Applications for Solar Thermal for Industrial Processes

Parthiv Kurup (with thanks to Carrie Schoeneberger and Colin McMillan)
November 15th, 2019
Agenda

1. Global View and U.S. projects with Solar Thermal
2. Manufacturing Energy Data Sets
3. High Temperature R&D paths
4. Analysis for Solar IPH on-going
Global View and U.S. Projects with Solar Thermal

Where is Solar Thermal already active today?
Why is Solar for IPH important?

- 32% of total global energy consumed is for Industry
  - 74% of the total Industrial energy is used for industrial process heat (IPH)
    - 90% of that energy provided comes from fuels such as coal, natural gas and oil
- Concentrating Solar Power (CSP) and non-concentrating collectors can readily provide the heat needed
  - Temperatures (upto 400°C) and quantity
  - Large fuel savings and volatility hedge
- There is growing demand for SIPH solutions
  - Food processing and brewery sectors key
  - E.g. Dairies, Breweries and Malting plants
Mexico has the most SIPH projects with 68, followed by India with 41. 14 total projects in the U.S., spread across country.
<table>
<thead>
<tr>
<th>Name</th>
<th>Location in U.S.</th>
<th>Manufacturing subsector</th>
<th>Year installed</th>
<th>Solar collector</th>
<th>Number of collectors</th>
<th>Installed collector area (gross), m²</th>
<th>Installed thermal power (actual), kWth</th>
<th>Unit operations</th>
<th>Total investment costs, $</th>
<th>Estimated annual CO2 emissions displaced, metric tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acme McCrory</td>
<td>Asheboro, North Carolina</td>
<td>Textiles</td>
<td>2012</td>
<td>FPC</td>
<td>-</td>
<td>743</td>
<td>520</td>
<td>Drying</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Adams Farm Slaughterhouse</td>
<td>Athol, Massachusetts</td>
<td>Meat products</td>
<td>2013</td>
<td>FPC</td>
<td>70</td>
<td>297</td>
<td>208</td>
<td>Cleaning</td>
<td>-</td>
<td>44</td>
</tr>
<tr>
<td>Barrington Brewery &amp; Restaurant</td>
<td>Great Barrington, Massachusetts</td>
<td>Beverages</td>
<td>2009</td>
<td>FPC</td>
<td>30</td>
<td>82</td>
<td>57</td>
<td>Other process heating</td>
<td>51611</td>
<td>7</td>
</tr>
<tr>
<td>Battenkill Valley Creamery</td>
<td>Salem, New York</td>
<td>Dairy products</td>
<td>-</td>
<td>FPC</td>
<td>20</td>
<td>53</td>
<td>37</td>
<td>Cleaning</td>
<td>34002</td>
<td>16</td>
</tr>
<tr>
<td>Brown's Brewing Co</td>
<td>Hoosick, New York</td>
<td>Beverages</td>
<td>-</td>
<td>FPC</td>
<td>20</td>
<td>53</td>
<td>37</td>
<td>Cleaning</td>
<td>35217</td>
<td>11</td>
</tr>
<tr>
<td>Carriers &amp; Sons</td>
<td>California</td>
<td>Food products</td>
<td>2002</td>
<td>Air collector</td>
<td>-</td>
<td>300</td>
<td>210</td>
<td>Drying</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Frito Lay</td>
<td>Arizona</td>
<td>Food products</td>
<td>2008</td>
<td>PTC</td>
<td>-</td>
<td>5068</td>
<td>3548</td>
<td>General process heating</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gatorade</td>
<td>Phoenix, Arizona</td>
<td>Beverages</td>
<td>2008</td>
<td>FPC</td>
<td>-</td>
<td>4221</td>
<td>2955</td>
<td>General process heating</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Keyawa Orchards</td>
<td>California</td>
<td>Food products</td>
<td>2003</td>
<td>Air collector</td>
<td>-</td>
<td>864</td>
<td>605</td>
<td>Drying</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Kreher’s Poultry Farms</td>
<td>New York</td>
<td>Food products</td>
<td>2002</td>
<td>Air collector</td>
<td>-</td>
<td>50.4</td>
<td>35</td>
<td>Drying</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Milwaukee Brewing Co.</td>
<td>Milwaukee, Wisconsin</td>
<td>Beverages</td>
<td>2013</td>
<td>FPC</td>
<td>28</td>
<td>104</td>
<td>73</td>
<td>Other process heating</td>
<td>94114</td>
<td>12</td>
</tr>
<tr>
<td>Prestige Foods</td>
<td>St Pauls, North Carolina</td>
<td>Food products</td>
<td>2012</td>
<td>FPC</td>
<td>-</td>
<td>7804</td>
<td>5463</td>
<td>Cleaning</td>
<td>5639098</td>
<td>-</td>
</tr>
<tr>
<td>Stapleton-Spence Fruit Packing Co.</td>
<td>San Jose, California</td>
<td>Fruit and vegetables</td>
<td>2012</td>
<td>Unglazed collector</td>
<td>500</td>
<td>2637</td>
<td>1846</td>
<td>General process heating</td>
<td>488722</td>
<td>150</td>
</tr>
<tr>
<td>Sunsweet Dryers</td>
<td>California</td>
<td>Food products</td>
<td>2004</td>
<td>Air collector</td>
<td>-</td>
<td>110</td>
<td>77</td>
<td>Drying</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Frito Lay</td>
<td>Modesto, California</td>
<td>Food products</td>
<td>2008</td>
<td>PTC</td>
<td>384</td>
<td>5017</td>
<td>492</td>
<td>Drying, roasting</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Horizon Nut</td>
<td>California</td>
<td>Food products</td>
<td>2017</td>
<td>PTC</td>
<td>-</td>
<td>72 (aper.)</td>
<td>50</td>
<td>Drying</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Where can solar thermal provide the temperature and the quantity?

- Across all temperature ranges needed by industry
  - Current technology <550°C
  - Next gen SIPH (i.e. towers and reactors), >1000°C
- PV driven heat is theoretically possible
  - e.g. PV + Induction is very early TRL
Manufacturing Energy Data Sets

Demand Side Considerations for Solar Thermal
Summary of Data Sets

• Manufacturing process heat data set
  – Characterizes the heat demand of 273 industries
    • End use: conventional boiler, combined heat and power (CHP)/cogeneration, process heating
    • Temperature
    • Fuel type
• Hourly heat load archetypes
  – Parameterized method for generating load shape by NAICS code and employment size class
  – Based on publicly available data from Census, EPA, and DOE
Data Set Implications for Analysis

• Heat load shape archetypes will be used in conjunction with annual energy data (process heat data set) to estimate hourly heat demand for the average facility by
  – County
  – Industry (NAICS code)
  – Employment size class
• This heat demand will then be allocated to individual unit processes with unit process models
  – Bottom-up and Top-Down effectively checked
Accessing Data Sets

Data submitted to NREL Data Catalog and available for download soon!

Manufacturing Thermal Energy Use in 2014

The first data set estimates thermal energy use (i.e., fuels combusted for process heating, boilers, and combined heat and power/generation) by end-use, temperature, county, and facility employment size class for U.S. manufacturing industries in 2014. The estimation methodology build off of prior estimates of industrial energy use (https://doi.org/10.7714/15.1491), which are based on hourly energy input from the 2014 U.S. Industrial Fuel Consumption Survey (https://www.eia.gov/energy-industry/industry-profiles/manufacturing/).

The second data set estimates hourly heat load (as a test for use on the energy source of industrial boilers and combined heat and power/generation plants, from LEAP's Air Markets Program Data (https://amps.ea.gov/amps.php), weekly operating hours in 2014 from Census Quarterly Survey of Plant Capacity Utilization (https://www.census.gov/energy/energy/leap/gas/gas.html), and annual production hours reported by assessments conducted by Industrial Assessment Centers (https:// Leia.energy/).

2 Resources

<table>
<thead>
<tr>
<th>Name</th>
<th>Size</th>
<th>Type</th>
<th>Resource Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating_burner_temperature_and_feedback.polar</td>
<td>25.96 MB</td>
<td>Archive</td>
<td>Parquet file partitioned by FIPS county code, compressed int, gzip.</td>
</tr>
</tbody>
</table>

Keywords

- NREL
- energy
- data
- manufacturing
- boilers
- process heat
- temperature
- thermal energy
- CHP
- generation

Submitted

National Renewable Energy Laboratory

Submitted by Colin McMillan, ORCID ID: 0000-0001-8346-475X

Authors

- Colin McMillan, National Renewable Energy Laboratory, ORCID ID: 0000-0001-8346-475X

License

Cite this dataset:


Accessions: 118
Process Heat Demand by Temperature for U.S.

2/3 of demand is for temperatures <300°C i.e. => Very suited for solar thermal
The ten largest industries account for nearly 70% of total manufacturing process heat use

<table>
<thead>
<tr>
<th>Industry</th>
<th>Process Heat Use (TBtu)</th>
<th>Portion of Total Process Heat Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum Refineries</td>
<td>2205</td>
<td>20%</td>
</tr>
<tr>
<td>Ethyl Alcohol Manufacturing</td>
<td>899</td>
<td>8%</td>
</tr>
<tr>
<td>Paper (except Newsprint) Mills</td>
<td>876</td>
<td>8%</td>
</tr>
<tr>
<td>Paperboard Mills</td>
<td>803</td>
<td>7%</td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
<td>601</td>
<td>5%</td>
</tr>
<tr>
<td>All Other Basic Organic Chemical Manufacturing</td>
<td>593</td>
<td>5%</td>
</tr>
<tr>
<td>Pulp Mills</td>
<td>503</td>
<td>5%</td>
</tr>
<tr>
<td>Plastics Material and Resin Manufacturing</td>
<td>466</td>
<td>4%</td>
</tr>
<tr>
<td>Petrochemical Manufacturing</td>
<td>378</td>
<td>3%</td>
</tr>
<tr>
<td>Other Basic Inorganic Chemical Manufacturing</td>
<td>355</td>
<td>3%</td>
</tr>
</tbody>
</table>
- Solar thermal can readily provide Renewable Heat for driving chemical processes
  - NREL currently working with a company on CH\textsubscript{4} and CO\textsubscript{2} conversion via solar thermal (to CO and H\textsubscript{2})

- Key chemical industries target:
  - Significant portions of low-temperature heat in Ethyl Alcohol and Chemical Manufacturing
  - Cement
  - Plastics and Petrochemicals
High Temperature R&D Pathways and Thermal Energy Storage (TES)

Insights into R&D paths for high temperatures
High Temperature Reactors for Industry

- **Overview**
  - *High temperature Solar-Heated Reactors for Industral Production of Reactive Particulates (SolPart)*
  - Summary/Objective: Develop, at a pilot scale, a high temperature (800-1000°C) 24h/day solar process for particle treatment in energy intensive non-metallic minerals’ industries
  - Key industries targeted: Cement, Lime, Phosphate Processing
  - Location: France
  - Timeline: 3yrs (ending in Dec. 2019)
  - Temperature: Solid particles at 800 - 1000°C, 950°C operation
  - *Solid particle heat exchangers exist today*

- **Funding**
  - Total = €4.6M (~$3.8M)

- **Partners**
  - CEMEX (Large cement producer)
  - DLR (German Aerospace Division)
  - CNRS (French National Research Center)

- **Significance and Impact**
  - 60 to 100% reduction in fossil fuels with solar heat
  - Cutting the greenhouse gas emissions by 40-60%
  - TRL from 4 => 5 or 6
  - Pilot built and results being disseminated

*Prototype fluidized bed reactor*
Long-Duration Energy Storage (LDES)

- **Overview**
  - *Economic Long-duration Electricity Storage by Using Low-cost Thermal Energy Storage and High-efficiency Power Cycle (ENDURING)*
  - Summary/Objective: Develop the ENDURING system & components for LDES to support grid resilience/security
  - => Applicable for industry
  - Location: USA
  - Timeline: 3yrs (Ending in 2021)
  - Temperature: Solid particles > 1000°C

- **$ amount**
  - Total = $2.8M; NREL budget = $1.6M

- **Partners**
  - NREL (Prime)
  - GE Global Research; Purdue University; Allied Minerals

- **Significance and Impact**
  - ENDURING system uses stable, inexpensive solid particles to store large-scale thermal energy (Fluidized Sand)
  - ENDURING LDES system provides power for several days

ARPA-E and NREL
Fast Charging Thermal Energy Storage

Overview
- High-efficiency, fast charging/discharging latent heat thermal energy storage system (TESS)
- Summary/Objective: TESS is a “thermal battery” developed originally for storing heat from solar thermal applications.
- Location: USA
- Timeline: 2yrs (Ending in 2021)

$ amount
- Total = $0.38M

Partners
- Argonne National Laboratory (Prime)
- Capstone Turbine Corp

Significance and Impact
- TESS incorporates a phase change material (PCM) in a high thermal conductivity porous preform, resulting in enhanced thermal performance
- Fast charging/discharging
- Tunability for specific applications through the selection of appropriate PCM.
- TESS’s high thermal energy density results in a small footprint. => Applicable for industry
Analysis for Solar IPH on-going

Insights into R&D paths for high temperatures
• Process parity is the point at which the levelized cost of heat (LCOH) from solar is equivalent to the levelized cost of heat from other sources, e.g. fuel
• Estimating process parity requires expanding datasets and carrying out detailed process level modeling.
Where Potential Meets Demand

- Locations of food processing across California with solar-thermal energy potential
- Use the NREL System Advisor Model (SAM) and other analysis tools, to model systems (e.g. solar IPH) and determine locations with good potential

- Central Valley provides good resource and industry proximity
- Industries such as Fruit and Veg clustered together in good thermal potential areas and with nearby available land

Example: Energy Profile of Brewing in the U.S.

- **Beverage sector**
  - ~43 TBtu for boiler and process heat
  - ~84% natural gas

- **Thermal demands by temperature**
  - Washing (70°C)
  - Cooking (100°C)
  - Mashing (70°C)
  - Brewing (100°C)
  - Drying (100°C)
  - Pasteurizing (65°C)

FY20

• Year 1 complete, Year 2 (FY20 ongoing)
• Technical opportunity mapping
  – Analysis at the county level that estimates how much process heat demand could be met with solar
  – Will consider temperature needs, hourly demand, general facility size, solar resource availability, and some land use constraints
• Process parity analysis
  – Deep-dive case studies that explore technologies and cost drivers, as well as non-energy benefits
  – Technology and industry selection informed by technical opportunity analysis, other input (e.g., TRP members)
• TRP engagement
  – Input and review on analysis methodology and results, including case study selection
  – Input on possible year 3 analysis ideas or pilot demonstration projects
Thank you!
Parthiv.Kurup@nrel.gov

www.nrel.gov

Publication Number

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.
Backup
Global Distribution of all Industry types

- Pharmaceutical products and preparations
- Beverages
- Chemicals and chemical products
- Electrical equipment
- Food products
- Furniture
- Leather and related products
- Machinery and equipment n.e.c.
- Metals
- Motor vehicles, trailers and semi-trailers
- Non-metallic mineral products
- Other manufacturing
- Other transport equipment
- Paper and paper products
- Rubber and plastic products
- Textiles
- Tobacco products
- Wearing apparel
- Wood, cork, straw and plaiting materials

Food and Beverage Industries

- Animal feed
- Bakery
- Beverages
- Dairy
- Fish
- Fruit and Vegetables
- Grain mill and starches
- Meat
- Vegetable and animal oils
- Other

U.S. distribution of industry types

- Food products, 9
- Beverages, 4
- Textiles, 1

Number of plants
Cleaning, drying, and pasteurization among most common unit processes
Case Studies by Collector Type and Total Investment

- Flat plate collectors are most used, followed by parabolic trough and evacuated tube collectors.

- Ranges of total investment, excluding VAT, by region per installed collector area (gross):

<table>
<thead>
<tr>
<th>Region</th>
<th>Europe</th>
<th>Asia</th>
<th>Middle East &amp; Africa</th>
<th>North America</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum (€/m²)</td>
<td>117</td>
<td>29</td>
<td>414</td>
<td>73</td>
</tr>
<tr>
<td>Maximum (€/m²)</td>
<td>2,191</td>
<td>1,363</td>
<td>957</td>
<td>1,204</td>
</tr>
</tbody>
</table>
Methods and Goals

• Model the heat demand from unit processes in the manufacturing industries
• Use bottom-up approach, modeling heating requirements at process level
• Start with food and beverage industries and apply method to others that have higher temperature requirements and capacities later
Models for Food and Beverage Industries

Unit processes evaluated with thermodynamic models so far:

- Blanching/Cooking
- Evaporation
- Dehydration
- Pasteurization
- Frying
- Baking/Roasting

<table>
<thead>
<tr>
<th>Sector</th>
<th>Process</th>
<th>Temperature Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foods &amp; beverages</td>
<td>Blanching</td>
<td>60–100</td>
</tr>
<tr>
<td></td>
<td>Scalding</td>
<td>45–90</td>
</tr>
<tr>
<td></td>
<td>Evaporating</td>
<td>40–130</td>
</tr>
<tr>
<td></td>
<td>Cooking</td>
<td>70–120</td>
</tr>
<tr>
<td></td>
<td>Pasteurization</td>
<td>60–145</td>
</tr>
<tr>
<td></td>
<td>Smoking</td>
<td>20–85</td>
</tr>
<tr>
<td></td>
<td>Cleaning</td>
<td>60–90</td>
</tr>
<tr>
<td></td>
<td>Sterilization</td>
<td>100–140</td>
</tr>
<tr>
<td></td>
<td>Tempering</td>
<td>40–80</td>
</tr>
<tr>
<td></td>
<td>Drying</td>
<td>40–200</td>
</tr>
<tr>
<td></td>
<td>Washing</td>
<td>30–80</td>
</tr>
</tbody>
</table>
• Pasteurization for milk production with plate heat exchanger
Thermodynamic models

• For pasteurization with a continuous plate heat exchanger

• Populate the model with typical values for product (e.g. fluid milk)

\[ Q = m\rho C_p \Delta T t \]

\[ \Delta T = (72-7)\degree C \quad C_p = 3.9 \text{ kJ/kg/}\degree C \quad \rho = 1030 \text{ kg/m}^3 \quad m = 0.0015 \text{ m}^3/\text{s} \quad t=15 \text{ s} \]

• Process characteristics and data collected during literature review

• Estimate steam requirement for unit process, the minimum kJ steam/kg of milk processed

Fellows, P.J. Food processing technology. 2009.
Production and plant data

• Determine steam requirement from production at state level (e.g. California)

2.4 billion kg, fluid milk produced
38 fluid milk plants in CA
63 million kg/plant → 16 million MJ/plant
3629 hr operating/yr → 1220 kW/plant
Review article status

• Received comments from TRP members in mid-September

• Submitted to the journal, *Energy*, earlier this month

• Currently under review
Hourly Heat Load Shapes

• Problems:
  – Matching heat demand to solar technologies requires knowing when demands occur
  – No known publicly available data source for sub-annual heat use

• Goal: develop a parameterized approach for estimating heat load shape archetypes and capturing heterogeneity of manufacturing operations (current parameters are NAICS, operating schedule, and size)
We devised an approach to estimate hourly heat load shape archetypes based on publicly-available data.
EPA Example Hourly Heat Load by Month and Day Type

EPA data used to identify typical load shapes by operating schedule and are not distinguished by NAICS or combustion unit type at this point.
Example Heat Load Shape: Animal Food Manufacturing

Uncertainty in weekly operating hours captured by confidence intervals