Solar Energy for Industrial Rooftops: An Economic and Environmental Optimization

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Solar Energy for Industrial Rooftops: An Economic and Environmental Optimization

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Energy systems/ Sustainable manufacturing

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Solar Energy for Industrial Rooftops: An Economic and Environmental Optimization

Photovoltaic PV [1]

Solar Thermal ST [2]

Compact linear Fresnel Collector [3]

PVT Collector [4]
Industrial Energy Demand

- **Transport Residential Commercial, 46%**
- **Industrial Processes, 54%**
  - Heat: 85 EJ
  - Electrical: 44 EJ
  - Low Temperature <100°C, 30%
  - Medium Temperature (100-400)°C, 27%
  - High Temperature >400°C, 43%

- **Industrial Processes: 129 EJ**
- **Other: 110 EJ**

**Low: 25.5 EJ**
**Medium: 23 EJ**
**High: 36.5 EJ**
Research Question: What is the right mix of technologies for industrial rooftops?

– Important Factors:
  • *Medium and high temperatures heat* are needed.
  • Environmental emissions reductions, (global variation in climate)
  • Limited rooftop space
  • Economics

Approach: Investigate global trade-offs to find an optimum solar technology mix using transient performance and life cycle analysis.

– Note: The ratio can be optimized based on many objectives (and there’s no prior literature to date on this topic)
Aims

• The right mix of the solar technologies for industrial applications
  – Technologies
    • Solar thermal
    • Photovoltaic
    • Photovoltaic + solar thermal
  – Objectives
    • Annual performance
    • Embodied energy
    • Embodied emissions
    • Economic (levelized cost of energy)
• A comparison between locations that has different irradiation and beam component.
Application - Process

• The annual performance of a sterilization process that requires steam at 134°C outlet temperature was modelled using TRNSYS.

• The collector output was maintained at 180°C to drive a heat recovery steam generator (HRSG).
System model (TRNSYS schematic diagram)
Side-by-Side PV and ST Systems and Geographical Locations

- ST versus PV was varied from 0-1
- Ratio = \( \frac{Solar\,\,collector\,\,area}{factory\,\,area} \)
- 0 presents a stand-alone PV system
- 1 presents the thermal-only system.
**Environmental impacts and savings analysis**

<table>
<thead>
<tr>
<th>Location</th>
<th>Installation capital cost ratio [%]</th>
<th>ST including Installation ($/m²)</th>
<th>PV panels with installation $/W (IRENA [8]) $/m² LCOE $/kWh_e [8]</th>
<th>Solar technologies estimated costs (including installation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>7.26</td>
<td>370</td>
<td>1.168 201 0.1059 0.084</td>
<td>ST-Embodied GHG_e (kg/m² aperture) 1.68 556 9 [Beijing ETS] 61.84</td>
</tr>
<tr>
<td>Australia</td>
<td>43.89</td>
<td>496</td>
<td>1.567 270 0.1026 --</td>
<td>PV-Embodied GHG_e (kg/m² aperture) 595 68 [Japan] 69.72</td>
</tr>
<tr>
<td>US</td>
<td>50</td>
<td>518</td>
<td>2.678 461 0.1545 0.112</td>
<td>CT or ETS ($/tonne) 15.10 461 66.74</td>
</tr>
</tbody>
</table>

**5 years average interest rates for several countries with interest variation**

<table>
<thead>
<tr>
<th>Location</th>
<th>Average interest rate</th>
<th>Minimum interest rate</th>
<th>Maximum interest rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>5.1</td>
<td>4.4</td>
<td>6</td>
</tr>
<tr>
<td>Australia</td>
<td>5.9</td>
<td>5.2</td>
<td>7</td>
</tr>
<tr>
<td>US</td>
<td>3.3</td>
<td>3.2</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**Environmental impacts of solar technologies**

**Global average annual Natural gas price variation**

![Graph showing global average annual Natural gas price variation](image)
Objective Functions

1. \( SF = \frac{Load(GJ_{th})-Aux(GJ_{th})}{Load(GJ_{th})} \)

2. \( EE\ PBT = \frac{EE(GJ_{th})}{SF*Load(GJ_{th}/year)} \)
   - \( EE = 2.62\ ST_{area} + 2.66\ PV_{area};\ EE_{ST} = 2.62\ GJ_{th}/m^2,\ EE_{PV} = 2.66\ GJ_{th}/m^2 \)

3. \( GHG_e\ PBT = \frac{Embodied\ GHG_e(kgCO2_{eq})}{SF*Load(GJ_{th}/year)*NG_e[\frac{kgCO2_{eq}}{GJ_{th}}]} \)
   - \( EGHG_e = PV_{CO2_{eq}}\left(\frac{kgCO2_{eq}}{m^2}\right) \cdot PV_{area} + ST_{CO2_{eq}}\left(\frac{kgCO2_{eq}}{m^2}\right) \cdot ST_{area} \)

4. \( LCOE($/(kWh_{th}) = \frac{System\ cost}{\sum_{t=1}^{LT} SF*Load(GJ_{th})/(1+i)^t} \)

5. \( LCC_{LCOE}($/(kWh_{th}) = \frac{LCC}{\sum_{t=1}^{LT} 0.0036*SF*Load(GJ_{th})/(1+i)^t} \)
   - \( System\ Cost = PV_{area}\ Cost_{PV} + ST_{area} \cdot Cost_{ST} \)
   - \( LCC = EE(GJ_{th}) \cdot NG \left(\frac{$}{GJ_{th}}\right) + EGHG_e(KgCo2_{eq}) \cdot CT \left(\frac{$}{KgCO2_{eq}}\right) + \text{system Cost ($)} \)
Optimization Flow Chart

1. Industrial Load
   - Weather Data
   - System Energy Simulation
   - Key Inputs
2. TRNSYS Environment
3. Design Parameters
4. Genopt Environment
5. Output Parameters
6. Select Optimization algorithm
7. Stopping Criteria Satisfied?
   - Yes: End
   - No: Update design variables
8. Cost Function
   - Technical Function
   - Environmental Function
Optimization Results

Optimum solar technology mix in various locations based on the performance objective function

Optimum solar technology mix in various locations based on the embodied objective functions: (A) Embodied energy function; (B) Embodied emission function
Optimization Results

Optimum solar technology mix in various locations based on cost functions:
(A) Levelized cost of energy; (B) Life cycle levelized cost of energy
Optimization Results – Cost variation

Economical objective function optimum distribution with ST to PV cost variation
System model (flow diagram)

- FU: Heat output per unit area
Multi-objective Optimization Results

Worldwide Profiling

- Irradiation
  - Beam radiation
  - 2472
  - 1981
  - 1490

- DNI
  - 0.83
  - 0.60
  - 0.37

- Temperature
  - 29.2
  - 22.2
  - 15.2

- Ratio
  - optimum ST/ Area ratio
  - \( \frac{ST \text{ area}}{Available \text{ area}} \)
Multi-objective Optimization Results

Optimization summary - Ratio of ST area to mixed solar system area
References

Cost Analysis

\[ X_{eq, PBT} = 1 - \frac{x}{SF} \]

\[ x = \frac{Total\ cost \times i(\%)}{Total\ savings\ (\$)} \]
$X_{eq\_IRR} = \frac{Annual\ savings}{Total\ cost}$
Initial Work-1\textsuperscript{st} Year

Solar thermal circuit flow diagram
Model validation/Tolerance

![Graph showing energy gains, losses, and tolerance across months]

- Energy (J) is measured on the y-axis, ranging from 0.00E+00 to 1.60E+08.
- Tolerance (%) is on the right y-axis, ranging from 0.00% to 0.90%.
- The graph compares energy gains (blue), losses (red), and tolerance (green) across months (Jan to Dec).

The graph indicates fluctuating energy values and tolerance percentages across different months.
\[ \Pi = F' \, \tau \alpha * IAM - c_1 \left( \frac{T_{avg} - T_a}{Gt} \right) - c_2 \left( \frac{(T_{avg} - T_a)^2}{Gt} \right) \cdot \left( \frac{G_b}{Gt} \right) \]
Incident angle modifier

Annual efficiency comparison
Parametric Study

The annual performance of a sterilization process that requires steam at 134°C outlet temperature was compared using TRNSYS software:

The collector output was maintained at 180°C to drive a heat recovery steam generator (HRSG).

1) Four different solar collectors for.
2) Six different transient load profiles.
3) Two tank configurations
4) Two controller methods.

Finally, all (4x6x2x2 = 96) systems were compared for two Australian locations, Sydney and Alice Springs (96x2 = 192).
2\textsuperscript{nd} year: Beam split PVT system

- Technology purpose
- PV performance
- Thermal collector performance
- Operating temperature
- Available literature (four filter designs)

Beam splitting strategy - from

<table>
<thead>
<tr>
<th></th>
<th>Wavelength range (nm)</th>
<th>Ratio- ST absorbed radiation</th>
<th>PV cell efficiency rise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crisostomo et al.</td>
<td>732-1067</td>
<td>71.5%</td>
<td>9%</td>
</tr>
<tr>
<td>Sabry et al.</td>
<td>450-920</td>
<td>41%</td>
<td>6%</td>
</tr>
<tr>
<td>Liu et al.</td>
<td>590-1082</td>
<td>51%</td>
<td>12.5%</td>
</tr>
<tr>
<td>Kandilli</td>
<td>400-800</td>
<td>46%</td>
<td>10%</td>
</tr>
</tbody>
</table>
Filter bandwidth effect on ‘uncoupled’ PV/T splitting collector output (bars, which correspond to the left y-axis) and solar contribution (lines, with correspond to the right y-axis) for two PV cell types (White background- Alice Springs, black background- Santiago)

DNI ratio and system contribution for different beam split technologies
Embodied energy requirements for solar silicon PV panels processes

![Embodied energy requirements for solar silicon PV panels processes](image)

**Case study [N°]**

- **Required energy (GJ/m²)**

**Equipment manufacturing**
- **Overhead operations**
- **Cell, module processing**
- **Substrate and encapsulation**
- **Cell material**
- **Frame**
- **Module Assembly**
- **Wafer Process**
- **CZ Process**
- **MG-Si**
- **Si Feedstock**
Some of the industrial processes required temperature range

<table>
<thead>
<tr>
<th>Industry</th>
<th>Process</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food &amp; Beverage</strong></td>
<td>Evaporating</td>
<td>40 – 130</td>
</tr>
<tr>
<td></td>
<td>Sterilisation</td>
<td>100 – 140</td>
</tr>
<tr>
<td></td>
<td>Drying</td>
<td>40 – 200</td>
</tr>
<tr>
<td></td>
<td>Cooking</td>
<td>70 – 120</td>
</tr>
<tr>
<td><strong>Tinned food</strong></td>
<td>Sterilization</td>
<td>110 – 120</td>
</tr>
<tr>
<td><strong>Textile</strong></td>
<td>Colouring</td>
<td>40 – 130</td>
</tr>
<tr>
<td><strong>Paper</strong></td>
<td>Bleaching</td>
<td>130 – 150</td>
</tr>
<tr>
<td></td>
<td>Drying</td>
<td>95 – 200</td>
</tr>
<tr>
<td><strong>Metal</strong></td>
<td>Drying</td>
<td>60 – 200</td>
</tr>
<tr>
<td><strong>Bricks curing</strong></td>
<td>Curing</td>
<td>60 – 140</td>
</tr>
<tr>
<td><strong>Plastics</strong></td>
<td>Separation</td>
<td>200 – 220</td>
</tr>
<tr>
<td></td>
<td>Drying</td>
<td>50 – 150</td>
</tr>
<tr>
<td><strong>Chemical</strong></td>
<td>Soups</td>
<td>200 – 260</td>
</tr>
<tr>
<td></td>
<td>Distillation</td>
<td>100 – 200</td>
</tr>
<tr>
<td></td>
<td>Cooking</td>
<td>85 – 110</td>
</tr>
<tr>
<td></td>
<td>Compression</td>
<td>110 – 170</td>
</tr>
</tbody>
</table>
Boundaries - System Level

Solar Technologies

- Photovoltaic only (PV)
  - Mono crystalline
  - Poly crystalline

- Solar Thermal only (ST)
  - Concentrated Linear Fresnel collector

- Photovoltaic Thermal (PVT)
  - Coupled PVT
  - Uncoupled beam - Split PVT
  - Side by side PV - ST

Inverter

Circulating pump

Installation - pipes

Thermal resistance or Solar assisted heat pump

Installation
PV manufacturing and inventory data
Methods/Approaches