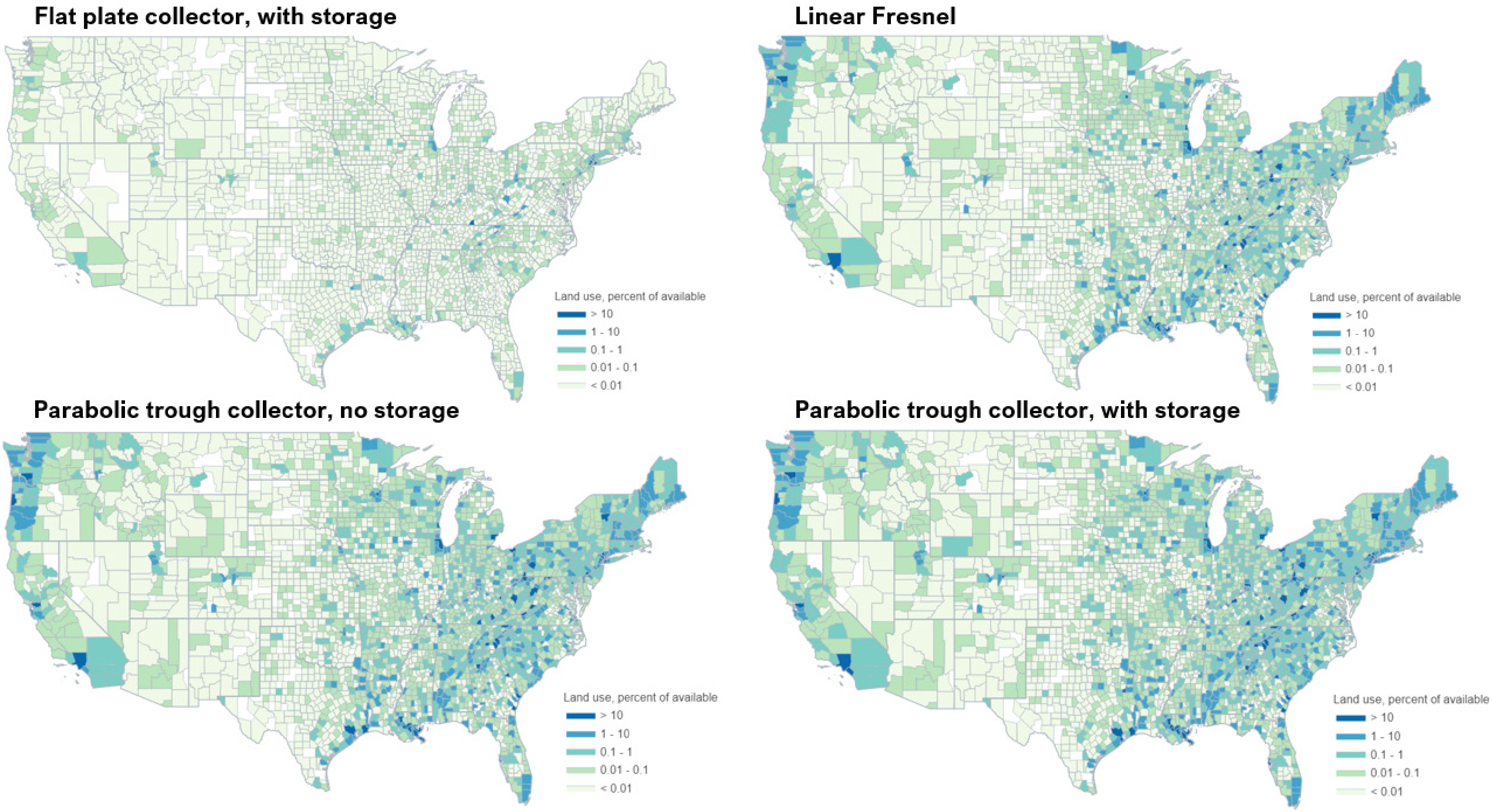

Figure 24. County-level maps showing land use as a percentage of the available land for the solar thermal technologies, summer sizing

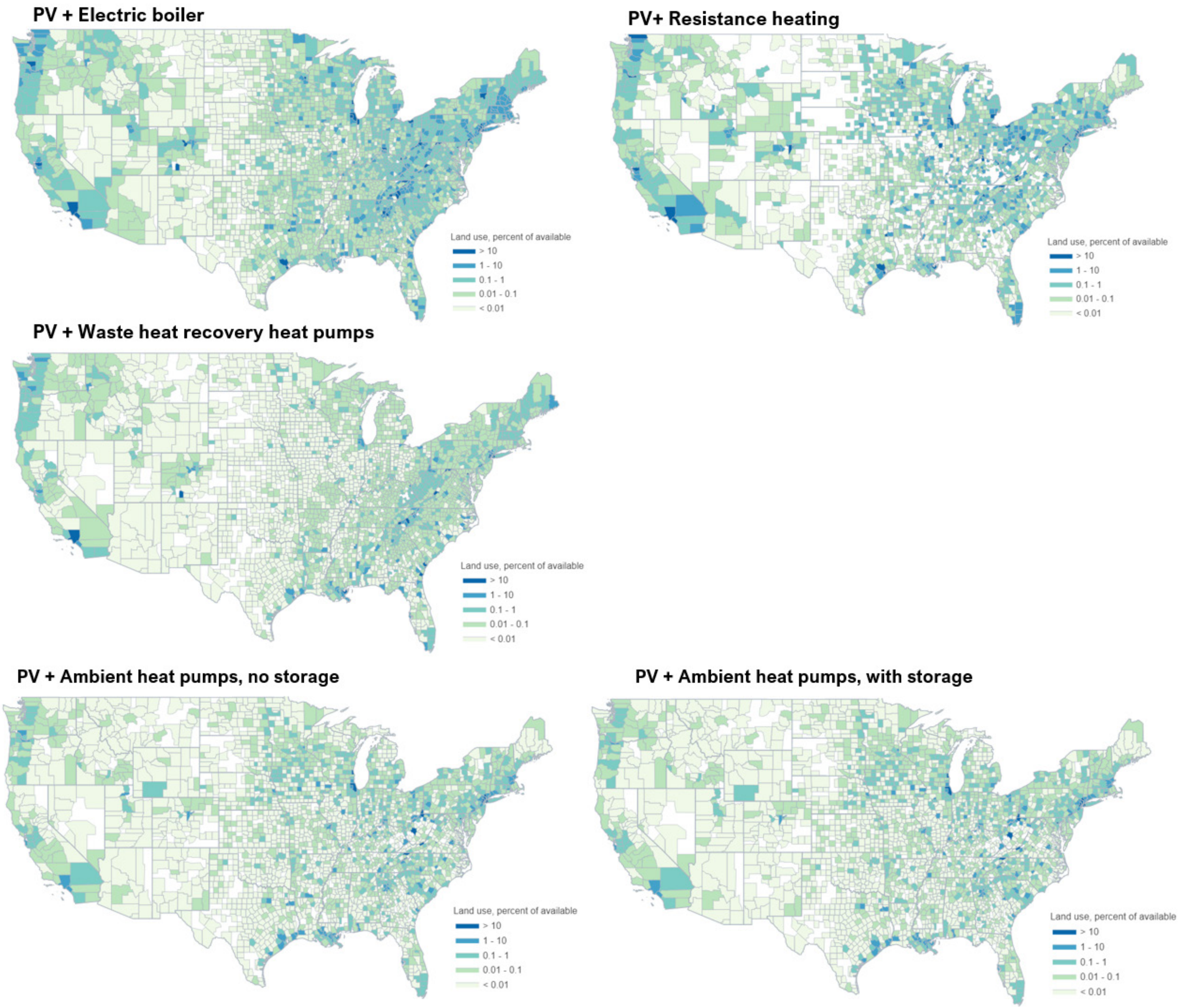

Figure 25. County-level maps showing land use as a percentage of available land for electrotechnologies, summer sizing

Based on the method for scaling the SIPH systems to meet peak load, land use reported here depends on the calculated load for each solar technology. In general, the LF and PTC cases have the highest calculated loads because of their ability to meet a broader portion of heat demand. However, the land use percentages of the electrotechnologies are very close to the percentages of these solar thermal cases (Figure 26). Despite having a smaller process heat load, the electrotechnologies require similar percentages of land use, signifying that the PV systems require more land than solar thermal systems per unit of thermal energy delivered.

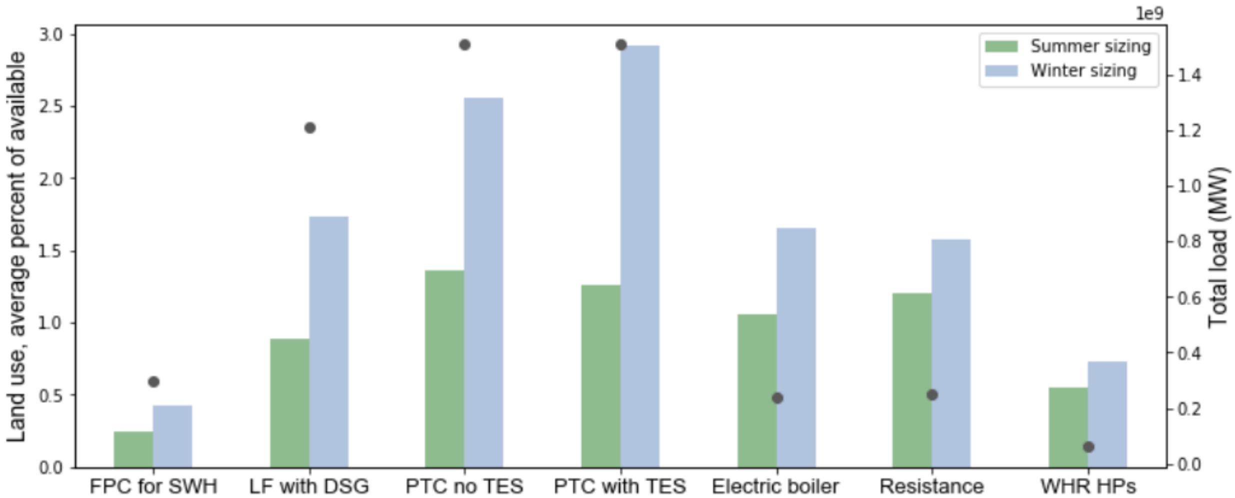

Figure 26. Land use as a percentage of available land, average values, (bars), and total load in megawatts (dots)

4.3.6 Process Temperature Analysis

The difference between the temperature of heat supplied by SIPH systems and required process temperatures is a significant factor in solar thermal systems' technical opportunity. Separate from the load versus generation analysis, an analysis of temperatures is another way to examine the feasibility of SIPH integration. Such an analysis also highlights the effects of solar heat's temporal dimension throughout the year. So, we evaluated the temperature difference between the minimum process temperature in a county in Texas and the temperature of hot water supplied by an FPC system at an hourly time scale (Figure 27, page 50). Note that the modeled FPC system includes 60 m^3 of TES per 1 MW.

The intermittent nature of solar heat is apparent at the hourly scale displayed in Figure 27. Each colored rectangle represents the hourly temperature difference, averaged for the month, between the solar supplied heat and the minimum process temperature in the county. Yellow, orange, and red rectangles signify that the solar supplied heat is achieving the necessary process temperature. The solar heat does not achieve the necessary process temperature for early morning or late evening hours in the winter and late fall months for this county, in which case auxiliary heating systems would be required for industries that operate on a continuous basis. Alternatively, more TES could increase the number of hours achieving temperature requirements, but the economic tradeoff between higher capital costs for storage and greater solar contribution would need to be addressed. The temperature difference in the winter months will likely be larger for counties in colder climates.

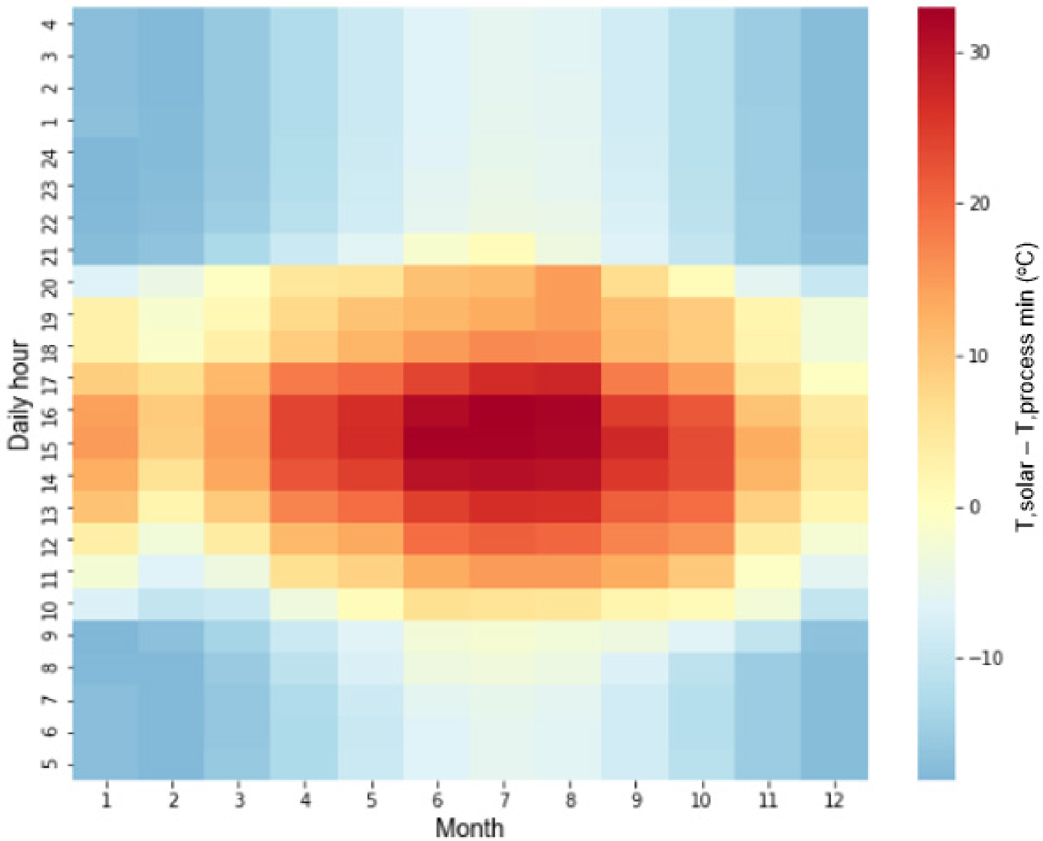

Figure 27. Heat map of the difference between the minimum required process temperature in Bee County in Texas (36°C) and the temperature of hot water supplied by an FPC system

4.3.7 PVHP Results

The primary results from the PVHP technical potential analysis are show in Table 8. The technical potential for installed PV ranges between 55 GW_p and 235 GW_p, which translates into a total land use between 696 km^2 and 3,016 km^2, which is less than 0.04% of the contiguous United States. The lower end of both ranges represents an ideal case of a highly effective PVHP system (low process temperature, higher COP) that is sized to meet summer demand (i.e., peak IPH demand in June). Table 8 shows the potential for the use of PVHP to meet IPH demands for process temperatures of 50°C and 90°C, sized by winter (i.e., December) and summer peak demand.

Table 8. Opportunity to Use PVHP to Meet Hot Water Demands

		Demand (Mean) -GWh		PV Installed (Mean)-GW		Land Use (Mean)-km^2	
		Winter	Summer	Winter	Summer	Winter	Summer
Process Temperature	50 °C	23,983	24,832	160	57	2,109	723
	90 °C	23,983	24,832	306	139	3,959	1,757

5 Discussion

The solar technologies modeled in this analysis, with the exceptions of PVHP and several counties in the FPC case, do not cover heat demand 100% of the time. This implies that direct solar thermal SIPH technologies may require fuel-based heating to remain as auxiliary systems for industries requiring continuous operation, whereas electrotechnology replacements would require grid electricity. As a result, the fuel reduction potential is limited and cannot be expected to cover all the required fuel. It is possible that the IPH demands of industries that do no operate continuously—but do operate for more than one shift per day—could be completely met with TES. TES has a large impact on solar heat potential, the frequency and counties for which solar can meet heat demand, and fuel savings. TES significantly increases the number of hours during the year when solar can fully meet heat demand, which consequently increases fuel savings.

We have made certain assumptions that likely understate the ability of solar technologies to meet IPH demand and overstate the need for TES. The existing combustion systems assume process heating equipment is maintained at a minimum load (specified by a turndown ratio) during nonoperating hours to avoid thermally induced stress on equipment components that is due to cold starts. This means a representative heat load shape for a facility that operates eight hours per day, five days per week—daylight hours, typically—and that has a turndown ratio of 4 operates at 25% of full load for about 75% of the year. Industries such as apparel manufacturers, leather product manufacturers, and ready-mix concrete manufacturers are likely to operate on this type of schedule. One exception is electrical resistance heating, which is assumed to fully replace the conventional process heating option and must utilize grid electricity when solar PV electricity is unavailable. The ability of resistance heating systems and other electrotechnologies to utilize grid electricity means that an on-site PV field is not required for electricity generation. As the grid incorporates more PV generation, grid-connected IPH electrotechnologies indirectly use more solar energy. The interactions between grid electricity and IPH demands are important topics for future research.

5.1 Implications of Operating Hour Assumptions

We also estimated the opportunities for SIPH using high and low estimates of average weekly operating hours. Using this range enabled us to explore the implications of variation in operating schedules with the same annual IPH demand; specifically, facilities operating on schedules that aligned to a greater or lesser degree to daylight hours. As discussed in Section 2.2, standard error estimates of average weekly operating hours by industry were used to develop high and low operating hour bounds. The differences in results for high and low operating hours scenarios (Appendix F) are small. The magnitude of their difference varies for each factor evaluated, but it is around 1% from the mean operating hour assumption. For example, fuel savings for the FPC case under the low operating hours scenario are 1.5% greater than the mean operating hours scenario, for both summer and winter sizing, while land use for the FPC case under the low operating hours scenario is 0% for summer sizing and 0.1% for winter sizing.

Aggregating results at the county level and across industries likely hides some of the variation in sensitivity to operating hour assumptions. Conversely, most IPH demand is associated with very large facilities in energy-intensive industries, which tend to operate continuously. IPH demand is likely required for these facilities outside daylight hours, even with a large lower bound of average weekly operating hours. This indicates a critical need for TES, which we discuss next.

5.2 Implications of Thermal Energy Storage

TES plays an important role in enabling opportunities for SIPH. Although this is anticipated, the results provide a large-scale quantification of how storage may enable SIPH to meet IPH demands across a greater geographic area, for a greater period of the year. For the PTC system without storage, in no single county is at least 50% of IPH demand met. By adding six hours of TES, slightly more than 30% of counties meet 50% of their IPH demands and the SIPH system meets demands nearly 50% of the year. This translates into an additional 750 TBtu of displaced fossil fuels and about 30–40 million metric tons of CO_2 of emissions savings. The implications of storage vary by industry, as shown in Figure 20 (page 42). Industries that are more likely to run operations continuously, such as the pulp and paper subsector, show a greater benefit from storage than industries that tend to operate fewer shifts.

The PVHP system assumes the hot water storage can be sufficiently sized and charged to meet all IPH demands that occur outside the hours of PV generation. TES enables on average nearly 60%—and as much as 73%—additional IPH demands to be met, based on winter sizing assumptions. This assumes, of course, that the heat pump is not grid-connected and there is no on-site electrical energy storage. Results by county in Figure 28 show that in summer 25%–40% of the generated thermal energy is wasted (or otherwise lost) without TES. In winter, 50%–65% is wasted. More energy is wasted in winter, as more storage is required because of shorter days and longer nights.

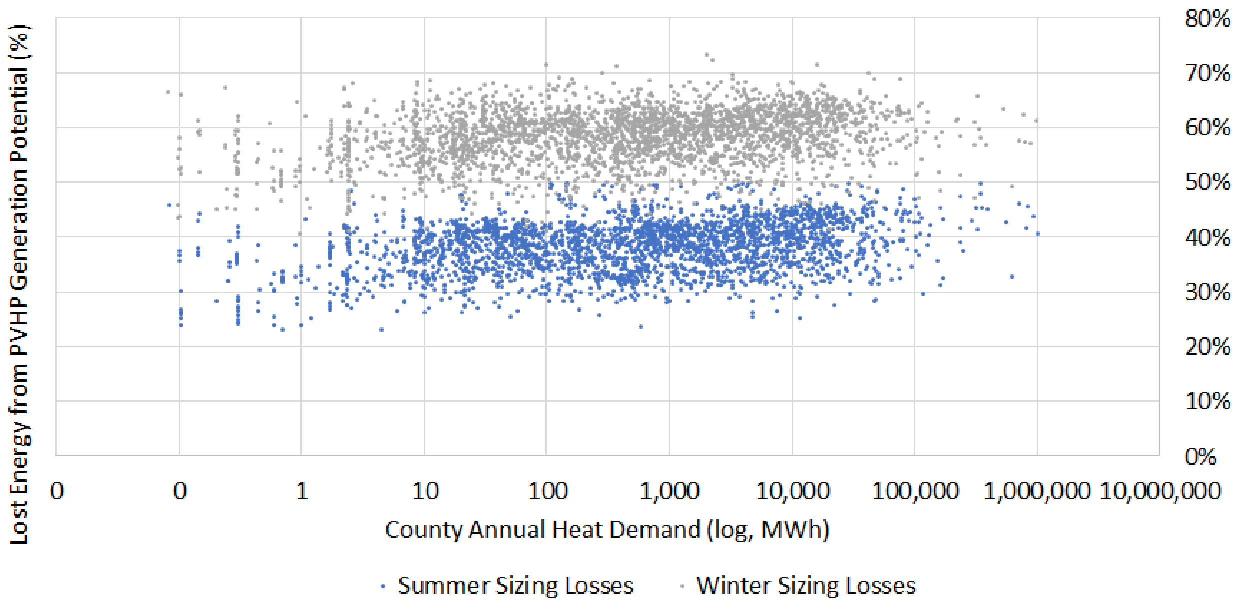

Figure 28. The fraction of energy wasted without TES for the summer and winter sizing cases

6 Conclusions and Additional Research

6.1 Conclusions

SIPH opportunities to reduce combustion fuel use and associated emissions exist across many industries and in all counties in the continental United States. However, the magnitude of these opportunities is limited by the ability to meet IPH demands that occur when sunlight is not available, particularly for industries that operate continuously. The ability to match the temporal aspect of IPH demand is a more significant barrier than matching solar technologies to IPH temperatures.

6.2 Additional Research

We intended this analysis from its inception to serve as a foundation for continued analysis and research of IPH demands and the role solar technologies can play in meeting those demands. The natural progression for additional research would continue toward a higher-resolution matching of solar technologies to IPH demands, addressing issues such as facility location and available land area, heat transport for solar thermal technologies, and individual facility operation, including operating schedule, and process temperature requirements and heating loads at the equipment level over time. Analysis of a broader array of storage options (including BES), as well as the exploration of optimal storage sizing, are also critical next steps. TES heated through PV (or grid) electricity would be an important future area of research. Such a system allows the grid to provide the transport of energy from the generator to the user without on-site land constraints or generation costs for the user. TES systems could also be HP or resistively heated. This could be attractive for steam-based systems where the boiler is heated by the TES and not directly by electricity.

Along with capturing facility-level characteristics, additional research is needed on integrating SIPH technologies both with existing industrial operations and in combination with load reduction (i.e., energy efficiency) measures. This may involve the development of a decision support tool to enable facilities to (1) compare SIPH solutions against conventional IPH technologies, (2) identify and more closely track SIPH installations and their performance, and (3) expand engagement with representatives of relevant manufacturing subsectors. A decision support tool could incorporate existing analysis capabilities and data, such as those developed in the IEA Solar Heating and Cooling (SHC) Task 49.[27] This tool could be expanded later to compare IPH solutions across other renewable energy technologies, such as geothermal and biomass.

The evaluation of SIPH technologies could also be expanded within an industrial ecology framework to capture life cycle emissions and material flow impacts of material production and end-of-life. Also, opportunities exist to explore technoeconomic and supply chain analyses of domestic SIPH manufacturing. This would be critical for analyzing the improvements necessary to make SIPH technologies more competitive with conventional IPH systems in the cases where they are not currently competitive.

[27] "Solar Heat Integration in Industrial Processes", IEA Solar Heating and Cooling, https://task49.iea-shc.org/.

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Appendix A. Electrotechnology Scoping

A.1 Electrotechnology descriptions

Brief descriptions of each electrotechnology in Table 3, and sources for further information, can be found below.

- Electric boilers are used to generate steam or hot water and can be divided into two types: (1) resistance-heating electric boilers and (2) electrode boilers, which can achieve much higher capacities in industrial applications than resistance-heating boilers. Both types of electric boiler have higher energy efficiencies than conventional fuel boilers, and they can also come with lower upfront costs (Knoke and Tidball 2011). Electric boilers are considered a "drop-in" replacement for stand-alone conventional boilers in all industrial subsectors, given that conventional boilers are not associated with combined heat and power (CHP) systems as defined in this study.
- Ambient heat pumps have wide applications in different industrial subsectors. In the industrial sector, most ambient heat pumps have been installed with a supply temperature ranging from 50°C to 90°C (Jensen 2016). High-temperature ambient heat pumps provide heat >80°C (EECA 2018), but their commercial availability is still limited because of higher maintenance requirements and limited experience (A2EP 2017). In the analysis reported here, the maximum supply temperature was set to be 100°C and the technical potential calculation is based on this assumption.
- Resistance heating and melting can be divided into direct and indirect resistance heating and melting. Their major advantages over conventional fuel-fired furnaces include rapid heating, faster start-up, no combustion gas, automatic control systems, lower maintenance costs, and higher production rates (Knoke and Tidball 2011). This technology has already been applied in many industrial subsectors, such as heating, drying, and heat treatment in the food, metals, cement, and chemicals industry, and plastic drying and forming (EECA 2019b; 2019c; Vicente 2020; Varghese et al. 2014; Beyond Zero Emissions 2018; D&M Plastic Inc 2020).
- Waste heat recovery heat pumps (WHRHPs) can recover waste heat from one process for use in another process, thereby reducing plant-level needs for purchased fuels. WHRHPs require an external energy source to valorize low-temperature heat to high-temperature heat. Three types of WHRHPs were considered in this study: mechanical compression cycle, mechanical vapor recompression cycle, and thermal vapor recompression cycle. Technical potentials for each type of WHRHP were estimated based on thermodynamic relations and applications data in DOE (2014), Zhang et al. (2016), and ; Chen and Xie (2012).
- Induction heating and melting heats or melts metals by placing metal parts inside a coil wherein the electric flow alternates. This electrotechnology is mainly used for heat treatment of metals, including melting, hardening, tempering, annealing, brazing, welding, and preheating processes (Beyond Zero Emissions 2018).
- Infrared processing is excellent at heating surfaces and has broad applications in many manufacturing subsectors, such as food drying, frying, baking, thawing, blanching, and pasteurizing, paper drying, ceramic processing, screen print on car windows drying, and

laminated glass or coating mirrors cutting (Beyond Zero Emissions 2018; Heraeus, n.d.; Krishnamurthy et al. 2008).

- Microwave heating and drying can provide higher power density (900–3,000 MHz) and can heat irregular-shaped materials (Beyond Zero Emissions 2018; EECA 2019a). Microwave heating and drying can be used in food heating, ceramic product drying, and a wide range of heating processes in the chemical subsector, such as drying, sintering, calcining, cooking, curing, and preheating (Beyond Zero Emissions 2018; Council 1AD; Pradeep et al. 2013).
- Radio-frequency heating and drying and microwave heating and drying are both dielectric heating technologies, and they have similar applications. The difference is that radio-frequency heating and drying is more suitable for uniform objects with greater depth of penetration because it has lower power density (10–30 MHz) and higher penetration capability (10–30 m) (Beyond Zero Emissions 2018).
- Direct arc melting is also called electric arc melting. This technology is mainly used to make steels from steel scraps using an electric arc furnace, which only consumes 10% of the energy used to produce primary steel through the blast furnace and basic oxygen furnace route (Beyond Zero Emissions 2018).
- Ultraviolet (UV) curing has several advantages over other technologies, including faster drying and curing speed, reduction or elimination of organic solids, the capability to coat sensitive materials, increased production rate, and more-efficient use of coating materials (Knoke and Tidball 2011). Industrial applications of UV curing include drying of inks, adhesives, and coatings in numerous subsectors (LightTech LightSources 2020).
- Plasma processing occurs in plasma arc furnaces and it can generate heat at temperatures as high as 5,000°C (Beyond Zero Emissions 2018). Plasma processing has better efficiency and power density than combustion heating, and its applications include surface treatment of metals, ceramic, and polymers (Bhosale et al. 2013; Council 1991; Joshi and Butola 2013).
- Vacuum melting was developed to produce superalloys in an induction-heated crucible under vacuum conditions, and it has applications in metal refineries (ASM Handbook 2008; Muller, Weingortner, and Leybold 2008).
- Laser processing uses laser beam projection to process the materials, including surface engineering, joining machining, coating, and deposition (Dutta Majumdar and Manna 2003; MachineMFG 2020).
- Ladle refining refers to the process that raises the temperature of and adjusts the chemical composition of molten metals to produce high-quality steel (Inductotherm 2020; Banerjee et al. 2000).

This study classified electrotechnology applications into three different end uses according to the MECS data convention discussed earlier in the report: conventional boilers, CHP, and process heating. The primary applicable end uses for the considered electrotechnologies, which are summarized in Table A-1, were determined in two steps. The first step was to identify the applicable unit processes for each electrotechnology within each major U.S. subsector, e.g., conventional baking ovens for microwave heating in the commercial baking industry, based on a literature review. The second step was to determine the primary energy source for each identified unit process in each subsector based on Brown et al. (1997) or other sources. The energy sources can be fuel, electricity, steam, or/and hot water. The end use of an electrotechnology was assigned process heating if it uses direct fuel as the energy source, while the end use was assigned as conventional boiler and CHP when it uses steam or/and hot water as energy source.

Table A-1. End Uses of Different Electrotechnologies Used for Process Heating in the Manufacturing Sector

	End Uses		
Electrotechnologies	**Conventional Boiler**	**CHP**	**Process Heating**
Electric boiler	×	×	
Ambient heat pump	×	×	×
Resistance heating and melting	×	×	×
Waste recovery heat pumps	×	×	×
Induction heating and melting			×
Infrared processing	×	×	×
Microwave heating and drying	×	×	×
Radio-frequency heating and drying	×	×	×
Direct arc melting			×
UV curing			×
Plasma processing			×
Vacuum melting	×	×	×
Laser processing			×
Ladle refining	×	×	×

A.2 Electrotechnology Screening Approach

As mentioned in Section 2.3, three criteria were used to down-select electrotechnologies for detailed analysis in this study: technical potential for conventional fuel replacement at the U.S. national level, data availability for credible modeling, and market growth outlook.

To estimate each electrotechnology's potential for replacing conventional fuels, we first summed the total fuel use associated with each identified end use (in Table A-1) in each subsector in which the electrotechnology could be applied. Next, we estimated the fraction of each end use that is associated with the specific unit processes that would be electrified in each subsector. These two steps enabled rough estimation of the total conventional fuel amounts that could be replaced by each electrotechnology in each subsector.

If the estimated technical potential at the U.S. national level was equal to or greater than 500 TBtu/year, the technical potential score was set to be 3; if the technical potential was in between 100 TBtu/year and 500 TBtu/year, the score was set to be 2; if the technical potential was equal to or less than 100 TBtu/year, the score was set to be 1.

The data availability score was based on a review of available case studies and engineering models in literature for each electrotechnology and applicable subsector. The rating rubric for modeling feasibility was:

- If sufficient technical information was available in case studies or engineering/mathematic models, the score of modeling feasibility was set to be 3
- If only limited technical information existed, either due to limited case studies or insufficiently generalizable engineering models, the score was set to be 2
- If no case studies or available engineering models were available, the score was set to be 1.

The market growth outlook of different electrotechnologies was based on the 5-year growth rate estimated from EPRI from 2015 to 2020 (EPRI 2016). If the growth rate was greater than or equal to 10%, the score was set to be 3; if the growth rate was 0%–10% (including 0%), the score was set to be 2; if the growth rate was negative, the score was set to be 1.

A.3 Electric Boiler Technical Potential

The technical potential of electric boilers (Table A-2) was estimated in three steps:

- The traditional fossil fuel consumed by conventional boilers was obtained from 2014 MECS survey data (EIA 2014c), while other fuel consumption (defined in this report as biomass, waste gas, or other byproduct fuels)was estimated from other EIA and DOE reports (EIA 2014c; 2014a; 2014b; DOE 2014b).
- The fraction of total fuel use for conventional boilers by size classification was estimated from industrial subsector boiler population and capacity estimates in Energy and Inc (2005).
- The fraction of fuel use for conventional boilers that can be replaced by electric boilers was estimated based on conventional boiler size distribution and maximum electric boiler capacity obtained from a review of different market data sources (Cleaver-Brooks 2020; Electro Industries 2020; Bryan Boilers 2020b; 2020a; WilsherCo 2020; Vapor Power 2020c; 2020a; 2020b).

Table A-2. Technical Potential of Using Electric Boilers to Replace Conventional Boilers

	2014 Conventional Boiler Fuel Use (TBtu/yr)			Technical Potential	
NAICS: Industry	**Fossil Fuels**	**Other Fuels**	**Total**	**Boiler Fuel Replacement**	**TBtu Replacem ent**
311: Food industry	163	130	293	74%	216
312: Beverage industry	23	4	27	74%	20
313–316: Textiles	8	2	10	80%	8
321: Wood product manufacturing	4	36	40	75%	30
322: Paper manufacturing	55	188	243	29%	70

	2014 Conventional Boiler Fuel Use (TBtu/yr)			Technical Potential	
NAICS: Industry	**Fossil Fuels**	**Other Fuels**	**Total**	**Boiler Fuel Replacement**	**TBtu Replacement**
324110: Petroleum refineries	109	331	440	30%	132
325: Chemicals	360	176	536	61%	329
326: Plastics	21	2	23	80%	18
331110: Iron and steel mills	14	50	64	57%	36
3312: Steel product manufacturing	31	0	31	57%	18
3313: Alumina and aluminum	3	3	6	57%	3
332: Fabricated metal products	4	0	4	80%	3
334,335: Computers, electronics	13	2	15	80%	12
336: Transportation equipment	19	8	27	72%	19
Total	827	932	1759	52%	916

A.4 Waste Heat Recovery Heat Pump (WHRHP) Technical Potential

The technical potential of waste heat recovery heat pumps (WHRHPs) was estimated in the following steps:

- Based on previous literature, for those subsectors with substantial quantities of waste heat, heat sources and heat sinks were identified from various sources (IETS 2013b; EPRI 2010; Nowicki and Gosselin 2012; Law, Harvey, and Reay 2016; Hita et al. 2011; Stefan et al. 2012; Hasanbeigi 2010).
- The input heat loss as waste heat was estimated based on two temperature references: 77°F (25°C) and 300°F (149°C). If an operation temperature was higher than 300°F and the working fluid was not water, the reference temperature was set to be 300°F to avoid flue gas condensation. If the operation temperature was lower than or equal to 300°F and the working fluid was not water, the reference temperature for waste heat loss calculation was set to be 77°C (room temperature) (Johnson, Choate, and Davidson 2008). When the working fluid is water, the reference temperature depends on the state of water (liquid or gas), and the waste heat loss was calculated based on enthalpy and temperature changes.
- The input heat for WHRHPs was calculated based on the multiplication of the heat source input fuel quantity obtained from our estimates of IPH demand, the waste heat fraction obtained from the previous step, and an assumed fraction of waste heat not already recovered as obtained from Johnson, Choate, and Davidson (2008).

- The technical potential/output heat was calculated by multiplying the input heat and COP obtained from different case studies and thermodynamic models built for mechanical compression cycle, mechanical vapor recompression, and thermal vapor recompression.

The WHRHP technical potential associated with different industrial subsectors is shown in Table A-3, and the technical potential with different end uses is summarized in Table A-4 and shown in Figure A-1.

Table A-3. Technical Potential of WHRHPs by Industrial Subsector

NAICS	Industrial Subsector	Input Work/ Heat (TWh)	Waste Heat Recovery (TBtu)	Output Heat (TBtu)
311	Food manufacturing	5.14E+00	7.12E+01	8.87E+01
312	Beverage	4.50E-01	5.01E+01	6.54E+01
313	Textile mills	4.67E-01	5.37E+00	6.97E+00
321	Wood product manufacturing	1.59E+00	1.63E+01	2.17E+01
322	Paper manufacturing	6.17E+00	6.68E+01	8.78E+01
324	Petroleum and coal products manufacturing	1.29E+01	6.26E+01	1.06E+02
325	Chemical manufacturing	5.12E+00	5.63E+01	7.38E+01
327	Nonmetallic mineral product manufacturing	1.25E-01	1.19E+00	1.62E+00
332	Fabricated metal product manufacturing	4.38E-02	4.72E-01	6.22E-01
	Total	**3.60E+01**	**3.30E+02**	**4.53E+02**

Table A-4. Technical Potential of WHRHPs with Different End Uses (Heat Sink)

Heat Sink End Uses	Input Work (TWh)	Waste Heat Recovery (TBtu)	Output Heat (TBtu)
Boiler/CHP	1.28E+01	1.45E+02	1.89E+02
Process heating	2.67E+00	3.98E+01	4.89E+01
Process heating/boiler/CHP	1.29E+01	6.26E+01	1.06E+02
Heating, ventilation, and air conditioning	7.68E+00	8.26E+01	1.09E+02
Total	**3.60E+01**	**3.30E+02**	**4.53E+02**

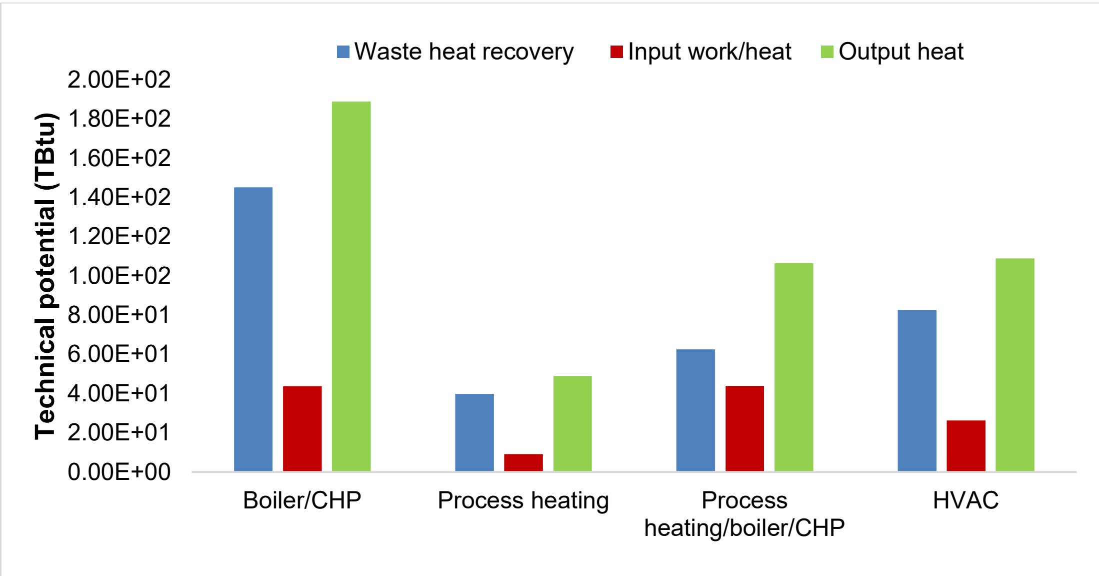


Figure A-1. Technical potential of WHRHPs associated with different end uses

HVAC = heating, ventilation, and air conditioning

A.5 Technical Potential of Resistance Heating

The unit processes and industries that can use resistance heating technology to replace conventional technologies were identified based on various literature (Vicente 2020; Varghese et al. 2014; EECA 2019b; Beyond Zero Emissions 2018; Jones et al. 2003; EPRI 1994; Silva, Santos, and Silva 2017; Sakr and Liu 2014; EECA 2019c; D&M Plastic Inc 2020). The total fuel use associated with each end use that contains the conventional unit process was obtained from our estimates of IPH demand. The fraction of conventional unit process energy use that can be replaced by resistance heating was estimated using the energy use fraction of the unit process within a representative process flow system for the subsector (Brown et al. 1997). Technical potential was calculated by multiplying fuel usage that contains the conventional unit process and the fraction of conventional unit process that can be replaced by resistance heating.

Estimated technical potential values in different subsectors are listed in Table A-5.

Table A-5. Technical Potential of Resistance Heating in Different Subsectors

NAICS	Industrial Subsectors	Technical Potential (TBtu)
311 and 312	Food and beverage	414
324	Petroleum and coal products manufacturing	170
325	Chemical manufacturing	432
326	Plastics and rubbers manufacturing	4
327	Nonmetallic mineral product manufacturing	420
331	Primary metal manufacturing	395
	Total	**1,834**

A.6 Combined Heat and Power: Estimation of Fuel Input and Electrical Output Changes

When the demand for steam produced from CHP systems is reduced, there are two important technical effects worthy of consideration. First, electricity output is also reduced, which either reduces the amount of electricity available for plant export or necessitates the need for purchased electricity from the grid. Second, as the capacity utilization of the prime mover decreases, so too do its electrical and thermal efficiencies. These changes were considered for SIPH technology packages that reduced steam demand in plants with installed CHP units based on CHP characteristics obtained from DOE (2016) and Darrow et al. (2015). Five combustion/gas turbine CHP systems with different capacities were selected to represent different types of combustion/gas turbines, and three steam CHP systems with different capacities were selected to represent different types of steam turbines. The electric efficiency curve based on different loads of combustion/gas turbine was obtained from Darrow et al. (2015), and the thermal efficiency curve based on different loads of steam turbine was obtained from Bresolin et al. (2006). The thermal efficiency of combustion/gas turbine and electric efficiency of steam turbine were back-calculated based on power-to-heat ratios and their efficiency curves were generated. Figures A-2 and A-3 show the thermal, electric, and overall efficiencies for these two CHP systems that were incorporated into our analysis.

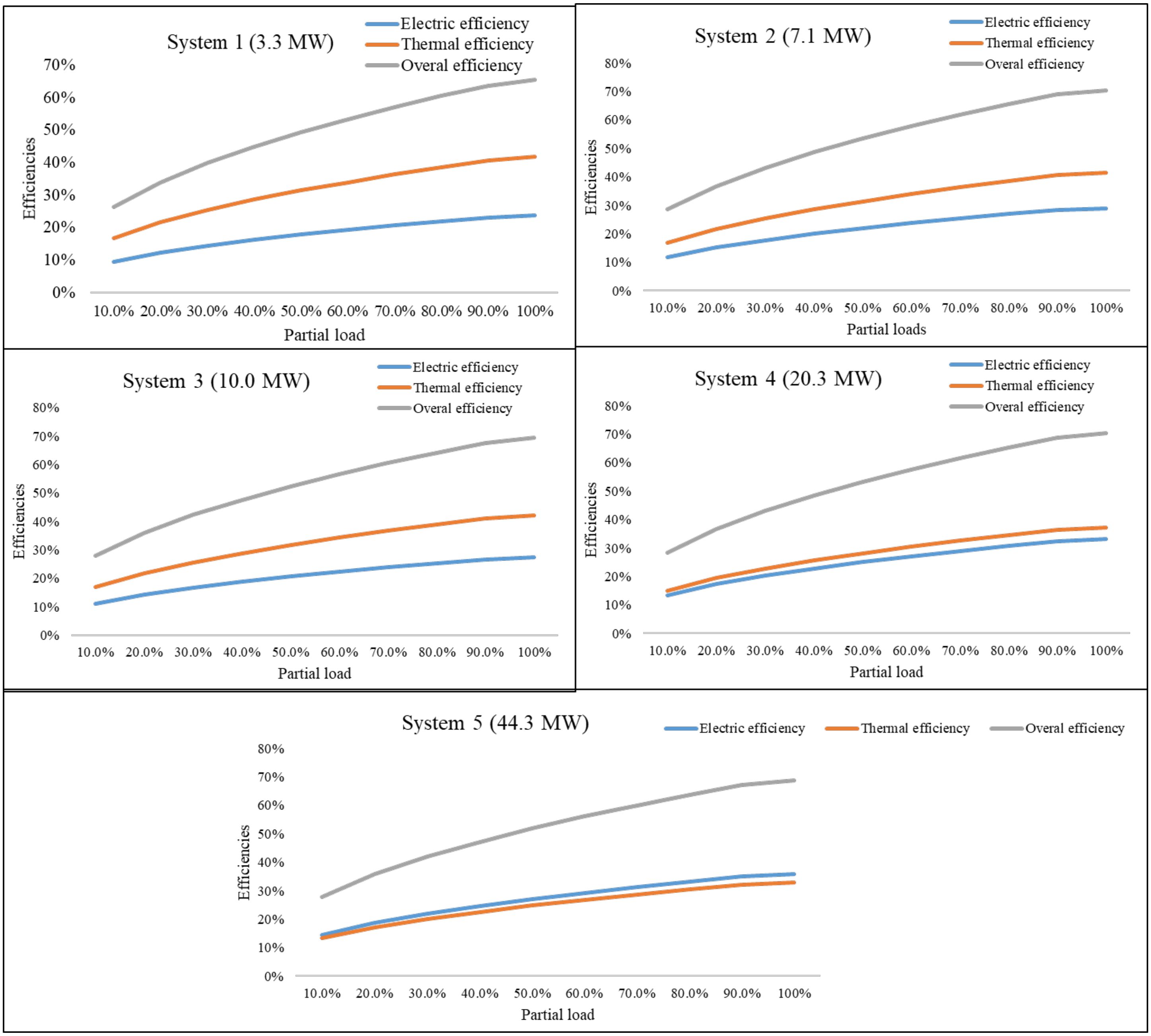


Figure A-2. Thermal, electric, and overall efficiencies of combustion/gas turbine CHP systems with different capacities

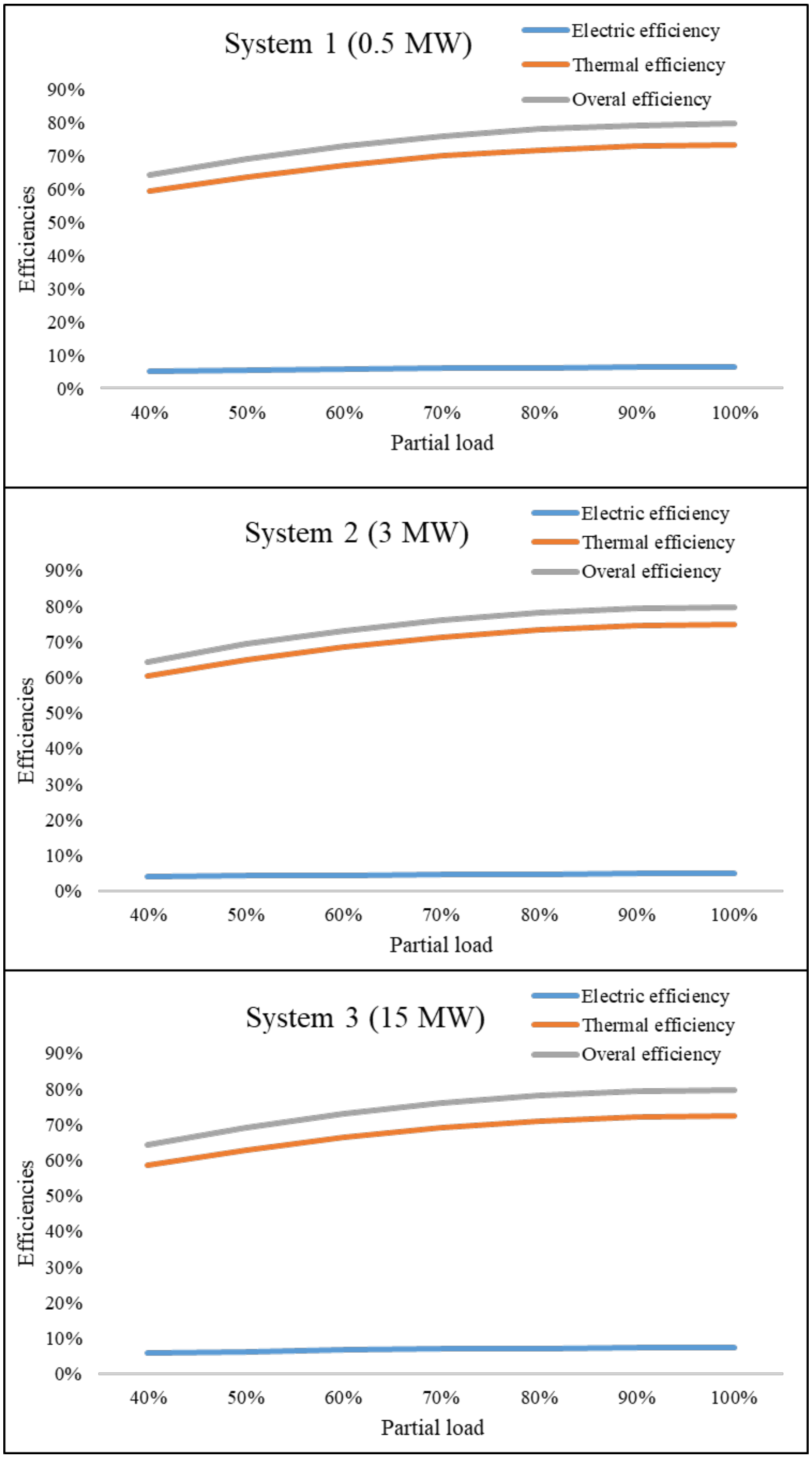


Figure A-3. Thermal, electric, and overall efficiencies of steam turbine CHP systems with different capacities

Appendix B. County-Level Process Heat Demand

Our general process for estimating county-level industrial heat demand in 2014 represents an evolution of the process first described by McMillan and Narwade (2018) and subsequently refined by McMillan and Ruth (2019). As with those in initial iterations, the updated process begins by distinguishing manufacturing facilities that report under the U.S. Environmental Protection Agency's Greenhouse Gas Reporting Program (GHGRP). In general, the reporting threshold is met by facilities that annually emit more than 25,000 $MTCO_2e$ from covered sources. The most extensive updates are related to the calculation process for GHGRP facilities and for disaggregating end-use energy by process temperature. These updates can be grouped into three categories:

- *Calculation methods were matched to GHGRP reporting Tier.* Previous estimates generally used EPA standard emissions factors to calculate energy values from reported emissions by fuel type. The new process for estimating annual facility energy instead was based on the method facilities use to report their combustion emissions (EPA n.d.). The update enables the use of higher heating values and other fuel-specific information to be used in estimating energy use.
- *Additional combustion unit detail was extracted from the GHGRP.* The energy estimates of GHGRP-reporting facilities are disaggregated into process heating end-use categories (i.e., process heating, conventional boiler, combined heat and power/cogeneration) using a combination of combustion unit information obtained from the GHGRP and industry-aggregated end-use estimates from MECS. The method for matching reported combustion unit information to end use was improved, reducing the reliance on MECS data.
- *Process temperatures were matched to end-use category.* A significant new feature of the calculation process disaggregates end-use energy into process temperatures using Brown et al. (1997) . This process is explained in detail below.

The general process for estimating county-level process heat demands is shown in Figure B-1. Overall, combustion energy by fuel type for manufacturing industries[28] is calculated by county using either facility level calculations for GHGRP reporters or energy intensity estimates developed from MECS (EIA 2017b) and county establishment counts (U.S. Census Bureau 2016). These data are then disaggregated into process heating end-use categories using a combination of GHGRP combustion unit information and MECS data.

The energy estimates are then disaggregated to process temperature following Brown et al. (1997) by matching to industry and end-use category. The reference book was published before the use of NAICS codes, and it was necessary to map to Standard Industry Classification codes to 2012 NAICS codes.

[28] all six-digit NAICS codes for the manufacturing sector

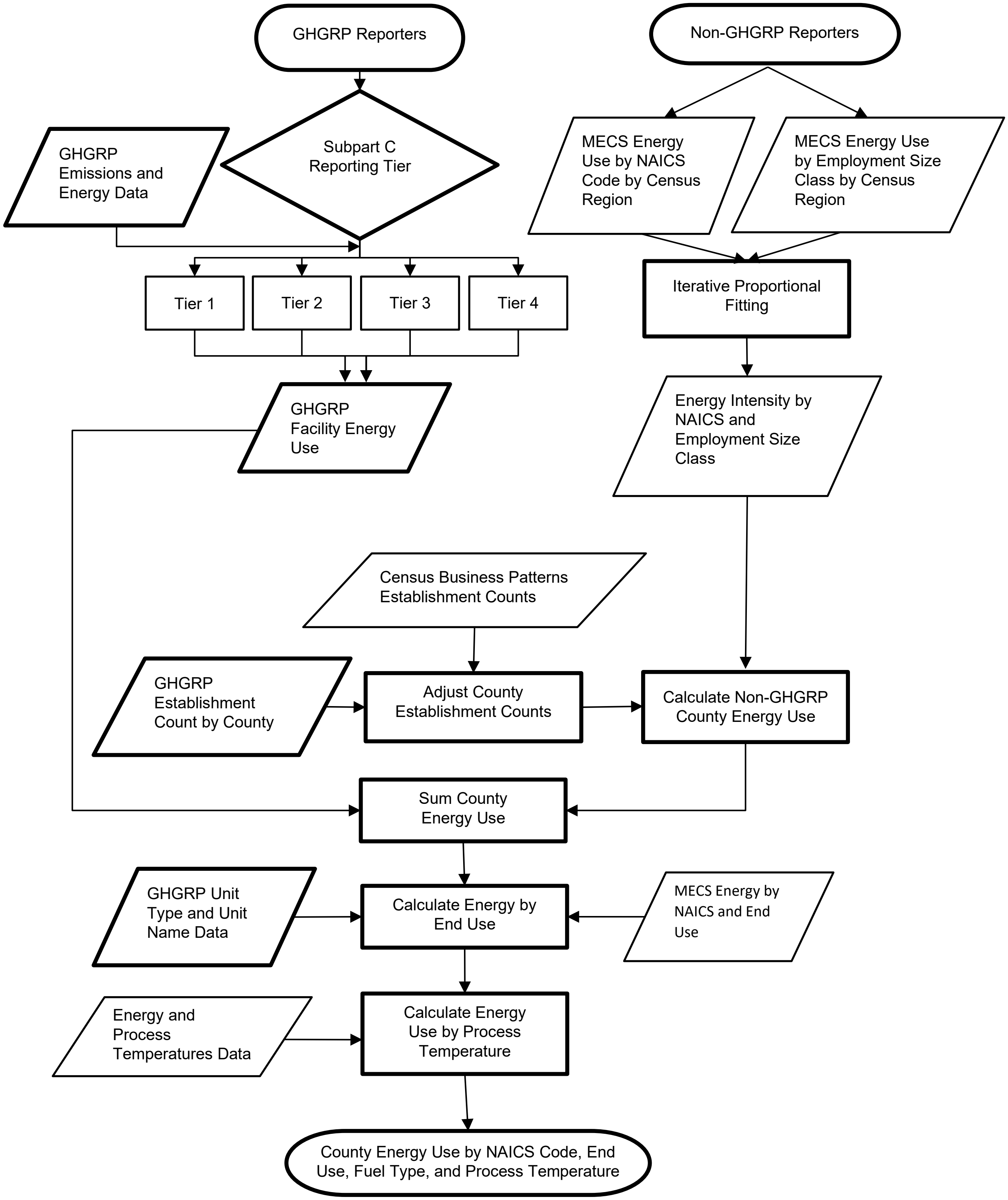


Figure B-1. General process for estimating 2014 county-level industrial process heat demand

It was not possible to match all industries with representative process temperature data. In all, about 156.4 TBtu, or 1.4%, of our estimated county-level process heat demand was not matched to process temperature data and therefore excluded from our analysis. This data gap is concentrated in the NAICS Electrical Equipment, Appliance, and Component Manufacturing, Computer and Electronic Product Manufacturing, and Leather and Allied Product Manufacturing, Printing and Related Support Activities Industries, for which there were no matching process temperatures available. These industries have relatively small process heat demands; we estimate their demand to be about 83 TBtu. They account for just over half of the missing process temperature data.

As first discussed by McMillan et al. (2016), there are inconsistencies with the extent of data made publicly available through the GHGRP for cement manufacturers. Our updated calculation process has revealed additional inconsistencies within the iron and steel industry, specifically how the combustion of byproduct gases are reported by facilities producing steel via the blast furnace/basic oxygen furnace route.[29] We estimate approximately 601 TBtu of process heat energy for NAICS 331110 compared to approximately 892 TBtu from MECS. The resolution of this discrepancy has been complicated by the fact that reporting methodologies of EPA and EIA are sometimes in conflict and by the withholding by EIA of data on nonfuel coal and coke use and by EPA on details of data reported under Subpart Q reporting. MECS tracks the fuel and nonfuel uses of coke, as well as the combustion of coke oven gas and blast furnace gas, and EIA is aware of issues of potential double-counting (EIA 2017c). Another source of the discrepancy could be the tightly coupled nature of blast furnace/basic oxygen furnace processes and EPA's distinction between process and combustion emissions (Environmental Protection Agency 2009). This could lead to inadvertent inclusion of combustion emissions in Subpart Q reporting, which would result in lower-than-expected energy estimates based on Subpart C data. However, the fidelity of publicly available data is limited for Subpart Q. Even after conferring with EIA and EPA staff, we were unable to resolve this discrepancy.

Ideally, these facility-level combustion energy estimates would be validated against another data source. The most comprehensive approach would be to compare these estimates to MECS confidential microdata, which would require access to a Census Research Data Center. The validation results would also need to be statistically aggregated in ways to maintain U.S. Census Bureau nondisclosure standards.

[29] https://github.com/NREL/Solar-for-Industry-Process-Heat/issues/6

Appendix C. Process Energy Calculations

C.1 Determining Process Heat Demand for Solar Technology Packages

Every solar technology is limited in its ability to supply heat by system performance characteristics, such as its operating temperature range and medium of heat delivery (e.g., hot water, steam, HTF, or electricity). These characteristics were compared to characteristics of conventional IPH demand (e.g., end-use, process temperatures, and relevant unit processes) to determine a portion of overall heat demand that could be feasible met by each solar technology.

Table C-1. Parameters Defining Feasible Process Heat Demand for Solar Technology Packages

Solar Technology	Characteristics of Solar Heat Supplied	Applicable IPH End Use	IPH Demand Limited to:
Flat plate collector	Temperature, <90°C Uses: hot water, boiler feedwater preheating	Conventional boiler, CHP	Hot water
Parabolic trough collector	Temperature, <400°C Uses: steam, direct processing heat	Conventional boiler, CHP, PH	Process temp <340°C
Linear Fresnel w/ direct steam generation (DSG)	Temperature, <250–400°C Uses: steam	Conventional boiler, CHP	Process temp <212°C
PV + electric boiler	Uses: steam, hot water	Conventional boiler	Capacity <50 MW
PV + resistance	Temperature, <1,800°C Uses: dryers, furnaces, ovens, kilns	Conventional boiler, CHP, PH	Relevant unit processes and industries
PV + heat pump (waste heat recovery and ambient)	Temperature, <160°C Uses: steam, hot water, hot air	Conventional Boiler, CHP, PH	Relevant unit processes and industries

Whereas Table C-1 describes how characteristics of solar heat technologies and of conventional IPH demand were used to determine a relevant portion of heat demand for technology group, Figure C-1 details the calculation process. This step varies for each solar technology:

- For FPC, the fraction of heat energy used for hot water heating by industrial subsector was determined based on process energy data by Brown et al. (1997). This fraction was multiplied by fuel inputs to find a heat demand for hot water heating with FPC.
- For the concentrating solar thermal technologies (LF and PTC), heat demand was filtered by maximum achievable process temperatures based on what the solar systems can provide: less than 212°C for LF, and less than 340°C for PTC, according to SAM outputs and assuming the use of a heat exchanger for the PTC system.
- For PV + electrotechnologies, the methods for determining a relevant heat demand are described in Section 2.3 and Appendix A.

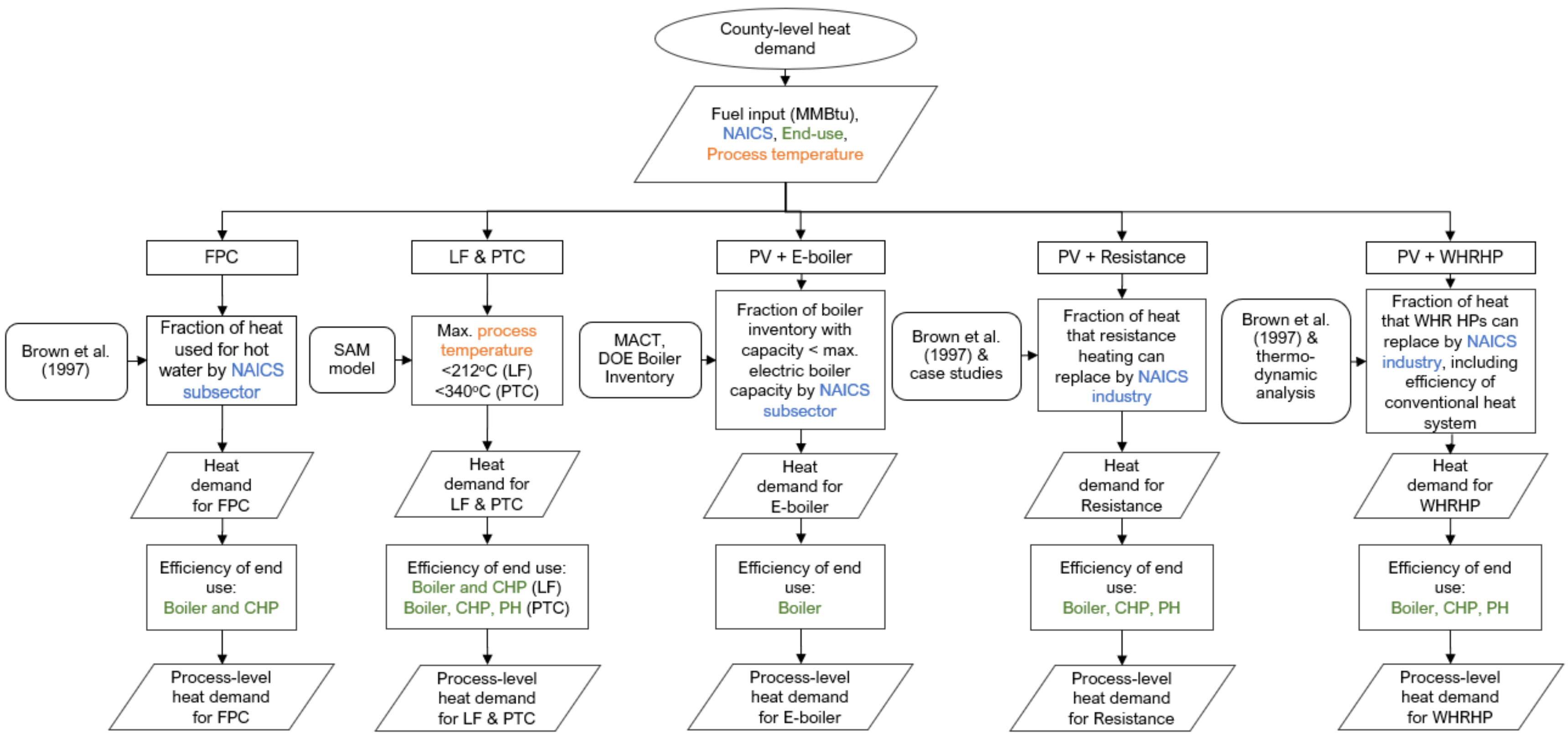


Figure C-1. Flowchart for calculating process energy for each solar technology package

Sources listed in rounded squares include Brown, Hamel, and Hedman (1997), Energy and Inc (2005), and EPA (EPA 2012).

The step involving the selection of relevant end uses and consideration of their system efficiencies is described below.

C.2 End-Use Efficiency Calculations

Once heat demand was calculated for each technology, their applicable end uses and the efficiencies of end uses were considered to arrive at process-level heat demand. The efficiency calculations are detailed in Figure C-2.

- The thermal efficiency of boilers depends primarily on fuel type. Efficiency values of different boilers were based on Walker, Lv, and Masanet (2013) and Wouter and Van Wortswinkel (2010).
- The thermal efficiency of CHP units depends on their prime-mover type. The main prime-movers are listed in Section 4.2.2. When accounting for CHP end-use efficiency in process energy calculations, we consider only boiler/steam turbines and gas turbines (combined cycle and combustion turbines) as prime-mover types because they make up more than 95% of capacity in the United States (DOE 2017). The values of thermal efficiency for boiler/steam turbines are based on DOE (2016), and for gas turbines on DOE (2016). DOE maintains a list of CHP units in the United States that includes their location, NAICS, and prime-mover type (DOE 2020). This CHP database was used to determine the breakdown of prime-mover type by capacity in each county, and based on this breakdown, a weighted efficiency for CHP was calculated per county and used to determine process energy for heat demand associated with CHP.
- Direct-fired process heating has inherent heat losses that are due to energy in a flue gas stream and conduction, convection, and radiation losses in the heating chamber. The useful heat load for the unit process operation is roughly 50% of the thermal energy of the fuel (DOE 2008).

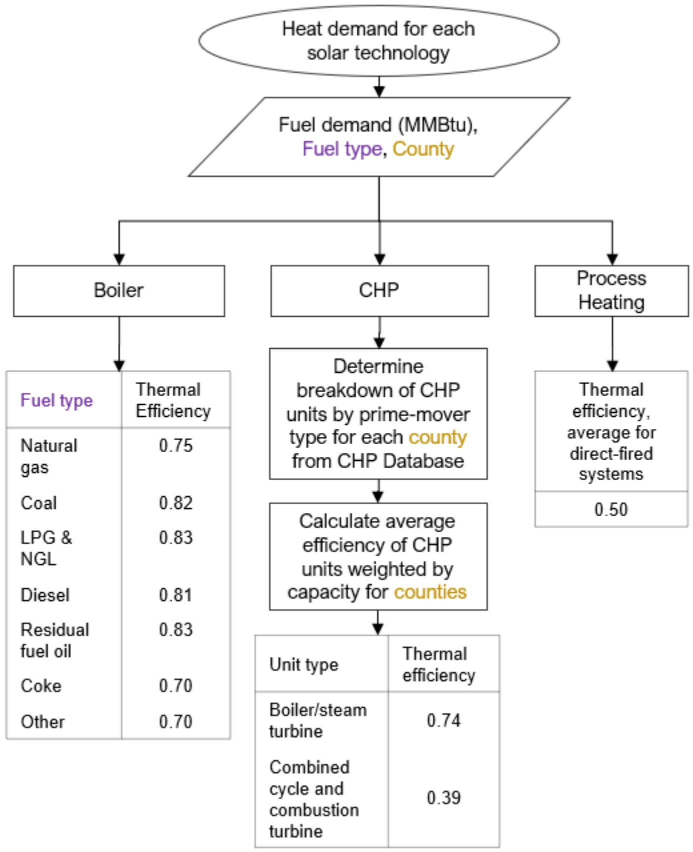


Figure C-2. Flowchart for determining efficiencies of IPH end uses

LPG = liquefied petroleum gas; NGL = natural gas liquids

The intermediate results of calculated process heat demand for each SIPH package, including calculations of efficiencies of end uses, is shown in figure C-3.

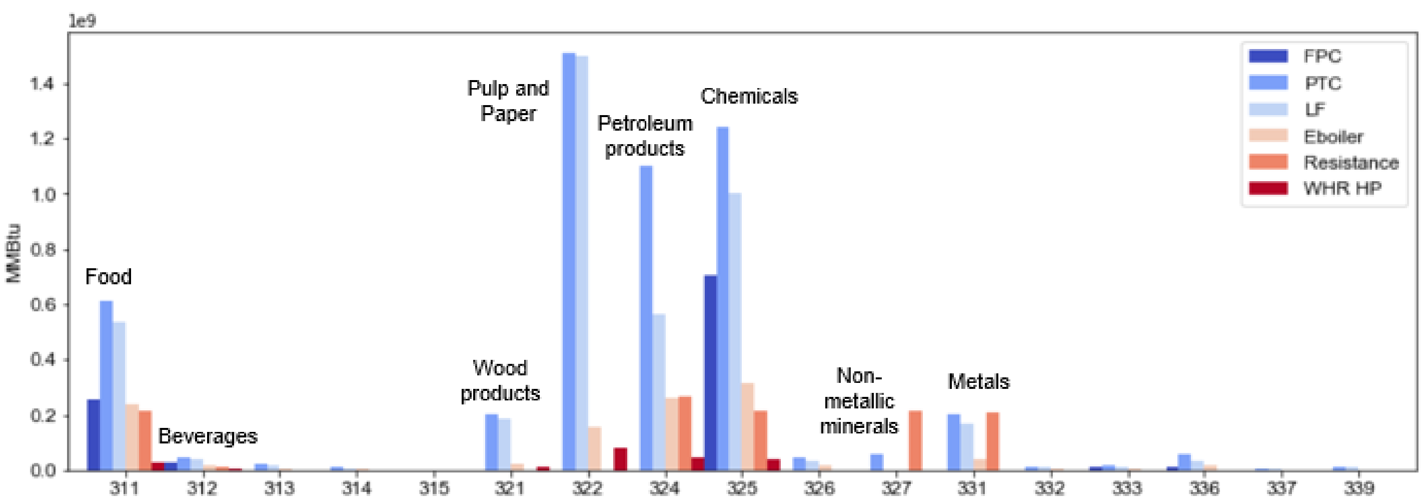
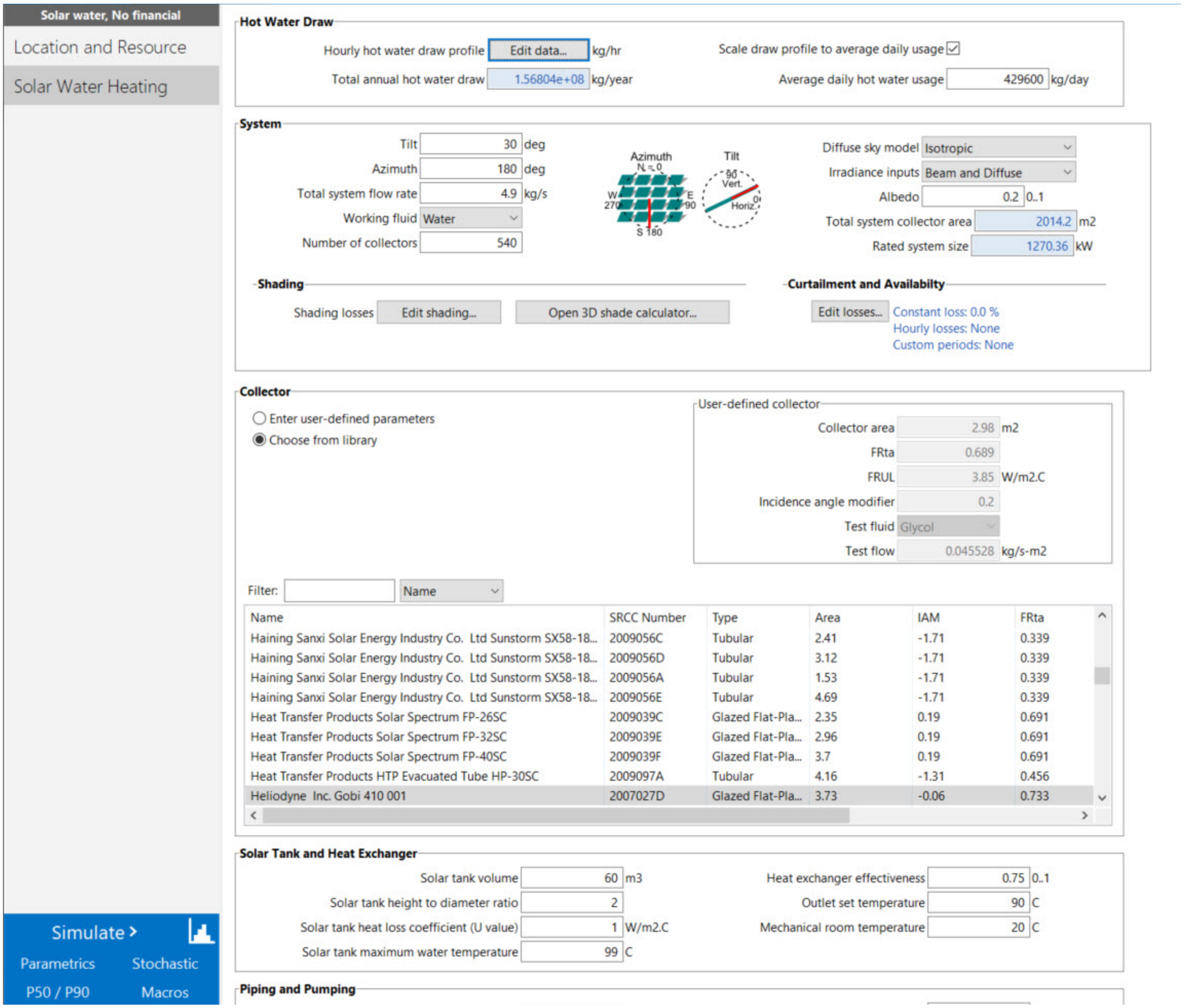


Figure C-3. Process heat demands for each solar technology package by industrial subsector

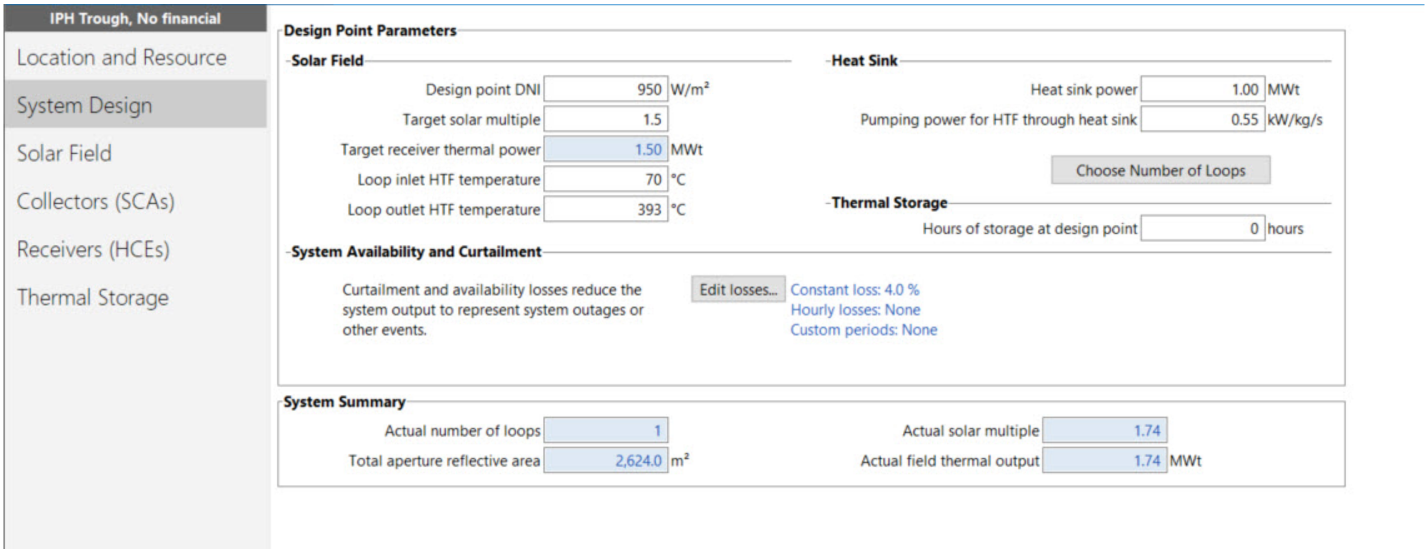
Appendix D. SAM parameters

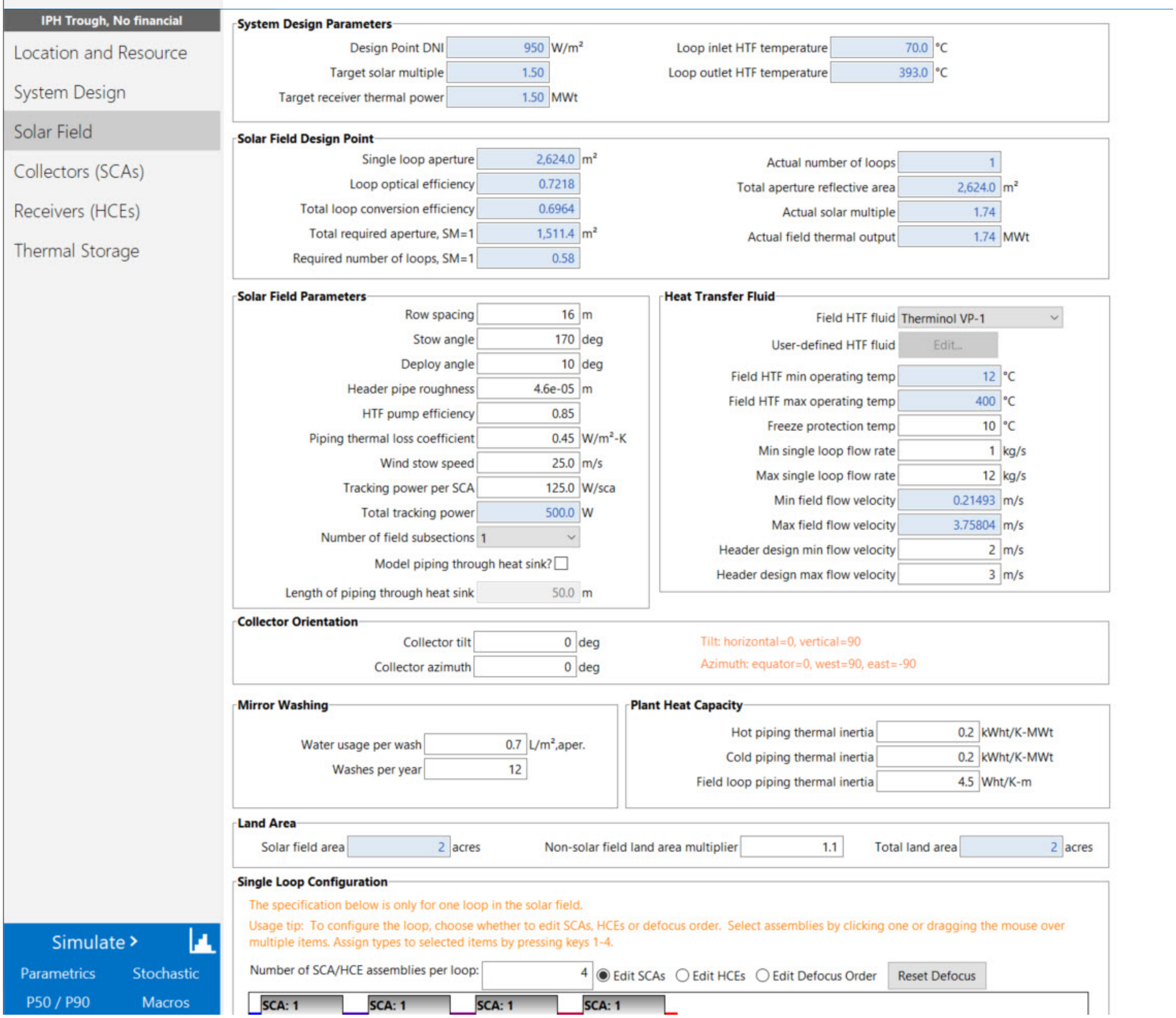
D.1 Direct Heat Technology Parameters

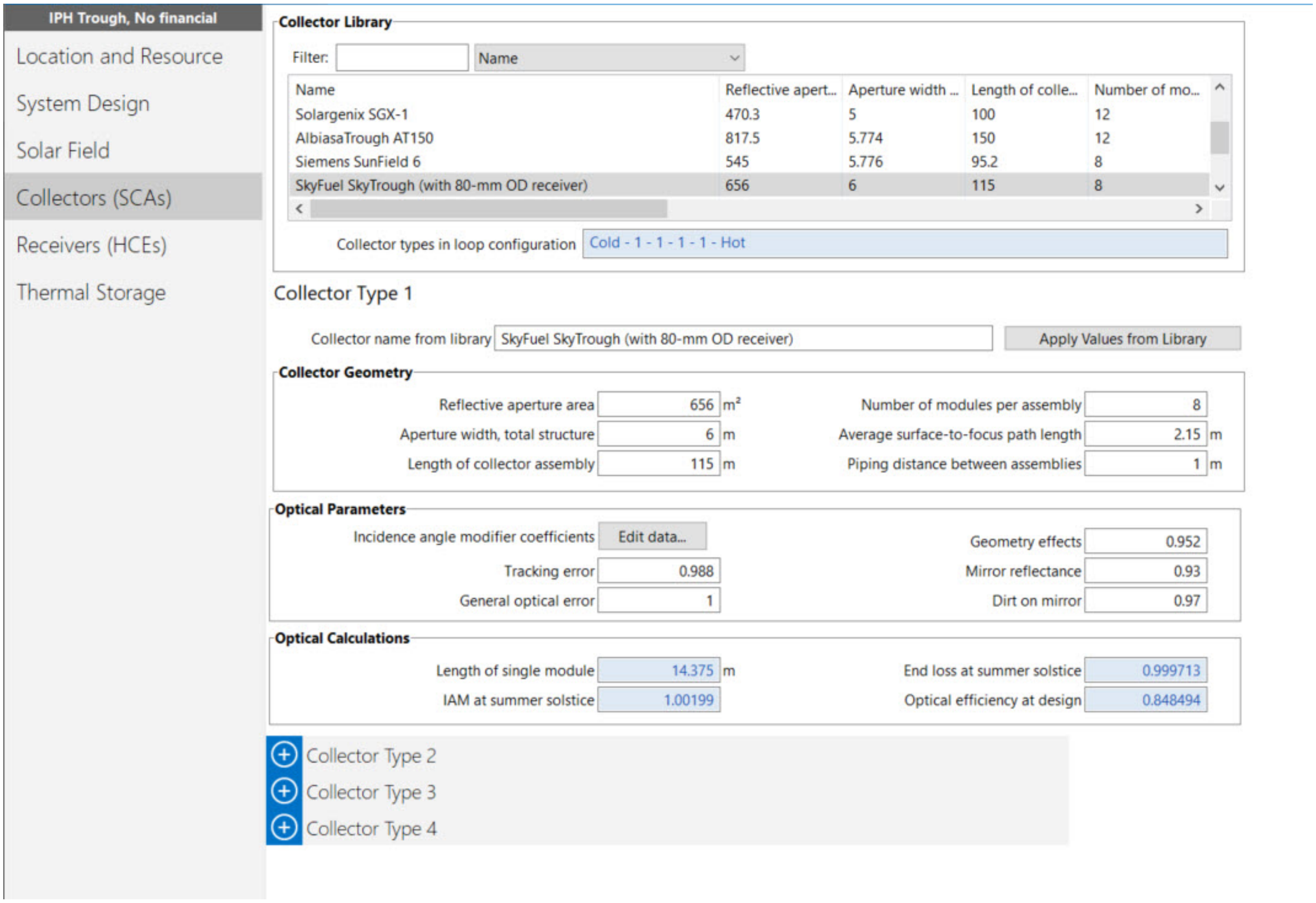
Flat Plate Collector



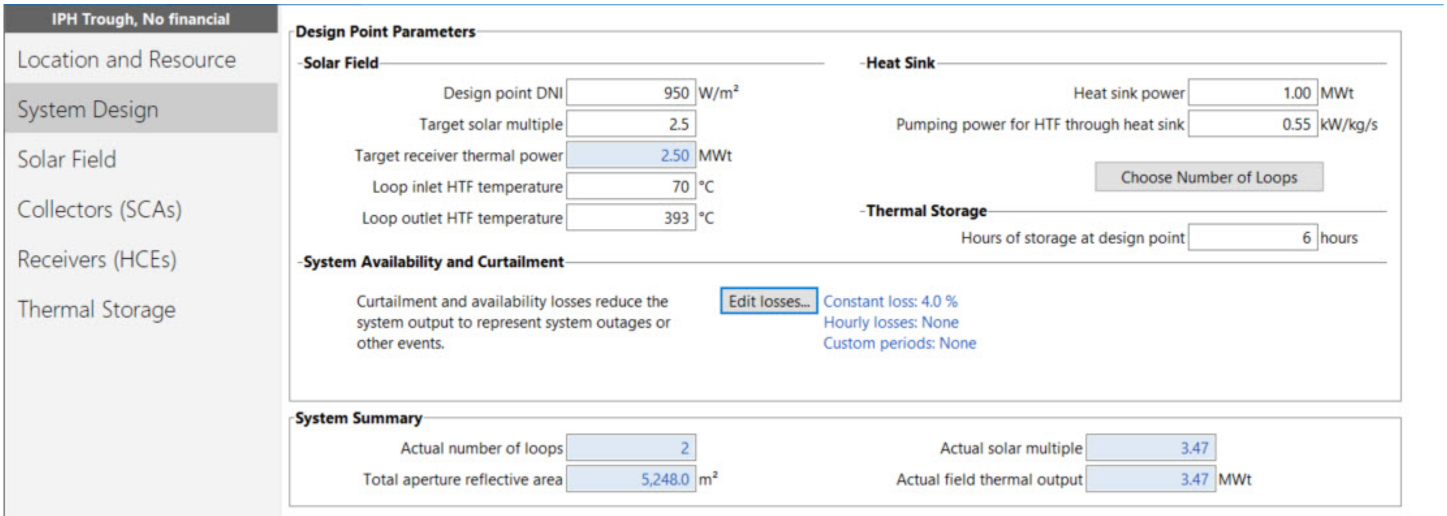
Parabolic Trough (without Storage)

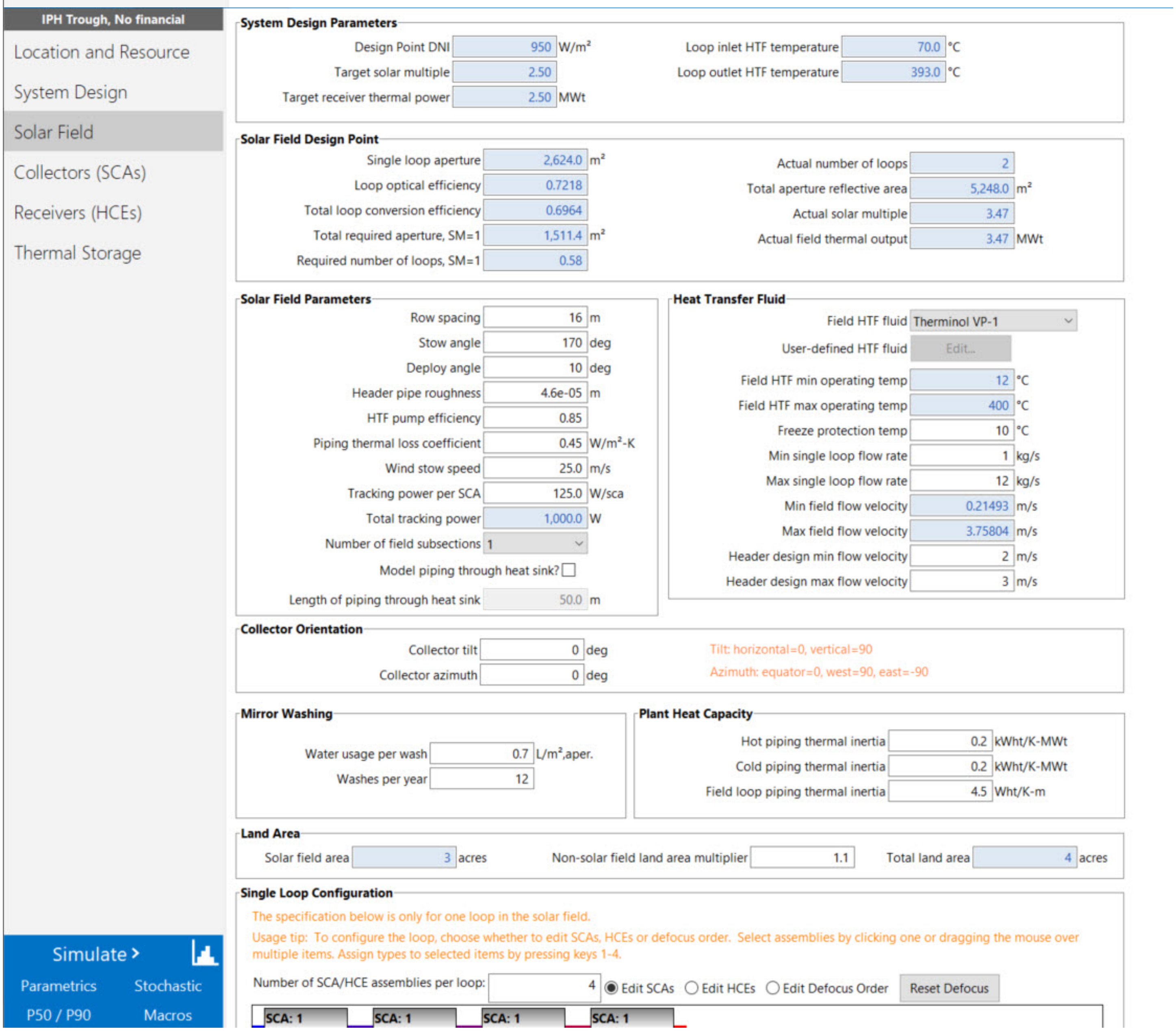




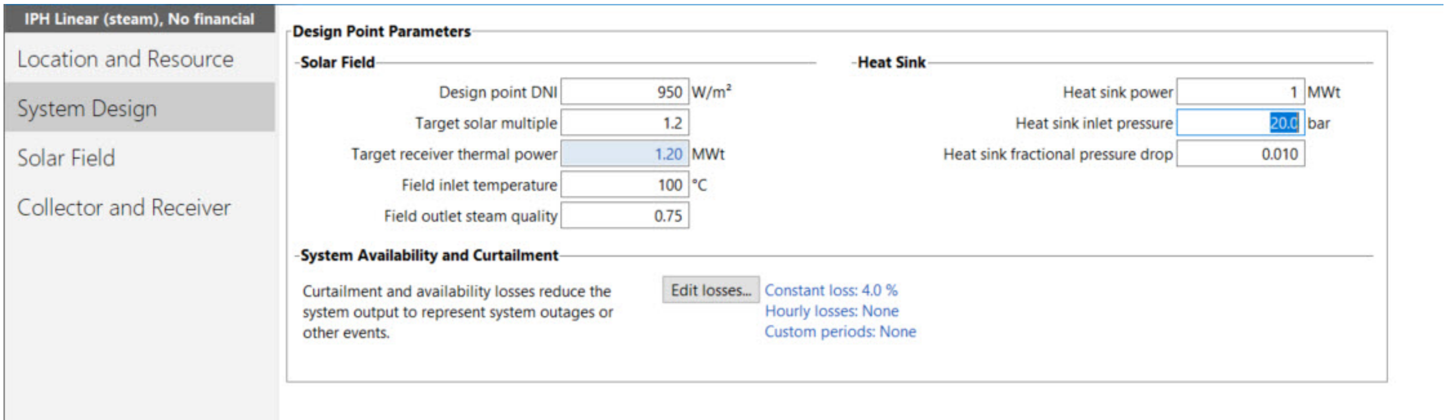

IPH Trough, No financial
Location and Resource
System Design
Solar Field
Collectors (SCAs)
Receivers (HCEs)
Thermal Storage
Collector Library
Filter:
Name
Name
Reflective apert...
Aperture width ...
Length of colle...
Number of mo...
Solargenix SGX-1
470.3
5
100
12
AlbiasaTrough AT150
817.5
5.774
150
12
Siemens SunField 6
545
5.776
95.2
8
SkyFuel SkyTrough (with 80-mm OD receiver)
656
6
115
8
Collector types in loop configuration
Cold - 1 - 1 - 1 - 1 - Hot
Collector Type 1
Collector name from library
SkyFuel SkyTrough (with 80-mm OD receiver)
Apply Values from Library
Collector Geometry
Reflective aperture area
656
m²
Aperture width, total structure
6
m
Length of collector assembly
115
m
Number of modules per assembly
8
Average surface-to-focus path length
2.15
m
Piping distance between assemblies
1
m
Optical Parameters
Incidence angle modifier coefficients
Edit data...
Tracking error
0.988
General optical error
1
Geometry effects
0.952
Mirror reflectance
0.93
Dirt on mirror
0.97
Optical Calculations
Length of single module
14.375
m
IAM at summer solstice
1.00199
End loss at summer solstice
0.999713
Optical efficiency at design
0.848494
Collector Type 2
Collector Type 3
Collector Type 4

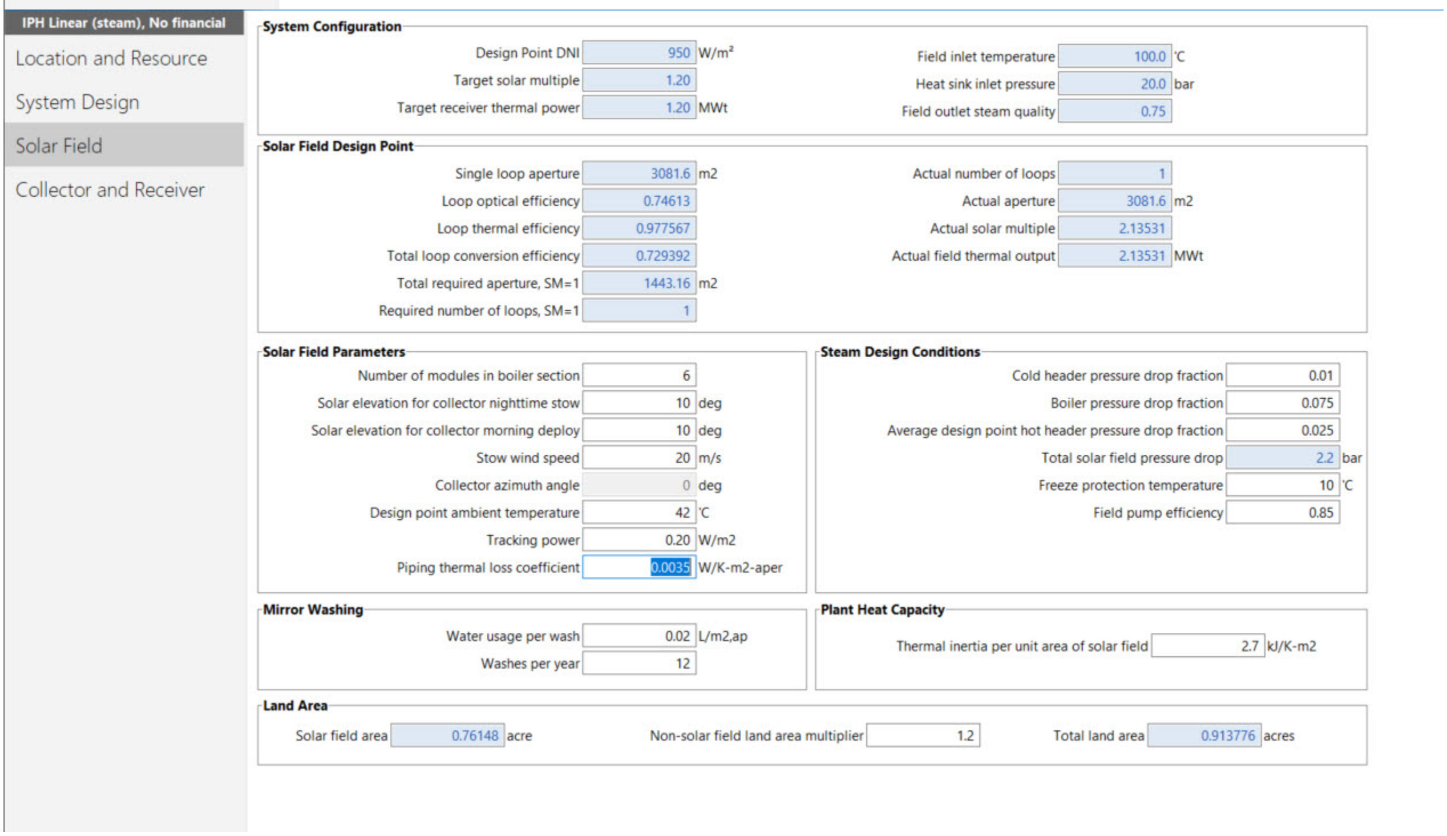
Parabolic Trough with 6 Hours of Storage



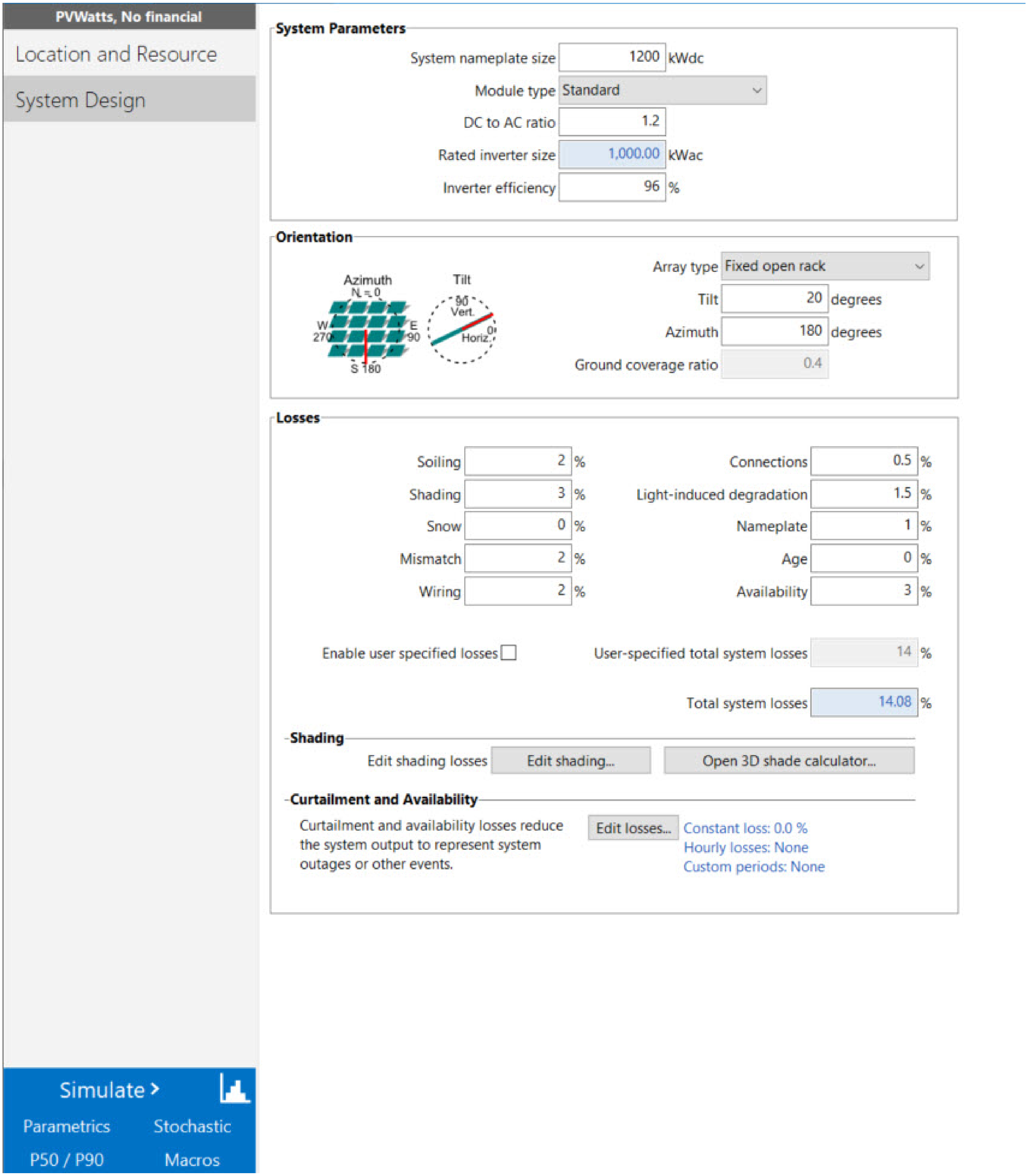


Direct Steam Generation Linear Fresnel Collectors





D.2 Indirect/PV Heating Technology



Appendix E. PV + Ambient Heat Pump Model: Process Heat Generation

The process heat generation potential on a per county basis (P_{PVi}) at hour i requires three major inputs: hourly solar irradiance, PV efficiency, and heat pump COP, summarized by the following equation:

$$P_{PV_i}\left(\frac{kW_{el}}{kW_{p,el}}\right) = G_{t_i} \cdot \eta_{PV}$$

The hourly solar irradiance on a tilted (at the county's centroid latitude) surface (G_t) and ambient temperature was provided by NREL's NSRDB[30] in W/m^2 and °C respectively. PV conversion efficiency (η_{PV}) from incident irradiance (G_t) to produce AC electrical power subsequently consumed the heat pump was assumed to be a modest 15%, a mix of both polycrystalline and monocrystalline silicon panels, which, on average, accounted for all system losses throughout the year based on our reV results.

The heat pump COP was modeled after a high-temperature heat pump from Viessmann (HT-Pro). A minimum COP was set to one (i.e., electrical resistance heating) and its maximum at six. The following formula and parameters (Table E-1) were used to estimate the COP, in kilowatt-thermal per kilowatt-electrical (kW_{th}/kW_{el}):

$$COP_i\left(\frac{kW_{th}}{kW_{el}}\right) = \theta_0 + \theta_1 \cdot T_{P_i}^2 + \theta_2 \cdot T_{P_i} \cdot T_{A_i} + \theta_3 \cdot T_{A_i}^2 + \theta_4 \cdot T_{P_i} + \theta_5 \cdot T_{A_i}$$

based on the hourly process heat (process, P) and air temperatures (ambient, A. The heat pump COP considered all electrical parasitic, inclusive of primary compressor, liquid pumps, and evaporator air fans. In addition, the heat pump was assumed to always generates heat at the process' demand temperature (i.e., no "preheating" was assumed).

Table E-1. Example parameters used to estimate COP

θ_0	θ_1	θ_2	θ_3	θ_4	θ_5
7.81	6.665e-4	-1.95e-3	6.35e-4	-0.127	-0.179

Figure E-1 shows the COP performance map for increasing ambient temperature (°C) and the process temperature needed to be met.

[30] "NSRDB: National Solar Radiation Database," NREL, https://nsrdb.nrel.gov/

COP	Ambient Temperature (°C)							
Process Temperature (°C)	0	5	10	15	20	25	30	35
40	3.8	4.3	4.9	5.5	6.0	6.0	6.0	6.0
45	3.4	3.9	4.4	5.0	5.5	6.0	6.0	6.0
50	3.1	3.5	4.0	4.5	5.0	5.6	6.0	6.0
55	2.8	3.2	3.6	4.1	4.5	5.0	5.6	6.0
60	2.6	2.9	3.3	3.7	4.1	4.5	5.0	5.5
65	2.4	2.6	3.0	3.3	3.7	4.1	4.5	5.0
70	2.2	2.4	2.7	3.0	3.3	3.6	4.0	4.5
75	2.0	2.2	2.4	2.7	2.9	3.2	3.6	4.0
80	1.9	2.0	2.2	2.4	2.6	2.9	3.2	3.5
85	1.8	1.9	2.0	2.2	2.3	2.6	2.8	3.1
90	1.8	1.8	1.9	2.0	2.1	2.3	2.5	2.7

Figure E-1. Ambient temperature and process temperature COP

Multiplying the two prior equations together results in the specific thermal energy generation per kilowatt of installed PV installed using a heat pump, as follows:

$$E_{PV+HP_i}\left(\frac{kW_{th}}{kW_{PV,el}}\right) = P_{PV_i} \cdot COP_i$$

Two different process heat temperatures were used for each county (50°C and 90 °C) and its respective meteorological conditions (G_t, T_A) to determine the specific thermal energy generation potential.

A few major assumptions were made to both allow for a comprehensive analysis and to maintain a high degree of accuracy. First, it was assumed that the heat pump can generate thermal energy at any PV electrical input, meaning it can operate at very low capacity factors. At most industrial facilities, because of their requirements for redundancy and control, any heat pump station would have multiple compressors and refrigerant loops with variable speed drives, allowing this assumption to be reasonable. The second assumption was that the PVHP thermal energy generation is independent of process load. To account for the temporal mismatch between energy demand and generation, a water storage tank was used. For the sake of modeling simplicity, an "ideal" tank was used, with perfect stratification and no thermal losses.

Example of the daily and monthly average results are shown for Philadelphia County, Pennsylvania (Federal Information Processing Standard [FIPS] 42121), in Figure E-2 and Figure E-3, respectively.

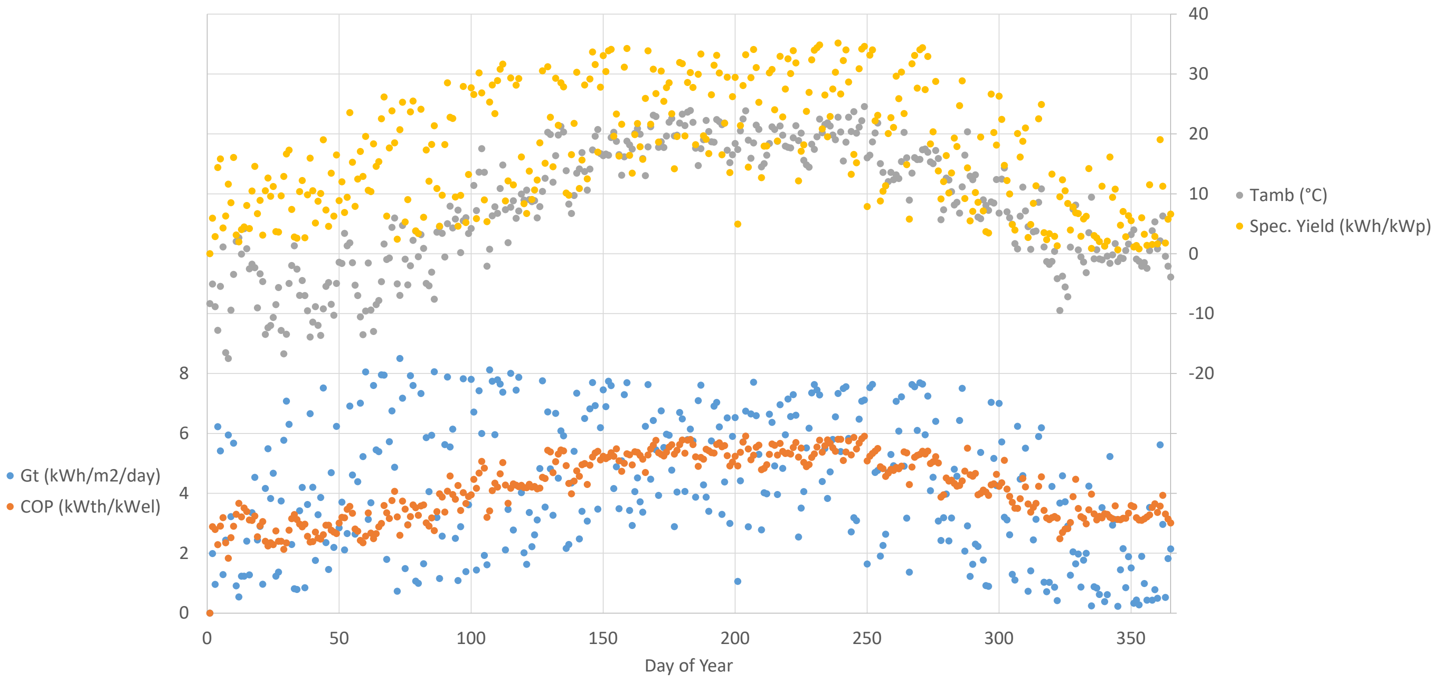


Figure E-2. Daily results for Philadelphia County, Pennsylvania, for one year

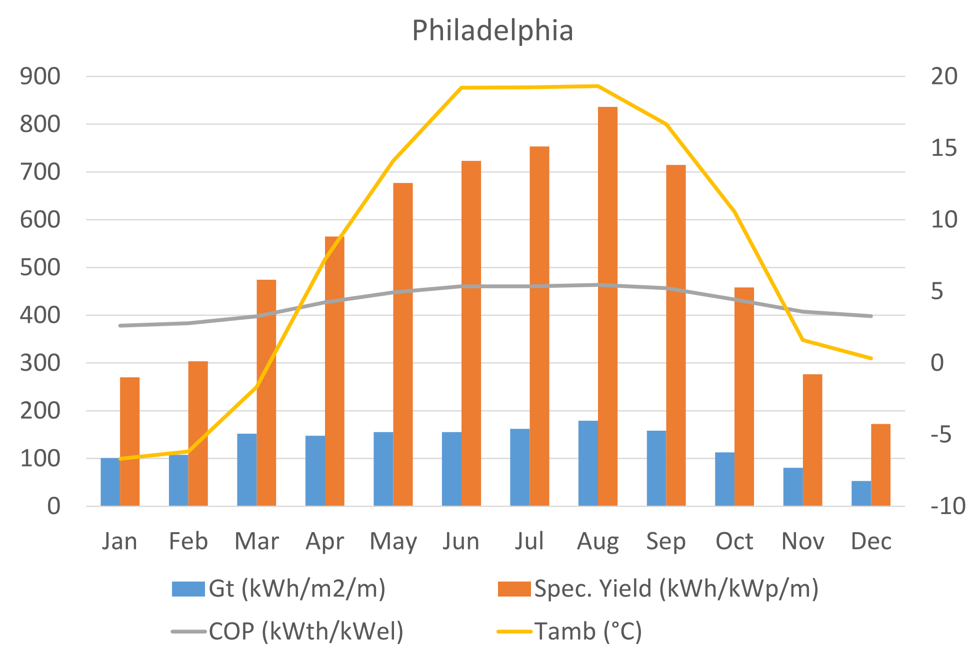


Figure E-3. Monthly thermal yield from the PV Heat Pump for Philadelphia County, Pennsylvania

The monthly industrial thermal energy demand ($D^{Jan,Jul}$ in MWh_{th}/month) are the same IPH demands identified for FPC technology. The demand for two the key months, December and June, are used for analysis to represent the range of technical potential. The monthly specific PVHP yields ($E_{PV+HP}^{Dec,Jun}$ in kWh_{th}/kW_p/month) per county were determined from the analysis in the prior section by summing the hourly values per month. To determine the required

PV technical potential capacity ($TP_{PV,kWp}^{Jan/Jul}$ in kWp) to meet the demand in that specific month or season, simply multiple the monthly demand by the monthly specific PVHP yield as follows:

$$TP_{PV,kWp}^{Dec/Jun} = D^{Dec,Jun} \cdot E_{PV+HP}^{Dec,Jun}$$

Once the required PV capacity per county and per season was determined, the required land use ($TP_{Land}^{Jan/Jul}$) was calculated by first determining the ground coverage factor that spaces the panels to avoid shading throughout the year (Meyers 2018). The ground coverage factor and the PV layout are shown in Figure E-4.

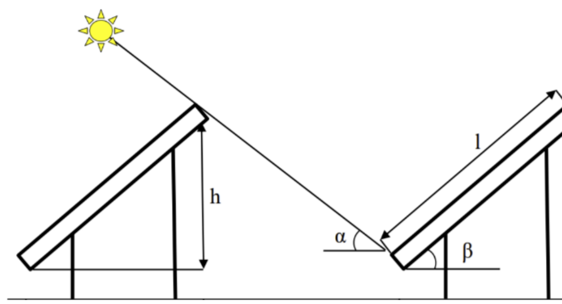


Figure E-4. Ground coverage factor (GCF) and the PV panels relative to the sun

The ground coverage factor (*GCF*) was estimated as:

$$GCF = \cos\beta + \frac{\sin\beta}{\tan\alpha}$$

with α representing the minimum solar angle (90-β-23.5) and β representing the PV inclination (also county latitude), in degrees. The fraction of technical potential land use relative to the available land on a per county basis ($TP_{Land}^{Jan/Jul}$) is calculated by dividing $TP_{PV,kWp}^{Jan/Jul}$ by the area of available land (η_{PV}), represented as the following:

$$TP_{Land}^{Jan/Jul} = \frac{TP_{PV,kWp}^{Jan/Jul}}{\eta_{PV}} \cdot GCF$$

Appendix F. Detailed Technical Opportunity Results

F.1 Additional Electricity Calculations

As mentioned in Section 4.2.2, certain electrotechnologies (resistance heating and WHRHPs) would require additional grid electricity, when solar is unavailable, as the integration of an electric heating system would fully replace combustion-based equipment. The additional electricity and the resulting fuel burdens were calculated.

First, additional electricity was determined based on the hours of the year when solar PV was not fully meeting process heat demand, from the hourly solar fraction and hourly load in each county. The electricity requirement was summed for each county and compared to grid electricity data. The EPA eGRID database contains the electric grid makeup by fuel for each county, as well as plant-level heat rate data, which gives the rate of fuel per electricity. Based on the fractions of fossil fuels contributing to each county's grid electricity and the corresponding fuel rate, the amount of fuel needed for the electricity requirement was calculated. The totals for each electrotechnology case are shown in Table F-1.

Table F-1. Additional Fuel Requirement (TBtu) from Grid Electricity During Non-PV hours, including (low, high) Operating Hour Results

	Resistance	WHRHP
Summer sizing	965	225
	(944, 975)	(221, 228)
Winter sizing	642	218
	(613, 659)	(215, 220)

Based on the make-up of current electric grids, the fuel burdens shown in Table F-1 surpass the annual fuel savings from resistance heating and WHRHP, 360 TBtu and 78 TBtu, respectively, for summer-sized systems (Table F-3). However, as electric grids adopt more renewable electricity in the future, the fuel burdens would be significantly reduced.

F.2 Solar Heat Potential by Technology Package as Fraction of Heat Demand

Figure F-1 shows the total solar heat potential (in TBtu), summed for all industrial subsectors, of each SIPH technology. The second y-axis relates the solar heat potential to the calculated portion of fuel demand each technology could replace and shows this as a fraction of heat demand for each technology.

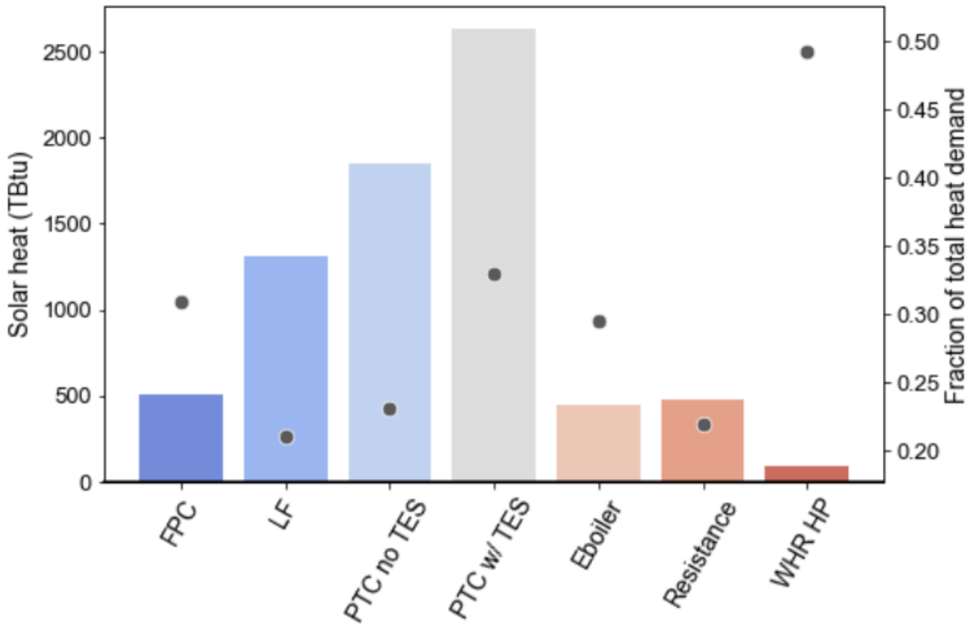


Figure F-1. Total annual solar heat potential (TBtu)

Table F-2 shows the solar heat potential of each SIPH technology by industrial subsector.

Table F-2. Solar Heat Potential (TBtu) by Industrial Subsector

NAICS Subsector	FPC	LF DSG	PTC no TES	PTC w/ TES	E-boiler	Resistance	WHRHP
311	132.8	190.9	241.3	344.2	103.9	93.3	13.8
312	15.3	14.9	17.6	24.9	8.5	4.4	1.6
313	0.1	7.0	10.1	14.3	2.5	0.0	0.3
314	0.0	2.0	3.7	4.6	1.8	0.0	0.0
315	0.0	0.5	0.5	0.7	0.2	0.0	0.0
321	0.0	68.8	81.4	108.5	11.2	0.0	5.1
322	0.0	430.7	487.0	699.6	57.7	0.0	32.8
324	0.0	178.4	386.8	564.6	97.2	103.6	18.2
325	346.8	326.7	462.2	658.7	125.2	82.7	15.8
326	0.0	13.1	18.4	25.6	8.5	0.0	0.0
327	0.0	0.6	25.3	34.7	0.2	102.4	0.7
331	0.0	58.0	78.5	108.5	18.6	94.3	0.0
332	0.0	3.7	4.1	5.6	1.2	0.0	0.3
333	5.2	4.2	5.8	7.8	1.8	0.0	0.0
336	5.7	11.3	22.6	31.3	7.6	0.0	0.0
337	0.0	1.5	3.0	3.7	0.2	0.0	0.0
339	0.0	3.9	0.0	0.0	0.3	0.0	0.0

F.3 Fuel Savings

Table F-3 shows the fuel savings calculated for each SIPH technology by fuel type, with summer sizing. Table F-4 shows total fuel savings, comparing summer and winter sizing, as well as different operating hours scenarios.

Table F-3. Fuel Savings (TBtu) Annual Totals by Fuel Type: Summer Sizing

Fuel type	FPC	LF DSG	PTC no TES	PTC w/ TES	E-boiler	Resistance	WHRHP
Biomass	19.0	139.1	155.7	218.1	14.2	16.4	9.6
Coal	58.4	118.4	142.2	203.0	27.9	40.1	7.1
Coke and breeze	0.4	0.5	3.3	4.5	0.0	3.9	0.1
Diesel	21.3	91.5	142.6	206.4	29.6	10.7	7.3
LPG & NGL	3.8	22.1	31.8	45.1	5.7	13.5	2.3
Natural gas	309.0	595.9	867.2	1234.0	195.5	238.7	36.8
Petroleum coke	0.1	7.8	12.8	18.1	1.1	3.2	0.4
Residual fuel oil	2.5	44.5	51.5	73.4	8.8	2.1	4.5
Purchased steam	30.8	52.8	63.8	89.9	1.0	7.7	1.8
Waste gas	40.2	119.4	235.9	345.1	30.2	22.7	8.0
Waste oils, tars, waste materials	5.0	8.9	11.5	15.9	3.0	1.2	0.3
	490.5	1201.0	1718.3	2453.5	317.1	360.3	78.2

Table F-4. Fuel Savings (TBtu) Annual Totals by Sizing Month, including (low, high) Operating Hour Results

	FPC	LF DSG	PTC no TES	PTC w/ TES	E-boiler	Resistance	WHRHP
Summer sizing	490.5 (495.2, 490.9)	1201.0 (1229.2, 1190.5)	1718.3 (1748.3, 1706.2)	2453.5 (2448.0, 2446.4)	317.1 (318.6, 322.8)	360.3 (369.8, 357.5)	78.2 (78.7, 78.6)
Winter sizing	589.6 (598.8, 584.3)	1287.2 (1319.6, 1272.4)	1902.5 (1942.9, 1878.5)	2469.4 (2465.9, 2461.5)	309.2 (308.8, 317.6)	319.2 (330.7, 314.1)	87.8 (89.1, 87.7)

F.4 Land Use

Table F-5 shows the total land use requirements for each SIPH technology with results of low and high operating hours scenarios.

Table F-5. Land Use (km^2) Totals, with (Low, High) Operating Hours Results

	FPC	LF DSG	PTC no TES	PTC w/ TES	E-boiler	Resistance	WHRHP	Ambient HPs no TES	Ambient HPs w/ TES
Summer sizing	221 (221, 222)	2711 (2709, 2726)	4515 (4511, 4537)	5463 (5459, 5491)	3875 (3789, 3990)	4958 (4937, 5031)	1130 (1126, 1140)	1757	1684 (1682,1672)
Winter sizing	521 (522, 517)	7385 (7390, 7351)	14620 (14629, 14553)	18960 (18972, 18869)	6533 (6299, 6765)	8127 (8117, 8067)	1911 (1910, 1910)	3959	3016 (3021,3029)