ELG4126- Sustainable Electrical Power Systems- DGD

Economics of Distributed Resources

Maryam Parsa

DGD 06- March 07, 2013

Winter 2013

Outline

- COMBINED HEAT AND POWER (CHP)
  - Energy-efficiency Measures of Combined Heat and Power (Cogeneration)
  - Impact of Usable Thermal Energy on CHP Economics

COMBINED HEAT AND POWER (CHP)

Distributed Generation (DG)

- Produce usable waste heat + electricity
  - Combustion turbines
  - Fuel cells

- Don't produce usable waste heat
  - Photovoltaics
  - Wind turbines

COMBINED HEAT AND POWER (CHP)

Value of waste heat

- Temperature
  - Higher temperature is better!
    - Process steam
    - Absorption cooling
    - Space heating
- Distance from generation to where it will be used
  - Transfer heat: Costly, Wasteful
- Relative timing
- Magnitude of electricity demand and thermal demand
- Cost of the fuel

Outline

- COMBINED HEAT AND POWER (CHP)
  - **Energy-efficiency Measures of Combined Heat and Power (Cogeneration)**
  - Impact of Usable Thermal Energy on CHP Economics

Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

Problem:

- With combined heat and power (CHP), it is a little tricky to allocate the costs and benefits of the plant
  - the value of a unit of electricity is so much higher than a unit of thermal energy, yet both will be produced with the same fuel source.

Solution:

- The simplest approach to describing the efficiency of a cogeneration plant is
  - simply divide the total output energy (electrical plus thermal) by the total thermal input
  - remembering to use the same units for each quantity

Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

$$\text{Overall thermal efficiency} = \left(\frac{\text{Electrical} + \text{Thermal ouput}}{\text{Thermal input}}\right) \times 100\%$$

- Problem of this formula:
  - it doesn't distinguish between the value of recovered heat and electrical output
- Ex.
- a simple 75% efficient boiler that generates no electricity would have an overall thermal efficiency of 75%,
- a cogeneration that delivers 35% of its fuel energy as electricity and 40% of it as recovered heat would also have the same overall efficiency of 75%.
- the true cogeneration plant is producing a much more valuable output

Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

A better way to evaluate CHP:

Compare (in the same unit)

- Cogeneration of heat and power

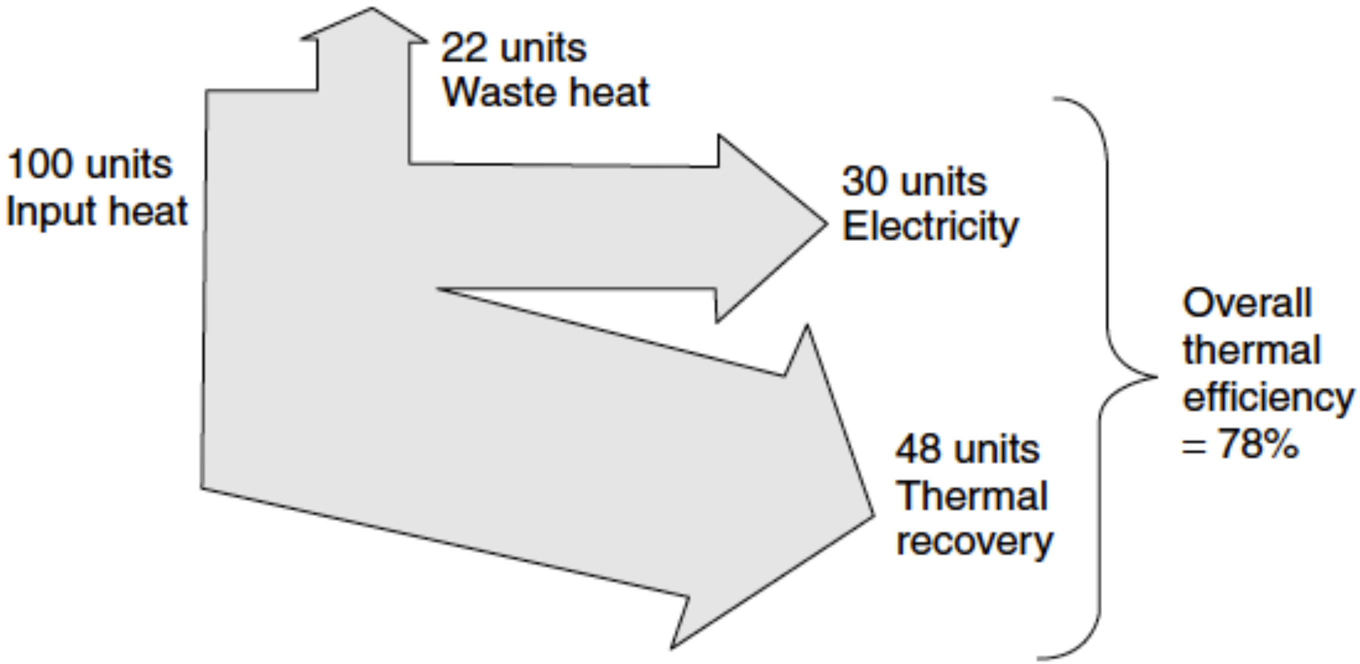
AND

- Generation of electricity in one unit + a separate boiler to provide the equivalent amount of heat

This method, however, requires an estimate of the efficiency of the separate boiler

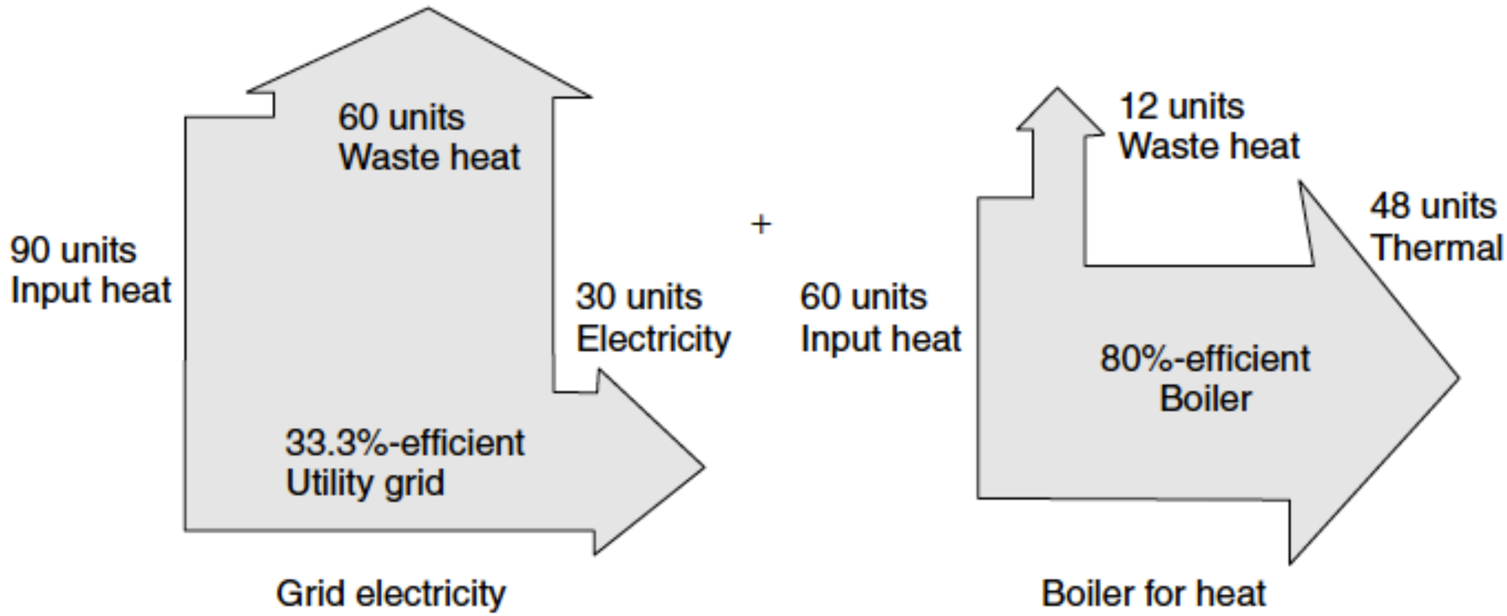
Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

- **Figure 1:** A cogeneration plant with an overall thermal efficiency of 78%



Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

- **Figure 2:** Separate generation of heat in an 80%-efficient boiler, and electricity from the grid at 33.3% efficiency, requires 150 units of thermal input compared to the 100 needed by the CHP plant of Fig. 1



uOttawa

Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

Figure 1:

- CHP plant converts 30% of its fuel into electricity while capturing 48% of the input energy as thermally useful heat, for an overall thermal efficiency of 78%

Figure 2:

- To generate the 30 units of electricity from the grid, at 33.3% efficiency, requires 90 units of thermal energy. And, to produce 48 units of heat from the 80% efficient boiler, another 60 units of thermal energy are required

Conclusion:

- Case 1: 100 unit input, Case 2: 90+60=150 unit input
- With Cogeneration: Saving of one-third

Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

Compare the overall thermal efficiency with and without cogeneration

$$\text{Overall thermal efficiency (with CHP)} = \left(\frac{30 + 48}{100}\right) \times 100\%$$
$$= 78\%$$

$$\text{Overall thermal efficiency (without CHP)} = \left(\frac{30 + 48}{90 + 60}\right) \times 100\%$$
$$= 52\%$$

- By comparing the overall thermal efficiencies, the improvement caused by CHP is easy to determine. The improvement is called the **overall energy savings**

Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

$$\text{Overall energy savings} = \left(1 - \frac{\text{Thermal input with CHP}}{\text{Thermal input without CHP}}\right) \times 100\%$$

- where the two approaches (with and without CHP) must deliver the same electrical and thermal outputs

- For figure 1 and 2:

$$\text{Overall energy savings} = \left(1 - \frac{100}{90 + 60}\right) \times 100\% = 33.3\%$$

uOttawa

Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

From **industrial facility** point of view:

- Under the assumption that the facility needs heat anyway, say for process steam, the **extra thermal input needed to generate electricity** using cogeneration can be described using a quantity called the **Energy-Chargeable-to-Power (ECP)**

$$\text{ECP} = \frac{\text{Total thermal input} - \text{Displaced thermal input}}{\text{Electrical output}}$$

- **Unit:** Btu/kWh or kJ/kWh

Example 1: Cost of Electricity from a CHP Microturbine

Q:

- An industrial facility that needs a continuous supply of process heat is considering a **30 kW microturbine** to help fill that demand. Waste heat recovery will offset fuel needed by its existing 75-percent efficient boiler. The microturbine has a 29% electrical efficiency and it recovers 47% of the fuel energy as usable heat. Find the Energy-Chargeable-to-Power (ECP)

We know:

1 kW = 3412.142 Btu/hr

uOttawa

Example 1: Cost of Electricity from a CHP Microturbine

Anwer:

- Finding the thermal input to the 29 percent efficient, 30 kW microturbine

$$\text{Microturbine input} = \left(\frac{30\ \text{kW}}{0.29}\right) \times 3412\ \text{Btu/kWh} = 352{,}966\ \text{Btu/hr}$$

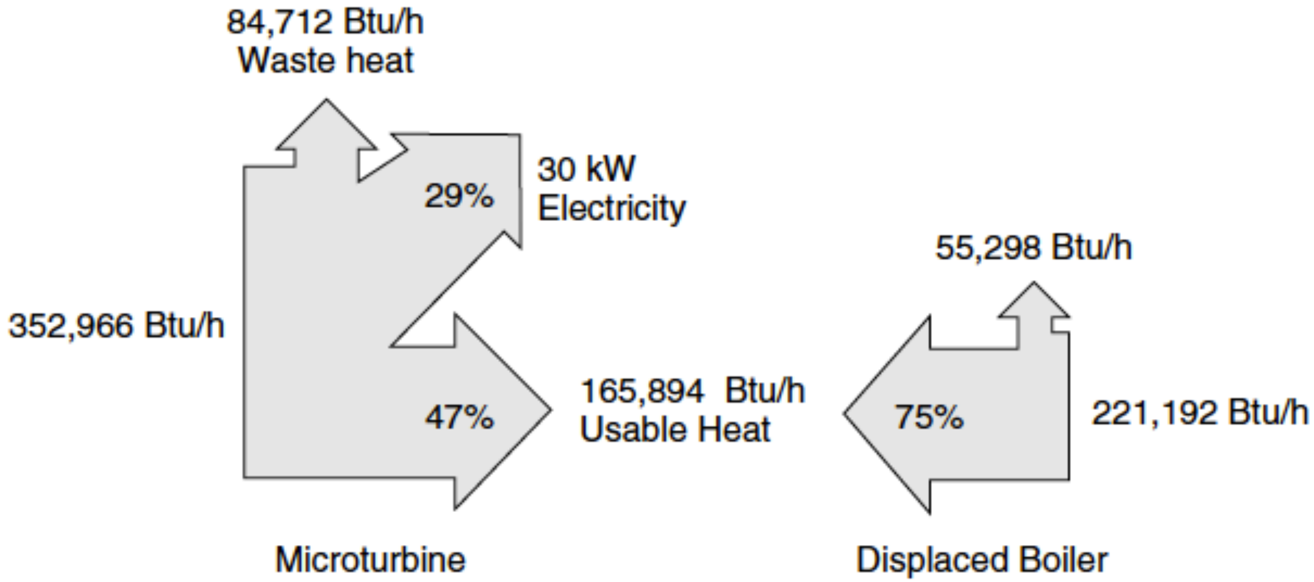
- Since 47 percent of that is delivered as usable heat

$$\text{Microturbine usable heat} = 0.47 \times 352{,}966\ \text{Btu/hr} = 165{,}894\ \text{Btu/hr}$$

- The displaced fuel for the 75 percent efficient boiler will be

$$\text{Displaced boiler fuel} = \frac{165{,}894\ \text{Btu/hr}}{0.75} = 221{,}192\ \text{Btu/hr}$$

Example 1: Cost of Electricity from a CHP Microturbine



$$\text{ECP} = \frac{\text{Extra CHP thermal input}}{\text{Electrical output}} = \frac{(352{,}966 - 221{,}192)\ \text{Btu/hr}}{30\ \text{kW}}$$

$$= 4393\ \text{Btu/kWh}$$

Example 1: Cost of Electricity from a CHP Microturbine

- This 4393 Btu/kWh can be compared with the heat rate of **conventional power plants**, which is typically around 10,300 Btu/kWh. That is, given the need for process heat anyway, it can be argued that **the bonus from CHP is the ability to generate electricity with less than half as much fuel as must be burned at an average thermal power plant.**

Outline

- COMBINED HEAT AND POWER (CHP)
  - Energy-efficiency Measures of Combined Heat and Power (Cogeneration)
  - **Impact of Usable Thermal Energy on CHP Economics**

Impact of Usable Thermal Energy on CHP Economics

- The energy chargeable to power (ECP) depends on
  - the amount of usable heat recovered
  - the efficiency of the boiler or furnace that would have generated the heat had it been provided separately
- When the ECP is modified to account for the **cost of fuel**, a simple measure of the added cost of electricity with cogeneration, called the **operating Cost chargeable to Power (CCP)**, can be found from

$$\text{Cost chargeable to power (CCP)} = \text{ECP} \times \text{Unit cost of energy}$$

- **Unit:** \$/kWh

Example 2. Cost Chargeable to Power for a CHP Microturbine

Q:

- Suppose the 30-kW microturbine in Example 1 costs \$50,000 and has an annual O&M cost of \$1200 per year. It operates 8000 hours per year and the owner uses a fixed charge rate of 12%/yr. Natural gas for the microturbine and existing boiler costs \$4 per million Btu.

  a. Find the operating cost chargeable to power (CCP)
  b. What is the cost of electricity from the microturbine?
  c. If the facility currently pays 6.0¢/kWh for energy, plus demand charges of \$7/kW-mo, what would be the annual monetary savings of the microturbine?

Example 2. Cost Chargeable to Power for a CHP Microturbine

Answer:

a. In Example 1, the energy cost chargeable to power for this microturbine was found to be 4393 Btu/kWh. The cost chargeable to power is

$$\text{Cost chargeable to power (CCP)} = \text{ECP} \times \text{Unit cost of energy}$$

$$\text{CCP} = 4393\ \text{Btu/kWh} \times \$4/10^6\ \text{Btu} = \$0.0145/\text{kWh}$$

That is, choosing to generate on-site power will cost 1.45¢/kWh for fuel.

Example 2. Cost Chargeable to Power for a CHP Microturbine

Remember:

Fixed Charege Rate

- ✓ Just as the future cost of fuel and O&M needs to be levelized, so does the capital cost of the plant.
- ✓ The fixed charge rate covers costs that are incurred even if the plant doesn't operate, including depreciation, return on investment, insurance, and taxes…

Example 2. Cost Chargeable to Power for a CHP Microturbine

b. The amortized cost of the microturbine:

$$\$50{,}000 * 0.12/\text{yr} = \$6{,}000/\text{yr}$$

Annual operations and maintenance = $1200/yr

Annual fuel cost for electricity:

$$30 \text{ kW} * 8000 \text{ hr/yr} * \$0.0145/\text{kWh} = \$3480/\text{yr}$$

$$\text{Electricity cost} = \frac{(\$6000 + \$1200 + \$3480)/\text{yr}}{30 \text{ kW} \times 8000 \text{ h/yr}} = \$0.0445/\text{kWh}$$

Example 2. Cost Chargeable to Power for a CHP Microturbine

c. The value of the energy saved would be

$$\text{Energy savings} = 30\text{ kW} \times 8000\text{ hr/yr} \times (\$0.06 - \$0.0445)/\text{kWh}$$
$$= \$3720/\text{yr}$$

Assuming the peak demand is reduced by the full 30 kW saves

$$\text{Demand savings} = 30\text{ kW} \times \$7/\text{mo-kW} \times 12\text{ mo/yr} = \$2520/\text{yr}$$

Notice the value of the demand reduction is a significant fraction of the total value.

$$\text{Total annual savings} = \$3720 + \$2520 = \$6240/\text{yr}$$

Impact of Usable Thermal Energy on CHP Economics

General Formulas:

$$\text{Electrical output (kWh)} = \frac{1\ \text{(Btu)} \times \eta_P}{3412\ \text{(Btu/kWh)}}$$

$$\text{Displaced thermal input (Btu)} = \frac{1\ \text{(Btu)} \times \eta_H}{\eta_B}$$

- where η_P is the efficiency with which 1 unit of CHP fuel is converted into electricity
- η_H is the efficiency with which 1 unit of CHP fuel is converted into useful heat
- η_B is the efficiency of the boiler/heater that isn't used because of the CHP.

uOttawa

Impact of Usable Thermal Energy on CHP Economics

- Energy Chargebale to Power (ECP)

$$\text{ECP} = \frac{\text{Total thermal input} - \text{Displaced thermal input}}{\text{Electrical output}}$$

$$= \frac{\left(1 - \dfrac{\eta_H}{\eta_B}\right)}{\eta_P} \times 3412\ \text{Btu/kWh}$$

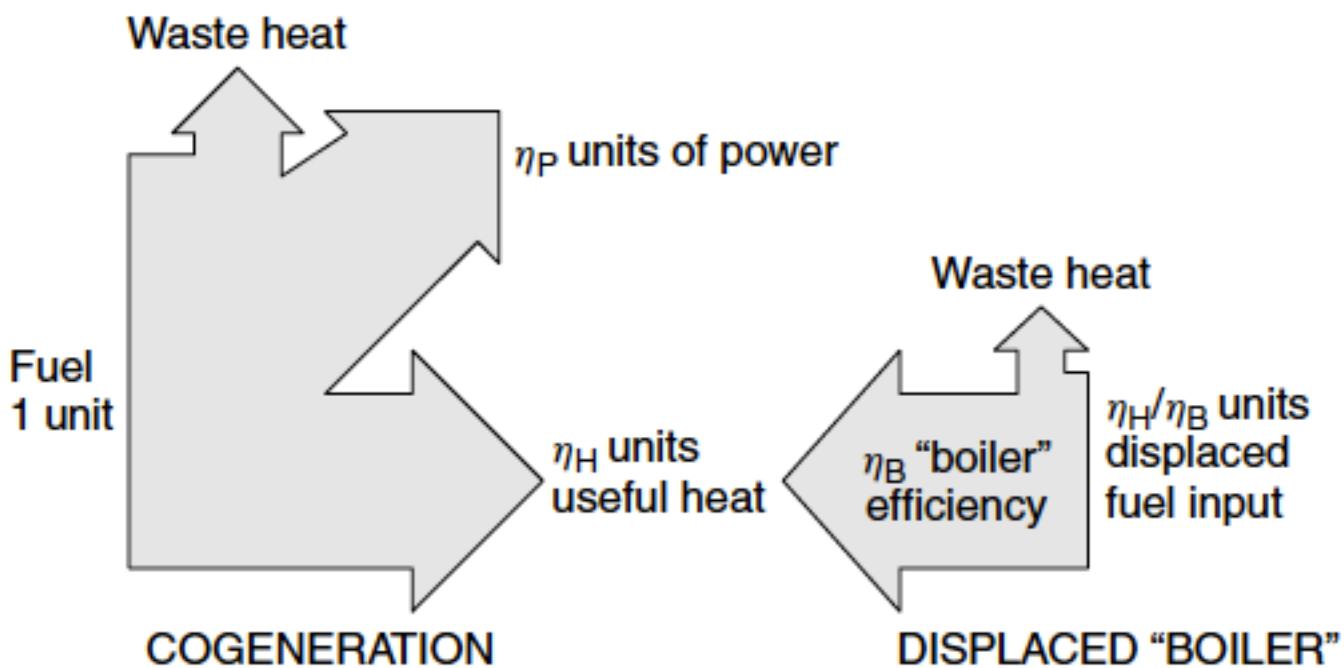
which simplifies to

$$\text{ECP} = \frac{3412}{\eta_P}\left(1 - \frac{\eta_H}{\eta_B}\right)\text{Btu/kWh} = \frac{3600}{\eta_P}\left(1 - \frac{\eta_H}{\eta_B}\right)\text{kJ/kWh}$$

uOttawa

Impact of Usable Thermal Energy on CHP Economics

- **Figure 3.** The economics of cogeneration are affected by the efficiency with which CHP fuel is converted into power and useful heat, as well as the efficiency of the boiler (or furnace or steam generator) that CHP heat displaces



Example 3. Cost of Electricity from a Fuel Cell

Q: A fuel cell with an integral reformer generates heat and electricity for an apartment house from natural gas fuel. The heat is used for domestic water heating, displacing gas needed by the apartment house boiler. The following data describe the system:

- Fuel cell rated output = 10 kW
- Capacity factor CF = 0.90
- Fuel cell/reformer electrical efficiency η_P = 0.40 (40%)
- Fuel to useful heat efficiency $\eta_H = 0.42$
- Boiler efficiency $\eta_B = 0.85$
- Capital cost of the system = $30,000
- Paid for with an 8%, 20-year loan
- Price of natural gas $0.80/therm ($8/10^6 Btu)

uOttawa

Example 3. Cost of Electricity from a Fuel Cell

a. Find the energy, and cost of fuel, chargeable to power?

The energy chargeable to power:

$$\text{ECP} = \frac{3412}{\eta_P}\left(1 - \frac{\eta_H}{\eta_B}\right)\text{ Btu/kWh} = \frac{3412}{0.40}\left(1 - \frac{0.42}{0.85}\right) = 4315 \text{ Btu/kWh}$$

The fuel cost chargeable to power:

$$\text{CCP} = 4315 \text{ Btu/kWh} \times \$8/10^6 \text{ Btu} = \$0.0345/\text{kWh}$$

Example 3. Cost of Electricity from a Fuel Cell

b. Find the cost of electricity (ignore inflation and tax benefits)?

With a 90% capacity factor, the annual electricity delivered will be

$$\text{Electricity} = 10\ \text{kW} \times 8760\ \text{h/yr} \times 0.90 = 78{,}840\ \text{kWh/yr}$$

The capital recovery factor is CRF(0.08,20)=0.1019/yr, so the annualized capital cost of the system is

$$A = P \times \text{CRF}(i, n) = \$30{,}000 \times 0.1019/\text{yr} = \$3057/\text{yr}$$

On a per kilowatt-hour basis, the annualized capital cost is

$$\text{Annualized capital cost} = \frac{\$3057/\text{yr}}{78{,}840\ \text{kWh/yr}} = \$0.0388/\text{kWh}$$

Example 3. Cost of Electricity from a Fuel Cell

b. The fuel plus capital cost of electricity is therefore

$$\text{Electricity} = 3.45¢/\text{kWh} + 3.88¢/\text{kWh} = 7.33¢/\text{kWh}$$

- This is about the same as the average U.S. price for electricity, and considerably less than the average residential price. The gas cost for the fuel cell will increase over time due to inflation, but so will the competing price of electricity, so these factors tend to cancel each other.

Example 3. Cost of Electricity from a Fuel Cell

c. How many gallons of water per day could be heated from 60◦ F to 140◦ F?

Since the system is 40% efficient at converting fuel to 10 kW of electricity, the thermal input for the fuel cell is

$$\text{Fuel cell input} = \frac{10\ \text{kW}_e}{0.40} \times 3412\ \text{Btu/kWh} = 85{,}300\ \text{Btu/h}$$

Since 42% of the fuel input is converted to usable heat, the energy delivered to hot water while the unit is running at full power is

$$\text{Hot water} = \frac{85{,}300 \times 0.42\ \text{Btu/h}}{8.34\ \text{lb/gal} \times 1\ \text{Btu/lb}^{\circ}\text{F} \times (140 - 60)^{\circ}\text{F}} = 53.7\ \text{gal/h}$$

uOttawa

Example 3. Cost of Electricity from a Fuel Cell

c. At a 90% capacity factor the daily hot water delivered would be

$$\text{Hot water} = 53.7\ \text{gal/h} \times 24\ \text{h/d} \times 0.90 = 1160\ \text{gal/day}$$

(Domestic consumption of hot water averages around 20 gal/person-day, so this is enough for almost 60 people.)