Solar Thermal Technology & Applications

NAEMI Solar Electric & Thermal Training Workshop

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NREL

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Outline

Solar Water Heating

Solar Air Heating
Building Hot Water Energy Use
average 125 kbtu/sf/year

Energy for Water Heating
kBtu/sf/year
Office 8.7
Mercantile 5.1
Education 17.4
Health Care 63.0
Lodging 51.4
Pub Assembly 17.5
Food Service 27.5
Warehouse 2.0
Food sales 9.1
Public Safety 23.4
Other 15.3
All Buildings 13.8
Renewables go hand-in-hand with Energy Efficiency
Solar Water Heating Is Not New!

- Before the advent of gas pipelines and electric utilities, the technology gained footholds in Florida and California before the 1920’s
- Over 1,000,000 systems are in use in American homes and business
- The technology is in widespread use in:
  - Caribbean basin
  - Israel
  - Japan
  - China
  - Greece
  - Australia
Technical And Economic Viability Of A Solar System Depends Upon:

- Amount of annual sunshine
- Capital cost of the solar system
- Prices of conventional fuels
- Solar system annual O&M cost
- Annual energy requirement and energy use profile
- Temperature of hot water
- Rate at which conventional fuels are escalating in price
- Other (e.g. legislative mandates, tax credits)
Solar Hot Water is Worth Investigating When:

1. Hot water is used in large amounts, daily (absolutely or in terms of gallons per person per day) -- 365 days per year
2. Hot water is produced using electricity and it costs at least $0.055/kwh, or hot water is produced using gas or oil costing at least $8.00/million BTU
3. Tax credits or rebates are available
4. The building is properly oriented with respect to the sun
5. Space is available (on the roof?) for the solar panels
6. There is no need to worry about aesthetics
7. Good-to-excellent solar resource
Solar Thermal Applications

• **Low Temperature (> 30°C)**
  – Swimming pool heating
  – Ventilation air preheating

• **Medium Temperature (30°C – 100°C)**
  – Domestic water and space heating
  – Commercial cafeterias, laundries, hotels
  – Industrial process heating

• **High Temperature (> 100°C)**
  – Industrial process heating
  – Electricity generation

• **Solar thermal and photovoltaics working together**
Technology Overview

• **Low-temperature collectors:**
  – Unglazed mats for water heating.
  – Perforated plates for air preheating.

• **Mid-temperature collectors:**
  – Glazed and insulated collectors.

• **High-temperature collectors:**
  – Evacuated tubes.
  – Focusing collectors.
Collector Types

Unglazed EPDM Collector

- Extruded "Mat" with Flow Passages
- Flow from Manifold Through Passages

Flat Plate

- Single or Double Glazing
- EPDM or Equivalent Grommet
- Box
- Flow Passages
- Absorber Plate
- Backing
- Temperature Tolerant Insulation

Evacuated Tubes

- Return Tube
- Supply Tube
- Glass Envelope
- Absorber Tube
- Reflector

Parabolic Trough

- Concentrator Reflective Surface
- Receiver
- Tracking Mechanism
Additional layers of glass improve insulation but increase reflection losses.

Orientation is important.
Which collector is best depends on the temperature...

Efficiency = % of solar captured by collector

- Unglazed are best for ~0 to 10°C above ambient (87% efficiency)
- Flat-plate are best for ~10°C to 50°C above ambient (70% efficiency)
- Evacuated tubes are best for more than 50°C above ambient (50% efficiency)

Stagnation Temperature Above Ambient

Temperature above ambient (°C) vs. solar radiation (W/m²)
Solar Rating and Certification Corp.

Contact information
Solar Rating and Certification Corporation
c/o FSEC, 1679 Clearlake Road
Cocoa, FL 32922-5703
Voice (321)638-1537
Fax (321)638-1010
E-mail: srcc@fsec.ucf.edu

- An independent nonprofit organization that tests performance and certifies almost every solar heater on the market today.
- Reports efficiency and annual performance for different climates and temperature uses.
Typical Low Temperature Application
Low Temperature Example:
Barnes Field House, Fort Huachuca, AZ

- 2,000 square feet of unglazed collectors
- 3,500 square feet indoor pool
- Installed cost of $35,000
- Meets 49% of pool heating load
- Saves 835 million Btu/year of natural gas
- Annual savings of $5,400
- Installed by the Army in June, 1980.
Mid-Temperature Example:
Chickasaw National Recreation Area, OK

Small Comfort Stations
- 195 square feet of flat plate collectors
- 500 gallon storage volume
- Cost $7,804
- Delivers 9,394 kWh/year
- Saves $867 / year

Large Comfort Stations
- 484 square feet of flat plate collectors
- 1000 gallon storage volume
- Cost $16,100
- Delivers 18,194 kWh/year
- Saves $1,789 / year
Mid Temperature Example:
USCG Kiai Kai Hale Housing Area, Honolulu HI

- 62 units installed 1998
- Active (pumped), Direct systems
- Average cost $4,000 per system
- 80 sf per system
- $800 per system HECO rebate
- Savings of 9,700 kWh/year and $822/year per system
- Simple Payback 4 years (with rebate)
USCG Housing, Honolulu HI

![Graph showing average hourly power per house with and without solar energy.](chart.png)

- **Y-axis**: Average hourly power per house (kWh/hour/house)
- **X-axis**: Time of day (hours)
- **Legend**:
  - With Solar
  - Without Solar

The graph illustrates the energy consumption pattern throughout the day with and without solar energy, highlighting the potential energy savings and efficiency gains from integrating solar technology.
High Temperature Example:
Phoenix Federal Correctional Institution

- 17,040 square feet of parabolic trough collectors
- 23,000 gallon storage tank
- Installed cost of $650,000
- Delivered 87.1% of the water heating load in 1999.
- Saved $77,805 in 1999 Utility Costs.
- The prison pays IST for energy delivered by the solar system at a rate equal to 90% of the utility rate (10% guaranteed savings), over 20 years.
High Temperature Example: Phoenix Federal Correctional Institution

Month Energy and Cost Savings

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<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
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Simple Evaluation Procedure

- Estimate Daily Water Heating Load
- Determine Solar Resource
- Calculate Solar System Size
  - meet load on sunniest day
  - undersize rather than oversize
- Calculate Annual Energy Savings
- Calculate Annual Cost Savings
- Estimate System Cost
- Calculate Savings-to-Investment Ratio and Simple Payback Period
Daily Water Heating Energy Load

\[ L = MC (T_{\text{hot}} - T_{\text{cold}}) \]

\( L = \) Daily Hot Water Energy Load (kWh/day)

\( M = \) mass of water per day (kg/day),
3.785 kg/gallon

\( C = \) specific heat of water =
0.001167 kWh/kg°C

\( T_{\text{hot}} = \) hot water delivery temperature (°C),
often 50 °C = 120 °F

\( T_{\text{cold}} = \) cold water temperature (°C),
often 13 °C = 55 °F

Typical Hot Water Usage:

- Dormitory 13 gal/day/person
- Motel 15 gal/day/unit
- Hospital 18 gal/day/bed
- Office 1 gal/day/person
- Food Service 2.4 gal/meal
- Residence 40 gal/day/person
- School 1.8 gal/day/student
Solar Energy Resource

- Collectors should face south (in northern hemisphere)
- Tilt Angle=latitude maximizes annual gain (lat+15° for winter, lat-15° for summer)

<table>
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<th>Location</th>
<th>I Max</th>
<th>I Ave (kWh/m²/day)</th>
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<td>San Diego, CA</td>
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<tr>
<td>Seattle, WA</td>
<td>5.7</td>
<td>3.7</td>
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For COMPLETE data on hundreds of sites, check out www.nrel.gov
Maximum Daily Solar Radiation Per Month

ANNUAL

Flat Plate Tilted South at Latitude

Collector Orientation

Flat-plate collector facing south at fixed tilt equal to the latitude of the site: Capturing the maximum amount of solar radiation throughout the year can be achieved using a tilt angle approximately equal to the site's latitude.

This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.

Maps are not drawn to scale.
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Solar Water Heating
System Size and Delivery

**Solar Water System Size**

\[ A_c = \frac{L}{\eta_{\text{solar}} I_{\text{max}}} \]

- \( A_c \) = collector area (m\(^2\))
- \( L \) = Daily Load (kWh/day)
- \( \eta_{\text{solar}} \) = efficiency of solar system (typically 0.40)
- \( I_{\text{max}} \) = maximum daily solar radiation (kWh/m\(^2\)/day)

**Annual Energy Saving**

\[ E_s = \frac{A_c I_{\text{ave}} \eta_{\text{solar}}}{\eta_{\text{boiler}}} \times 365 \]

- \( I_{\text{ave}} \) = average solar radiation (kWh/m\(^2\)/day)
- \( \eta_{\text{boiler}} \) = auxiliary heater efficiency
  - gas = 0.43 to 0.86, assume 0.57
  - electric = 0.77 to 0.97, assume 0.88
  - heat pump assume 3.0
  - propane = 0.42 to 0.86, assume 0.57
  - oil = 0.51 to 0.66, assume 0.52

Source: GAMA
Solar System Cost

\[ C = c_{\text{solar}} A_c \]

- \( C \) = Installed Cost of Solar System ($)
- \( c_{\text{solar}} \) = per-unit-area cost of installed solar system ($/m^2), typically
  - $400/m^2 for large system
  - $1000/m^2 for small systems
  - $750/m^2 might be average

Annual Cost Savings

\[ S = E_s C_e \]

- \( S \) = annual cost savings ($/year)
- \( C_e \) = cost of auxiliary energy
  - typically:
    - Electricity $0.084/kWh
Solar Water Heating
System Cost Effectiveness

**Savings-to-Investment Ratio**

\[ \text{SIR} = \frac{S \cdot \text{pwf}}{C} \]

*project is cost effective if SIR > 1.*

\[ \text{pwf} = \text{present worth factor for future savings stream}, = 17.4 \text{ years for 25 year lifetime and 3\% real discount rate (specified by NIST for 2003).} \]

**Simple Payback Period**

\[ \text{SPB} = \frac{C}{S} \]
Example: 4 person residence in Chicago against electricity

- \( M = 4 \text{person} \times 40 \text{gal/person/day} \times 3.785 \text{ kg/gal} = 606 \text{ kg/day} \)
- \( L = MC \left( T_{\text{hot}} - T_{\text{cold}} \right) = 606 \text{ kg/day} \times 0.001167 \text{kWh/kgC} \times (50C - 18C) = 22.6 \text{kWh/day} \)
- For Chicago IL, \( I_{\text{max}} = 5.7 \) and \( I_{\text{ave}} = 4.4 \text{kWh/m2/day} \)
- \( A_c = \frac{L}{\eta_{\text{solar}} I_{\text{max}}} = \frac{22.6 \text{kWh/day}}{0.4 \times 5.7 \text{kWh/m2/day}} = 9.9 \text{m2} \)
- \( E_s = A_c I_{\text{ave}} \eta_{\text{solar}} \frac{365}{\eta_{\text{boiler}}} = 9.9 \text{m2} \times 4.4 \text{kWh/m2.day} \times 0.4 \times \frac{365 \text{days/year}}{0.88} = 6,556 \text{kWh/year} \)
- \( C = c_{\text{solar}} A_c = $1000/\text{m2} \times 9.9 \text{m2} = $9,900 \)
- \( S = E_s C_e = 7,227 \text{kWh/year} \times $0.084/\text{kWh} = $607/\text{year} \)
- \( SIR = S \times pwf / C = $607/\text{year} \times 17 \text{years} / $9,900 = 1.04 \)
- **SO IT IS COST EFFECTIVE!**
Solar Hot Water: Electricity Rate Corresponding to Savings to Investment Ratio = 1

Assumptions:
1. Annual average solar resource potential using a tilt = latitude collector
2. System cost = $900 per sq. m.
3. System efficiency = 40%
4. Present worth factor = 16.66
System Types

• Passive Systems **(no pumps)***
  – Integral Collector Storage
  – Thermosyphon

• Active Systems **(pumps & controls)***
  – Open Loop:
    • Direct
    • Drain Down
  – Closed Loop:
    • Drain Back
    • Antifreeze
Passive, Integral Collector Storage (ICS) Direct System

- Moderate freeze protection (pipes at risk)
- Minimal hard water tolerance
- Very low maintenance requirements
Passive, Thermosyphon, Direct System

- Auxiliary element can also be in tank above collector, eliminating the auxiliary tank altogether.
- No freeze protection
- Minimal hard water tolerance
- Low maintenance requirements
Active, Open-loop, Pumped Direct System

- No freeze protection
- Minimal hard water tolerance
- High maintenance requirements
Active, Closed-loop (antifreeze), Indirect System

- Excellent freeze protection
- Good hard water tolerance
- High maintenance requirements
Active, Closed-loop, Drainback, Indirect System

- Good freeze protection
- Good hard water tolerance
- High maintenance requirements
Tempering Valve to Prevent Scalding: Extremely Important for Safety!
Promising Potential Candidates For Solar Water Heating Systems

1. Residential
   • Single family homes
   • Low-income or subsidized homes and housing developments
   • Apartment buildings with central boilers

2. Commercial
   • Casinos, Hotels and motels
   • Health care facilities
   • Restaurants
   • Spas, pools and health clubs

3. Government
   • Single family housing units
   • Food service facilities
   • Correctional facilities
   • Hospitals and clinics
   • Dormitories
   • Recreational facilities/swimming pools
Procuring Solar Water Heating Systems

• Look for the best opportunities within your Tribe:
  – Large water heating loads.
  – High cost of backup energy.
  – Constant loads throughout week and year.
  – Area for collectors.
  – Facility “champions.”
Requirements for Success

- Appropriate Application (Provide a Reasonable Payback)
- Proven Design
- Freeze Protection
- Properly Sized (undersized, not oversized)
- Require No Manual Intervention
- Operational Indicators or Monitoring

- Conservation First
- Verify Load
- Performance Guarantee
- Require Operations and Maintenance Manual and Training
- Acceptance Test
A Tribal Energy Service Organization (TESO) could bring the following to the table:

- Establish a basis for local economic development
- Save homeowners, renters, and housing departments money
- Help reestablish pride of ownership (personal sovereignty) through energy independence
- Aggregate community for lower-cost financing
- Provide steady employment that goes hand-in-hand with home efficiency and weatherization improvements.
Help in implementing your solar water heating project:

- Solar Energy Industries Association and local chapters.
- Experienced private-sector suppliers & installers.
- National Laboratories.
- State energy offices.
Resources and References

• **American Society of Heating, Air Conditioning and Refrigeration Engineers, Inc.**
  - ASHRAE 90003 -- Active Solar Heating Design Manual
  - ASHRAE 90336 -- Guidance for Preparing Active Solar Heating Systems Operation and Maintenance Manuals

• **Solar Rating and Certification Corporation**
  - SRCC-OG-300-91 -- Operating Guidelines and Minimum Standards for Certifying Solar Water Heating Systems
Outline

Solar Water Heating

Solar Air Heating
Objectives

- Explain the operating principle of a transpired solar collector.
- Explain solar ventilation air preheating systems and their appropriate applications.
- Discuss how to assess the viability (cost and performance) of a solar ventilation preheating system at a specific site.
Topical Outline

- Technology Overview
- Cost and Performance
- Examples of Successful Systems
- Requirements for Successful Systems
- Design Considerations
Transpired Collector Principle

- Sun warms the surface
- Heat conducts from surface to thermal boundary layer of air 1 to 3 mm thick
- Velocity boundary layer of air is drawn into hole before heat can escape by convection
Transpired Collector Principle

- Efficient radiant-to-air heat exchanger
- Once-through process, no recirculation to collector inlet.
Solar Ventilation Preheating System

- Fan Unit
- To Distribution Ducting
- Heat Loss Through Wall Brought Back by Incoming Air
- Air Space
- Solar Heat Absorber

y y
Air Temperature Rise versus Solar Radiation

![Graph showing the relationship between Air Temperature and Solar Radiation]

- Labelled lines A through E represent different airflow rates:
  - (A) 1.0 cfm/ft² (0.005 m³/s/m²)
  - (B) 2.0 cfm/ft² (0.01 m³/s/m²)
  - (C) 4.0 cfm/ft² (0.02 m³/s/m²)
  - (D) 5.4 cfm/ft² (0.027 m³/s/m²)
  - (E) 7.0 cfm/ft² (0.035 m³/s/m²)
Summer Operation

- Bypass damper brings outside air directly in, bypassing solar wall.
- The stack effect causes outside air to enter the solar cladding along the bottom and rise to the top where it exits through holes in the outer skin.
- The net result is that any unwanted solar gain will be transferred to the air and not to the interior of the wall. (collector shades the south wall)
- Sun is higher in the sky in summer, shines primarily on the roof, not on the south wall.
Typical Applications

- Preheating ventilation air for:
  - Industrial and maintenance buildings.
  - School and institutional buildings.
  - Apartment buildings.
  - Commercial and penthouse fans.
  - Aircraft hangars.
- Crop drying
- Process air heating
When to Consider

- New construction.
- Requirements for outside air and fan intake near south wall (includes penthouse walls--retrofit and new) exist.
- For retrofit, south wall is uninsulated and requires new cladding.
- Available south wall area.
- High ventilation requirements.
- High air quality needed.
…other benefits

- Ventilation air introduced high in high-bay space destratifies air, resulting in lower ceiling and exhaust air heat loss.
- Positive pressure on building reduces incoming drafts, increasing comfort.
- Looks better than an old, dilapidated facade
Advantages of Transpired Collectors

- Very low cost.
- Extremely reliable (no moving parts but fan).
- No maintenance.
- High Efficiency (up to 80%).
- Operates near ambient temperature.
- No problems with freezing or fluid leaks.
- No storage required.
Solar Ventilation
Preheat System Costs

- Installation Costs in Retrofit Applications
  - Absorber: $3.50/ft²
  - Supports, Flashing, Etc.: $2.50/ft²
  - Installation: $4.00/ft²
  - Other Costs: $4.00/ft²
  - Total: $14.00/ft²

- In new construction, subtracting $4 to $7 for displaced facade gives net installed cost of $7 to $10 per ft²
Solar Vent Preheat: Electricity Rate Corresponding to Savings to Investment Ratio = 1

Assumptions:
1. All potential energy savings (kWh per sq. m. per year) are utilized.
2. System cost (retrofit) = $151 per sq. m.
3. Present worth factor = 16.66

U.S. Department of Energy
National Renewable Energy Laboratory
Example: NREL Chemical Storage

- 300 ft$^2$
- Saves 14,310 kWh/year
- 3,000 CFM
- Saves $360/year of electric heat (no flames allowed in building)
- Payback = 4.7 years
Example: Ford Engine Assembly, Canada

- 20,000 ft²
- Saves $30,000/year
  - 17% of plant’s air heating costs
- 5 year payback period
Example: GM Battery Plant, Canada

- 4,520 ft²
- 40,000 CFM
- Saves 940 Mbtu/year
  - Q solar = 678 Mbtu/yr
  - Q htrec = 262 Mbtu/yr
- Saves $10,200/year
- Cost $66,530 ($14.72/ft²), including duct modifications
- Payback period = 6 years
Example: Federal Express Denver, CO

- 5,000 ft\(^2\) (465 m\(^2\)) system
- 45,000 cfm
- Saves 2,300 million BTU/year
- Saves $12,000 per year
- Lease payments $4,800/ year
- FEDEX saves $7,200 /year for the 10 year term of the lease.

Federal Express in Denver
Summary

- More than 1,000,000 square feet of solar ventilation preheat systems installed.
- Multiple systems monitored, including Ford, General Motors, and NREL (63% efficiency over 3 years).
- Computer design program available.