6.15 You are to design a 24-V, all-DC, stand-alone PV system to meet a 2.4 kWh/d demand for a small, isolated cabin. You want to size the PV array to meet the load in a month with average insolation equal to 5.0 kWh/m²/d.

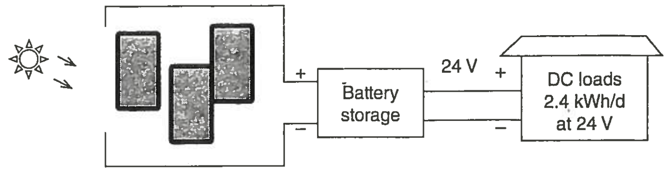


FIGURE P6.15

Your chosen PVs have their 1-sun MPP at $V_R = 18$ V and $I_R = 5$ A. Assume a 0.80 derate factor for dirt, wiring, module mismatch (i.e., 20% loss). You will use 200-Ah, 12-V batteries with 100% Coulomb efficiency.

a. How many PV modules are needed (you may need to round up or down)? Sketch your PV array.

b. How many 200-Ah, 12-V, deep-cycle batteries would be required to cover 3 days of no sun if their maximum discharge depth is 75%? Show how you would wire them up.

CABIN DEMAND − BATTERYS RATED IN A·h

SO A·h REQUIREMENT: $I = \frac{P}{V} = \frac{2400\,\text{Wh}}{d} \cdot \frac{1}{24\text{V}}$

$I = 100\ \text{A·h/d}$

a. NEED TO WIRE 2 MODULES IN SERIES TO DELIVER >24V TO BATTERY SYSTEM

+ → 5A PER PANEL SERIES

$V_R = 2 \times 18 = 36$

−

1-SUN PANELS DELIVER $5\frac{\text{kWh}}{\text{m}^2}$ DAILY

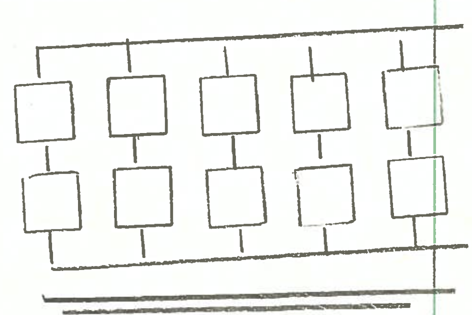
$\left(1\frac{\text{kW}}{\text{m}^2}\right)$

$\Rightarrow h = \frac{5\,\text{kWh}}{\text{m}^2} \cdot \frac{\text{m}^2}{1\,\text{kW}} = 5$ hours/DAY

DETERMINE # 2-PANEL MODULES (N): TO MEET 100 A·h/d REQT:

$5\text{A} \cdot \underbrace{.8}_{\text{DERATING}} \cdot N \cdot 5\frac{\text{hr}}{\text{day}} = 100$

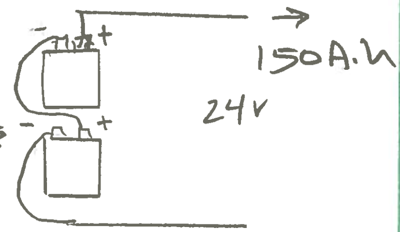
$N = \frac{100}{20} = \underline{\underline{5}}$ ANS.



ANS.

∴ REQUIRE $\underline{10 \text{ PANELS}}$ ANS

b. SYSTEM VOLTAGE IS 24 V, THEREFORE NEED TO WIRE 2 BATTERIES IN SERIES TO MEET VOLTAGE REQT.



EACH BATTERY PROVIDES CURRENT

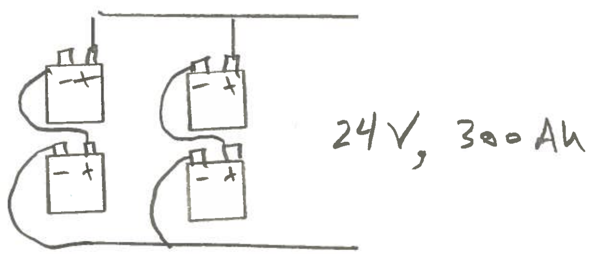
$200\ Ah \cdot 75\%$ } DISCHARGE DEPTH

$= Ah$ . .

LOAD REQUIRES $100 \frac{A \cdot h}{day} \cdot 3 days \cdot 75\%$ DISCHARGE

$=$

∴ REQUIRE 2 SETS OF BATTERIES WIRED IN SERIES TO STORE REQD ENERGY



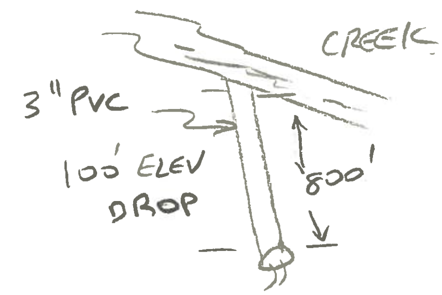
8.8 Suppose 200 gal/min of water is taken from a creek and delivered through 800 ft of 3-in diameter PVC pipe to a turbine 100 ft lower than the source. If the turbine/generator has an efficiency of 40%

a. Find the electrical power that would be delivered by the generator.

b. What diameter pipe would be needed to keep the flow speed around 5 ft/s or less?

c. Assuming locally available PVC pipe comes in 1-in diameter increments (2-in, 3-in, etc.), pick a pipe size closest to the above suggested diameter and find the power delivered by the generator with this pipe.

a) $\eta_{gen} = 40\%$



HEAD LOSS FROM FIG 8.35

FRICTION HEAD LOSS $= \frac{6'}{100\,ft} \cdot \frac{800'}{} =$

$= 48'$ HEAD LOSS

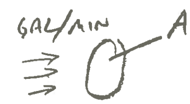
NET HEAD = GROSS HEAD − FRICTION HEAD

GROSS HEAD INCLUDES: $z = 100'$

NET HEAD $= 100' - 48' = 52'$

(8.20) $P_d\,(kW) = \frac{\eta\, Q(gpm)\, H_N(ft)}{5300}$

$= \frac{.4(200)(52)}{5300} = \underline{.78\,kW}$ ANS.



b) $Q = 200\,\frac{GAL}{MIN}$; $v = \frac{Q}{A}$

$\frac{1\,ft^3}{s} = \frac{448.8\,GAL}{MIN}$

$\frac{200\,GAL}{MIN} \cdot \frac{MIN}{448.8\,GAL} \cdot \frac{ft^3}{s} = .445\,\frac{ft^3}{s}$ $\quad 1 = \frac{448.8\,GAL}{MIN} \cdot \frac{s}{ft^3} =$

$v = \frac{Q}{A}$; $A = \frac{Q}{v} = \frac{.445\,ft^3/s}{5\,ft/s} = .08912\,ft^2 \Rightarrow 12.833\,IN^2$

$A = \pi R^2 \Rightarrow R = \sqrt{\frac{12.833}{\pi}} = 2.02''$

$D = 2R = \underline{4.04''} \Rightarrow 4''$ ANS

c) USE $\underline{4''}$ DIA PIPE ANS.

c) CONT - USE 4" DIA PIPE

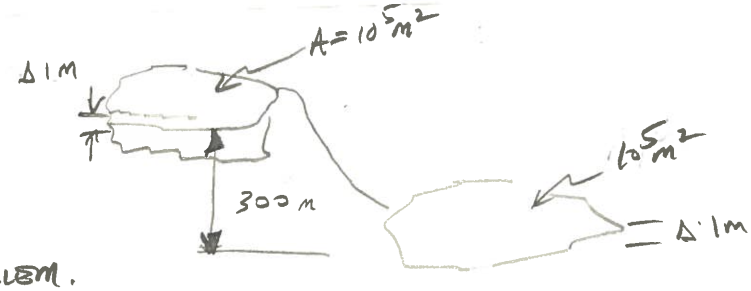
FROM Pa, FIND NEW HEAD LOSS FROM FIG 8.35

$$\text{FRICTION HEAD LOSS} = \frac{2'}{100'} \cdot 800' = 16' \text{ LOSS}$$

$$\text{NET HEAD LOSS}: H_N = 100' - 16' = 84'$$

$$P_d = \frac{\eta Q H_N}{5300} = \frac{.4(200)(84)}{5300} = \underline{\underline{1.268\,KW}} \text{ ANS.}$$

8.10 Suppose 300-m of elevation separate the upper and lower reservoirs of a pumped-hydro system. Each has an average surface area of 10 ha (100,000 m^2) and their surfaces are allowed to vary in elevation by 1 m. If the penstock efficiency is 90% and the turbine/generator efficiency is 80% what is the average power that could be delivered over a 12-h period?



POTENTIAL ENERGY PROBLEM.

$$E = Mgh = \underbrace{\overset{d}{1m} \cdot 10^5 m^2}_{\text{VOL OF WATER}} \cdot \underbrace{\rho}_{\text{WATER DENSITY}} \cdot 9.8 \frac{m}{s^2} \cdot 300m$$

$$= 10^5 m^3 \cdot 10^3 \frac{kg}{m^3} \cdot 9.8 \frac{m^2}{s^2} \cdot 300m$$

$$= 294 \times 10^6 \frac{kg\, m^3}{s^2} = (J) \qquad E = F \cdot d = \frac{kg\, m}{s^2} \cdot m = \frac{kg\, m^2}{s^2}$$

$$= 81{,}666 \text{ kWh} \qquad 3.6 \times 10^6 \frac{J}{kWh}$$

$$P_{12h} = \frac{81{,}666}{12\ h} \cdot (.9)(.8)$$

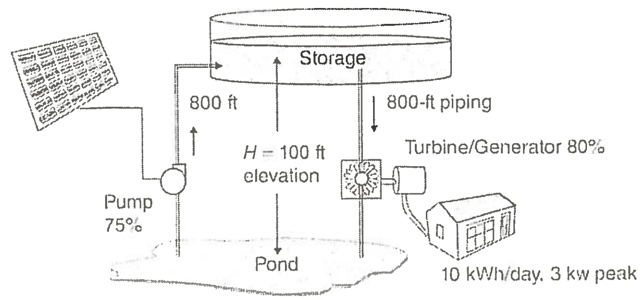
(.8) ← TURBINE/GEN EFFICIENCY

(.9) ← PENSTOCK EFFICIENCY

$$= \underline{\underline{4900 \text{ kW}}} \text{ ANS}$$

← AVG PWR DELIVERED OVER 12 HR PERIOD; ASSUMING 1 CYCLE OF AVAILABLE WATER

8.11 Consider the design of an off-grid, pumped-hydro system for a PV-powered small cabin located next to a pond. Suppose the demand is estimated to be 10 kWh/d with a peak demand of 3 kW. A tank will be placed on a nearby hilltop 100 ft above the turbine/generator. Connecting pipe runs to and from the tank are each 800 ft.



a. Assuming an average of 15% head losses in the pipeline and 80% conversion efficiency for the turbine/generator, how many gallons of water needs to flow from the upper tank to the pond in a day's time?

b. Size the upper storage tank (gallons) to provide a full day's worth of back-up energy when the renewables do not supply any power. Assume maximum allowed tank drainage is 75%.

c. Assuming piping losses are 20% during peak demand, what flow rate from the tank would be needed to supply the 3-kW peak?

d. Using the choices in Fig 8.35, what size pipe would keep losses to around 20% at peak demand?

e. How much energy would a PV system have to provide to meet the average daily demand for energy? Assume 15% piping losses in each piping run and a 75%-efficient pump.

f. In an area with 5.5 kWh/m²/d insolation, size a PV system to supply the 10 kWh/d needed by the household. Assume a derate factor of 0.75.

a) POTENTIAL ENERGY PROBLEM (APPROACH)

$$E = Mgh$$

TURBINE EFFICIENCY

NET HEAD (15% LOSSES)

$$\frac{10\,kWh}{day} = \underset{GAL}{Vol} \cdot \frac{8.34\,LB}{GAL} \cdot \frac{1}{\left[\left(737.5\,\frac{ft\cdot lb}{s}\right)\left(\frac{60\,s}{MIN}\right)\frac{60\,MIN}{hr}\right]} (.8)(.85)(100') \leftarrow z$$

$$Vol = \frac{10\,kWh}{day} \cdot \frac{2.655\times10^{6}}{8.34(.8)(.85)100}$$

$$= \underline{\underline{46,819\ GAL}}\ \text{(PER DAY)}$$

ANS.

b) UPPER STORAGE TANK MUST ACCOUNT FOR 75% MAX DRAINAGE

$$\frac{Vol}{.75} = \frac{46,819}{.75} = \underline{\underline{62420\ GAL}}$$

ANS.

c) USING EQN (8.20) w/ 85% HEAD LOSSES AND $\eta = 80\%$ AT PEAK DEMAND

$$P_{dec}(kW) = \frac{\eta Q(gpm) H_N'}{5300} = 3kW$$

$$Q = \frac{P\,5300}{\eta H_N} = \frac{(3).5300}{(.8)\underset{100}{H}(1-.2)} = \underbrace{248.4 \ \frac{gal}{MIN}}_{\text{PEAK DEMAND FLOW RATE}}$$

d) FROM FIG 8.35

WITH ASSUMED HEAD LOSS OF 20% (160') IN 800' RUN (20' PER 100' LENGTH)

$\frac{20}{100} = .2$ loss/ft ⇒ 2.5 ft/100ft @ 250 GAL/MIN from (c)

⇒ 4" DIA PVC 3ft/100ft ← HEAD LOSS PER 100' PIPE ⇒ 24' HEAD LOSS OVER 800'

⇒ THEREFORE SELECT 5" DIA PIPE TO KEEP LOSSES BELOW 20% @ PEAK FLOW RATE.

THUS ABOUT 1.5'/100' HEAD

⇒ 12' HEAD LOSS IN 800' RUN

$12' \Rightarrow \underbrace{12\% < 20\%}_{\text{LOSS CRITERIA MET.}}$

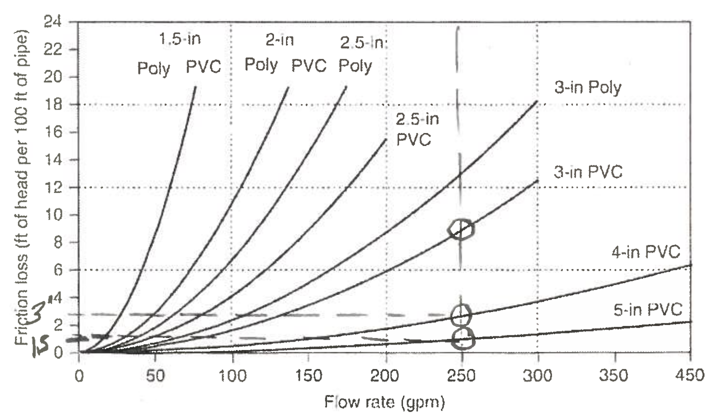


Fig. 8.35 Friction Head Loss

e) HOUSE REQT = 10 kWh/day

PUMP η = 75%

15% PIPING LOSSES EACH 800' RUN.

GEN η = 80%

$$\text{ROUND TRIP EFFICIENCY} = \eta_{PUMP} \cdot \underbrace{2 \cdot 15\%}_{\text{2 PIPE RUNS}} \cdot \eta_{GEN}$$

$$= .75 \times .70 \times 80\%$$

$$= .42$$

$$\text{TOTAL DEMAND} = \frac{10 \frac{kWh}{d}}{.42} = \underline{23.8\ kWh/day}$$

ENERGY REQD FROM PV SYSTEM

ANS.

f) $23.8\ kWh/d = P_{DC,STC} \times h/day \text{ full sun} \times \text{derate}$ MASTERS EQN 6.7

$$= kWh \times 5.5 \frac{kWh}{m^2} \times .75$$

Peak Power dc, stc rating = $\underline{\underline{5.77\ kW}}$ ANS. $= \frac{23.8}{5.5 \times .75}$

6.14 Consider the design of a small PV-powered LED flashlight. The PV array consists of eight series cells, each with rated current 0.3 A at 0.6 V. Storage is provided by three series AA batteries that each store 2 Ah at 1.2 V when fully charged. The LED provides full brightness when it draws 0.4 A at 3.6 V.

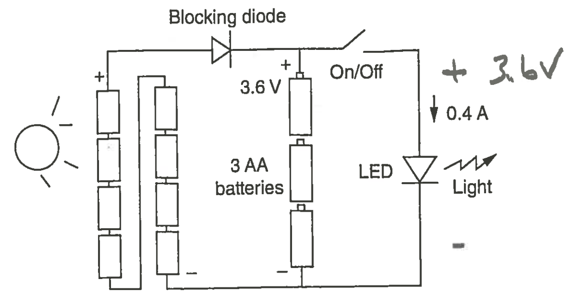


FIGURE P6.14

The batteries have a Coulomb efficiency of 95% and for maximum cycle life can be discharged by up to 80%. Assume the PVs have a 0.90 derating due to dirt and aging.

a. How many hours of light could this design provide each evening if the batteries are fully charged during the day?

b. How many kWh/m²/d of insolation would be needed to provide the amount of light found in (a)?

c. With 14%-efficient cells, what PV area would be required?

a) BATTERY SPEC = 2 Ah @ 1.2V, MAX DISCHARGE 80%

∴ EACH BATTERY HAS $2 \cdot .8 = 1.6\ Ah$ / BATTERY

LED REQUIRES 3 BATTERIES IN SERIES FOR $\underbrace{3.6V}_{\text{LED}}$ LOAD

$$\frac{1.6\,Ah}{.4\,A} = \underline{4h \text{ OF LIGHT}} \text{ ANS.}$$

b) USING THE SIMPLIFIED BATTERY SIZING APPROACH IN SECT 6.5.10 (PV ARRAY w/o MPPT)

$$Ah_{(BATTERY)} = \underset{\substack{\uparrow \\ \text{PV RATED} \\ \text{CURRENT}}}{I_R} \cdot \underbrace{(h @ \text{FULL SUN})}_{kWh/m^2\text{-day OR INSOLATION}} \cdot PV \cancel{\text{DERATE}} \cdot \text{COULOMB EFF.}$$

$$\text{INSOLATION}\left(\frac{kWh}{m^2 d}\right) = \frac{Ah_{(BATTERY)}}{I_R \cdot PV_{DERATE} \cdot \text{COULOUMB EFF}}$$

$$= \frac{1.6}{.3 \cdot .90 \cdot .95} = \underline{6.24 \frac{kWh}{m^2 \cdot d}} \text{ ANS}$$

c) EACH 14%-EFFICIENT CELL PRODUCES:

$$.3A \cdot 6V = 0.18\ W\ @\ STC$$

$$P_R(W) = 1000\ \frac{W}{M^2} \cdot \eta \cdot A(m^2)$$

$$A = \frac{.18\ W/CELL \cdot 8\ CELL}{1000 \cdot 0.14}$$

$$= \underline{\underline{.01028\ m^2 \cong 16\ in^2}}\ \text{ANS}$$

6.16 Analyze the following simple PV/battery system, which includes four PV modules each with rated current and voltage as shown, and four 160-Ah, 6-V batteries with 90% Coulomb efficiency. An 85%-efficient inverter feeds the AC load. Note there is no MPPT.

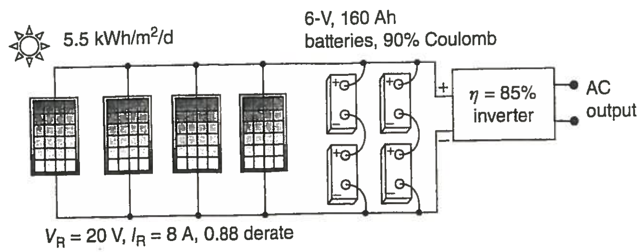


FIGURE P6.16

a. With 5.5 kWh/m²/d of insolation, and 12% module loss due to dirt, wiring losses, and so on, estimate the kWh/d that would reach the loads (assume all PV current passes through the batteries before it reaches the inverter).

b. If the load requires 1 kWh/d, for how many cloudy days in a row can previously fully charged batteries supply the load with no further PV input? Assume 80% of their ampere-hour capacity is available.

a) USING "PEAK HOUR" APPROACH (SECT 6.5.10)

UNDER PEAK HOUR APPROACH

AN AREA w/ $X\left(\frac{kWh}{m^2\text{-day}}\right)$ IS TREATED AS $X\left(\frac{h}{day}\right)$ OF 1-SUN IRRADIATION

SO $5.5\frac{kWh}{m^2 \cdot day}$ IS TAKEN TO BE 5.5 h/day OF 1-SUN INSOLATION

⇒ USING I_R @ 1-SUN × PEAK HOURS ⇒ A-h PROVIDED TO BATTERIES

$$\frac{Wh}{day} = \frac{kWh}{day} \cdot I_R \cdot \underbrace{\eta_{DERATE}}_{\text{PV DERATE}} \cdot \underbrace{\#\,MODULES}_{} \cdot \underbrace{V_{BAT}}_{} \cdot \eta_{INV} \cdot \eta_{BAT}$$

$$= \frac{5.5h}{day} \cdot 8A \cdot (.88) \cdot \overset{MOD}{4} \cdot \overset{V}{12} \cdot \overset{\eta_{INV}}{.85} \cdot \overset{\eta_{BAT}}{.9}$$

$= \underline{\underline{1.422\ kWh/d}}$ REACHES THE LOAD ANS.

b) BATTERIES DELIVER:

$$P = (2 \times 6) \cdot 160\,Ah/_{SERIES} \cdot 2\,SERIES \cdot \underbrace{.80}_{\text{MAX DISCHARGE}} \cdot \underbrace{.85}_{\eta_{INV}}$$

$= 2611\,Wh$ } ENERGY AVAILABLE (ACCOUNTING FOR 80% MAX DISCHARGE)

SO w/ 1 kWh/day LOAD,

EXPECT $\underline{\underline{2.61 \text{ DAYS}}}$ OF BATTERY PROVIDED ENERGY
ANS

6.19 Consider a directly coupled PV pump system with PV I–V curves and pump/system H–Q curves as shown below. Note that the startup characteristics of the pump motor as it tries to overcome static friction before it can actually start pumping.

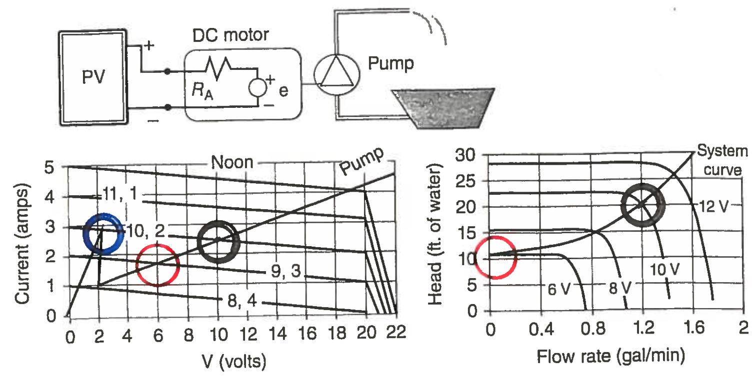


FIGURE P6.19

a. At what time in the morning will the water start to flow?
b. What will the flow rate be a little after 10:00 A.M.?
c. At what time in the afternoon will the flow stop?
d. Assuming the equivalent circuit shown above for the pump motor, what is the motor's armature resistance, R_A?

a) SEE BLUE CIRCLE ON THE I-V CURVE.

THE CURRENT INCREASES LINEARLY UNTIL SUDDEN DROP @ 10 am. THIS IS THE POINT AT WHICH CURRENT PRODUCES A FORCE IN THE DC MOTOR TO OVERCOME INTERNAL MECHANICAL RESISTANCE → DC MOTOR SHAFT BEGINS ROTATING.

10 am ANS

b) SEE BLACK CIRCLES THE HYDRAULIC CHARACTERISTIC CURVES. AND I-V CHARACTERISTIC CURVES.

ROTOR ACCELERATES UNTIL IT ROTATION PRODUCES A NEW EQUILIBRIUM (PUMP I-V CURVE ON PV I-V CURVE) VALUE e. THIS IS THE INTERSECTION OF 10:00 TIME CURVE & PUMP I-V CURVE

10 V PUMP VOLTAGE AND FLOW RATE CURVE INTERSECTION IS 1.2 GAL/MIN ANS.

c) SEE RED CIRCLES ON EACH CURVE SET.

FROM HYDRAULIC CURVE, FLOW STOPS WHEN VOLTAGE < 6V

FROM PV I-V CURVE, VOLTAGE DROPS BELOW 6V

@ 3 PM ANS

∴ WATER FLOWS BETWEEN 10 AM & 3 PM ON SUNNY DAYS.

d) R_A IS THE SLOPE OF THE I-V CURVE WHEN DC MOTOR'S SHAFT IS NOT TURNING

$$R = \frac{\Delta V}{\Delta I} = \frac{2-0}{3-0} = .67\,\Omega$$ ANS.

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

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

b. With local utility electricity costing $0.11/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? Use Figure A.3 and assume the buyers discount rate is 15%.

a) $A = P \cdot CRF(i,n) = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$ — $i = .06$, $n = 20$

$= 15000 \left[\frac{.06(1.06)^{20}}{(1.06)^{20}-1}\right]$

$= \$1307/\text{YEAR}$ TO REPAY INFRASTURURE LOAN

$LCOE = \frac{\$1307}{8000\,kWh} = \$0.16/kWh$ Ans.

b) LEVELIZING FACTOR = LF

LEVELIZED ANNUAL COST ($/kWh) = LAC

LAC($/kWh) = BASE YEAR LOCAL UTILITY ($/kWh) ANNUAL COST × LF

$\frac{.16(\$/kWh)}{.11(\$/kWh)} = LF = \frac{.16}{.11} = 1.4545$

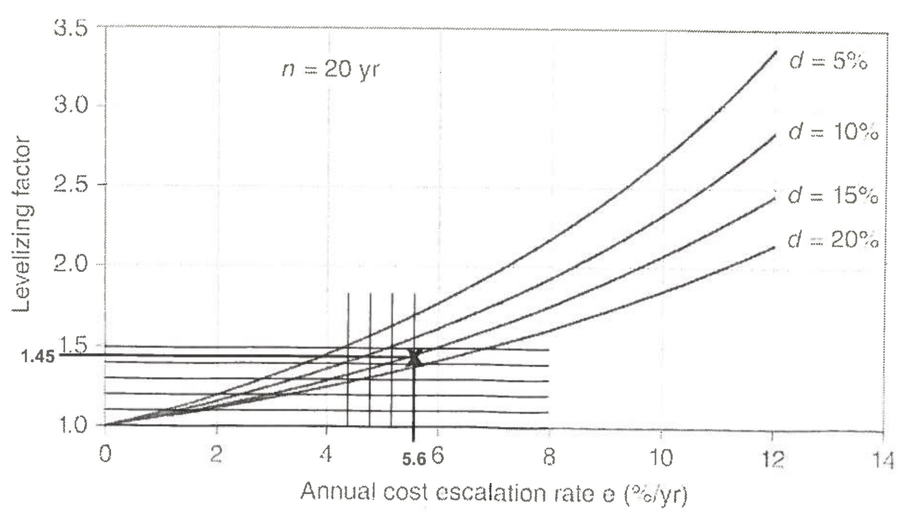


Fig. A.3 Levelizing factor of a function of the escalation rate of annual costs *e*, with the owner's discount rate *d* as a parameter.

b) CONT FROM ANNOTATED FIG A.3 THE LEVELIZING FACTOR CORRESPONDS TO $e \approx 5.6\%$ FOR BUYERS' DISCOUNT RATE = 15%

$\Rightarrow$ $\underline{\underline{e \doteq 5.6\%}}$ ANS. ANNUAL ESCALATION RATE FOR PV COST (\$/kWh) TO MATCH LOCAL UTILITY PRODUCTION COST OVER 20 YEARS

2. Demand Side Management (DSM):

a. What is the purpose of DSM?

In the 1980s, regulators began to recognize that energy conservation could be treated as a "source" of energy that could be directly compared with traditional supply sources. If utilities could help customers be more efficient in their use of electricity, delivering the same energy service with fewer kilowatt-hours, and if they could do so at a lower cost than supplying energy, then it would be in the public's interest to encourage that to occur. Sometimes called *integrated resource planning* (IRP)

The new and defining element of IRP was the incorporation of utility programs that were designed to control energy consumption on the customer's side of the electric meter. These are known as demand-side management (DSM) programs. While DSM most often refers to programs designed to save energy, it has been defined in a broader sense to refer to any program that attempts to modify customer energy use. As such it includes

- *Conservation/energy efficiency programs* that have the effect of reducing consumption during most or all hours of customer demand.
- *Load management programs* that have the effect of reducing peak demand or shifting electric demand from the hours of peak demand to non-peak time periods.
- *Fuel substitution programs* that influence a customer's choice between electric or natural gas service from utilities. For example, the electricity needed for air conditioning can be virtually eliminated by replacing a compressive refrigeration system with one based on absorption cooling.

b. What are the necessary conditions for successful DSM programs? Briefly explain why these make sense.

Three conditions necessary for DSM to be successful:

- Decoupling utility sales from utility profits.
- Recovery of DSM program costs to allow utilities to earn profits on DSM.
- Incentives to encourage utilities to prefer DSM over generation.

c. Provide five examples of DSM programs including an explanation of its objective and contribution to DSM.

Many possible examples:

- Power industry subsidies for LED light bulbs.... Same light – 16 % of the energy
- Old, low-efficiency appliance replacement $ incentives
- Voluntary participation in Air Conditioning reduction during peak periods
- Conservation awareness programs .....