Renewable Thermal Energy Systems: Characterization of the Most Important Thermal Energy Applications in Buildings and Industry (Report 1)

Parthiv Kurup, Colin McMillan, and Sertaç Akar

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
NREL/TP-7A40-83019
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Errata

This report, originally published in February 2023, has been revised in March 2023. The changes are described here:

- Text changed from "The relatively small energy demand between 200°C and 400°C revealed in Figure 9 is even more pronounced for process heating. Nearly 80% of process heating energy demands are above 400°C." to "The relatively small energy demand between 200°C and 400°C revealed in Figure 9 is even more pronounced for demands met by ovens, kilns, and other related technologies (shown in Figure 10 as process heating). Nearly 80% of these non-boiler and non-CHP process heating energy demands are above 400°C. Figure 9 shows that a significant portion, nearly two-thirds of the industrial thermal demand in 2014 in the United States, was less than or equal to 300°C."
    - An external contact and developer in concentrating solar thermal (CST), found the language associated with the "Nearly 80% of process heating energy demands are above 400°C" in the original text confusing, as Figure 9 highlights that the cumulative energy demand to 400°C was approximately 80%
    - This new text allows clarity of the language associated with Figure 9, and connects to specific language used in Report 3 of the report series (i.e., the "nearly two-thirds of the industrial thermal demand in 2014 in the United States, was less than or equal to 300°C."
- For Figure 4, whilst we received approval and authorization from KTH Sweden to use the image, after release of the report it was found that the credit and the hyperlink reference for the image needed to be changed:
    - A new reference (Sommerfeldt and Madani 2019) was added instead of (KTH Sweden 2018). The article is the main publication output from the project from Nelson Sommerfeldt, as such the link to a publication in the reference will remain constant compared to a university webpage where the link can be frequently changed
    - In Sweden researchers own all of the IP they generate, so there is no formal release from the university needed, and as such the credit for the image is Nelson Sommerfeldt not KTH Sweden.

Preface

This report is the first in a three-report series that evaluates the provision of renewable heat for industry and buildings via current and prospective renewable thermal energy system (RTES) technologies. The RTES project has undertaken initial research focused on technologies that could be suited for industrial process heat applications at different temperature levels, and, where possible, gathered performance and cost data for these technologies. This project does not directly evaluate RTES for distributed residential or commercial applications, nor does it yet include documented cases or modeling of RTES using geothermal, biomass, waste heat, renewable fuels like renewable natural gas, or hydrogen production.

The three technical reports are summarized as follows:

- ***Renewable Thermal Energy Systems: Characterization of the Most Important Thermal Energy Applications in Buildings and Industry (Report 1)*, this report: summary of thermal demands of U.S. industry and buildings, and relevant hybrid RTES configurations.**
- *Renewable Thermal Energy Systems: Systemic Challenges and Transformational Policies (Report 2)*: discussion of socio-technical characteristics of RTES, innovation challenges, and supporting policies. Available at: https://www.nrel.gov/docs/fy23osti/83020.pdf.
- *Renewable Thermal Energy Systems: Modeling Developments and Future Directions (Report 3)*: Energy yield and performance modeling of RTES, techno-economic analysis via case studies, and proposed development of a user decision support tool. Available at: https://www.nrel.gov/docs/fy23osti/83021.pdf.

Acknowledgments

The authors would like to thank Aalborg CSP, Institut de Recherche en Energie Solaire et Energies Nouvelles, IRESEN, and Rackam for sharing data, and Jordan Cox, Mark Ruth, and Amy Allen from NREL and Samuel Baldwin from DOE for their technical review for this report.

List of Acronyms

CBECS	Commercial Buildings Energy Consumption Survey
CBM	Commercial Buildings Module
CSP	concentrating solar power
DKK	Danish Kroner
EIA	U.S. Energy Information Administration
EPCM	encapsulated phase change material
ft^2	square feet
FPC	flat plate collector
GJ	gigajoule
GSHP	ground-source heat pump
IPH	Industrial Process Heat
IRESEN	Moroccan Solar Research Institute
LCOH	levelized cost of heat
MMBtu	million British thermal units
NAICS	North American Industrial Classification System
nd	not disclosed
NREL	National Renewable Energy Laboratory
MECS	Manufacturing Energy Consumption Survey
PTC	parabolic trough collectors
PV	photovoltaics
PVT	photovoltaic thermal
RTES	renewable thermal energy systems
TES	thermal energy storage
TBtu	trillion British thermal units
sLCOH	system levelized cost of heat

Executive Summary

This study highlights heat demands in commercial buildings and industrial processes for the application of both stand-alone and hybrid configurations of renewable thermal energy systems (RTES). Based on the U.S. Energy Information Administration (EIA) Commercial Buildings Energy Consumption Survey (CBECS) data (EIA 2018b), there are 10 significant end uses for the energy consumed within the commercial building sector. Space heating constitutes 25% of the total energy consumption, whereas cooling is approximately 9%, water heating is 7% and cooking is 7% for commercial buildings. The significance of commercial heating loads also varies by building type and by geographic location. On a geographic basis, the largest space heating demands occur in the East North Central census division. Space heating comprises 38% of total energy use in the East North Central region compared to 15% in the South Atlantic division (EIA 2016b). The Commercial Buildings Module of the National Energy Modeling System provides more disaggregated descriptions of space heating and water heating technologies than CBECS, including technologies such as solar water heating in the Commercial Buildings Module.

The use of hybrid RTES for heat provision to buildings and district heating can be considered a developing field. Adoption of heating technologies such as heat pumps and passive thermal energy storage, photovoltaic thermal collectors coupled with ground-source heat pumps, and flat plate collectors coupled with parabolic trough collectors and thermal energy storage could have potential economic benefits. Hybrid RTES solutions can be both economically and energetically viable. Examples of economically feasible systems have already been established in Denmark and Sweden. It is worth noting that in Denmark there are financial incentives from the Danish government that help to incentivize the use of hybrid RTES solutions to reduce natural gas consumption.

Another important application of hybrid RTES is industrial processes to produce raw materials and manufacture finished products. Thermal energy demands in industrial processes are larger than the space and water heating demands of industrial buildings and the heat loads of commercial buildings combined. The heat loads of industrial processes are highly application-dependent. The Industrial Process Heat Database[1] developed by the National Renewable Energy Laboratory helps to characterize energy use, temperature, heat rate, the nature of the process as batch or continuous, continuous, or seasonal operation, and heat transfer media for industrial processes. Few realized examples of hybrid RTES solutions for industrial process heat applications exist today, and therefore future R&D is warranted to make potential solutions possible. These example studies from Australia, Morocco, and the United States will be explained in the report. Research activities across the world are looking at various temperature levels to provide renewable heat for industrial process heat through hybrid RTES possibilities.

[1] Industrial Process Heat database can be accessed from https://data.nrel.gov/submissions/118.

Table of Contents

List of Figures

List of Tables

1 Introduction

This report characterizes the most important buildings (e.g., by type), heat uses for buildings, and temperature demands for industries and industrial processes. This type of characterization is likely to be important when considering how renewable thermal energy systems (RTES), in both stand-alone and hybrid configurations, could interact with buildings or district heating systems. Stand-alone refers to a single renewable thermal source such as geothermal, flat plate collectors (FPCs) or parabolic trough collectors (PTCs). To note: geothermal, waste heat, biomass, renewable fuels, and hydrogen production, while suited as RTES technologies, are currently outside the scope of this work.

A key hypothesis of the project is that coupling RTES solutions (i.e., into hybrid RTES solutions) can be both economically and energetically viable. This task has also addressed the challenge that few hybrid RTESs are in operation; because of this, examples or modeling efforts of hybrid RTESs are provided where possible.

The examples highlighted are either modeled or specific operating systems. The cases and representative examples have been chosen to highlight a variety of geographies, solar and resource availability, delivery or application temperature for the process, and integration into existing sites. They should be considered as informational and as a start for further investigation. For industrial process heat (IPH), the heterogeneity and complexity of industrial processes that need heat makes detailed characterizations of IPH difficult. Each industry would need to be characterized by the varying loads (e.g., batch or continuous), temperature level, and daily heat load profile. As such, the specific example of a brewery is provided, because this is a known and understood use case of RTES (Lauterbach et al. 2009; 2012) and because of the data availability and modeling for a potential brewery site in the United States. Further modeled examples are provided to assist the reader in understanding representative sizes for RTES used for IPH applications in decreasing natural gas consumption (Jacob et al. 2019).

The remaining sections of the report are Heat Use in Commercial and Industrial Buildings (Section 2), Industrial Heat Use (Section 3), and Initial Data Gaps that need further consideration (Section 4).

2 Heat Use in Commercial and Industrial Buildings

The last complete U.S. Energy Information Administration (EIA) Commercial Buildings Energy Consumption Survey (CBECS) was undertaken in 2012, and the data were made available in 2016 (EIA 2018b). There are 10 significant end uses for the energy consumed within the commercial building sector, and the percentage contribution of each has been reproduced from the CBECS 2012 data (EIA 2016a), as shown in Figure 1.

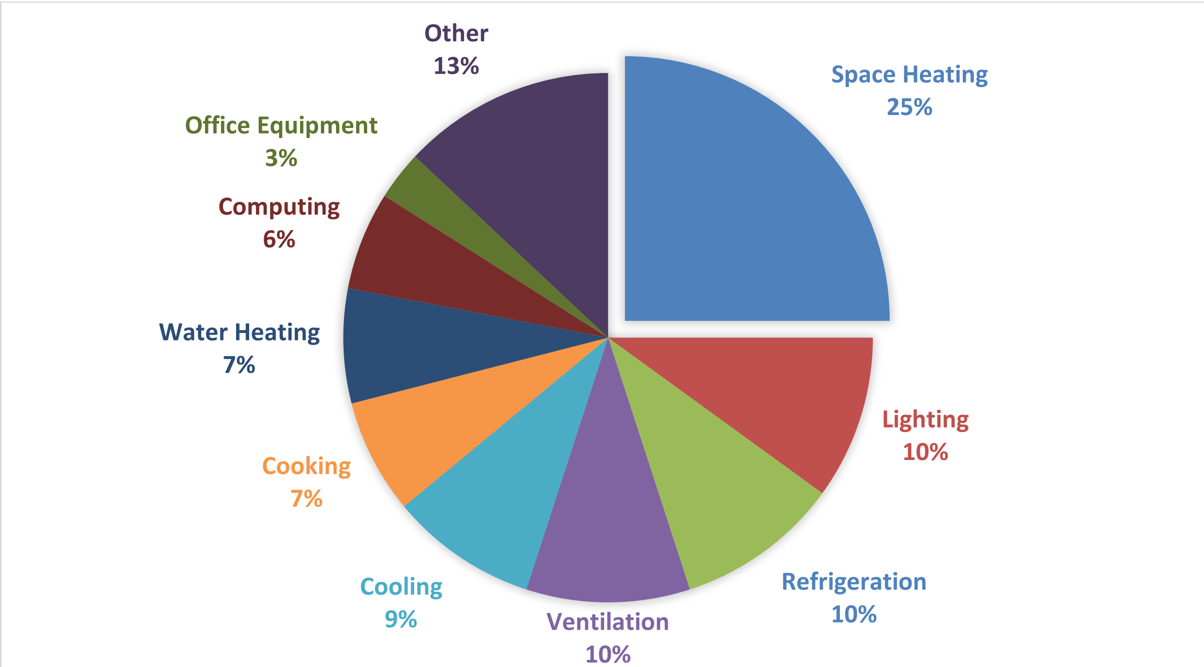

Figure 1. Energy end use by percentage for the commercial building sector in the United States for 2012 (data from EIA 2016a)

As shown in Figure 1, in the United States the three most significant heat-related commercial building end uses are space heating (25%), water heating (7%), and cooking (7%). Together, these end uses were responsible in 2012 for 39% of commercial building site energy use, whereas energy used for cooling was approximately 9% (EIA 2016a). Significant portion of space heating and water heating, which currently use fossil fuels could be offset by RTES. Cooking, however, is not likely to have an RTES solution and can readily be electrified using an induction stove/oven. There are also trade-offs between electrified heating for commercial buildings, including ground-source heat pumps (GSHPs), versus RTES.

The significance of commercial heating loads varies by building type and by geographic location. As shown in Table 1, the largest commercial building type in terms of total energy use, office buildings, is nearly an order of magnitude greater than the smallest type, public order and safety (EIA 2016b). As highlighted in Table 1, the largest space heating demand in absolute terms occurs in office buildings, whereas the largest demand relative to total energy occurs in service and religious worship buildings. Unlike space heating, building types with the largest absolute energy uses for water heating and cooking are also the largest users relative to total energy. Water heating in buildings for lodging accounts for 24% of the total energy use, and cooking in food service buildings accounts for nearly 40% of total energy use (EIA 2016b).

District heating, while not directly part of commercial building heating use, amounts to 341 trillion British thermal units (TBtu) and is used in roughly 7% of commercial building floorspace (i.e., 5,964 million square feet [ft^2]) (EIA 2016b).

Table 1. Summary of Commercial Building Heat Use, in Absolute Energy Use and Relative to Total Site Energy Use by Building Type (data from EIA 2016b)

Building Type	Floorspace (million ft^2)	Total Site Energy (TBtu)	Energy Intensity ($kBtu/ft^2$)	Space Heating (TBtu (%))	Water Heating (TBtu (%))	Cooking (TBtu (%))
Office	15,952	1,241	78	305 (25%)	35 (3%)	nd
Education	12,239	842	69	299 (36%)	68 (8%)	15 (2%)
Mercantile: enclosed and strip malls	5,890	644	109	106 (16%)	61 (9%)	64 (10%)
Lodging	5,826	564	97	67 (12%)	136 (24%)	69 (12%)
Health care: inpatient	2,374	549	231	164 (30%)	78 (14%)	47 (9%)
Food service	1,819	514	283	46 (9%)	43 (8%)	199 (39%)
Public assembly	5,559	480	86	189 (39%)	7 (1%)	14 (3%)
Warehouse and storage	13,077	429	33	116 (27%)	11 (3%)	nd
Mercantile: retail (other than mall)	5,439	364	67	76 (21%)	5 (1%)	8 (2%)
Other	2,002	286	143	69 (24%)	2 (0.7%)	1 (0.3%)
Service	4,630	272	59	118 (43%)	22 (8%)	1 (0.4%)
Food sales	1,252	262	209	31 (12%)	3 (1%)	29 (11%)
Religious worship	4,557	173	38	75 (43%)	nd	11 (6%)
Health care: outpatient	1,781	169	95	46 (27%)	4 (2%)	4 (2%)
Public order and safety	1,440	133	92	36 (27%)	21 (16%)	4 (3%)
Vacant	3,256	41	13	13 (32%)	nd	nd
Total	87,093	6,963	1,701	1,756	496	466

(nd: not disclosed)

The EIA defines nine census regions and divisions for the CBECS (EIA 2016c), as shown in Figure 2. On a geographic basis, the largest space heating demands occur in the East North Central census division. As shown in Table 2, the geographic variation in space heating demands is larger than water heating and cooking, which is expected based on the variation in climate compared to other parts of the United States. Space heating comprises 38% of total energy use in the East North Central division compared to 15% in the South Atlantic division (EIA 2016b). The relative contributions of water heating and cooking are more evenly distributed by division across the regions.

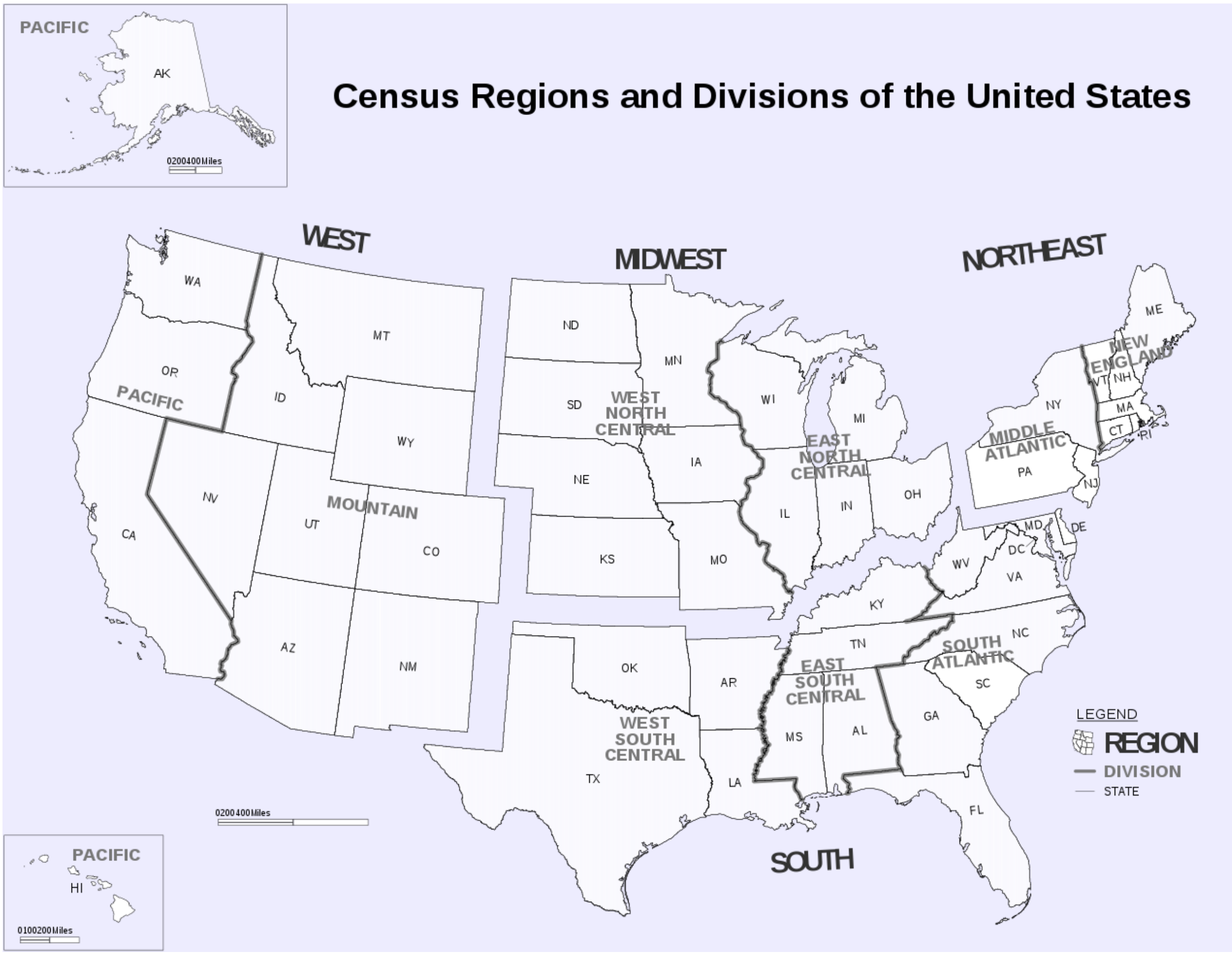

Figure 2. Census regions and divisions of the United States

(https://www2.census.gov/geo/pdfs/maps-data/maps/reference/us_regdiv.pdf)

Table 2. Summary of Commercial Building Heat Use, in Absolute Energy Use and Relative to Total Site Energy Use by Census Division

Census Division	Floorspace (ft^2)	Total Site Energy (TBtu)	Energy Intensity ($kBtu/ft^2$)	Space Heating (TBtu (%))	Water Heating (TBtu (%))	Cooking (TBtu (%))
South Atlantic	17,981	1,358	76	203 (15%)	92 (7%)	103 (8%)
East North Central	12,742	1,131	89	431 (38%)	67 (6%)	58 (5%)
Middle Atlantic	11,232	1,092	97	344 (32%)	85 (8%)	74 (7%)
Pacific	13,379	954	71	167 (18%)	95 (10%)	91 (10%)
West South Central	11,394	839	74	128 (15%)	56 (7%)	67 (8%)
West North Central	6,178	435	70	143 (33%)	27 (6%)	24 (6%)
Mountain	4,981	417	84	108 (26%)	35 (8%)	nd
East South Central	4,904	369	75	73 (20%)	35 (9%)	30 (8%)
New England	4,302	368	86	159 (43%)	15 (4%)	17 (5%)

Natural gas comprises 51% of the energy used to satisfy commercial building heating demand, followed by electricity (42%), district heating (5%), fuel oil (2%), and propane (1%) (EIA 2016b). Fuel use disaggregated by heating end use largely follow this overall allocation, but large differences emerge on a geographic basis as shown in Table 3. For example, fuel oil use is most prevalent in New England, where it accounts for 18% of space heating fuel use and 14% of water heating fuel use (EIA 2016b). Electricity is most prevalent in the South Atlantic, where it accounts for 54% of space heating, 51% of water heating, and 46% of cooking energy (EIA 2016b). The East North Central division is the most reliant on natural gas, which comprises 60% of space heating, 62% of water heating, and 54% of cooking (EIA 2016b).

Table 3. Fuel Portion of Commercial Building Heating End Use by Census Division (%)

End Use	Fuel	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South central	Mountain	Pacific
Space heating	Electricity	38	30	33	34	54	45	50	45	43
	Natural gas	41	46	60	52	36	45	42	54	51
	Fuel oil	18	8	3	nd	2	nd	nd	nd	nd
	District heat	nd	14	4	8	7	8	8	nd	5
	Propane	3	1	nd	5	1	1	nd	1	1
	Other	nd	nd	nd	nd	nd	nd	nd	nd	nd
Water Heating	Electricity	39	29	33	42	51	49	49	37	41
	Natural gas	44	52	62	55	41	51	51	63	55
	Fuel oil	14	5	nd	nd	nd	nd	nd	nd	nd
	District heat	nd	14	5	nd	7	nd	nd	nd	4
	Propane	3	nd	nd	4	1	nd	nd	nd	nd
Cooking	Electricity	41	39	46	53	46	50	48	39	43
	Natural gas	43	61	54	42	51	50	52	61	57
	Propane	16	nd	nd	5	3	nd	nd	nd	nd

Heat use by manufacturing buildings[2] in the United States is described with lower resolution than commercial buildings and is reported in aggregation with other end uses. For example, the Manufacturing Energy Consumption Survey (MECS) reports relevant non-process end uses for

[2] Commercial building floorspace (87.093 billion ft^2, [EIA 2016b]) is more than 7 times larger than manufacturing building floorspace (11.722 billion ft^2 [EIA 2018a]).

facility heating, ventilating/ventilation, and air conditioning, other facility support,[3] and other non-process energy use. Based on the 2014 MECS released in 2018, together these categories amount to 755 TBtu, or 5% of total manufacturing energy use (EIA 2018a). Natural gas accounts for 55% (418 TBtu) and electricity accounts for 310 TBtu (41%) of these end uses (EIA 2018a).

2.1 Commercial Building Heating End-Use Technologies

As highlighted, the three largest heat-related end uses for commercial buildings are space heating, water heating, and cooking. As such, it is worth understanding the current technologies used to provide this heat. The resolution of technology description reported by CBECS varies by heating end use. Space heating is reported for heat pumps, furnaces, individual space heaters, district heat, boilers, packaged heating units, and other. In general, district heating is supplied by a boiler or heat pump or through heat recovery in a combined heat and power process. Table 4 shows the heating equipment used for commercial building heating and the total floorspace occupied in CBECS 2012. As shown in Table 4, the largest heating equipment by floorspace used for commercial buildings are packaged heating units[4] (49,188 ft^2), followed by boilers (22,443 ft^2) (EIA 2016b).

Table 4. Commercial Building Space Heating Equipment by Floorspace (data from EIA 2016b)

Heating Equipment[a]	Total Floorspace (million ft^2)
Heat pumps	11,846
Furnaces	8,654
Individual space heaters	20,766
District heat	5,925
Boilers	22,443
Packaged heating units	49,188
Other	1,574

[a] More than one equipment type may apply.

Water heating technologies, conversely, are identified as either centralized or distributed systems. CBECS does not report individual cooking technologies. The Commercial Buildings Module (CBM) of the National Energy Modeling System provides more disaggregated descriptions of space heating and water heating technologies than CBECS, such as, solar water heating technologies are included in the CBM.

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[3] According to EIA, facility support "includes energy used in diverse applications that are normally associated with office or building operations such as cooking in cafeterias; operation of office equipment such as personal computers and copying machines; and operation of elevators" (https://www.eia.gov/consumption/manufacturing/terms).
[4] EIA defines packaged heating units as a subset of "packaged unit." A packaged unit is a type of heating and/or cooling equipment that is assembled at a factory and installed as a self-contained unit. Packaged units are in contrast to engineer-specified units built up from individual components for use in a given building. They are generally mounted on the roof of the building, but also sometimes located on a slab outside the building. Packaged units produce warm or cool air directly and distribute it throughout the building by ducts or a similar distribution system. Some types of electric packaged units are also called "Direct Expansion," or DX, units (https://www.eia.gov/consumption/commercial/terminology.php#P).

2.1.1 Observed Data

Specific data for district heat regions or specific towns in the United States have not yet been compiled by the authors, but there is an earlier assessment of the district heating potential in the United States (Gils et al. 2013). Some data are available for district heating demand from the Tårs district heating plant in Denmark with a latitude of 57.39°N and longitude of 10.11°E (Tian et al. 2018), which supplies heat for 840 households (Aalborg CSP 2015b). The daily average load for a year is shown in Figure 3. As expected, the heat demands are highest in the winter (e.g., January to March [days 0–90] and November and December [days 300–360]).

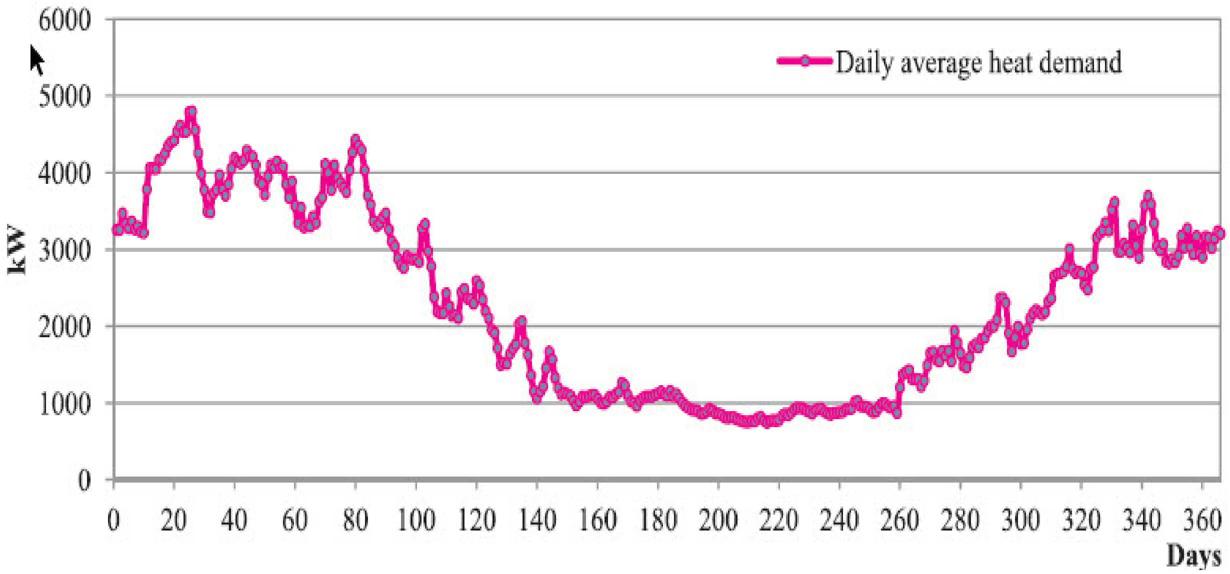

Figure 3. Daily average heat demand in kilowatts (kW) at the Tårs district heating plant in Denmark (Tian et al. 2018)

2.1.2 Modeled/Estimated Data

The Commercial Buildings Stock or ComStock is a "highly granular, bottom-up model that uses multiple data sources, statistical sampling methods, and advanced building energy simulations to estimate annual sub-hourly energy consumption of commercial buildings across the United States" (Hale et al. 2018). ComStock has undergone extensive validation and calibration to both whole-building and end-use data time series through the End-Use Load Profiles project and was fully released in October 2021. ComStock results were used to model county-level heat load profiles for 16 building types, corresponding to the U.S. Department of Energy (DOE) prototype buildings (Hale et al. 2018). This can be utilized to understand where hybrid RTES solutions could be suitable. Deru et al. (2011) summarizes operation schedule assumptions and other characteristics of the DOE prototype buildings. It is worth noting that the National Energy Modeling System uses CBECS for many of its assumptions for heat demands.

2.2 Modeled and Real Examples of Hybrid RTES

The use of hybrid RTES for heat provision to buildings and district heating is a developing field. Research is growing to better understand hybrid RTES options (Nakomcic-Smaragdakis and Dragutinovic 2015; Bloeß, Schill, and Zerrahn 2017), but there are few built realizations. When residential heating is considered, Bloeß et al. highlight that the sector coupling of power and heat sectors for residential heating would allow for greater flexibility, increased renewable energy integration, and increased adoption of heating technologies such as heat pumps and passive thermal energy storage (TES), but even with potential economic benefits these still are considered niche markets (Bloeß, Schill, and Zerrahn 2017).

Another area of considerable research, modeling, and analysis is the use of photovoltaics (PV) or photovoltaic thermal (PVT) coupled with solar thermal and a heat pump for the provision of building demands (Sanz Martinez, Fuente Dacal, and Martín Miranda 2018; Gritzer et al. 2018). The Austrian project "SolarHybrid" was focused on the optimization and hybridization of both the solar thermal and the PV technologies that could then couple to a variety of heat pumps and chillers to meet the heating and cooling loads of a building (Gritzer et al. 2018). Gritzer et al. found that while the capital expenditures were higher than current solutions, if there was a cooling requirement as well as a heating load, the hybrid RTES could reduce energy costs by up to 70% (Gritzer et al. 2018). Similarly, when PVT was coupled with heat pumps as a hybrid RTES, the thermally driven heat pump (which also had grid backup when the PV was not generating electricity), was not economically viable under conditions at that time, but could be valuable over a 20-year period (Sanz Martinez, Fuente Dacal, and Martín Miranda 2018).

For the residential building sector, there are organizations beginning to demonstrate and test hybrid RTES. In Sweden, where grid-connected GSHPs are common and approximately 20% of the buildings use GSHP (Steel 2016), a demonstration of a GSHP, borehole TES, and PVT system is being built to allow for these technologies to be coupled for multifamily houses (Sommerfeldt and Madani 2019). The purpose of coupling the technologies is to increase heat pump efficiency and use the local PVT heat generation to stabilize the borehole temperature (Sommerfeldt and Madani 2019). The schematic of the system is shown in Figure 4.

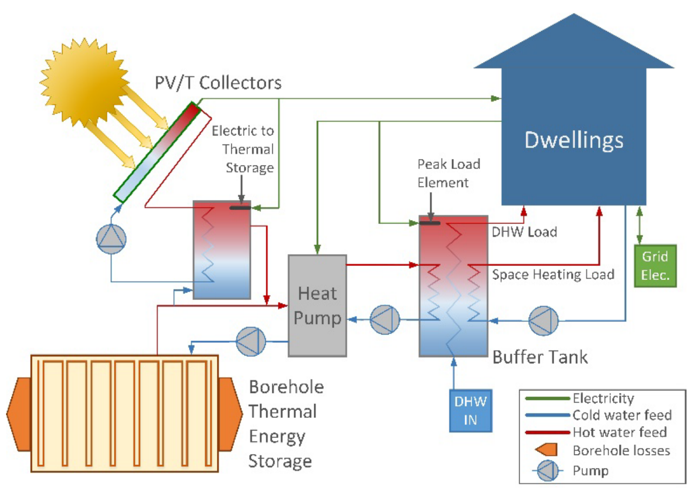

Figure 4. Illustration of PVT collectors coupled with GSHP for dwellings (Sommerfeldt and Madani 2019)

Image from Nelson Sommerfeldt.

The PVT and GSHP hybrid solution could be scaled to industrial activities and for multifamily dwellings in the north and northeast of the United States, which could have similar winter ambient conditions as Sweden. Within the United States, the use of PV for electricity coupled to a GSHP is being deployed by companies such as Dandelion Energy, a spin-off of Google X

(Field 2019). GSHP is most needed during the winter, particularly for polar vortexes (most challenging times), when the contribution of PV is likely very low. While this type of hybridization is not directly related to this project, it is valuable to highlight the hybrid RTES approach for heating and can link to offices such as the DOE's Geothermal Technologies Office and their goals.

District heating could be a significant target and opportunity for developing hybrid RTES solutions in the United States. Recently there have been some examples of district heating systems, including the geo-exchange heat pump system at Colorado Mesa University (CMU 2022) and Whisper Valley community in Austin, Texas, which includes a high-quality geothermal heat pump, a solar PV, and a smart home technology package that serves 7,500 homes (EcoSmart 2022). Another example is the solar-based district heating system coupled to borehole thermal energy storage in Drake Landing, Canada, was able to provide 96% of the community's annual space heating needs (Tian et al. 2018).

Denmark is a prime example where district heating is seen as incredibly valuable and hybrid RTES solutions are being deployed, which are cost-competitive with today's regional natural gas costs in Denmark. As of 2017, approximately 1.7 million Danish homes (~64% of all households) were supplied by district heating (Dansk Fjernvarme 2017). Furthermore, 52% of the energy supplied for the district heat came from green or renewable energy sources such as waste heat from industry, biomass, and solar thermal (Dansk Fjernvarme 2017).

The town of Tårs in Denmark has an important hybrid RTES solution that could be very suitable for the northern parts of the United States. Tårs had a solely natural-gas-based district heating system with heat demand as shown in Figure 3. Since July 2015, FPCs and concentrating solar power (CSP) parabolic troughs coupled in series with water storage were installed to connect to the existing gas system, decrease natural gas use, and decrease the cost to end users. The peak water temperature of the hybrid RTES is 98°C in summer, and the combined solar field output is approximately 6,082 megawatt-hours thermal (MWh_{th}) annually (Aalborg CSP 2015b). The FPCs have an aperture area of 4,039 square meters (m^2), the troughs an aperture area of 5,960 m^2, and the water storage tank is approximately 2,430 m^3 (Perers et al. 2016; Tian et al. 2018). The Tårs hybrid RTES installation is able to provide a solar fraction of approximately 21% (Tian et al. 2018). Denmark's high price of natural gas makes the hybrid RTES viable and economic.

Prior to the hybridization of the district heating system, the end-user consumer price of the heat from Tårs was approximately 0.57 Danish Kroner (DKK) per kilowatt-hour thermal (kWh_{th}), and after the hybrid installation, the system levelized cost of heat (sLCOH) was 0.54 DKK/kWh_{th} (Tian et al. 2018). In U.S. dollars, based on the cost of natural gas staying the same, this is a move from approximately \$0.093/kWh_{th} to 0.089/kWh_{th}. However, as of July 2022, natural gas prices have increased to \$0.166/kW_{th}, and there is intense motivation to sharply curtail or end the use of natural gas for both national security and climate reasons. The sLCOH value includes the investment in the existing conventional natural gas boiler/heater, the hybrid RTES investment, and the net natural gas operation costs over the 30-year operational life of the solar collectors (i.e., the reduced natural gas cost due to the hybrid thermal input). The key benefits of the hybrid RTES are that the mixed solar field of the FPC and troughs offers key advantages such as increased temperature of the output water, operational flexibility, and lower cost in operations, particularly as the natural gas costs increase or collector costs decrease (Perers et al. 2016).

Figure 5 shows the FPC and the parabolic troughs of the Tårs hybrid RTES that connects to the existing natural gas heat network.

Figure 5. Tårs, Denmark hybrid RTES site utilizing parabolic trough and flat plate collectors for district heat provision (Aalborg CSP 2015b).

Photo from Aalborg CSP.

Note that wind turbines can also be seen in Figure 5. It can be envisioned that for areas in the U.S. Northeast where district heating is needed, high gas prices are present, and excess or low-cost wind generation is available that could provide electricity for low-cost electrolysis (Ruth et al. 2019), a hybrid RTES solution could be coupled for district heating and hydrogen generation.

Another important operational hybrid RTES solution for district heating (which could also have higher temperature applications), is the hybrid district heating plant at Marstal in Denmark. Denmark has enabling policies for the use of solar thermal and RTES for district heating, coupled with the high costs of natural gas (Akar et al. 2023; McMillan et al. 2023). This example was chosen to highlight another operating hybrid RTES configuration in the colder northern latitudes, which is similar to the U.S. Northeast. As demonstrated in Tårs, the FPC and PTC RTES hybrid solution highlights the layering of technology options to cover low and higher temperature needs or demands. From 2012, the original 18,000 m^2 solar field of glazed FPCs connected to a natural gas boiler was expanded to approximately 33,000 m^2 of FPCs (Lovegrove et al. 2015). After further upgrades, the Marstal hybrid RTES site now includes 75,000 m^3 of seasonal pit storage where hot water can be stored at 70°C–75°C (up to 95°C in summer), a 1.5-MW_{th} heat pump, and a 4.4-MW_{th} biomass burner connected to a 0.75-megawatt electric (MW_e) organic Rankine cycle turbine (Lovegrove et al. 2015; Backen et al. 2018). The biomass burner and heat pump were recently installed to remove any dependency on the back-up fossil fuel boiler and system (Lovegrove et al. 2015). The significance of this example is the unique combination of solar thermal, heat pumps, and biomass, which serves as the stored fuel when the solar and electric heating from the heat pump are insufficient.

With decreasing CSP costs allowing utilization in two hybrid RTES district heating plants in Denmark (Aalborg CSP 2015b; 2015a), and concern for the sustainability of biomass woodchips, Backen et al. (2018) investigated whether the Marstal hybrid RTES district heating plant could be further improved with the addition of PTCs, and if the biomass consumption could be reduced significantly. Figure 6 shows the additional PTC field with a life of 25 years to increase the efficiency and annual operation of the organic Rankine cycle turbine and feed the excess heat to the district heat network, thereby reducing the fuel consumption of the biomass.

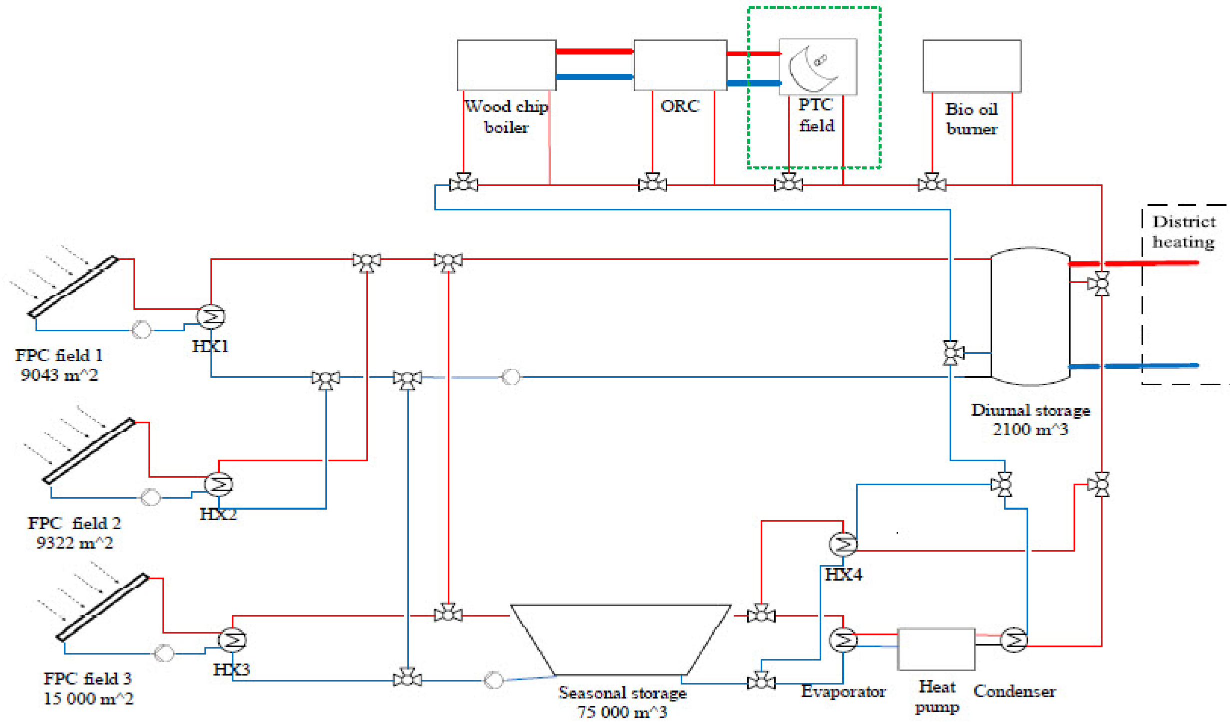

Figure 6. Schematic of the Marstal hybrid RTES district heating system with additional PTC (Backen et al. 2018)

The total investment cost of the PTC solar field of 8,088 m^2 was estimated to be $2.48 million in 2017 (Backen et al. 2018) (i.e., a fully installed cost of \$307/m^2). Under the study's conditions, it was found that the fuel savings from the biomass and the electricity generation from the organic Rankine cycle turbine revenues, the net present value of the addition of the PTC was negative, and that the simple payback was nearly 31 years (Backen et al. 2018). The increased hybridization effort was found to be economically unviable, even at the end of the 25-year life. But, if the hybrid RTES including the PTC was moved to Turin, Italy, which has significantly better direct normal irradiance, and assuming the same fuel costs and electricity prices, the simple payback drops to 14 years, and the hybridization is nearly economically viable at a positive net present value of 26 years (Backen et al. 2018). Depending on the fuel source (e.g., natural gas in the United States), even inadequate global horizontal irradiance and direct normal irradiance areas, this type of hybrid RTES could be viable. This type of hybrid RTES could also be augmented by hydrogen or ammonia burning as a backup. It is worth noting that for Denmark, there are financial incentives from the Danish government that are helping to incentivize the use of hybrid RTES solutions to reduce natural gas consumption (Perers et al. 2016; Tian et al. 2018).

3 Industrial Heat Use

Thermal energy is used in manufacturing processes to produce raw materials from natural resources and to produce finished products. Thermal energy demands in manufacturing[5] processes are larger than the space and water heating demands of manufacturing buildings and the heat loads of commercial buildings combined. At least[6] 6 quads (or 40%) of manufacturing energy used as fuel[7] is used for process heating and boiler fuel (EIA 2018a).

Although demand for process heat is larger than all commercial and manufacturing building thermal demand, the heterogeneity and complexity of industrial processes make detailed characterizations of IPH difficult. The types of IPH operations and generalized temperature ranges are shown in Table 5.

Table 5. Summary of IPH Operations and Temperature Ranges[a] (Thirumaran 2020)

Manufacturing Operation	Applications	Typical Temperature Range	Estimated U.S. Energy Use (2014)
Non-Metal Melting	Plastics and rubber manufacturing; food preparation; softening and warming	200°F–400°F	276 TBtu
Smelting and Metal Melting	Casting; steelmaking and other metal production; glass production	600°F–3,000°F	1,340 TBtu
Calcining	Lime calcining	1,150°F–2,140°F	547 TBtu
Metal Heat Treating and Reheating	Hardening; annealing; tempering; forging; rolling	500°F–2,200°F	282 TBtu
Coking	Ironmaking and other metal production	710°F–2,010°F	125 TBtu
Drying	Water and organic compound removal	320°F–800°F	1,627 TBtu
Curing and Forming	Coating; polymer production; enameling; molding; extrusion	280°F–1,200°F	151 TBtu
Fluid Heating	Food preparation; chemical production; reforming; distillation; cracking; hydrotreating	230°F–1,000°F	2,205 TBtu
Other	Preheating; catalysis; thermal oxidation; incineration; other heating	210°F–2,000°F	964 TBtu
Total			**7,517 TBtu**

[a] Figures based on EIA (2018a)

[5] The thermal demands in agriculture, construction, and mining industries are not included in this project. These demands are not well studied, and limited data on their nature exist.
[6] About 5.8 quads (nearly 40%) of manufacturing energy used for fuels was not assigned to an end use (EIA 2018a).
[7] Non-fuel (i.e., feedstock) energy use in 2014 was nearly 5.3 quads (EIA 2018a).

Detailed, comprehensive, and systematic characterization and analysis of U.S. manufacturing process heat demand has not been published in the public domain, since Brown et al. (1996) conducted mass and energy balances of 108 industrial processes. Concurrent research performed by the Solar Energy Research Institute (the National Renewable Energy Laboratory's [NREL's] precursor organization) produced an Industrial Process Heat Database that characterized energy use, temperature, heat rate, batch or continuous process, continuous or seasonal operation, and heat transfer media for industrial processes in six U.S. cities (Brown et al. 1980). Since 1985, MECS has provided an ongoing survey of industrial process heat demands by fuel type and industry, but the survey does not include characteristics of the heat demand, such as the temperature and heat transfer medium.

3.1 Representative Thermal Loads and Profiles

3.1.1 Observed Data

The use of solar thermal for breweries has been investigated in Europe and shows viability, as the temperature and heat load requirements (e.g., between the brewery's heating processes and the solar thermal temperatures) can be readily provided by solar thermal. German breweries have been investigated using a process and use case for the integration of solar thermal into the brewery (Lauterbach et al. 2009; 2012). In the United States, studies have been undertaken, but there are few operating systems of hybrid RTES integration at breweries; however, there is significant potential for application. Other industries of interest for solar thermal include plastics and food processing (Kurup and Turchi 2015a).

Engagement by the authors with Rackam, which is a private company working on solar thermal solutions for industrial process heat, has enabled access to the thermal load profile of a brewery 30 miles east of Los Angeles, California. This brewery was considering the installation of a PTC solar field as a heat input into brewery processes. The relatively constant heat loads for each month are shown in Figure 7 (blue bars), where the estimated natural gas burned (MWh_{th}/month) to meet the demand is in red. The annual thermal load of the brewery is 2,201 MWh_{th}/year, with a daily average load of 6 MWh_{th}/day. The hourly load is approximately 0.25 MWh_{th}/hour. Prior NREL analysis for the brewery found that dependent on costs of the solar field integration and the assumed income tax utilized, a positive net present value could be attained, indicating a viable project (Kurup and Turchi 2020).

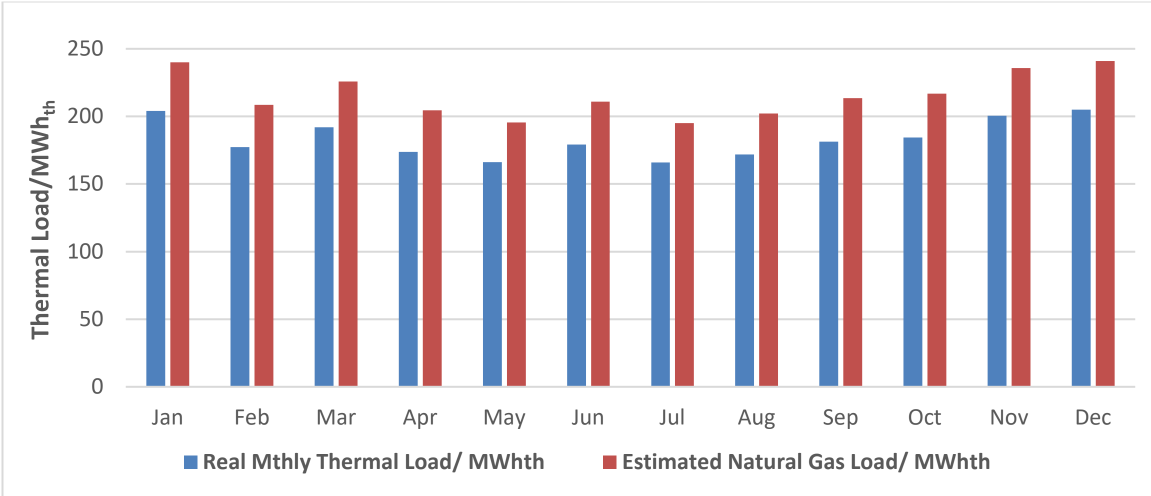

Figure 7. Monthly thermal load profile (MWh$_{th}$/month) for a brewery in Los Angeles, California (blue bars), and the estimated natural gas thermal energy (MWh$_{th}$/month) consumed to meet the demand (red bars)

The Moroccan Solar Research Institute (IRESEN) was heavily investigating the use of solar thermal systems and then subsequently coupled with TES to form hybrid RTES solutions for the supply of renewable heat to key industries like automotive, plastics, and food processing (Laadel et al. 2018; 2019). This is an important area for industries in Morocco due to Morocco's high reliance on foreign imported fuels such as oil and natural gas—97% of fuel needs are imported (World Bank 2017), and energy generation costs are high (Laadel et al. 2018).

It has been possible to estimate the thermal load profile of an existing plastic rotational molding facility in Casablanca, Morocco, that is expected to install a linear Fresnel solar field for IPH application. The plastic rotational molding facility currently uses costly natural gas to provide heated air to the molds and furnace. The plant is estimated to run 24 hours per day, 365 days per year (Laadel et al. 2018). The gas burner provides air at 300°C, and the hourly thermal load is approximately 0.3 MW$_{th}$ (Laadel et al. 2018). The simulations and modeling for the linear Fresnel solar field, undertaken with the software EBSILON, used a synthetic oil heat transfer fluid in the solar field connected to a heat exchanger, which would heat air before it was fed into the rotational molding furnace (Iqony 2023). If insufficient heat input was available from the heated air exiting the heat exchanger, the modeled existing natural gas burner would make up the difference to raise the air to 300°C. The estimated monthly thermal load profile of the facility (MWh$_{th}$/month) is shown in Figure 8 (blue bars), and the estimated solar thermal yield (MWh$_{th}$/month) is also shown (green bars). As shown in Figure 8, it is expected that the modeled solar IPH solution without a TES could, in the best solar resource months (e.g., June to September), meet greater than 20% of the facility's thermal demands (Laadel et al. 2018).

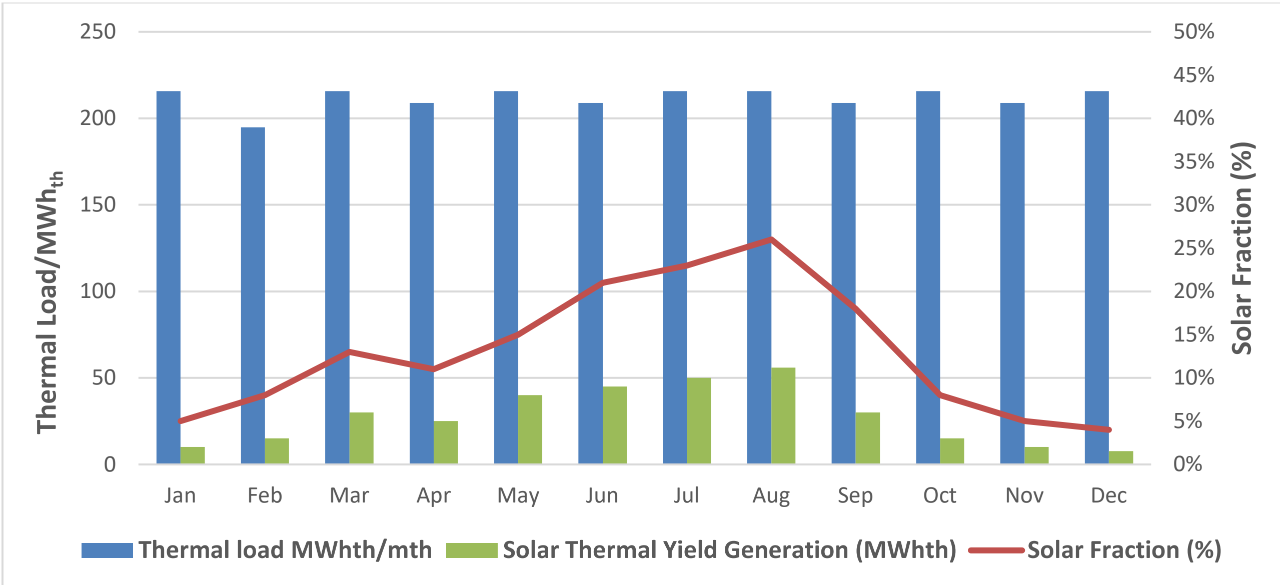

Figure 8. Estimated monthly thermal load profile (MWh_{th}/month) for an existing rotational molding site in Casablanca, Morocco, and the potential solar thermal input (MWh_{th}/month) (Laadel et al. 2018)

It is expected that the use of a hybrid RTES (i.e., CSP and TES) would increase the renewable heat fraction (e.g., above 26%), as in Figure 8 (Laadel et al. 2018). It is worth mentioning that the authors of this paper are working closely with members of IRESEN to gain access to operational data to industrial plants in Morocco to allow for the development of hybrid RTES solutions.

3.1.2 Modeled/Estimated Data

As mentioned above, although MECS provides the most detailed survey-based manufacturing energy data, it does not include the temperatures and other characteristics of energy used for boilers and process heat. Recent efforts have used MECS and other publicly available data sources to develop more detailed descriptions of how thermal energy is used in manufacturing. Most recently, we have revised the methods developed by McMillan et al. (2016) and McMillan and Narwade (2018b) to estimate U.S. manufacturing energy use to include updated data and approaches (McMillan et al. 2021). The results provide detailed estimates of energy used in 2014 for manufacturing process heat (including energy used in boilers) at the county and six-digit North American Industrial Classification System (NAICS) code level (McMillan 2019).

We estimate that just over 11 quads were used for boilers (including combined heat and power) and process heat. Figure 9 shows that a significant portion is associated with demands less than or equal to 300°C. There is relatively little demand for temperatures between 200°C and 600°C; energy use at temperatures above 600°C represent roughly 2 quads. Previous work on the thermal demands of the most significant greenhouse gas-emitting U.S. industries found a similarly large portion of energy use at temperatures below 200°C, but a larger portion of energy use at temperatures above 600°C (McMillan and Ruth 2019). The differences in distributions are a result of high-temperature processes in certain industries, such as calcination in cement and lime manufacturing and iron ore reduction in steelmaking.

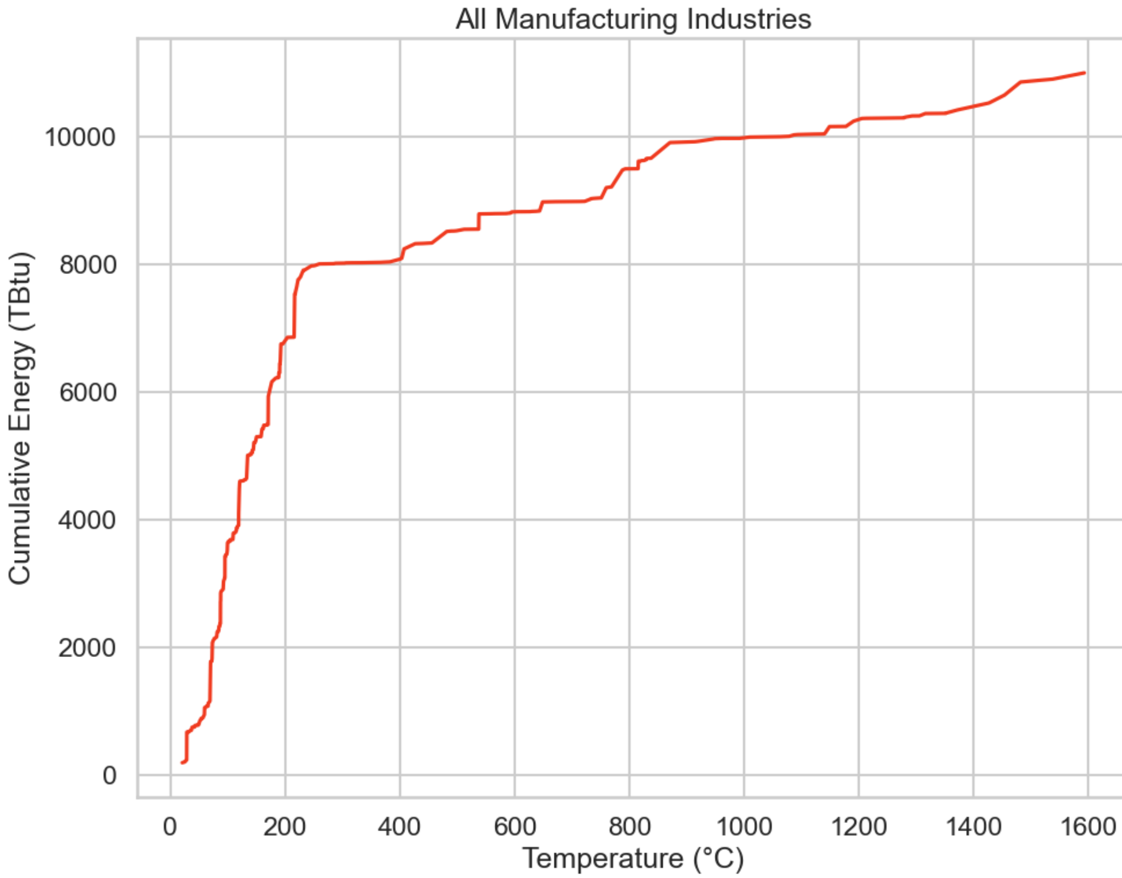

Figure 9. Temperature profile of manufacturing thermal energy use for the United States in 2014 (McMillan 2019)

A first step in developing a more detailed understanding of manufacturing thermal demands is to disaggregate energy by general end use (i.e., process heating, conventional boiler, and CHP/cogeneration). This general disaggregation reveals stark differences in temperature requirements, as shown in Figure 10. About 50% of the energy used in conventional boilers and for CHP/cogeneration is for temperatures less than 150°C. Conversely, process heating demand occurs over a much wider temperature range. The relatively small energy demand between 200°C and 400°C revealed in Figure 9 is even more pronounced for demands met by ovens, kilns, and other related technologies (shown in Figure 10 as process heating). Nearly 80% of these non-boiler and non-CHP process heating energy demands are above 400°C. Figure 9 shows that a significant portion, nearly two-thirds of the industrial thermal demand in 2014 in the United States, was less than or equal to 300°C.

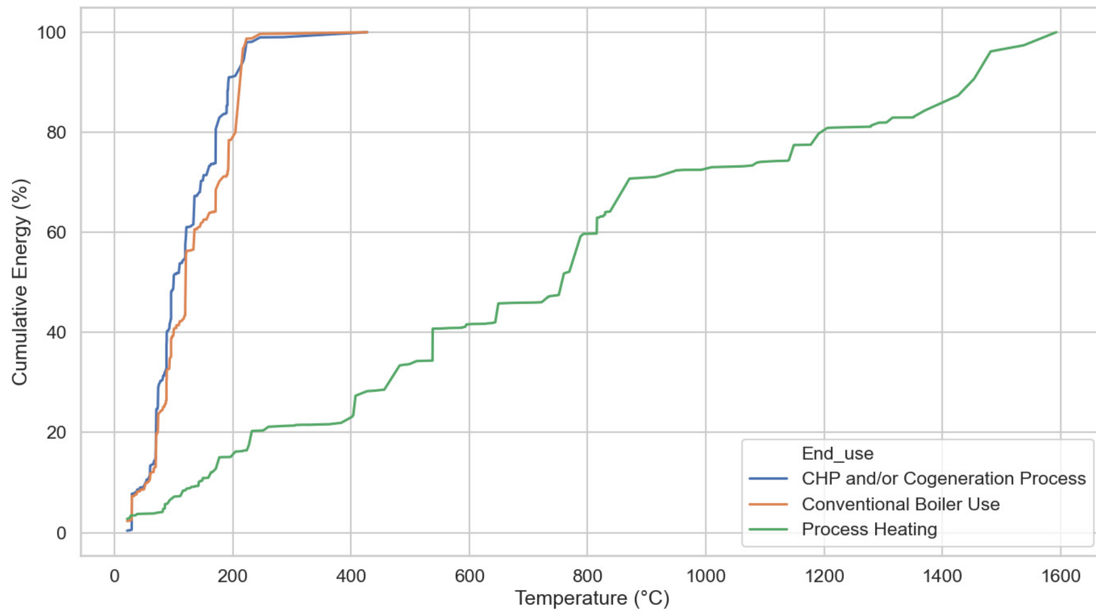

Figure 10. Cumulative energy use by temperature and end use

Kurup and Turchi (2015a) focus their analysis of solar thermal potential on industrial steam demands in the southwest United States. Their analysis of steam demands found that the majority occurs at less than 260°C, as shown in Figure 11. The largest steam users in the United States include the food, paper, and chemicals industries. This work builds off of analysis of low-temperature demand conducted in the context of geothermal resources (Fox, Sutter, and Tester 2011).

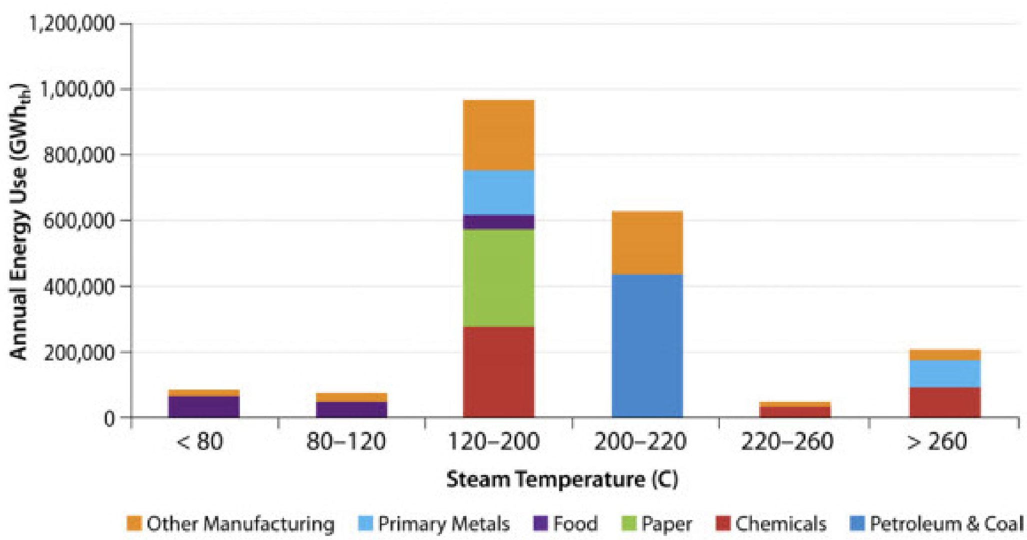

Figure 11. Steam temperature and energy use in key U.S. industries (Kurup and Turchi 2015a)

In addition to analyzing manufacturing heat demand by end use, the recently developed manufacturing thermal demand data make it possible to analyze individual industries at a much higher granularity than previously possible. Figure 12 compares the energy and temperature demands of three industries[8] that use very different heating processes: food manufacturing, machinery manufacturing, and cement manufacturing. For example, food manufacturing uses over 4 times the thermal energy as cement manufacturing and nearly all its thermal energy use is for temperatures below 200°C. Conversely, almost all thermal energy use in cement manufacturing occurs around 1,500°C. Machinery manufacturing uses about 40% of its thermal energy for temperatures between 400°C and 800°C.

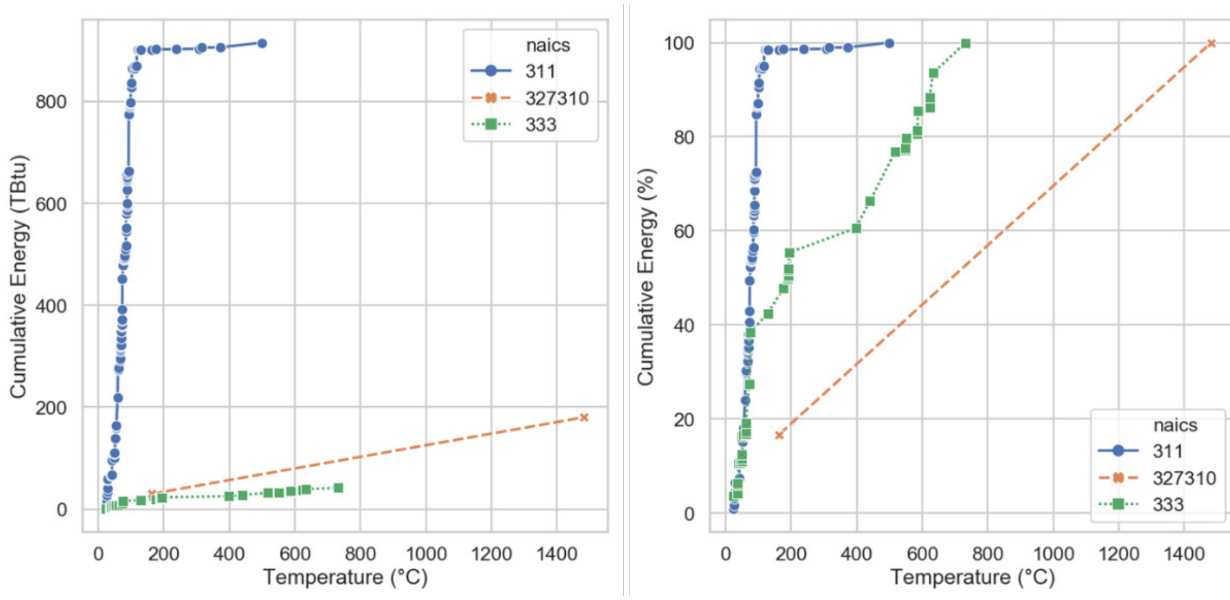

Figure 12. Comparison of thermal energy use by food manufacturing (NAICS 311), machinery manufacturing (NAICS 333), and cement manufacturing (NAICS 327310)

Manufacturing heat use has also been estimated at the county resolution. Figure 13 shows that the counties with the largest heat use tend to be located around the Gulf of Mexico and around Chicago. These are also areas with high concentrations of very energy-intensive industries, such as petroleum refining, petrochemicals, and iron and steel. Energy mapping could also be performed with data on renewable energy resources to identify counties that have heat demands within suitable temperature ranges for alternative heat technologies.

[8] Note that food manufacturing and machinery manufacturing are subsector aggregations comprising many individual, national industries. Conversely, cement manufacturing is an individual national industry. For more information about the NAICS hierarchy, see https://www.census.gov/programs-surveys/economic-census/guidance/understanding-naics.html.

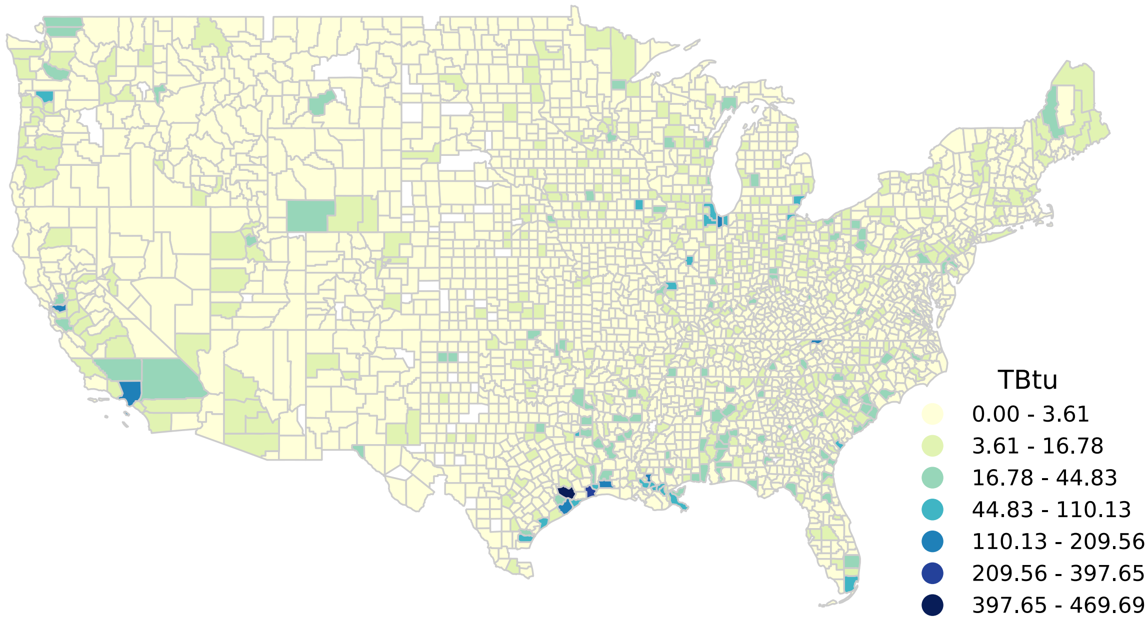

Figure 13 Estimated manufacturing process heat use by county in 2014 (McMillan et al. 2021)

3.2 Modeling and Analytical Studies of Hybrid RTES

Few realized examples of hybrid RTES solutions for IPH applications exist today, therefore warranting future R&D to make potential solutions possible. Research activities across the world are looking at various temperature levels to provide renewable heat for IPH through hybrid RTES possibilities.

In Australia, investigations into CSP connected to a packed bed of encapsulated phase change materials (EPCM) are under significant consideration for the provision of high-temperature heated air for industrial processes. Effectively, the hybrid RTES solution being developed models and simulates a direct air CSP cycle connected to a TES that uses EPCM and provides heat to a 1 MW_{th} process load that would normally be supplied by natural gas only (Jacob et al. 2018). In this first important study, Jacob et al. varied the CSP system size (0–10 MW_{th}), the EPCM TES capacity (0–100 MWh_{th}), and CSP installation cost ($1.1 million/$MWh_{th}$, $1.75 million/$MWh_{th}$, and $2.4 million/$MW_{th}$) for small systems providing IPH compared to Adelaide potential natural gas prices of AU$10–35 (where AU$ indicates Australian dollars) per gigajoule (GJ). This was to determine whether this hybrid RTES could be competitive against natural gas heat delivery. To note, a gigajoule of natural gas is approximately 0.948 million British thermal units (MMBtu) (Conversion Measurement Units 2019), which would indicate that for Adelaide the average industrial natural gas price could be approximately AU$9.48/MMBtu at the low end in 2017; when converted to U.S. dollars, it was approximately $7.21/MMBtu (X-Rates 2019). For 2017, this is comparable to the annual California state-reported average industrial price of $6.80/MMBtu (EIA 2019).

Figure 14 shows the potential heat supplied from the hybrid RTES (heated air from the CSP cycle and heat delivered from the EPCM) for a year, and the remainder of the heat supplied by natural gas for a continuous 1 MW_{th} hourly demand at a mid CSP cost and natural gas cost of $12.85/MMBtu (AU$18.94/MMBtu) (X-Rates 2019; Jacob et al. 2018).

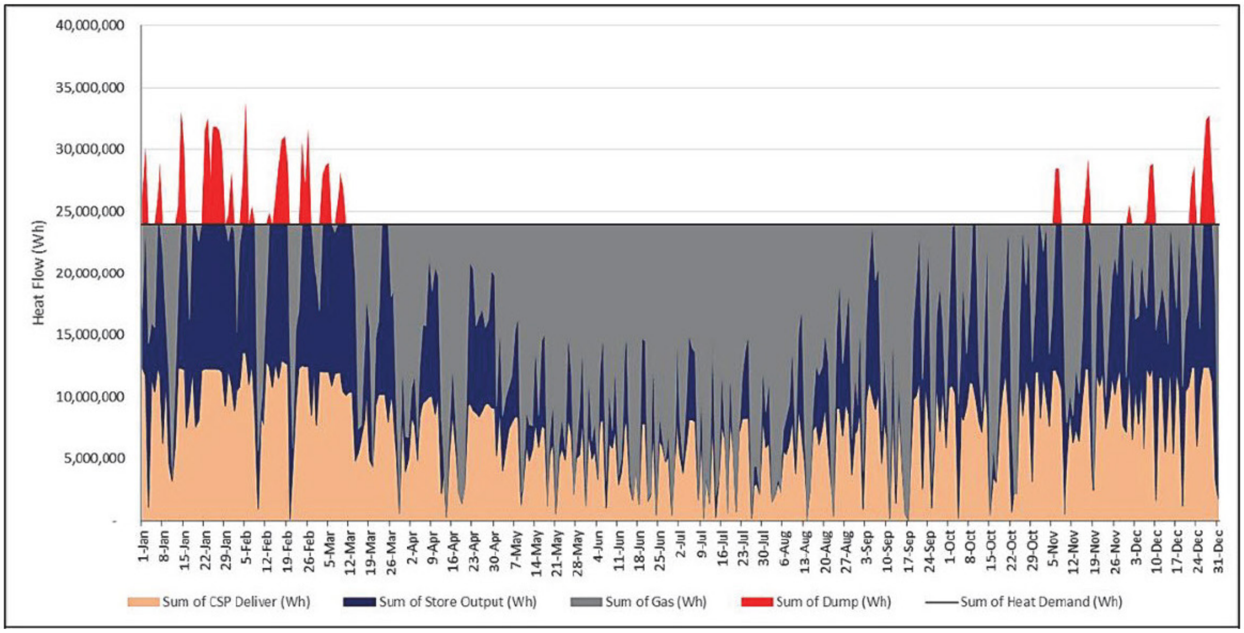

Figure 14. Energy delivery from the CSP air cycle, EPCM TES, and remainder by the natural gas backup (Jacob et al. 2018)

As seen in Figure 14, the hybrid RTES solution can reduce the consumption of natural gas competitively across the year, and it was found to be approximately a 46% reduction (Jacob et al. 2018). The hybrid RTES configuration was also potentially competitive compared to natural gas when the process demand was reduced to 8 hours/day, when, for example, gas prices were higher (e.g., AU$18.94–AU$33.15/MMBtu) (Jacob et al. 2018; X-Rates 2019). It is worth highlighting that in Australia, like in the United States, smaller industrial sites tend to have significantly higher gas costs (and perhaps more variable thermal demands) than large industrial gas users (Lovegrove et al. 2015; Kurup and Turchi 2015b).

Jacob et al. (2019) continued this modeling and investigation with the inclusion of a PV-generated heat system, also coupled to the EPCM TES. Both CSP- and PV-based hybrid RTES solutions for Australia show promise for the displacement of natural gas for high-temperature industrial applications. The second modeling study (which has been validated through experiments) investigated the effects of how much of a continuous 1-MW_{th} process load in the solar conditions of Adelaide, Australia, could be met by either an air cycle CSP power tower or air heated via PV and resistive electrical elements (Jacob et al. 2019). The value of 1 MW_{th} is a known representative size for industrial steam boilers, which can provide information for similar industries in the United States. The air was heated either via the CSP or PV-electric resistance up to 660°C and was sent to a packed bed with spheres of EPCM (Jacob et al. 2019), from which the air was further heated by the natural gas heater, if needed, to deliver 600°C hot air to the process load. Figure 15 shows the modeled systems of the CSP or concentrating solar thermal closed air cycle (top), and the PV and electrically heated system (bottom), coupled to the EPCM TES and the gas heater.

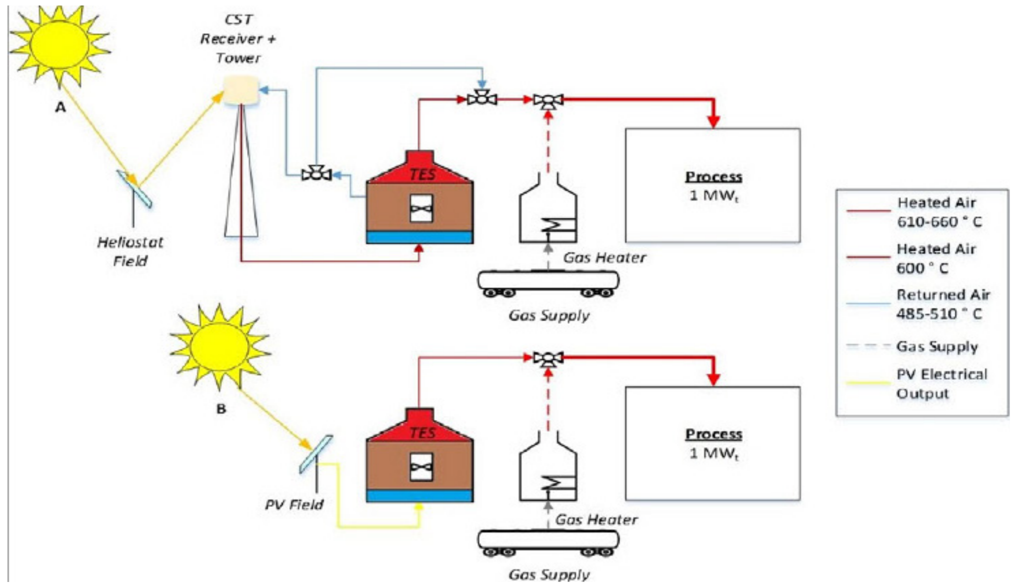

Figure 15. System schematic for air cycle CSP plant and PV and resistive heat coupled to an EPCM TES in conjunction to a natural gas burner (Jacob et al. 2019)

Figure 16 shows the amount of process load by day across 1 year that could be potentially met with the CSP direct air cycle coupled to the EPCM TES, where the LCOH of the hybrid RTES is competitive to a natural gas cost of $28.43/MMBtu. For a 2.1-$MW_{th}$ air receiver and 9.8-MWh_{th} TES, it was estimated that approximately 46% of natural gas usage to meet the process load could be displaced during the year (Jacob et al. 2019). The choice for modeling a 9.8-MWh_{th} TES in Australian conditions could be comparable to parts of California, which has similar direct normal irradiance conditions (SolarGIS 2019). The size of the tower and TES help optimize the solar heat production to meet most of the natural gas heat load for colder conditions (April to September), as shown in Figure 16.

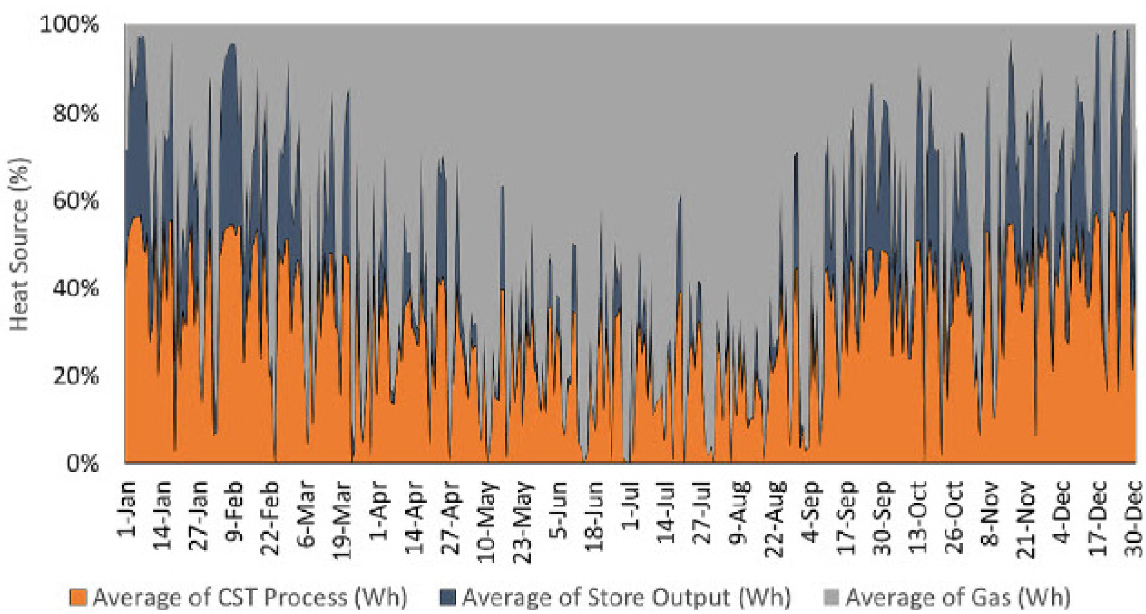

Figure 16. Process load met by air cycle CSP tower and EPCM TES (Jacob et al. 2019)

Figure 17 shows the amount of the process load by day across 1 year that could be potentially met with the PV resistive air heating coupled to the EPCM TES, where the LCOH of the hybrid RTES is competitive to a natural gas cost of $28.43/MMBtu. With this configuration, approximately 67% of natural gas use could be displaced to meet the process load. As is shown between Figure 16 and Figure 17, winter in Australia (April to September) increases the natural gas used, as the solar portion is less able to provide sufficient heat to the process. A larger concentrating solar thermal EPCM or PV and TES configuration could reduce the natural gas use further but would lead to higher cost and increased space requirements. The modeling efforts from Jacob et al. (2018; 2019), assume that the 1-MW_{th} maximum load can be met for the majority of the colder months, when natural gas use would be most expensive.

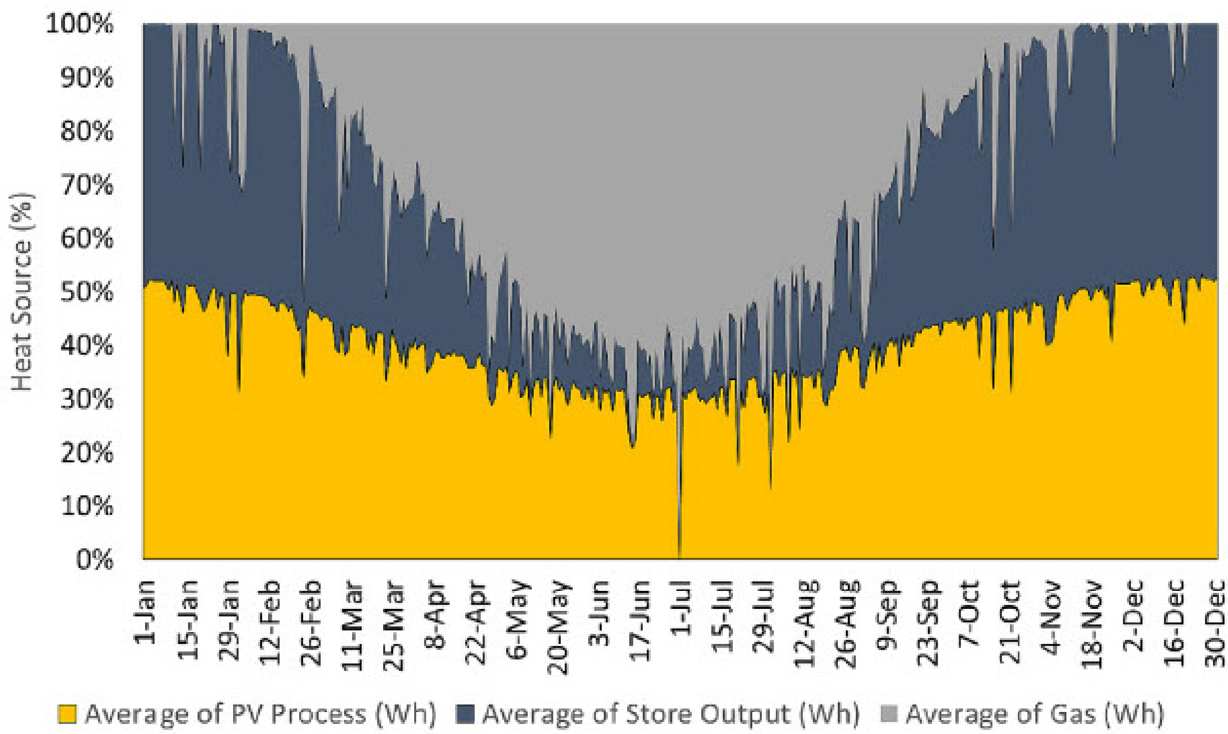

Figure 17. Process load met by PV and resistive heat and EPCM TES (Jacob et al. 2019)

It is worth noting that the numerical study for the PV and resistive heating of air (e.g., Figure 17) highlighted that this hybrid RTES could provide heat without significant perturbation from transient events like clouds, as global horizontal irradiance is less sensitive than direct normal irradiance, and that the storage can readily provide the heated air required by the process. An important finding from the recent study was that for industrial sites with large heat demands (e.g., 25–1,000 MW_{th}), the CSP hybrid RTES (i.e., air heated via CSP and connected to the EPCM) can remain competitive, even with small natural gas price drops (Jacob et al. 2019).

4 Initial Data Gaps

This project has begun identifying initial gaps where further data and validation are needed. Identified gaps include:

- Obtaining or estimating cost information regarding RTES options (e.g., the costs of heat pumps and different collectors in the U.S. market)
- Further analysis of RTES hybrid options and their modeling (see Report 3 in this series [Akar et al. 2023])
- Detailed heat demands for specific types of buildings (e.g., temporal and seasonal variation of heating loads for specific buildings)
  - Utilizing ComStock to investigate prototype building heat loads/demand profiles
- Further review of policies and business models for RTES for industry in the United States
  - See Report 2 in this series (McMillan et al. 2023) for initial work
  - Further review and evaluation of examples of policies and business models being used globally could be utilized in U.S. conditions
- Further analysis to disaggregate water heating technologies for buildings and therefore to determine hybrid RTES suitability
- Detailed heating demands by region that could be met by district heating systems
  - A case study for the application of heat pumps for a district energy system was explored in the Solar World Congress 2021 paper (Akar et al. 2021)
- Detailed analysis of industrial processes and temperatures, particularly at less than 300°C, to allow for suitable matching to potential RTES and hybrid RTES solutions
  - This includes updated temperatures and thermal profiles of selected industries that include temporal estimation of the process
- Upgrades to the System Advisor Model or the use of tools like TRNSYS:
  - Load profiles that can be selected by the user representing various industries, or allowing the user to input their own time-varying heat demand profile
  - PV and heat pumps coupled together; modeling of other select PV and heat generation technologies identified in this report, such as PV and resistive heating
  - Further RTES components and technologies modeled to form hybrid RTES options
    - See Report 3 in this series (Akar et al. 2023) where (1) flat plate collectors and parabolic trough collectors and (2) direct steam generation linear Fresnel collectors coupled with phase change material storage were co-modeled
  - Hydrogen or ammonia burners
    - Initial analysis was undertaken for hydrogen mixed with natural gas
    - Hydrogen burners operating on 100% hydrogen were not modeled
- Proposed decision support tool is under initial development
  - See Report 3 in this series (Akar et al. 2023) for discussion of a future decision support tool for highlighting the value of RTES (either in stand-alone or hybrid configuration) for IPH needs
  - Gaps can be further determined through workshops with decision makers, national labs, and industrial end users that could benefit from such a tool.

Going forward, further gaps will be assessed and addressed, and as characterization data are found or estimated, they will be added to data sets to allow for continued research. It is important to note that further modeling and analytical work will be undertaken to help increase the understanding and adoption of RTES options for industries.

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