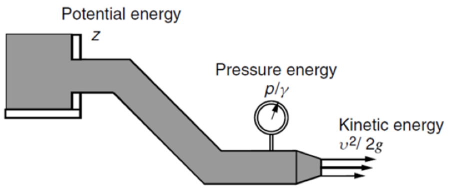
1. Describe how a Run-of-the-rive mini hydro power plant works.

Run-of-the-river (ROR) hydro power plants generate electricity using the natural flow of a river, without requiring a large dam or reservoir. Key steps in the operation:

The energy associated with water manifests itself in three ways:

as potential energy (mgz due to the water level in the dam) pressure energy (pV in the penstock) and kinetic energy ($\frac{1}{2}mv^2$ as water flows).

m – mass
g – acceleration due to gravity
z – elevation of water
p – pressure
V – Volume
v – velcity pf water



2. A Run-of-the-river mini hydro power plant has following operational parameters.

Water Flow rate = 1000 litres/min
Height difference between source of water and the location of the turbine/generator = 50 meter
Length of the PVC pipe = 100m
Diameter of the PVC pipe = 100mm = 0.1 m
Efficiency of the turbine/generator combined = 50%

1 m = 100 cm
1 cm = 10 mm
1 m³ = 1000 L.

a) What is the power output of the plant neglecting the losses in the PVC pipe?
b) How much energy will be produced in a month if the PVC pipe friction loss is 20%?

$$Power = \frac{Energy}{Time} = \frac{Weight}{Voume} \times \frac{Volume}{Time} \times \frac{Energy}{Weight} = \rho g Q H$$

where,
$Power$ in (W)
ρ is density (Kg/m^3)
g is gravitational acceleration (m/s^2)
Q is volume flow rate (m^3/s)
H is the head (m)

g = 9.81 m/s²

assume 20% loss

Energy head, $H = z + \frac{p}{\gamma} + \frac{v^2}{2g}$

where,
z is the elevation above a reference height (m),
p is the pressure (N/m^2),
γ is specific weight (N/m^3), γ = 9810 N/m³
v is the average velocity (m/s)
g is gravitational acceleration (m/s^2)

$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}0.1^2 \, m^2$

$v = \frac{Flow\left(\frac{Litres}{min}\right) \times 10^{-3}}{60 \times A(m^2)}$ m/sec

$v = \frac{1000 \times 10^{-3}}{60 \times \frac{\pi}{4} \times 0.01} = 2.12$ m/s

$H = z + \frac{P}{\gamma} + \frac{v^2}{2g} = 50 + \frac{P}{\gamma} + \frac{v^2}{2g}$

a) $P = \eta \cdot \rho \cdot g \cdot Q \cdot H$ → 50 × 0.8 = 40 m

$\eta = 0.5$ ρ = water density (1000 kg/m³)

$Q = 1000 L/min = 1000/60 = 16.67 L/s = 0.01667 m^3/s$

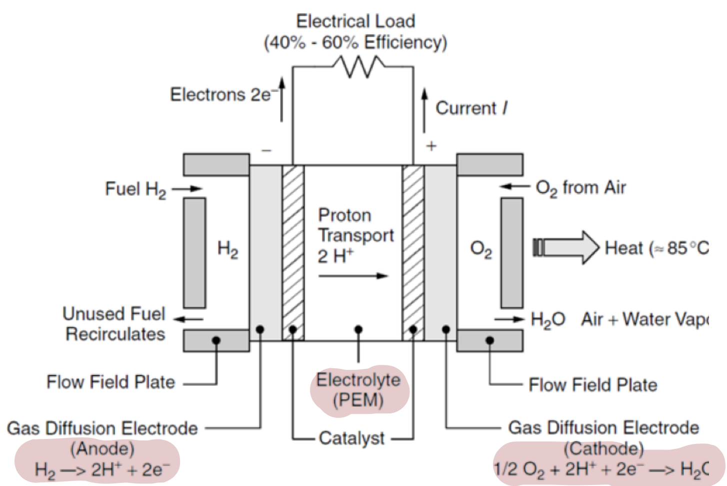
∴ P = ~

b) Friction loss reduces efficiency to $0.5 \cdot (1 - 0.2) = 0.4$ $P' = P \cdot \frac{0.4}{0.5} =$ ____

$E = P' \cdot time =$ kW × (30 × 24) h = kWh = MWh

3. Using appropriate diagram and equation, describe the basic operation of a proton exchange membrane (PEM) fuel cell.

Basic Operation of Fuel Cells



Basic Operation of Fuel Cells

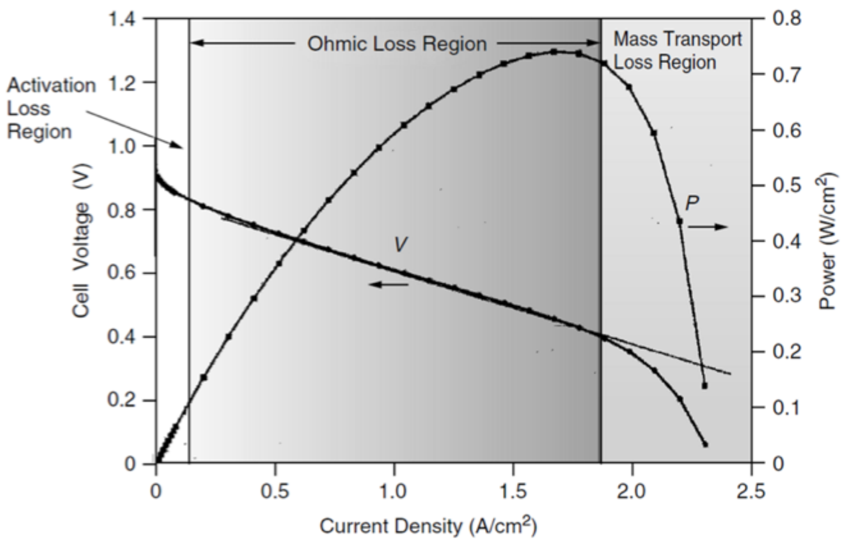
- A single cell consists of two porous gas diffusion electrodes separated by an electrolyte.
- It is the choice of electrolyte that distinguishes one fuel cell type from another.
- The electrolyte consists of a thin membrane that is capable of conducting positive ions but not electrons or neutral gases.
- The entering hydrogen gas has a slight tendency to dissociate into protons and electrons as follows:

$$H_2 \leftrightarrow 2H^+ + 2e^-$$

- This dissociation can be encouraged by coating the electrodes or membrane with catalysts to help drive the reaction to the right.

4. Draw the typical electrical characteristics of a PEM fuel cell, clearly marking different operating regions.

Electrical Characteristics of Real Fuel Cells



5. Describe various types of losses in a Fuel cell which reduces its performance.

Losses in the Fuel Cell

- *Activation losses* result from the energy required by the catalysts to initiate the reactions. The relatively slow speed of reactions at the cathode, where oxygen combines with protons and electrons to form water, tends to limit fuel cell power.
- *Ohmic* losses result from current passing through the internal resistance posed by the electrolyte membrane, electrodes, and various interconnections in the cell.
- Another loss, referred to as *fuel crossover*, results from fuel passing through the electrolyte without releasing its electrons to the external circuit.
- And finally, *mass transport losses* result when hydrogen and oxygen gases have difficulty reaching the electrodes. This is especially true at the cathode if water is allowed to build up, clogging the catalyst.

- For these and other reasons, real fuel cells, in general, generate only about 60–70% of the theoretical maximum.

6. What are the key advantages of Direct Methanol Fuel cell over PEM fuel cell?

Uses liquid methanol, which is easier to store and transport than hydrogen gas.
Suitable for portable devices like laptops and phones.

7. Describe the key characteristics of Alkaline Fuel cell?

Electrolyte: Potassium hydroxide (KOH).
Operates at 90–100 °C.
Highly efficient and reliable but sensitive to CO2, requiring pure oxygen.

8. What are the key advantages of Fuel cell over fossil fuel based power plants?

- Fuel cells convert chemical energy contained in a fuel (hydrogen, natural gas, methanol, gasoline, etc.) directly into electrical power.
- Fuel-to-electric power efficiencies as high as 65% are likely, roughly twice as efficient as the average central thermal power stations.
- The usual combustion products (SOx, particulates, CO, and various unburned or partially burned hydrocarbons) are not emitted.
- They are inherently modular in nature, so that small amounts of generation capacity can be added as loads grow.

9. Describe Electrolysis of water for production of Hydrogen.

- When an electrical current is forced through water added with an electrolyte, water molecules can be broken apart, releasing hydrogen and oxygen gases: $2H_2O \longrightarrow 2H_2 + O_2$
- De-ionized water introduced into the oxygen side of the cell dissociates into protons, electrons, and oxygen.
- The oxygen is liberated, the protons pass through the membrane, and the electrons take the external path through the power source to reach the cathode where they reunite with protons to form hydrogen gas.

Process:

- Electricity splits water into hydrogen and oxygen.
- At the anode: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
- At the cathode: $4H^+ + 4e^- \rightarrow 2H_2$
- Overall: $2H_2O \rightarrow 2H_2 + O_2$

$$A = P \times CRF(i,n)$$

$$CRF(i,n) = Capital\ recovery\ factor(yr^{-1}) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

10. A wind farm project has fifty (50) 2000-kW turbines with 80-m blades. Capital cost is \$100 million and the O&M cost for the first year is \$2 million. The O&M cost is escalating at the rate of 5% per year. The project will be financed with a \$100 million, 30-yr loan at 8% interest. Turbines are exposed to Rayleigh winds averaging 8.5 m/s. What is LCOE for the wind farm?

→ e   P   n=30   g   G=10^9

The ratio of the equivalent annual cost (\$/yr) to the annual electricity generated (kWh/year) is called the levelized cost of electricity (LCOE).

① $CF = 0.087\bar{V} - \frac{P_R(kW)}{[D(m)]^2} = 0.087 \times 8.5 - \frac{2000}{80^2} = 0.427$

② For 50 such turbines, the annual electrical production will be

Annual energy $= 50 \times 2000\,kW \times 8760\ h/yr \times 0.427 = 374 \times 10^6\ kWh/yr$

③ The debt payments will be $(i = g = 0.08)$

$A = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = 100{,}000{,}000 \times \left[\frac{0.08(1+0.08)^{30}}{(1+0.08)^{30} - 1}\right] = \$8.8 \times 10^6/yr$

④ The levelized O&M cost is $= 2 \times 10^6 \times \left[\left(\frac{1.328}{0.0665}\right) \cdot \left(\frac{0.805}{9.0626}\right)\right] = 3.55 \times 10^6\ \$$

O&M cost $= A_0 [PVF(d',n) \cdot CRF(d,n)] = 2 \times 10^6 \times \left[\left[\frac{(1+d')^n - 1}{d'(1+d')^n}\right] \cdot \left[\frac{d(1+d)^n}{(1+d)^n - 1}\right]\right]$

⑥ The levelized price at which electricity needs to be sold is

Selling price $= \frac{8.8 \times 10^6 \times 30 + 3.55 \times 10^6}{30 \times 374 \times 10^6\ kWh/year} = 0.238\ \$/kWh = 23.8\ ¢/kWh$

NPV and IRR with Fuel Escalation

- The chances are that the cost of fuel in the future will be higher than it is today.
- Fuel price escalation factor (e) is used in the present worth analysis:

$$PVF(d,n) = \frac{1+e}{1+d} + \frac{(1+e)^2}{(1+d)^2} + \cdots + \frac{(1+e)^n}{(1+d)^n} = \frac{(1+d)^n - 1}{d(1+d)^n}$$

- The fuel price escalation can be captured through the equivalent discount rate.

$$\frac{1+e}{1+d} = \frac{1}{1+d'} \text{ where } d' = \frac{d-e}{1+e}$$

Annualizing the Investment

- Extra capital required for an energy investment will be borrowed from a lending company.
- The extra capital cost is converted into a series of n equal annual payments (A) that eventually pay off the loan(P) with interest (i).

$$A = P \times CRF(i,n)$$

$$CRF(i,n) = Capital\ recovery\ factor(yr^{-1}) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$CRF(i,n)\ per\ month = \frac{(i/12)[1+(i/12)])^{12n}}{[1+(i/12)])^{12n} - 1}$$

Levelized Costs

- The cost of a power plant has two key components - an up-front fixed cost to build the plant plus an assortment of costs that will be incurred in the future.
- In the usual approach to cost estimation, a present value calculation is first performed to find an equivalent initial cost, and then that amount is spread out into a uniform series of annual costs.
  - Levelized annual costs = A_0[PVF(d', n) · CRF(d, n)]
- The ratio of the equivalent annual cost ($/yr) to the annual electricity generated (kWh/year) is called the levelized cost of electricity (LCOE).

Levelizing Factor

Levelizing factor (LF)= $\left[\frac{(1+d')^n - 1}{d'(1+d')^n}\right] \cdot \left[\frac{d(1+d)^n}{(1+d)^n - 1}\right]$

Price of Electricity from a Wind Farm - Example

A wind farm project has 40 1500-kW turbines with 64-m blades. Capital costs are $60 million and the levelized O&M cost is $1.8 million/yr. The project will be financed with a $45 million, 20-yr loan at 7% plus an equity investment of $15 million that needs a 15% return. Turbines are exposed to Rayleigh winds averaging 8.5 m/s.

What levelized price would the electricity have to sell for to make the project viable?

Solution

$$\text{CF} = 0.087\overline{V}\ (\text{m/s}) - \frac{P_R(\text{kW})}{[D(\text{m})]^2} = 0.087 \times 8.5 - \frac{1500}{64^2} = 0.373$$

For 40 such turbines, the annual electrical production will be

$$\text{Annual energy} = 40 \text{ turbines} \times 1500 \text{ kW} \times 8760 \text{ h/yr} \times 0.373$$
$$= 196 \times 10^6 \text{ kWh/yr}$$

The debt payments will be

$$A = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = \$45{,}000{,}000 \cdot \left[\frac{0.07(1+0.07)^{20}}{(1+0.07)^{20} - 1}\right]$$
$$= \$4.24 \times 10^6/\text{yr}$$

The annual return on equity needs to be

$$\text{Equity} = 0.15/\text{yr} \times \$15{,}000{,}000 = \$2.25 \times 10^6/\text{yr}$$

The levelized O&M cost is $1.8 million, so the total for O&M, debt, and equity is

$$\text{Annual cost} = \$(4.24 + 2.25 + 1.8) \times 10^6 = \$8.29 \times 10^6/\text{yr}$$

The levelized price at which electricity needs to be sold is therefore

$$\text{Selling price} = \frac{\$8.29 \times 10^6/\text{yr}}{196 \times 10^6 \text{ kWh/yr}} = \$0.0423 = 4.23¢/\text{kWh}$$

11. A photovoltaic system that generates 8000 kWh/yr costs $15,000. It is paid for with a 6%, 20-year loan.

$L = 15000 \quad r = 0.06 \quad n = 20$

a) Ignoring any tax implications, what is the cost of electricity from the PV system?

b) With local utility electricity costing 11¢/kWh, at what rate would that price have to escalate over the 20-year period in order for the levelized cost of utility electricity be the same as the cost of electricity from the PV system?

a) $P = \frac{L \cdot r \cdot (1+r)^n}{(1+r)^n - 1} = \$1307.3/yr$

the cost of electricity:

$$\text{LCOE} = \frac{\text{Annual Loan Payment}}{\text{Annual Electricity Generation}}$$

$$\text{LCOE} = \frac{1,307.3}{8000} = 0.1634\,\$/\text{kWh}$$ $= 16.34¢/kWh$

b) $P_{final} = P_{initial} \cdot (1+g)^n$

$16.34 = 11 \cdot (1+g)^{20}$

$g \approx 2.01\%$

The utility price must escalate at 2.01% per year.

12. A small business uses 100 kW of power and 24,000 kWh/month during peak period. It uses 20 kW peak power and 10,000 kWh/month during off-peak period. Calculate its monthly electricity bill if:

a) Time of Use (TOU) rate schedule is used
On-peak : 12¢/kWh and Off-peak 7¢/kWh.

b) Demand Charge Schedule is used with
Energy charge 6¢/kWh and demand charge of $9/mo-kW.

a) peak cost $= 24000 \times 0.12 = 2880\,\$$ off-peak cost $= 10000 \times 0.07 = 700\,\$$

Total bill $= 2880 + 700 = 3580\,\$$

b) Energy cost $= (24000 + 10000) \times 0.06 = 2040\,\$$

Demand cost $= (100 + \cancel{20}) \times 9 = 900\,\$$ Total = —

13. A commercial customer uses demand charge schedule and consumes 20,000 kWh power month with a peak demand charge of 100kW. The rate schedule used is energy charge 6¢/kWh and demand charge of $9/mo-kW. A sales engineer proposes to install an equipment that would reduce the peak demand to 80kW and increase energy efficiency by 10%. What should be cost of the equipment if the pay-back period is less than 3 years?

$$\textit{Simple payback} = \frac{\textit{Extra first cost } \Delta P\ (\$)}{\textit{Annual savings } S(\$/yr)}$$

① Energy reduction → Energy savings: $20000 \times 0.1 = 2000$ kWh/mo

Energy cost savings: $2000 \times 0.06 = 120$ \$/mo

② Demand reduction → Demand savings: $(100-80) \times 9 = 180$ \$/mo

③ Total savings: $(120+180) \times 12 = 3600$ \$/year

④ cost $= 3600 \times 3 = 10800\,\$$

14. Two customers use 10,000kWh per month and pay according to a demand charge schedule with energy charge 6¢/kWh and demand charge of \$9/mo-kW. One customer has a load factor of 15% whereas the other has a load factor of 60%. What is difference in their monthly energy bills?

They both have the same energy costs:

10000 kwh/mo × 0.06/kwh = \$600/mo

$$Load\ factor\ (\%) = \frac{Average\ Power}{Peak\ Power} \times 100\%$$

$$Peak(A) = \frac{10000\ kwh/mo}{15\% \times 24h/day \times 30\ day/mo} \times 100\% = 92.59\ kw$$

which, at \$9/mo-kw, will incur demand charges of \$833.31/mo

Bill(A) = (10000 × 0.06) + (92.6 × 9) = 1433.4\$

$$Peak(B) = \frac{10000\ kwh/mo}{60\% \times 24h/day \times 30\ day/mo} \times 100\% = 23.15\ kw$$

costing \$208.35/mo

Bill(B) = (10000 × 0.06) + (23.1 × 9) = 807.9\$

Example 5.7 Net Present Value of Premium Motor with Fuel Escalation. The premium motor in Example 5.6 costs an extra \$500 and saves \$192/yr at today's price of electricity. If electricity rises at an annual rate of 5% (e), find the net present value of the premium motor if the best alternative investment earns 10% (d).

Solution. Using (5.15), the equivalent discount rate with fuel escalation is

$$d' = \frac{d - e}{1 + e} = \frac{0.10 - 0.05}{1 + 0.05} = 0.04762$$

From (5.9), the present value function for ($n=$) 20 years of escalating savings is

$$\mathrm{PVF}(d', n) = \frac{(1 + d')^n - 1}{d'(1 + d')^n} = \frac{(1 + 04762)^{20} - 1}{0.04762(1 + 0.04762)^{20}} = 12.717 \text{ yr}$$

From (5.10), the net present value is

$$\mathrm{NPV} = \Delta A \times \mathrm{PVF}(d', n) - \Delta P \quad = \$192/\text{yr} \times 12.717 \text{ yr} - \$500 = \$1942$$

(Without fuel escalation, the net present value of the premium motor was only \$1135.)

TABLE 5.2 Example Residential Time-of-Use (TOU) Rate Schedule

	November–April		May–October	
On-peak	7–10 A.M., 5–8 P.M.	8.335 ¢/kWh	2–8 P.M.	19.793 ¢/kWh
Off-peak	All other times	7.491 ¢/kWh	All other times	8.514 ¢/kWh

Example 5.2 PVs, TOU Rates, and Net Metering. During the summer a rooftop PV system generates 10 kWh/day during the off-peak hours and 10 kWh/day during the on-peak hours. Suppose too, that the customer uses 2 kWh/day on-peak and 18 kWh/day off-peak. That is, the PVs generate 20 kWh/day and the household consumes 20 kWh/day.

	PV supply	Demand
On-peak	10kWh	2kWh
Off-peak	10kWh	18kWh
Total	20kWh/day	20kWh/day

For a 30-day month in the summer, find the electric bill for this customer if the TOU rates of Table 5.2 apply.

TABLE 5.3 Electricity Rate Structure Including Monthly Demand Charges

	Winter Oct–May	Summer June–Sept
Energy charges	$0.0625/kWh	$0.0732/kWh
Demand charges	$7/mo-kW	$9/mo-kW

Example 5.3 Impact of Demand Charges. During the summer, a small commercial building that uses 20,000 kWh per month has a peak demand of 100 kW.

a. Compute the monthly bill (ignoring fixed customer charges).
b. How much does the electricity cost for a 100-W computer that is used 6 h a day for 22 days in the month? The computer is turned on during the period when the peak demand is reached for the building. How much is that in ¢/kWh?

Solution During the on-peak hours, the customer generates 10 kWh and uses 2 kWh, so there would be a credit of

$$\text{On-peak credits} = 8\ \text{kWh/day} \times \$0.19793/\text{kWh} \times 30\ \text{day/mo} = \$47.50$$

During the off-peak hours, the customer generates 10 kWh and uses 18 kWh, so the bill for those hours would be

$$\text{Off-peak bill} = 8\ \text{kWh/day} \times \$0.08514/\text{kWh} \times 30\ \text{day/mo} = \$20.43/\text{mo}$$

So the net bill for the month would be

$$\text{Net bill} = \$20.43 - \$47.50 = -\$27.07\text{mo}$$

That is, the utility would owe the customer $27.07 for this month. Most likely in other months there will be actual bills against which this amount would be credited.

Notice that the bill would have been zero, instead of the $27.07 credit, had this customer elected the standard rate schedule of Table 5.1 instead of the TOU rates.

Solution

a. The monthly bill is made up of energy and demand charges:

$$\text{Energy charge} = 20{,}000\ \text{kWh} \times \$0.0732/\text{kWh} = \$1464/\text{mo}$$

$$\text{Demand charge} = 100\ \text{kW} \times \$9/\text{mo-kW} = \$900/\text{mo}$$

For a total of $1464 + $900 = $2364/mo (38% of which is demand)

b. The computer uses 0.10 kW × 6 h/d × 22 day/mo = 13.2 kWh/mo

$$\text{Energy charge} = 13.2\ \text{kWh/mo} \times \$0.0732/\text{kWh} = \$0.97/\text{mo}$$

$$\text{Demand charge} = 0.10\ \text{kW} \times \$9/\text{mo-kW} = \$0.90/\text{mo}$$

$$\text{Total cost} = \$0.97 + \$0.90 = \$1.87/\text{mo}$$

On a per kilowatt-hour basis, the computer costs

$$\text{Electricity} = \frac{\$1.87/\text{mo}}{13.2\ \text{kWh/mo}} = \$0.142/\text{kWh}$$

Notice how the demand charge makes the apparent cost of electricity for the computer (14.2¢/kWh) nearly double the 7.32 ¢/kWh price of electric energy.

Example 5.4 Impact of Ratcheted Demand Charges on an Efficiency Project. A customer's highest demand for power comes in August when it reaches 100 kW. The peak in every other month is less than 70 kW. A proposal to dim the lights for 3 h during each of the 22 workdays in August will reduce the August peak by 10 kW. The utility's energy charge is 8¢/kWh and its demand charge is \$9/kW-mo with an 80% ratchet on the demand charges.

a. What is the current annual cost due to demand charges?
b. What annual savings in demand and energy charges will result from dimming the lights?
c. What is the equivalent savings expressed in ¢/kWh?

Solution

a. At \$9/kW-mo, the current demand charge in August will be

$$\text{August} = 100\ \text{kW} \times \$9/\text{kW-mo} = \$900$$

For the other 11 months, the minimum demand charge will be based on 80 kW, which is higher than the actual demand:

$$\text{Sept–July demand charge} = 0.8 \times 100\ \text{kW} \times \$9/\text{kW-mo} \times 11\ \text{mo} = \$7920$$

So the total annual demand charge will be

$$\text{Annual} = \$900 + \$7920 = \$8820$$

b. By reducing the August demand by 10 kW, the annual demand charges will now be

$$\text{August} = 90\ \text{kW} \times \$9/\text{kW-mo} = \$810$$
$$\text{Sept–July} = 0.8 \times 90\ \text{kW} \times \$9/\text{kW-mo} \times 11\ \text{mo} = \$7128$$
$$\text{Total annual demand charge} = \$810 + \$7128 = \$7938$$
$$\text{Annual demand savings} = \$8820 - \$7938 = \$882$$

e.g. The demand charge for every month may be based on 80% of the annual peak demand.

$$\text{August energy savings} = 3\ \text{h/d} \times 10\ \text{kW} \times 22\ \text{days} \times \$0.08/\text{kWh} = \$52.80$$

$$\text{Total Annual Savings} = \$882 + \$52.80 = \$934.80$$

Notice that the demand savings is 94.4% of the total savings!

c. Dimming the lights saved 3 h/d × 10 kW × 22 d = 660 kWh and \$934.80, which on a per kWh basis is

$$\text{Savings} = \frac{\$934.80}{660\ \text{kWh}} = \$1.42/\text{kWh}$$

In other words, the business saves \$1.42 for each kWh that it saves, which is about 18 times more than would be expected if just the \$0.08/kWh cost of energy is considered.