**CACHE Modules on Energy in the Curriculum**

**The Power of Solar Energy**

**Module Title:** Solar Steam Turbine

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**References:**

[1] VIS Industrial Company. *“Condensing Steam Turbine Driven Alternating Generator (1MW),*30 November 2011. Retrieved from: http://vtsindustrial.com/gen.html

[2] Spirax Sarco. *Dry Saturated Steam Line- Steam Table,* 30 November 2011. Retrieved from: http://www.spiraxsarco.com/resources/steam-tables/saturated-steam.asp

[3] Heat Transfer Fluids by Solutia. *Therminol VP-1*, 30 November 2011. Retrieved form: http://twt.mpei.ac.ru/TTHB/HEDH/HTF-VP1.PDF

[4] *Renewable Energy: Power for a Sustainable Future*, 2nd Edition, Oxford University press, 2001, Edited by Godfrey Boyle

[5] *Solar Parabolic Trough*, 30 November 2011. Retrieved from:http://www.solarpaces.org/CSP\_Technology/docs/solar\_trough.pdf

# [6] TLC Green Living Tips, *How many solar cells would I need in order to provide all of the electricity that my house needs?,* 12 December 2012, Retrieved from: http://tlc.howstuffworks.com/home/question418.htm

**Concepts:** Solar power directed at a concentrator can produce significant power levels

**Problem Motivation:**

Concentrated solar power (CSP) collectors such as parabolic troughs, solar towers, or dish/engine systems operate at high temperatures and use a liquid or gas that is then used in a steam or gas turbine to drive an electrical generator. The CSP collector concentrates all of the solar power into one area which results in high temperatures to create steam and electricity.

**Example Problem Statement:** Design a parabolic trough solar power system to make steam to power a 1MW steam turbine.

**Data:**

Siemens steam turbine SST-060 (up to 6 MW)

Inlet pressure [1]: up to 131 bar/ 1,900 psi

Inlet temp dry saturated steam [1]: up to 530 C/ 985 F

Exhaust pressure [1]: back pressure: up to 29 bar/ 420psi or vacuum

Steam Table at 131 bar [2]:

Temperature: 331.45 °C (628.61 °F) (605.136 K)

Specific Enthalpy of Water [2]: 1538.89 kJ/kg (661.6038 Btu/lb)

Specific enthalpy of dry saturated steam [2]: 2657.06 kJ/kg ( 1142.33 Btu/lb)

Difference between water and steam [2]: 2657.06 – 1538.89 = 1118.17 kJ/kg

Temperature of oil leaving solar collector: 390 °C

Specific heat of therminol VP-1 at 345 °C [3]: 2439.5 kJ/ kgK

Efficiency loss of heat from the sun to the collector [4]: 18%

Solar constant: 1000 W/m2

Total hour of sun: 6 hours

Solar trough collector area [5]: 564 m2 (5.7 m wide by 99 m long)

**Example Problem Solution:**

**Part a) Solve for the mass flow rate of steam**:

1MW= mass flow rate of steam (*kg/s*) \* enthalpy difference (*kJ/kg*)\* product of efficiencies of the process

The formula for Carnot efficiency is: *μC = (Ti - To) / Ti*

*where*

*μC =* efficiency of the Carnot cycle

*Ti =* temperature at the engine inlet *(K)*

*To =* temperature at engine exhaust *(K)*

*μC =*(605 K – 298 K)/ 605 K

*μC =* 0.51 or 51%

Conversion of mechanical work into electricity is assumed at 80%.

1MW = 1000 kW, 1 kW = 1 kJ/s

Dividing the power of the converted 1MW by the enthalpy difference and the product of the efficiencies gives us:

Mass flow rate of steam (*kg/s*) $={1000 {kJ}/{s}}/{(1118.17{kJ}/{kg}×\left(0.51 ×0.80\right))}$

Solving the previous equation results in:

Mass flow rate of steam = 2.2 kg/s

**Part b) Solve for the flow rate of oil:**

The steam is formed at 331 oC. Assuming a 15 oC difference in temperature in the steam boiler, the exit oil should be at 346 oC.

Now multiply the mass flow rate of therminol VP-1, the synthetic oil used, by the difference between the enthalpies of water and the steam, to give the energy input rate to produce the steam:

$2.2 {kg}/{s}×1118.17{kJ}/{kg}=2.46 MW$ = 2460 kJ/s

This rate can be set equal to the rate of energy input into the oil, which is the mass flow rate of oil multiplied by the heat capacity of the synthetic oil multiplied by the change in temperature of the oil. This can be rearranged to give the mass flow of oil as:

$2460\frac{kJ}{s}÷\left(2439{kJ}/{kgK}×\left(390-346 C\right)\right)=0.023 kg/s$ = 23 g/s oil.

**Part c) Solve for the number of solar troughs**

The total solar power required is found by dividing the power input to the steam by the efficiency losses from the transfer of heat from the sun to the collector.

$$2460{kJ}/{s}÷0.18=13670{kJ}/{s}$$

Use the insolation to determine the total area of the CSP system needed.

$$1{kW}/{m^{2}}×6 hours=6{kWhr}/{m^{2}}$$

Convert from kWhr/m2 to kJ/m2

$$6 {kWhr}/{m^{2}×(3.6×10^{6}{J}/{kWhr)×1{kJ}/{1000 J}=2.16×10^{4}{kJ}/{m^{2}}}}$$

The total energy needed for a day’s supply of 1 MW of electrical power is.

$$13670{kJ}/{s}×24 hr×3600{s}/{hr}=1.18×10^{9}kJ$$

Divide the required energy by the insolation in kJ/m2 to give the area as:

$$1.18 ×10^{9} kJ÷\left(2.16{×10^{4}kJ}/{m^{2}}\right)=54,666 m^{2}$$

To find how many solar trough concentrators needed divide the needed by the area of the concentrator.

$$54,666 m^{2}÷564 m^{2}per panel=97 troughs$$

**Homework Problem Statement:**

Design a CSP system to power a neighborhood in which 150 average homes with families of four.

**Data:**

Average home energy consumption [6]: 14,400 watt-hours per day