Design and Simulation of Micro-Power System of Renewables

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2. Renewable Energy Sources

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*NOTE: Contents and examples of this part of lecture are based on “Renewable and Efficient Electric Power Systems” (G. M. Masters) 2004.

Renewable Energy Sources and Characteristics

WIND

- Our focus
  - Wind Power
  - Solar Power
- Applications
  - Home and cottage
  - Mobile, RV and Marine
  - Commercial Industrial
- Major Resources
  - SWERA (Solar and Wind Energy Resources Assessment)
  - http://maps.nrel.gov/SWERA
  - http://en.openei.org/apps/SWERA/
  - National Renewable Energy Laboratory (NREL): http://www.nrel.gov/
  - Windfinder: www.windfinder.com

Brief on Wind Energy

- Wind is the circulation of air caused by the uneven heating of earth's surface, by the sun heating the land more than the water. The warm air over land rises and cooler air moves in to take its place, producing convection current.
- Wind Energy: Wind turns the blades (usually 3) in the wind that turns a turbine and the drive shaft to the generator, which produces electricity
- Clean, renewable energy Source
- Intermittent Energy Source (operation time is about 75%)
- In the U.S., Texas and California have the most wind energy production → windfarm

Typical Wind Turbine Schematic

- Tower
- Blades
- Rotor
- Gearing
- Generator
- Speed Sensor
- Control Device
- Power Conditioner

Wind Speed and Scale

- Wind Speed Conversion
- 1 knot = 0.5144 m/s
- 1 mph = 0.447 m/s

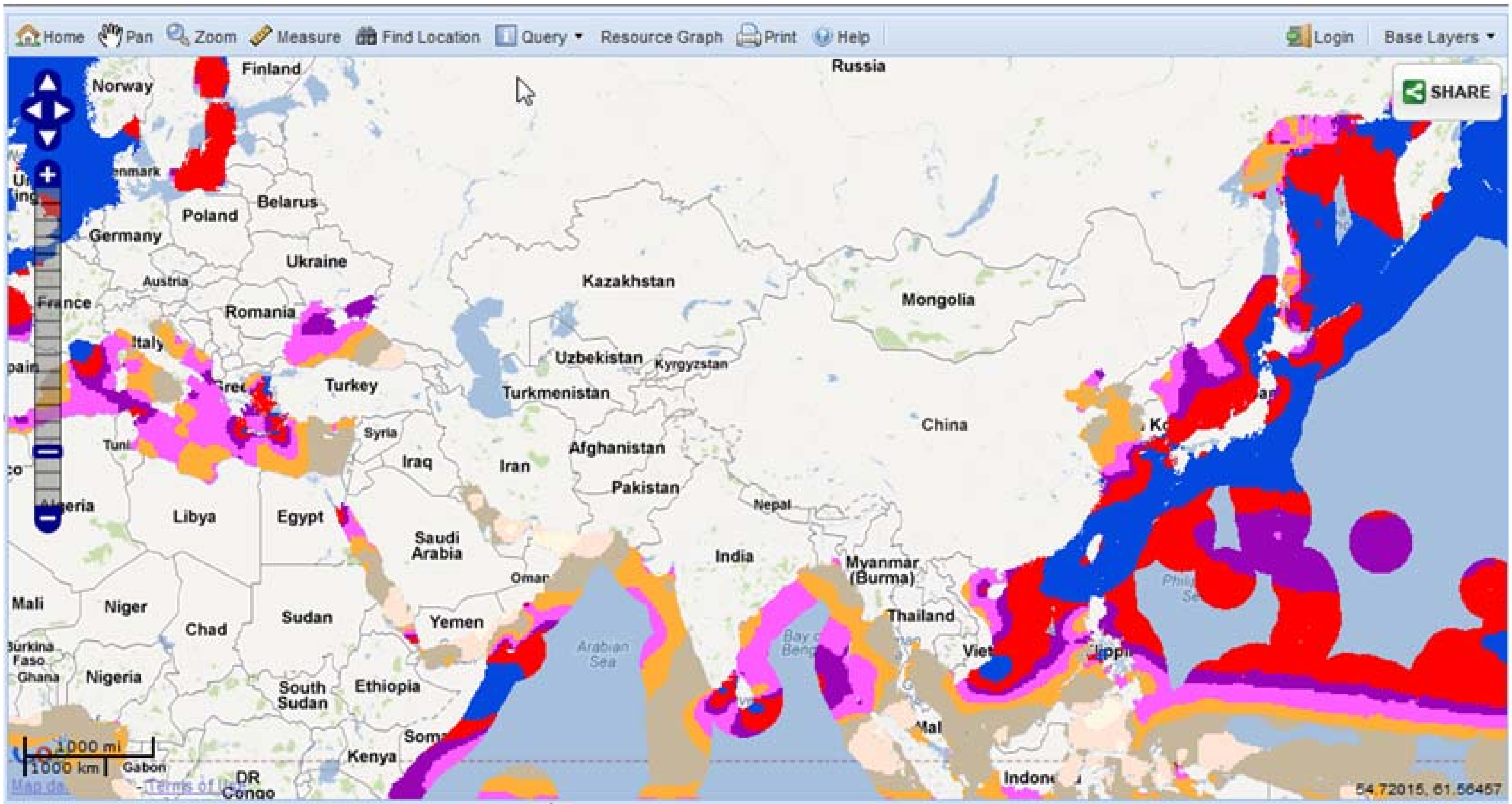
Beaufort Scale

- $V=0.836*B^{3/2}$

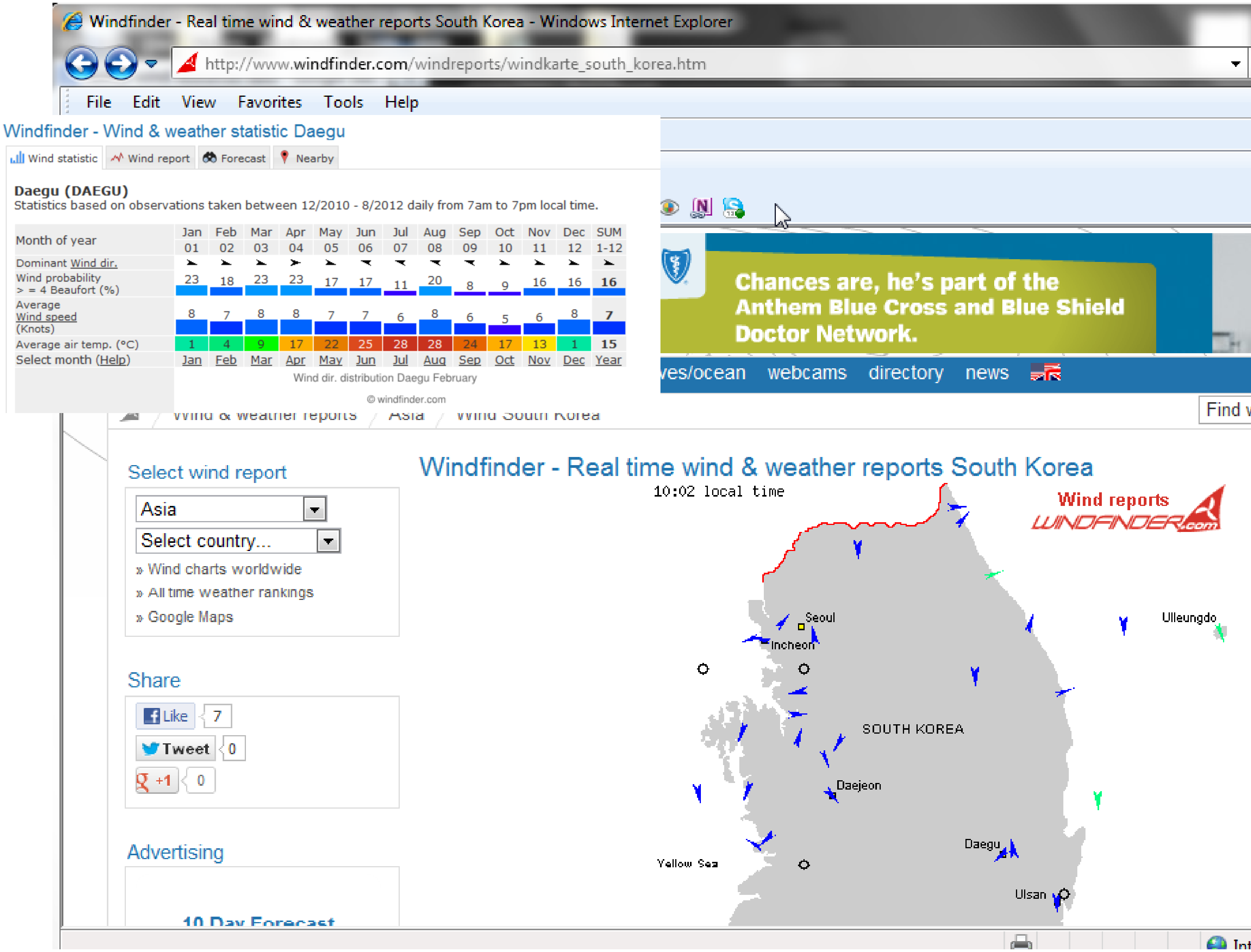
```
>>>
>>> B=5
>>> v=0.836*B**(3/2.)
>>> v
9.346764145949121 5 m/s
>>> _/0.447
20.909986903689308 mph
>>>
>>> B=12
>>> v=0.836*B**(3/2.)
>>> v
34.751867403061951 m/s
>>> _/0.447
77.744669805507712 mph
>>>
```

Solar and Wind Energy – SWERA site

- SWERA(Solar and Wind Energy Resource Assessment)
- http://maps.nrel.gov/SWERA



Windfinder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Windfinder - Wind & weather statistic Daegu
Wind statistic Wind report Forecast Nearby
Daegu (DAEGU)
Statistics based on observations taken between 12/2010 - 8/2012 daily from 7am to 7pm local time.
Month of year Jan 01 Feb 02 Mar 03 Apr 04 May 05 Jun 06 Jul 07 Aug 08 Sep 09 Oct 10 Nov 11 Dec 12 SUM 1-12
Dominant Wind dir.
Wind probability > = 4 Beaufort (%) 23 18 23 23 17 17 11 20 8 9 16 16 16
Average Wind speed (Knots) 8 7 8 8 7 7 6 8 6 5 6 8 7
Average air temp. (°C) 1 4 9 17 22 25 28 28 24 17 13 1 15
Select month (Help) Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Year
Wind dir. distribution Daegu February
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Chances are, he's part of the Anthem Blue Cross and Blue Shield Doctor Network.
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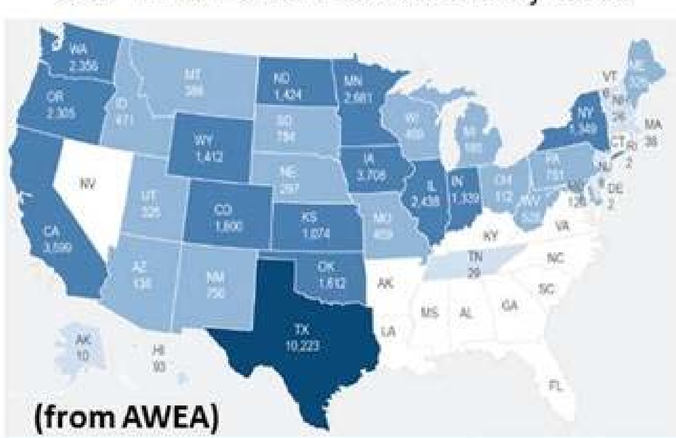
10 Day Forecast
Windfinder - Real time wind & weather reports South Korea
10:02 local time
Wind reports WINDFINDER.com
Seoul
Incheon
Ulleungdo
SOUTH KOREA
Daejeon
Daegu
Yellow Sea
Ulsan

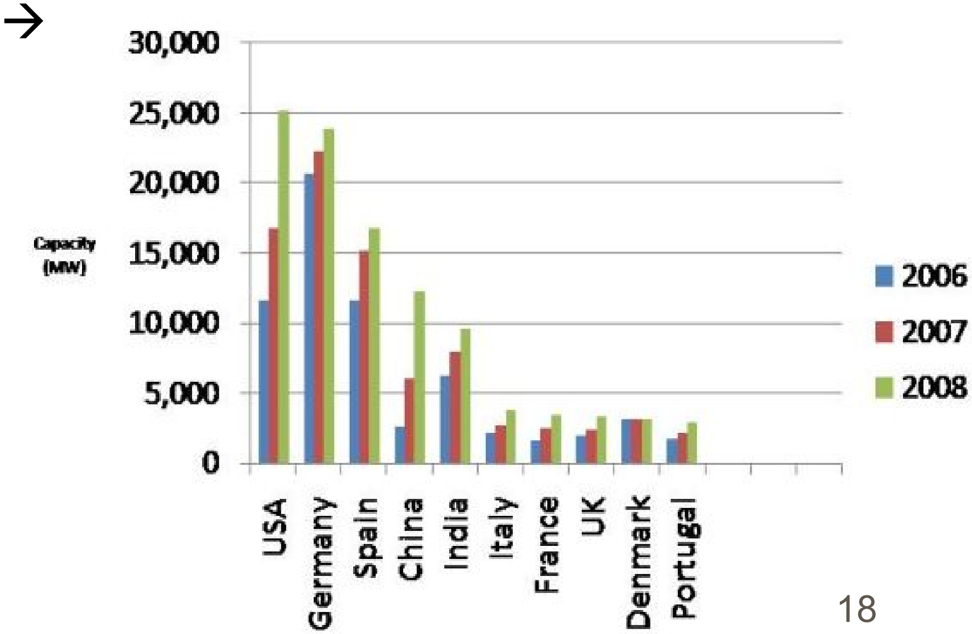
Wind Power History

- 1891 – Danish scientist Poul la Cour used wind turbine to generate electricity, from which he produced hydrogen for gas lights in the local schoolhouse.
- 1930s and 1940s: Hundreds of thousands of small-capacity wind-electric systems were in use in US in rural areas which were not yet electrified.
- 1980s: Oil price and tax credit programs made and broke the wind power boom in US
- 1990s: Europeans (Denmark, Germany, and Spain) made technology development and sold the wind turbines.
- Total installed capacity by country →
- US installed capacity

U.S. Wind Power Installations by State

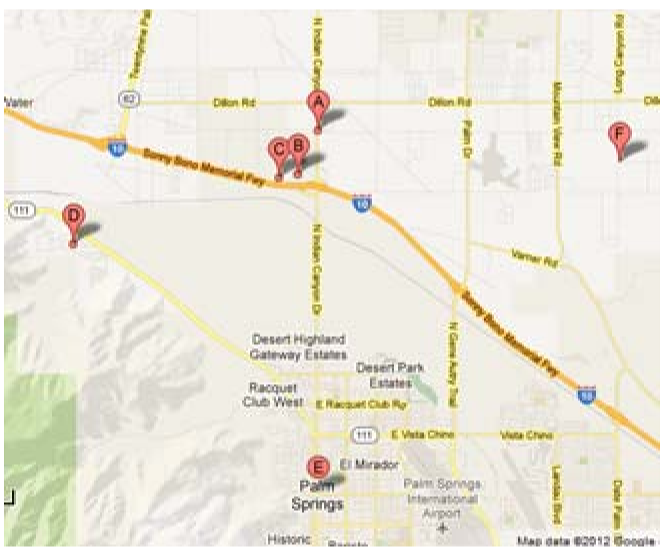


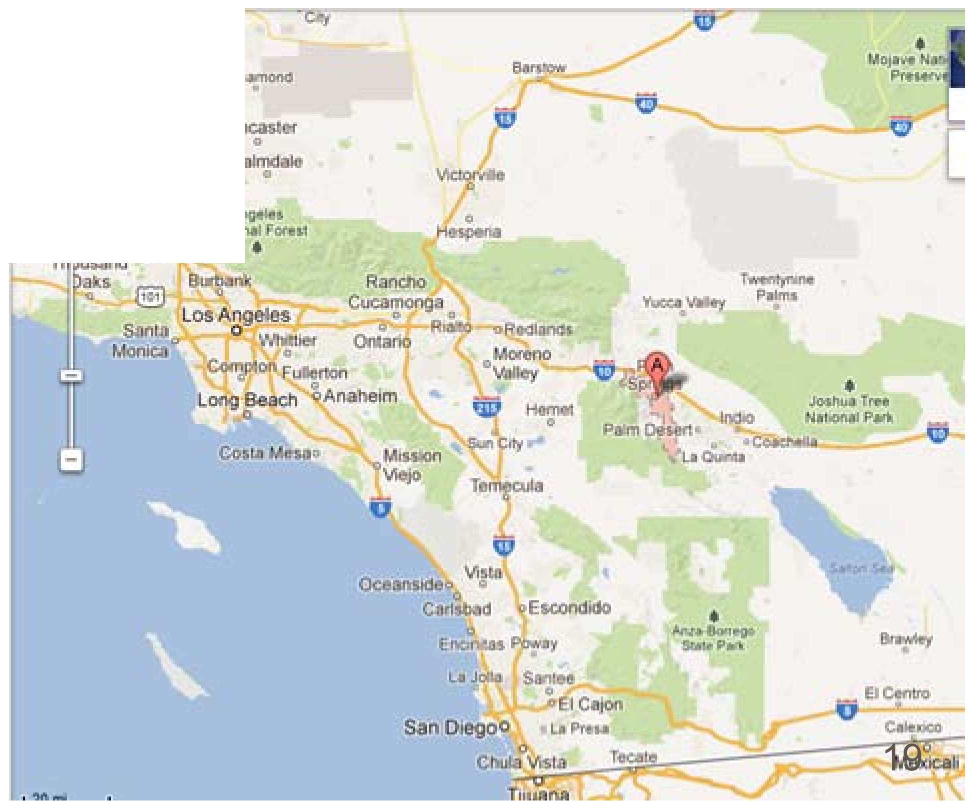
Installed wind Power Capacity of Ten Countries



A Wind Farm in California

- San Gorgonio Pass Wind Farm





Near Palm Springs

⌘ San Gorgonio Pass Wind Farm. 2007.

Location of San Gorgonio Pass Wind Farm

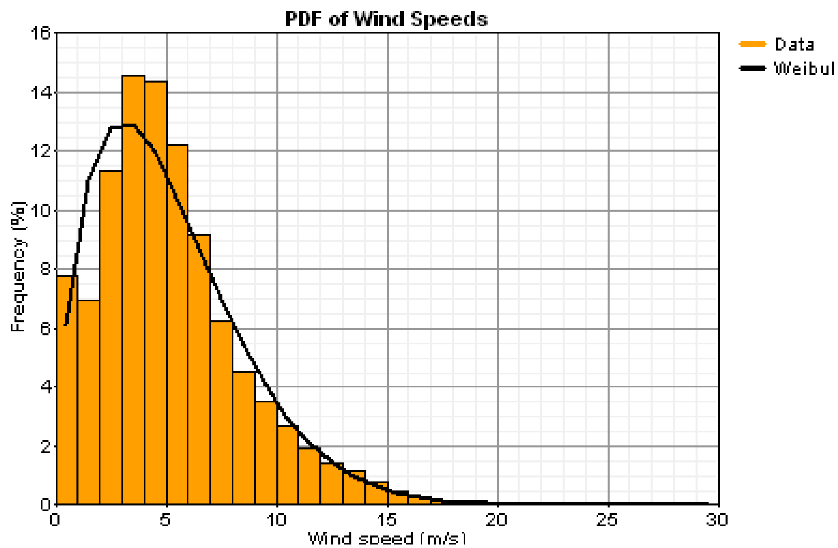
Country	United States
Location	Riverside County, California
Coordinates	33°54′N 116°35′W
Status	Operational
Construction began	1980s
Turbine information	
Turbines	3,218
Hub height	160 ft (49 m) (*max*)
Power generation information	
Installed capacity	615 MW

Wind Turbine

- Classified by Rated Power at a certain rated wind speed.
- $$\text{Power} = \frac{1}{2}\rho A v^3$$
- P [W]= 0.5*SweptArea [m^2]* AirDensity [kg/m^3] * Velocity^3[m/s]
- Capacity Factor: Wind Turbine's <u>Actual energy output</u> for the year divided by the <u>expected energy output</u> if the turbine operated at its rated power output for entire year.
- Important to know the capacity factor at the average wind speed of the intended site, for estimating annual energy output.
- Range of capacity factor: 0.4 (very good), 0.25-0.30 (reasonable)
- Annual Energy Output is important
  - Energy = Power * Time
  - Bill is on kWh

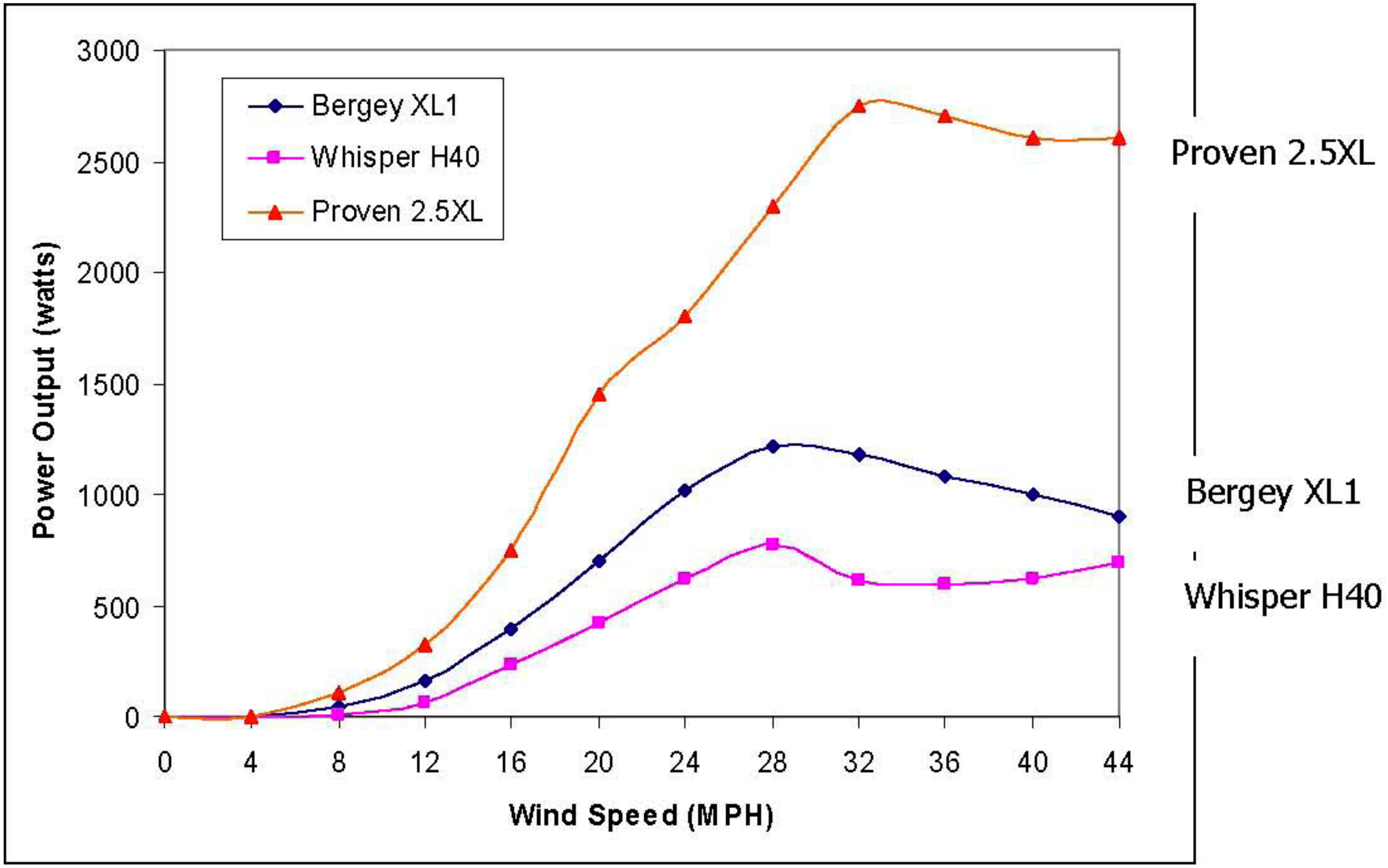
Capacity Factor

- Capacity Factor: Wind Turbine's Actual energy output for the year divided by the expected energy output if the turbine operated at its rated power output for entire year.
- Rough Capacity Factor (RCF): Percentage of the rated power produced at the average wind speed
- Energy production per year = Rated power * RCF*8760 Hour/Year
- Example: 100kW*0.2*8760=175,200 kWh
- How do we get Average Wind Speed?
- Wind Power Distribution: Percentage time the wind blows at various wind speeds over the course of an average year → How do we know this?
- Two common wind distributions to make energy calculation (More to come)
  - Weibull Distribution
  - Rayleigh Distribution



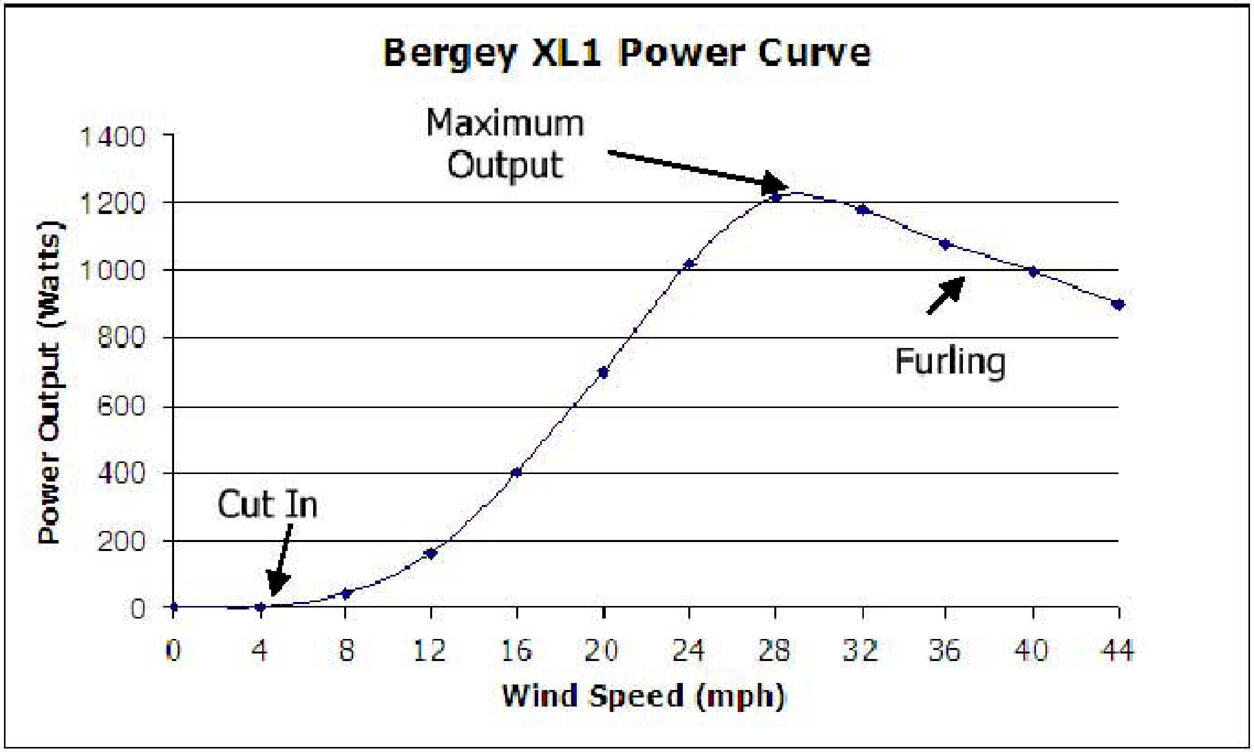
Power Output

- Which one do you choose for your max load of 1000 – 1200 [W]?



Wind Power Curve

- Wind power curve: How much power a wind turbine can extract from the wind at a variety of different wind speeds – wind power curves are different for different wind turbines:
- Cut In Speed: wind transfers enough force to the blades to rotate the generator shaft (is close to Start Up Wind Speed --- electricity is generated)
- Example Curve for Bergey XL1 Wind Turbine
  - Max Power: 1.2 kW at 29 mph
  - Rated Power : 1 kW → wind speed 24 mph
  - Furling Speed: Too high wind speed (>40 mph) → New method of blade



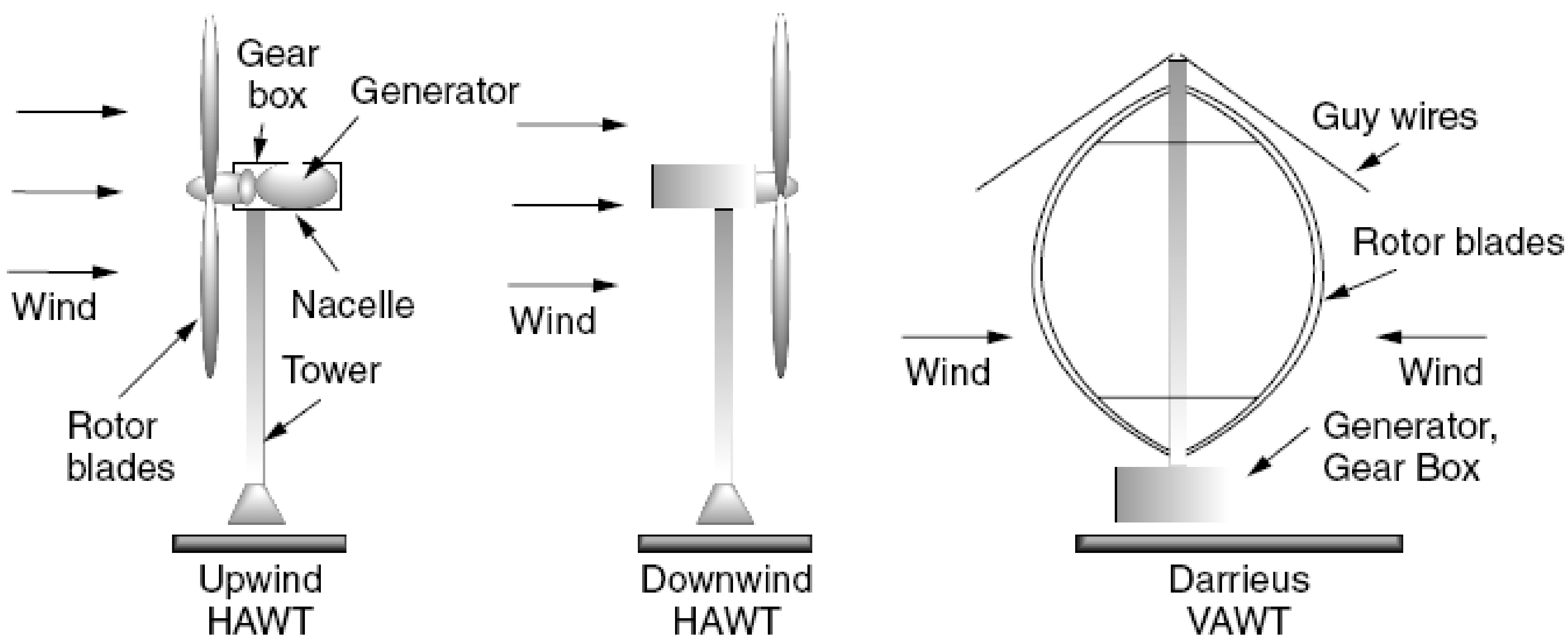
Wind Turbine Power Spec

	Manufacturer:	NEG Micon	NEG Micon	NEG Micon	Vestas	Whisper	Wind World	Nordex	Bonus
	Rated Power (kW):	1000	1000	1500	600	0.9	250	1300	300
	Diameter (m):	60	54	64	42	2.13	29.2	60	33.4
Avg. Windspeed									
v (m/s)	v(mph)	kW	kW	kW	kW	kW	kW	kW	kW
0	0	0	0	0	0	0.00	0	0	0
1	2.2	0	0	0	0	0.00	0	0	0
2	4.5	0	0	0	0	0.00	0	0	0
3	6.7	0	0	0	0	0.03	0	0	4
4	8.9	33	10	9	0	0.08	0	25	15
5	11.2	86	51	63	22	0.17	12	78	32
6	13.4	150	104	159	65	0.25	33	150	52
7	15.7	248	186	285	120	0.35	60	234	87
8	17.9	385	291	438	188	0.45	92	381	129
9	20.1	535	412	615	268	0.62	124	557	172
10	22.4	670	529	812	356	0.78	153	752	212
11	24.6	780	655	1012	440	0.90	180	926	251
12	26.8	864	794	1197	510	1.02	205	1050	281
13	29.1	924	911	1340	556	1.05	224	1159	297
14	31.3	964	986	1437	582	1.08	238	1249	305
15	33.6	989	1006	1490	594	1.04	247	1301	300
16	35.8	1000	998	1497	598	1.01	253	1306	281
17	38.0	998	984	1491	600	1.00	258	1292	271
18	40.3	987	971	1449	600	0.99	260	1283	259
19	42.5	968	960	1413	600	0.97	259	1282	255
20	44.7	944	962	1389	600	0.95	256	1288	253
21	47.0	917	967	1359	600	0.00	250	1292	254
22	49.2	889	974	1329	600	0.00	243	1300	255
23	51.5	863	980	1307	600	0.00	236	1313	256
24	53.7	840	985	1288	600	0.00	230	1328	257
25	55.9	822	991	1271	600	0.00	224	1344	258
26	58.2	0	0	0	0	0.00	0	0	0

Source: Mostly based on data in www.windpower.dk.

Types of Wind Turbines

- Horizontal Axis Wind Turbines (HAWT)
  - Upward Machine
  - Downward Machine
- Vertical Axis Wind Turbines (VAWT)
  - Accept wind from any direction



Wind Speed Impact on Tower Height and Friction

$$v = v_0 \left(\frac{H}{H_0}\right)^{\alpha}$$

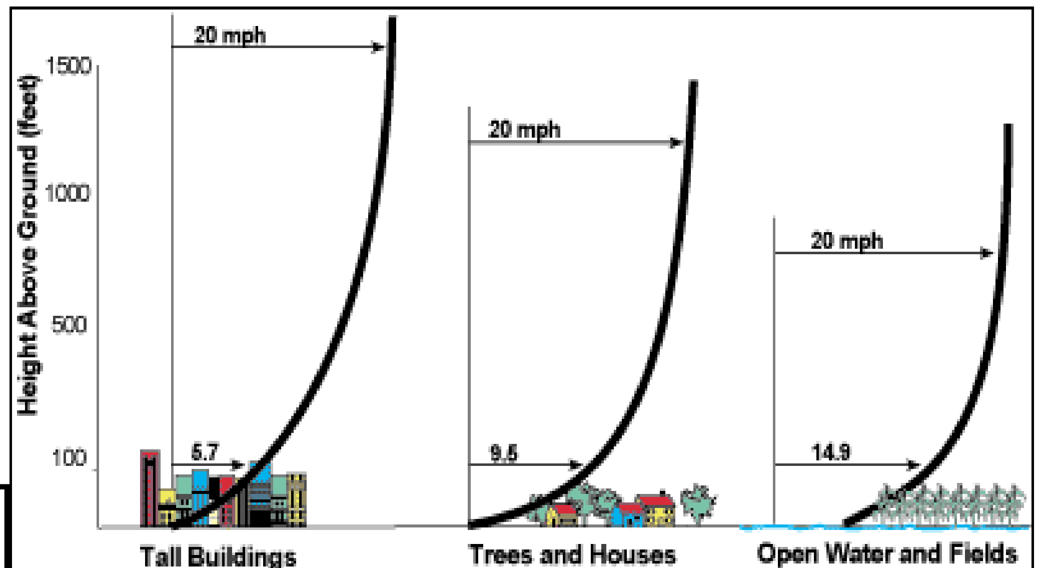
- v : wind speed at height H
- v_o : wind speed at height H_o (usually 10m)
- α: friction constant (1/7. "one-seventh" rule of thumb)

```
>>>
>>>
>>> 1/7.
0.1428571
>>>
```

- Smooth Surface
  - Height has little impact on wind speed
- Rough Surface
  - Height has greater impact in wind speed

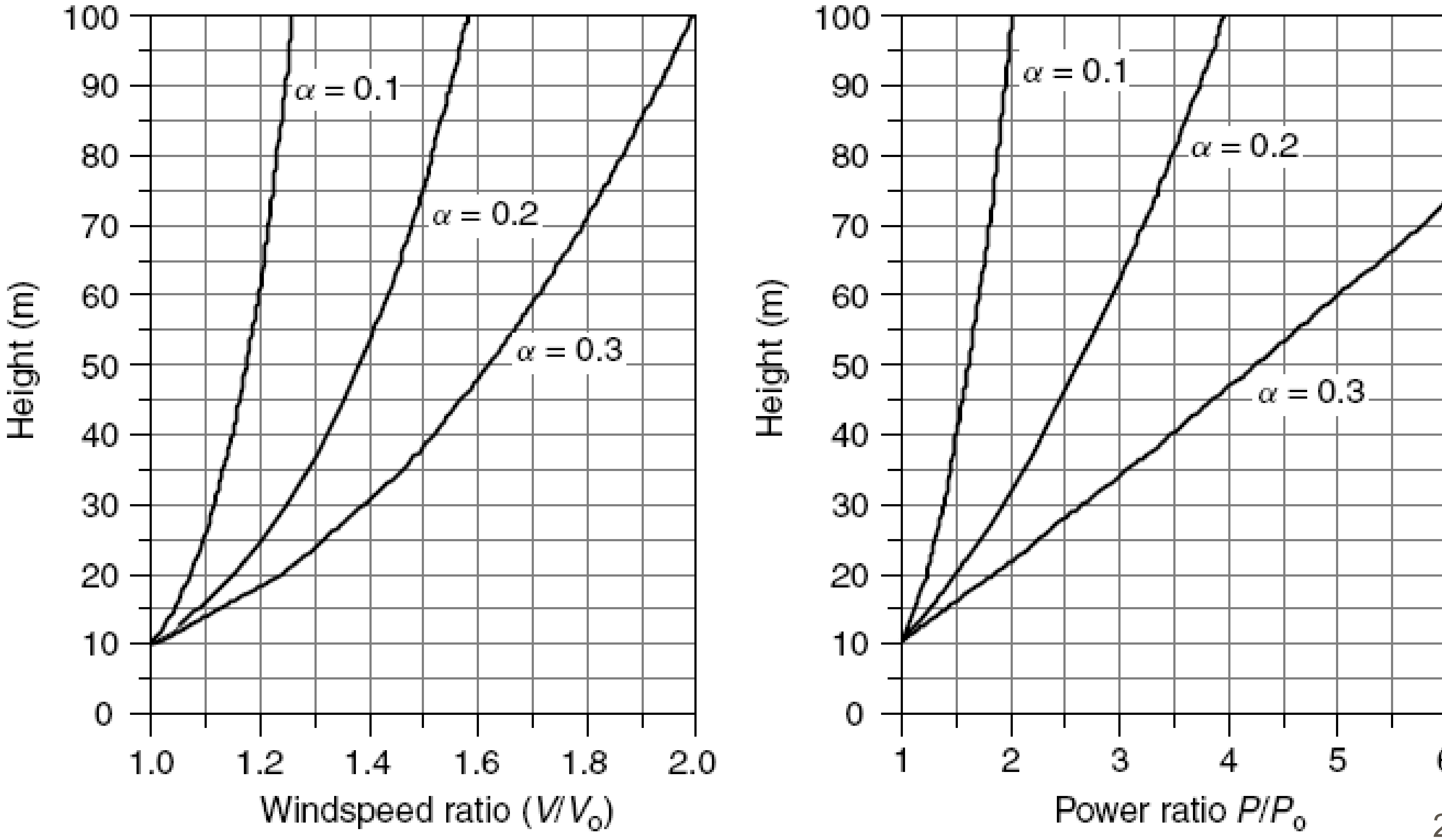
$$\left(\frac{P}{P_0}\right) = \left(\frac{1/2\rho A v^3}{1/2\rho A v_0^3}\right) = \left(\frac{v}{v_0}\right)^3 = \left(\frac{H}{H_0}\right)^{3\alpha}$$

Terrain Characteristics	Friction Coefficient α
Smooth hard ground, calm water	0.10
Tall grass on level ground	0.15
High crops, hedges and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40



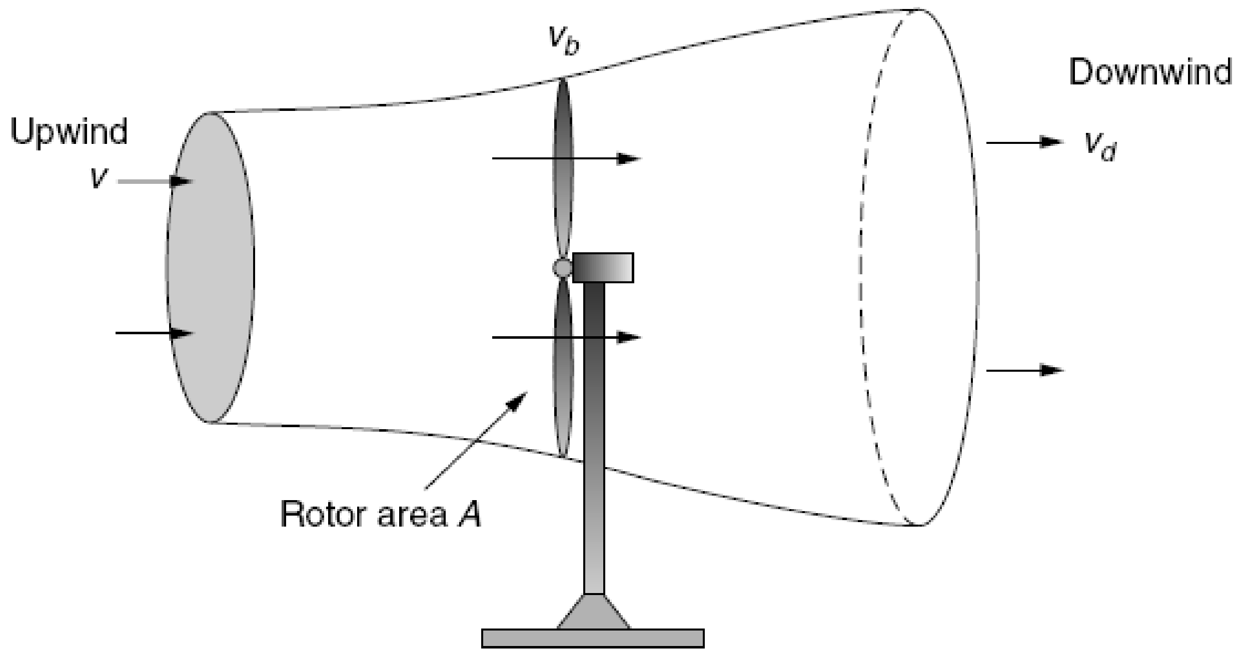
Impact of Height on Different Friction Coefficients

- In the condition of hedges and crops (alpha=0.2), at 50m, the wind speed increase by a factor of nearly 1.4 and wind power increase by about 2.4.
- CAVEAT: Under the same wind condition, the wind speed in higher friction would be much lower than in lower state.



Maximum Power Conversion

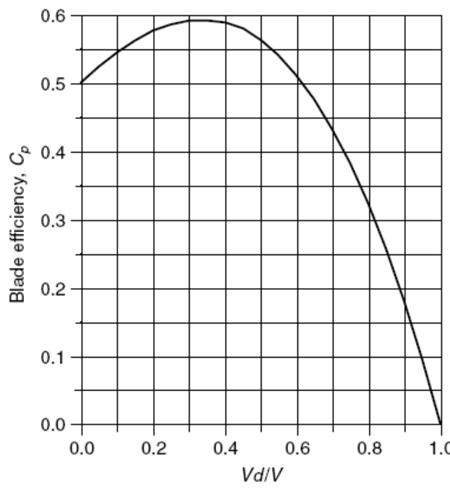
- Fundamental Constraints that restrict the maximum possible conversion efficiency from one form of energy to another
- Maximum power that a turbine can extract from the wind – formulated by Albert Betz (German Physicist) in 1919, with concept of Steam Tube.
- Wind →Turbine→Wind (slower with a portion of kinetic energy extracted by turbine → Air expanded)



- Question: Why can't the turbine extract all of the kinetic energy in the wind?

Betz' Law

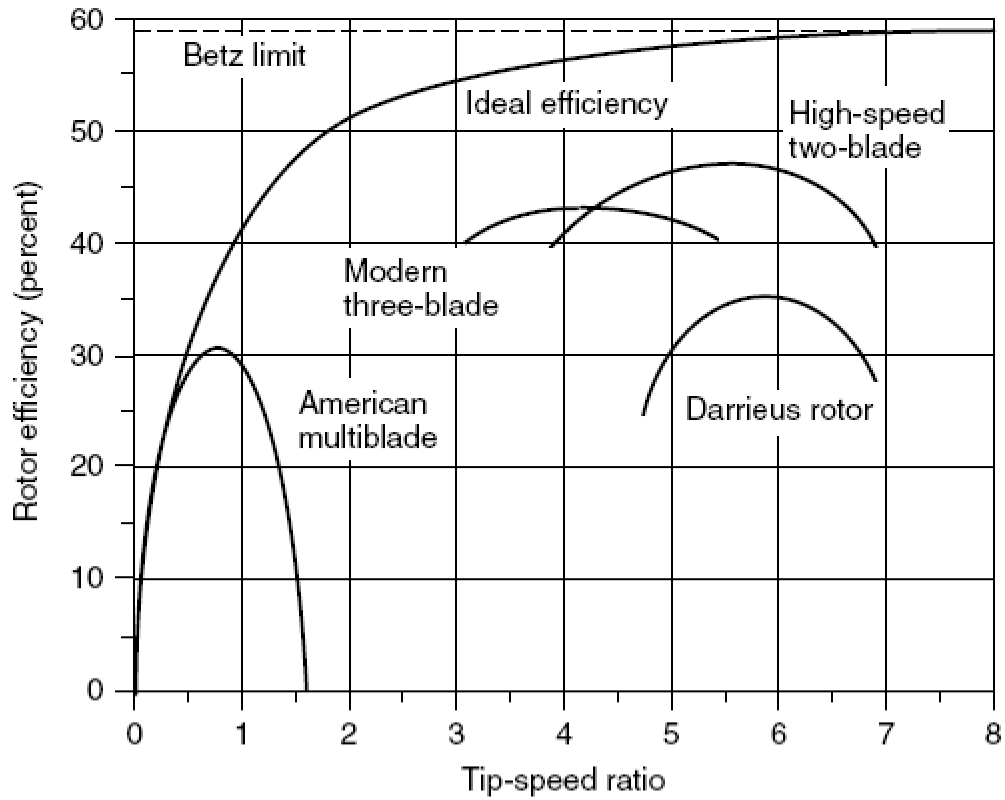
- Question: Why can't the turbine extract all of the kinetic energy in the wind?
  - If it did:
    - The air would have to a complete stop behind the turbine, which with no where to go, would prevent any more of the wind to pass through the rotor → **But** the downwind velocity cannot be zero.
  - Therefore, there must be some ideal slowing of the wind that will result in maximum power extracted by the turbine → Betz showed (using kinetic energy difference relationship) that an ideal turbine would slow the wind to the 1/3 of its original speed.
  - $r = v_d/v = 1/3$
- Rotor Efficiency (C_p)= Fraction of the wind's power extracted by the rotor blade: $C_p=0.5^* (1+r)(1-r^2)$
- Maximum Rotor Efficiency (at r = 1/3) : 0.593
- 59.3% → "Betz Efficiency" or "Betz' Law"



How close to the Betz limit are modern wind turbines?

- Under the best operating conditions: 80% of the limit → 45 – 50% efficiency in converting power in the wind into the power of a rotating generator shaft
- TSR (tip speed ratio): the speed of the outer tip of the blade divided by the wind speed: TSR = (Rotor Tip Speed)/ (Wind Speed)
- Typical efficiency for various rotor types vs. TSR

- Darrieus Rotor
  - VAWT
  - 1931 Georges Jean Marie
  - Darrieus, French Aeronautical engineer



Average Power in the Wind

- Important to know the **capacity factor at the average wind speed** of the intended site, for estimating **annual energy output.**
- Average Wind Power:

$$P_{\text{avg}} = (\tfrac{1}{2}\rho A v^3)_{\text{avg}} = \tfrac{1}{2}\rho A (v^3)_{\text{avg}}$$

- Example for average power: for a 10-h period [3-h no wind, 3-h at 5mph, and 4h at 10mph]:

$$v_{\text{avg}} = \frac{\text{Miles of wind}}{\text{Total hours}} = \frac{3\ \text{h} \cdot 0\ \text{mile/hr} + 3\ \text{h} \cdot 5\ \text{mile/h} + 4\ \text{h} \cdot 10\ \text{mile/h}}{3 + 3 + 4\ \text{h}}$$

$$= \frac{55\ \text{mile}}{10\ \text{h}} = 5.5\ \text{mph}$$

$$v_{\text{avg}} = \left(\frac{3\ \text{h}}{10\ \text{h}}\right) \times 0\ \text{mph} + \left(\frac{3\ \text{h}}{10\ \text{h}}\right) \times 5\ \text{mph} + \left(\frac{4\ \text{h}}{10\ \text{h}}\right) \times 10\ \text{mph} = 5.5\ \text{mph}$$

$$v_{\text{avg}} = \frac{\sum_i [v_i \cdot (\text{hours @ } v_i)]}{\sum \text{hours}} = \sum_i [v_i \cdot (\text{fraction of hours @ } v_i)]$$

$$v_{\text{avg}} = \sum_i [v_i \cdot \text{probability}(v = v_i)]$$

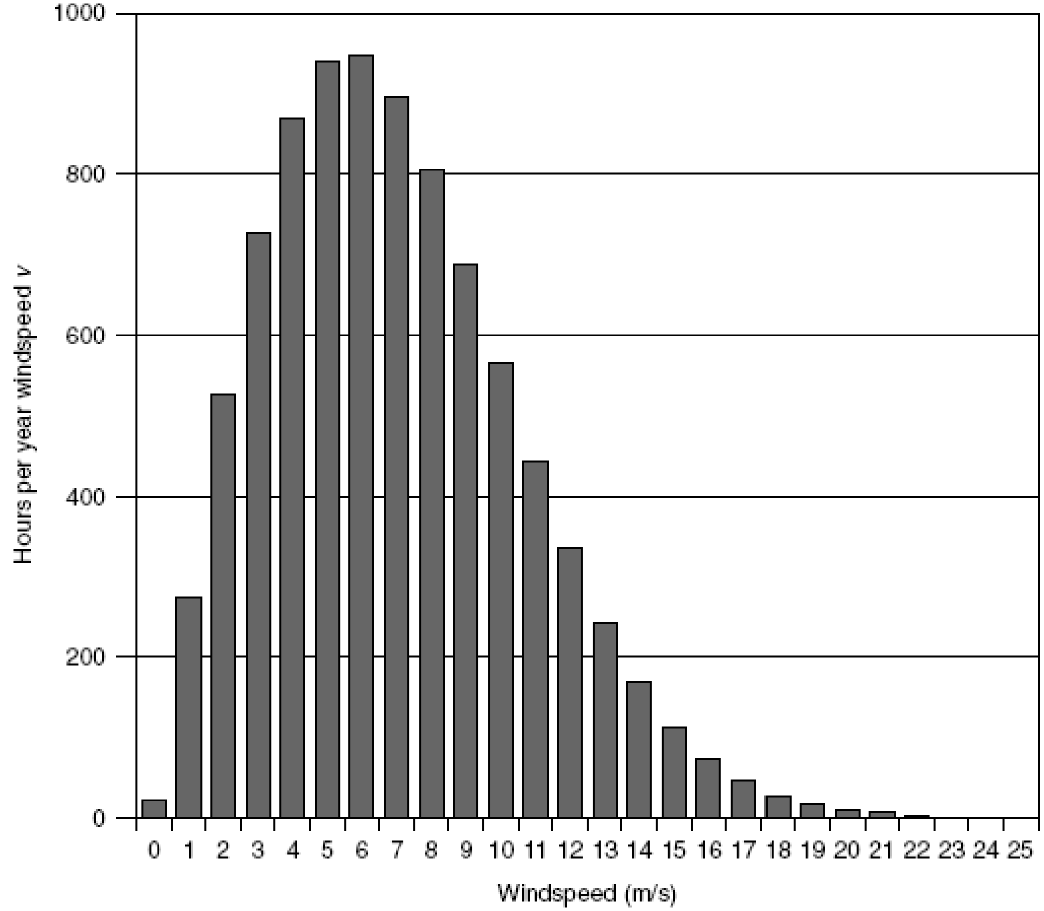
Wind Speed Histogram- Example

- Prob(v= 8 m/s)= 805/8760=0.0919
- V_{avg} = Sum $\{v_i * p(v=v_i)\}$=7.0 m/s
- $(V^3)_{avg}$= Sum $\{v_i^3 * p(v=v_i)\}$=653.24
- for A=1.225

$$P_{\text{avg}} = \frac{1}{2}\rho A (v^3)_{\text{avg}}$$

$$P_{\text{avg}} = \frac{1}{2}\rho (v^3)_{\text{avg}} = 0.5 \times 1.225 \times 653.24 = 400 \text{ W/m}^2$$

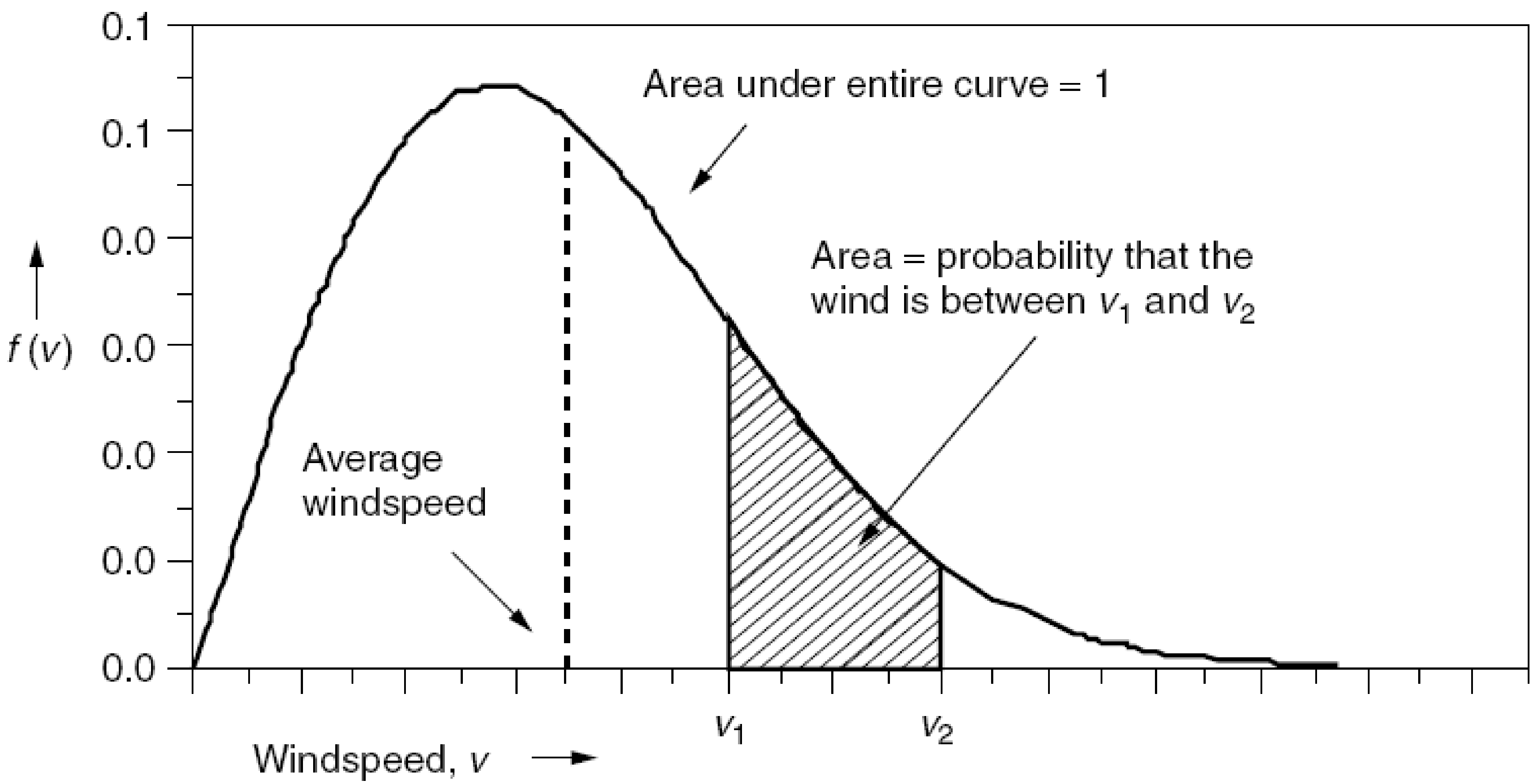
v (m/s)	Hrs/yr
0	24
1	276
2	527
3	729
4	869
5	941
6	946
7	896
8	805
9	690
10	565
11	444
12	335
13	243
14	170
15	114
16	74
17	46
18	28
19	16
20	9
21	5
22	3
23	1
24	1
25	0
Total hrs	8,760



PDF

- Continuous format of histogram → pdf

$f(v)$ = windspeed probability density function



Wind Power Probability Density Functions

- Pdf features
  - the area under the curve is equal to unity (1.0)

$$\text{probability } (0 \leq v \leq \infty) = \int_0^\infty f(v)\, dv = 1$$

  - The area under the curve between any 2 wind speeds equal to the probability that the wind is between those 2 speeds.

$$\text{probability } (v_1 \leq v \leq v_2) = \int_{v_1}^{v_2} f(v)\, dv$$

  - Number of hours per year that the wind blows between any two wind speeds:

$$\text{hours/yr } (v_1 \leq v \leq v_2) = 8760 \int_{v_1}^{v_2} f(v)\, dv$$

  - The average value:

$$v_{\text{avg}} = \int_0^\infty v \cdot f(v)\, dv$$

$$(v^3)_{\text{avg}} = \int_0^\infty v^3 \cdot f(v)\, dv$$

Wind Speed Distribution – Weibul statistics

- The starting point for characterizing the statistics of wind speed is Weibull pdf.
- k : shape parameter
- c : scale parameter

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$$

- Weibull pdfs **with c=8** with k=1(similar to exp),**2 (Rayleigh pdf)** ,and 3 (similar to normal)

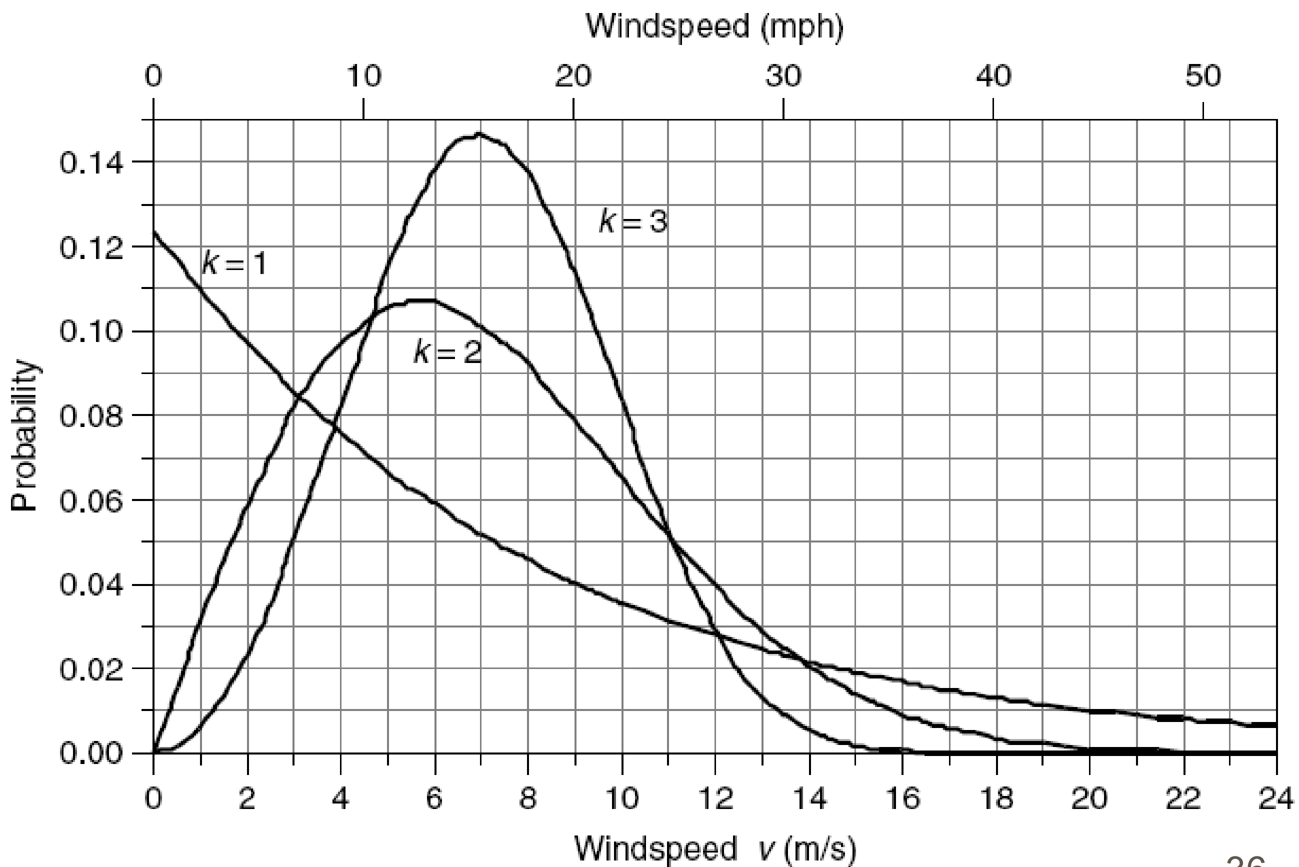
Rayleigh p.d.f.

$$f(v) = \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^{2}\right]$$

$$\begin{aligned}\overline{v} &= \int_0^\infty v \cdot f(v)\, dv \\ &= \int_0^\infty \frac{2v^2}{c^2} \exp\left[-\left(\frac{v}{c}\right)^{2}\right] \\ &= \frac{\sqrt{\pi}}{2} c \\ &\cong 0.886c\end{aligned}$$

Gaussian integral

$$\int_{-\infty}^{\infty} e^{-x^2}\, dx = \sqrt{\pi}.$$



Rayleigh pdf

- Weibul pdf at k=2
- Most realistic for a likely wind turbine site
- Winds that are mostly pretty strong, with periods of low and some really high-speed winds as well.
- When wind details are not known, the usual starting point is to assume Rayleigh pdf

$$(v^3)_{\text{avg}} = \int_0^\infty v^3 \cdot f(v)dv = \int_0^\infty v^3 \cdot \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right] dv = \frac{3}{4} c^3 \sqrt{\pi}$$

$$\boxed{(v^3)_{\text{avg}}} = \frac{3}{4}\sqrt{\pi}\left(\frac{2\bar{v}}{\sqrt{\pi}}\right)^3 = \boxed{\frac{6}{\pi}\bar{v}^3} = 1.91\ \bar{v}^3$$

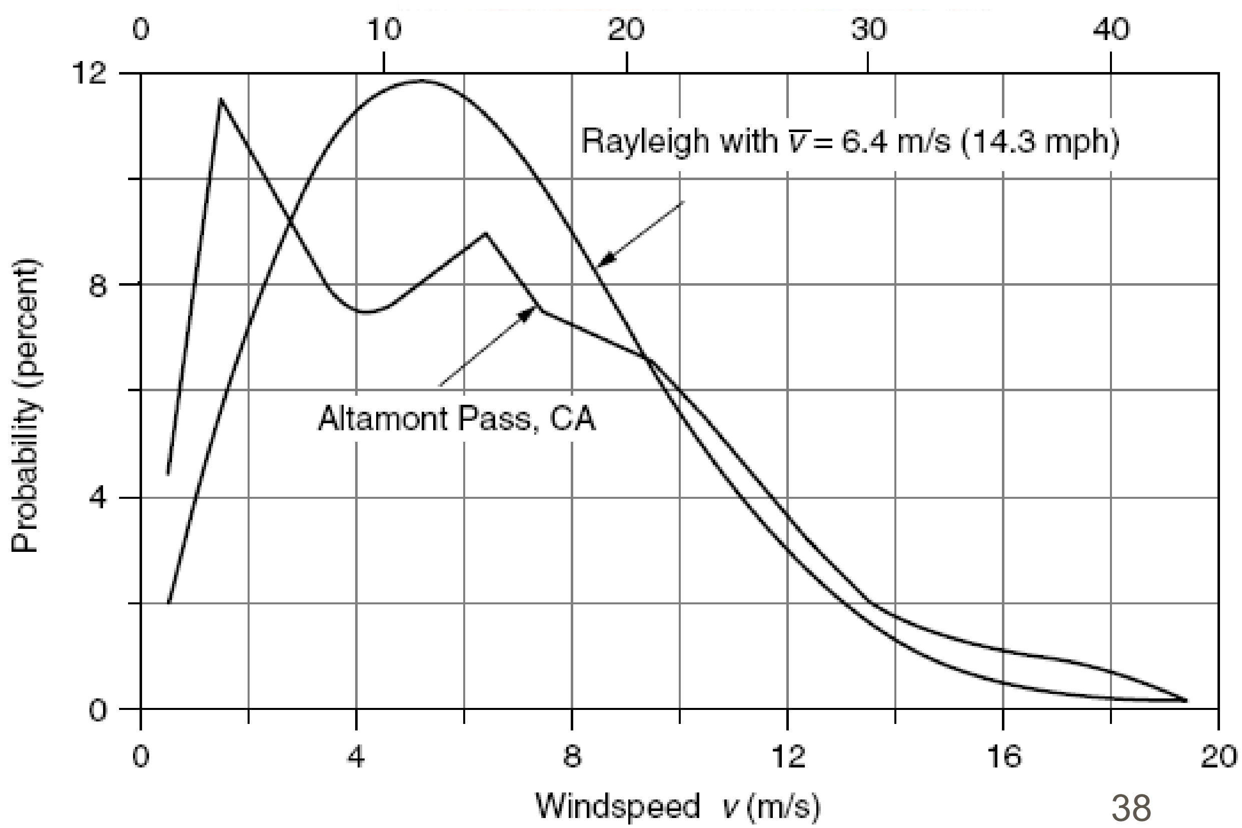
$$\boxed{\begin{gathered}\bar{v} = \frac{\sqrt{\pi}}{2}c \\ \Downarrow \\ c = \frac{2}{\sqrt{\pi}}\bar{v}\end{gathered}}$$

- If we assume Rayleigh statistics, the <u>average of the cube of wind speed</u> is just 1.91 times the <u>average wind speed cubed</u>.

average power in the wind $$\boxed{\overline{P} = \frac{6}{\pi} \cdot \frac{1}{2}\rho A \bar{v}^3}$$

Real vs. Rayleigh pdf comparison

- Altamont Pass, CA (between SF and Sacramento)



Wind Power Density - Calculation Example

Average Power in the Wind. Estimate the average power in the wind at a height of 50 m when the windspeed at 10 m averages 6 m/s. Assume Rayleigh statistics,

a standard friction coefficient $\alpha = 1/7$,

and standard air density $\rho = 1.225\ \mathrm{kg/m^3}$.

- P: Average Power [W]
- P/A = Power Density [W/m$_2$]

Wind Power Density - Calculation Example - SOLUTION

Average Power in the Wind. Estimate the average power in the wind at a height of 50 m when the windspeed at 10 m averages 6 m/s. Assume Rayleigh statistics, a standard friction coefficient $\alpha = 1/7$, and standard air density $\rho = 1.225 \text{ kg/m}^3$.

⌘ **SOLUTION**

We first adjust the winds at 10 m to those expected at 50 m

$$\overline{v}_{50} = \overline{v}_{10}\left(\frac{H_{50}}{H_{10}}\right)^{\alpha} = 6 \cdot \left(\frac{50}{10}\right)^{1/7} = 7.55 \text{ m/s}$$

So, the average wind power density would be

$$\overline{P}_{50} = \frac{6}{\pi} \cdot \frac{1}{2}\rho\overline{v}^3 = \frac{6}{\pi} \cdot \frac{1}{2} \cdot 1.225 \cdot (7.55)^3 = 504 \text{ W/m}^2$$

Wind Power Classification - Summary

- Classification by the estimated average wind power density (W/m^2)
- Average wind speed using an anemometer at 10m high → estimate the average wind speed and power density at 50m above the ground.
- Standard Assumption:
  - Rayleigh pdf
  - Friction coefficient 1/7
  - Sea level air density at 0 C = 1.225 kg/m^3.

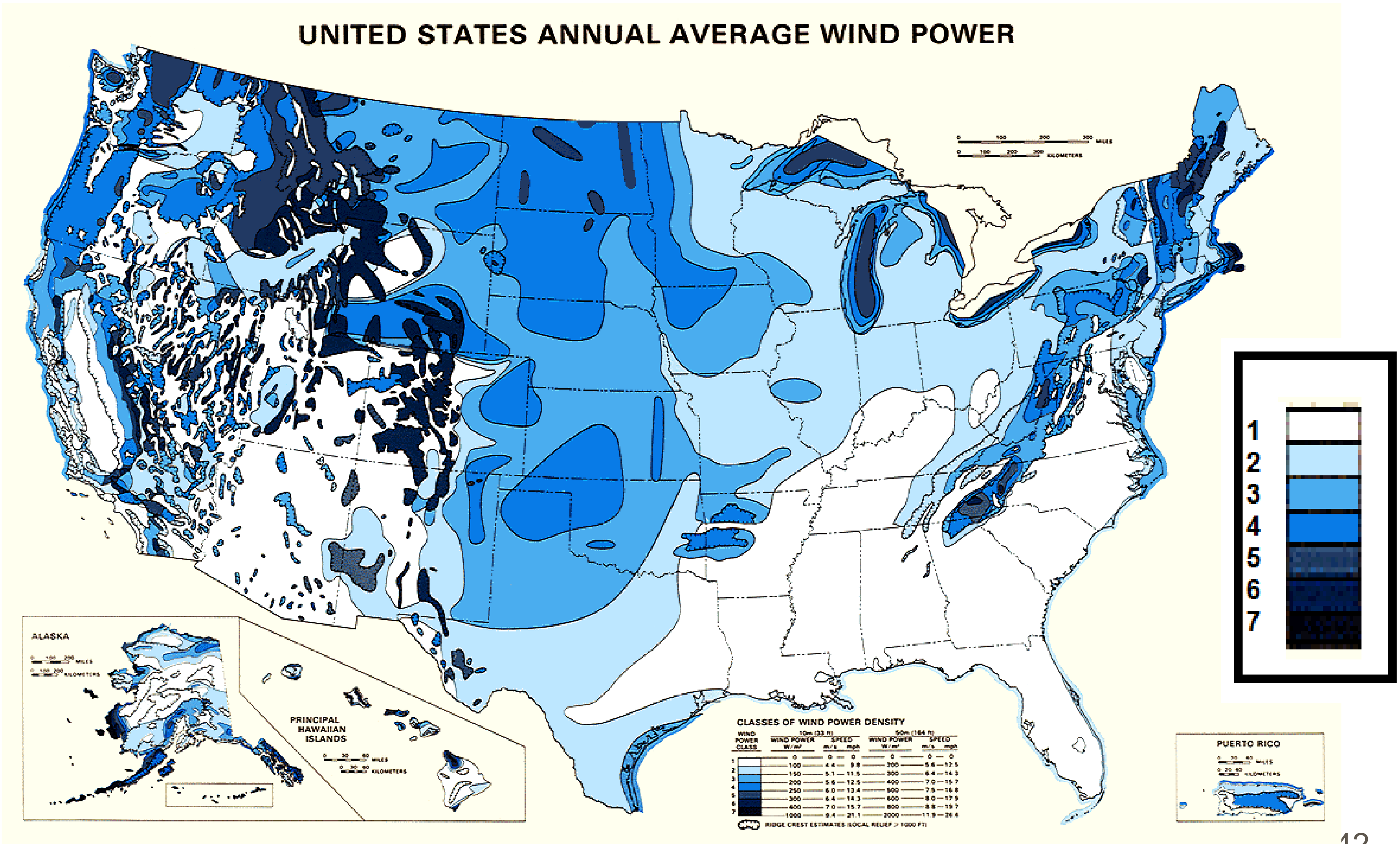
Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
1	Poor	0 - 200	0.0 - 6.0	0.0 - 13.4
2	Marginal	200 - 300	6.0 - 6.8	13.4 - 15.2
3	Fair	300 - 400	6.8 - 7.5	15.2 - 16.8
4	Good	400 - 500	7.5 - 8.1	16.8 - 18.1
5	Excellent	500 - 600	8.1 - 8.6	18.1 - 19.3
6	Outstanding	600 - 800	8.6 - 9.5	19.3 - 21.3
7	Superb	> 800	> 9.5	> 21.3

[a] Wind speeds are based on a Weibull k of 2.4 at 500 m elevation.

Wind Potential in US

- > class4: Band of states stretching from Texas to North Dakota



Wind Power in Korea (plan for 2020)

- **South Korea plans three-phase 2.5GW offshore Wind-gens by 2020**
- First phase would be in the 3MW to 7MW class.
- Eight major domestic industrial groups involved: Doosan Heavy Industries, Daewoo Shipbuilding & Marine Engineering, Samsung Heavy Industries, Unison, Hyundai Heavy Industries, Hyosung Heavy Industries, DMS, STX Heavy Industries.

Estimation of Wind Turbine Energy

- How much of the energy in the wind can be captured and converted into electricity?
- Factors
  - Machine (rotor, gearbox, generator, tower, etc)
  - Terrain (topography, surface roughness, obstruction, etc)
  - Wind regime (velocity, timing, predictability, etc)
- Rough Estimation Logic
  - **Wind Power Density** is evaluated at the site
  - **Betz' limit** at 59.3% maximum conversion potential
  - **Modern rotor at optimum condition can deliver 3/4** of the potential
  - **Gearbox and generator delivers 2/3 of the shaft power** created by the rotor
  - Combining all three above, the **power conversion efficiency is 30%**

Energy Calculation Example

- A NEG Micon 750/48 (750-kW generator , 48m rotor) wind turbine is mounted on a 50m tower in an area with 5 m/s average winds at 10m height.
- Estimate the annual energy (kWh/year) delivered, under the assumption that:
  - standard air density of 1.225
  - Rayleigh pdf
  - friction coefficient of 0.1524,
  - overall power conversion efficiency of 30%
  - Annual energy (kWh/year) = Efficiency *Average Power Density (kW/m^2)*Area (m^2)* 8760 (h/year)

$$\overline{P} = \frac{6}{\pi} \cdot \frac{1}{2} \rho A \overline{v}^3$$

Calculation Example - SOLUTION

- A NEG Micon 750/48 (750-kW generator , 48m rotor) wind turbine is mounted on a 50m tower in an area with 5 m/s average winds at 10m height.
- Estimate the annual energy (kWh/year) delivered, under the assumption that:
  - standard air density of 1.225
  - Rayleigh pdf
  - friction coefficient of 0.1524,
  - overall power conversion efficiency of 30%

SOLUTION

$$\overline{v}_{50} = \overline{v}_{10}\left(\frac{H_{50}}{H_{10}}\right)^{\alpha} = 5\cdot\left(\frac{50}{10}\right)^{0.1524} = 6.39 \text{ m/s}$$

$$\overline{P}_{50} = \frac{6}{\pi}\cdot\frac{1}{2}\rho\overline{v}^{3} = 1.91 \times 0.5 \times 1.225 \times (6.39)^{3} = 304.5 \text{ W/m}^{2}$$

$$\text{Energy} = 0.3 \times 304.5 \text{ W/m}^{2} \times \frac{\pi}{4}(48 \text{ m})^{2} \times 8760 \text{ h/yr} \times \frac{1 \text{ kW}}{1000 \text{ W}}$$

$$= 1.45 \times 10^{6} \text{ kWh/yr}$$

Capacity Factor - Revisited

- Rated Power: How many kW it can produce on a continuous full-power basis.
- Wind Turbine: Do not run at full power all year
- **Capacity Factor (CF)= [Energy_delivered] / [Rated Power * Hour]**

$$\text{Annual energy (kWh/yr)} = P_R\ \text{(kW)} \times 8760\ \text{(h/yr)} \times \text{CF}$$

$$\text{CF} = \frac{\text{Actual energy delivered}}{P_R \times 8760}$$

$$\text{CF} = \frac{\text{Actual energy delivered/8760 h/yr}}{P_R} = \frac{\text{Average power}}{\text{Rated power}}$$

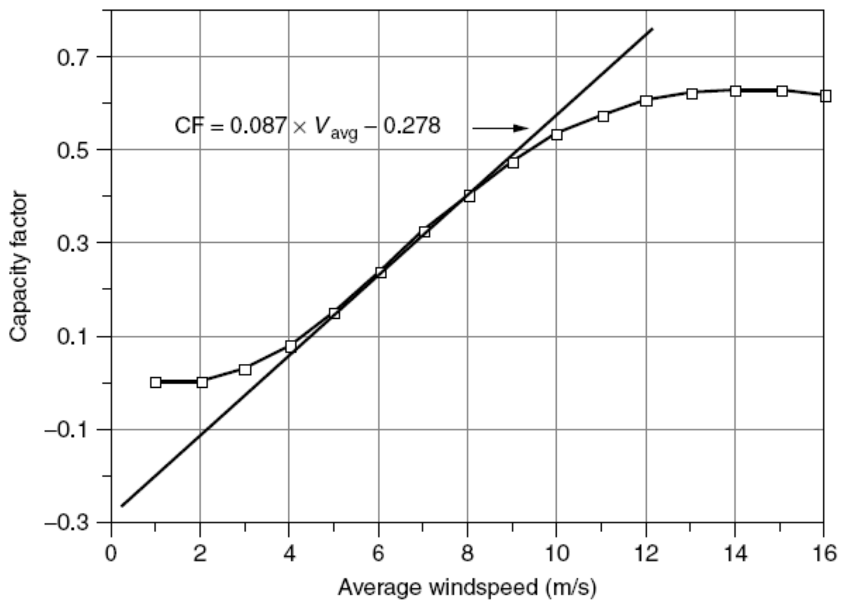
- **What is the capacitor factor for the NEG Micon 750/48 in the previous example? 22%**

```
>>> 1450000/8760.
165.52511415525115
>>> _/750.
0.22070015220700154
>>>
```

Estimation of Energy Production

⌘ **Rough Estimation: Linearization**

$$CF = 0.087\overline{V} - \frac{P_R}{D^2} \qquad \text{(Rayleigh winds)}$$



$\overline{V}$ is the average windspeed (m/s)

P_R is the rated power (kW).

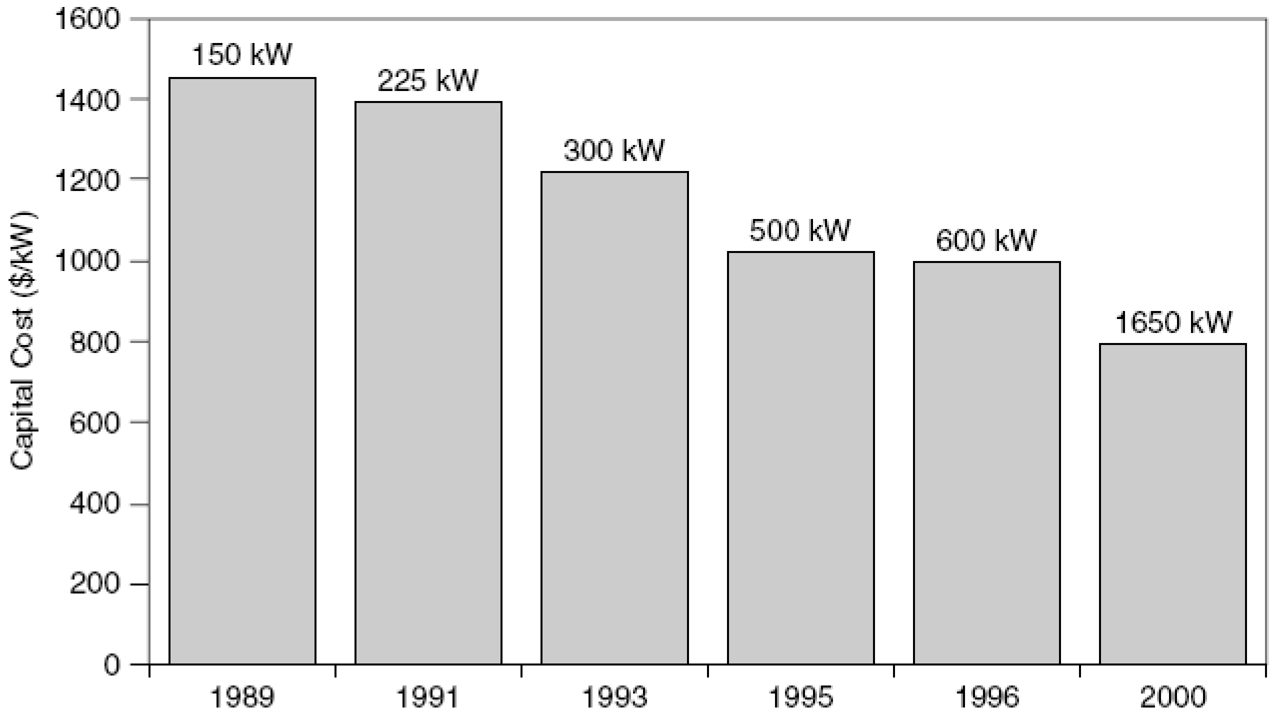
D is rotor diameter (m).

⌘ **Estimation of Energy produced using Capacity Factor = POWER*Hour*CF**

$$\text{Annual energy (kWh/yr)} = 8760 \cdot P_R(\text{kW}) \left\{ 0.087\overline{V}(\text{m/s}) - \frac{P_R(\text{kW})}{[D(\text{m})]^2} \right\}$$

Wind Turbine Economics

- Capital Cost
  - Includes: Turbine, tower, grid connection, site preparation, controls, and land
  - \$1500/kW (1989) [150 kW Turbine] → \$800/kW (2000) [1650 kW Turbine]



- O&M Cost
  - Regular maintenance, repairs, stocking repair parts, insurance, land lease fees, and administration

Cost Analysis - Example

- 60 MW Wind farm
  - 1.5 MW turbines (x 40)

Capital Costs	Amount ($)	Percentage
40 1.5-MW turbines @ $1.1 M, spare parts	46,640,000	76.6
Site prep, grid connections	9,148,000	15.0
Interest during construction, contingencies	3,514,000	5.8
Project development, feasibility study	965,000	1.6
Engineering	611,000	1.0
Total Capital Cost	60,878,000	100.0
Annual Costs	**Amount ($/yr)**	**Percentage**
Parts and labor	1,381,000	70.3
Insurance	135,000	6.9
Contingencies	100,000	5.1
Land lease	90,000	4.6
Property taxes	68,000	3.5
Transmission line maintenance	80,000	4.1
General and miscellaneous	111,000	5.6
Total Annual Costs	1,965,000	100.0

Source: Ministry of Natural Resources, Canada.

Levelized Cost

- LCOE (Levelized Cost of Energy) [$/kWh]:
  - constant unit cost (per kWh) of a payment stream that has the same present value as the total cost of building and operating a generating plant over its life.
- Annual Cost divided by annual energy delivered
- Annual cost [$/yr]
  - Spread the capital cost out over the lifetime using an appropriate factor
  - Add the annual O&M cost
  - Example
    - A financed wind farm project by debt – principal amount (***P*** [$])
    - Annual Payment (***A*** [$/yr]) with Capital Recovery Factor (CRF): with interest rate ***i*** [decimal fraction] and loan term ***n*** [yr]:

$$A = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] = P \cdot \mathrm{CRF}(i, n)$$

    - Annual Cost = A + O&M Cost
- Annual Energy Production [kWh/yr]
- LCOE = Annual cost [$/yr] / Annual Energy Production [kWh/yr]

Example Calculation for Cost/kWh

- Suppose that a 900-W Whisper H900 wind turbine with 7-ft (2.13 m) blade costs \$1600. By the time the system is installed and operational, it costs a total of \$2500, which is to be paid from with a 15-yr, 7% interest. Assume O&M costs of \$100/yr.

$$A = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] = P \cdot \mathrm{CRF}(i, n)$$

$$\text{Annual energy (kWh/yr)} = 8760 \cdot P_R(\mathrm{kW}) \left\{ 0.087\overline{V}(\mathrm{m/s}) - \frac{P_R(\mathrm{kW})}{[D(\mathrm{m})]^2} \right\}$$

- **Question:** Estimate the cost per kWh over the 15-year period if average wind speed at the hub height is 15 mph (6.7m/s).

Solution

- P=2500; i = 0.07; n=15
- CRF(0.07,15) = $\frac{i(1+i)^n}{(1+i)^n - 1} = \frac{0.07(1+0.07)^{15}}{(1+0.07)^{15} - 1} = 0.1098/\text{yr}$
- Annual Payment(A):

$$A = P \times \text{CRF}(0.07, 15) = \$2500 \times 0.1098/\text{yr} = \$274.49/\text{yr}$$

- Annual Cost = A + O&M= \$274.49 + \$100 = \$374.49/yr
- Capacity Factor (CF)

$$\text{CF} = 0.087\overline{V}(\text{m/s}) - \frac{P_R(\text{kW})}{D^2(m^2)} = 0.087 \times 6.7 - \frac{0.90}{2.13^2} = 0.385$$

- Annual Energy Production

$$\text{kWh/yr} = 0.90 \text{ kW} \times 8760 \text{ h/yr} \times 0.385 = 3035 \text{ kWh/yr}$$

- Average Cost per kWh

$$\text{Average cost} = \frac{\text{Annual cost (\$/yr)}}{\text{Annual energy (kWh/yr)}} = \frac{\$374.49/\text{yr}}{3035 \text{ kWh/yr}} = \$0.123/\text{kWh}$$

Cost Analysis Example 2

- A wind farm project has 40 1500-kW turbines with 64-m blades.
- Capital cost is $60 million and the 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 $15 million that needs a 15% return.
- Turbines are exposed to Rayleigh winds averaging 8.5 m/s.
- Question: What price [$/kWh] would the electricity have to sell for to make the project viable?

Solution 2

- CF:

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

- Annual Energy Production

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

- Annual Debt Payment:

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

- Annual Equity Return:

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

- Annual Cost (with O&M cost of $1.8M):

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

- Selling Price:

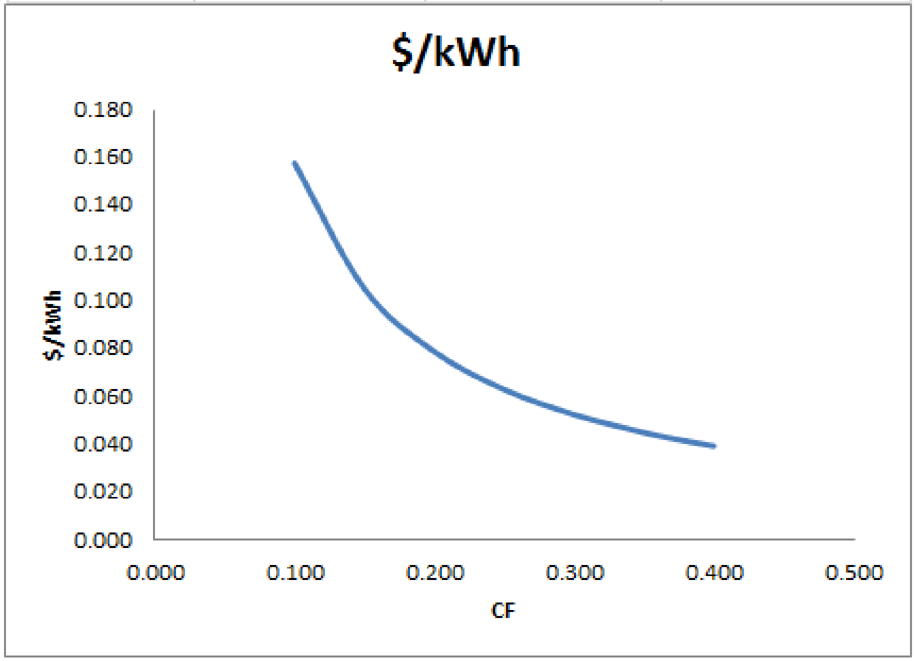
$$\text{Selling price} = \frac{\$8.29 \times 10^6/\text{yr}}{196 \times 10^6 \text{ kWh/yr}} = \$0.0423 = 4.23¢/\text{kWh}$$

Sensitivity Analysis for different CFs

- The price [$/kWh] found in the example, $0.0423 is a pretty good price – cheaper than grid electricity

- Scaling the $/kWh for varying capacity factors for Sensitivity Analysis

CF	kWh/yr	Annual Cost	Price[$/kWh]
0.1	52560000	8290000	0.158
0.15	78840000	8290000	0.105
0.2	105120000	8290000	0.079
0.25	131400000	8290000	0.063
0.3	157680000	8290000	0.053
0.35	183960000	8290000	0.045
0.373	196048800	8290000	0.042
0.4	210240000	8290000	0.039



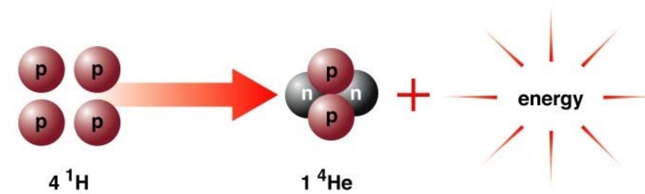
Environmental Impacts of Wind Turbines

- Negative Impacts
  - Bird kills
  - Noise
  - Aesthetic impacts
- Positive Impacts
  - Displacement of polluting energy systems

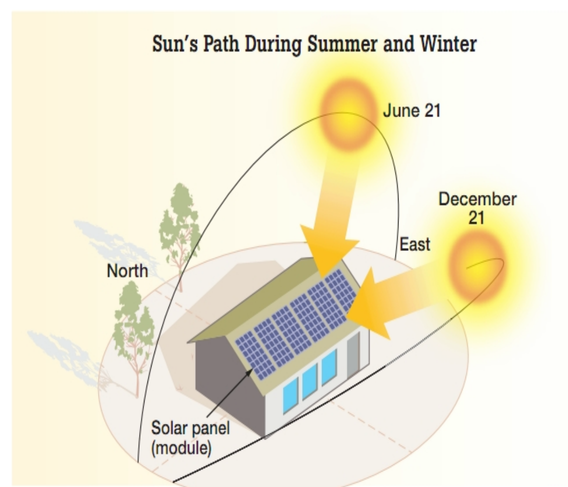
Brief on Solar Energy

- Solar Energy: Radiant energy from the sun that travels to Earth in electromagnetic waves of rays.
- Solar energy is produced in the sun's core when hydrogen atoms combine ["fusion" process] to produce helium. During the fusion, radiant energy is emitted.

$$4\ {}^{1}H + 2\ e \dashrightarrow {}^{4}He + 2\ \text{neutrinos} + 6\ \text{photons}$$



- We capture solar energy with solar collectors [Photovoltaic Cells] that turn radiant energy into electricity
- Clean and renewable energy source
- Solar Radiation Information Critical
- Intermittent source

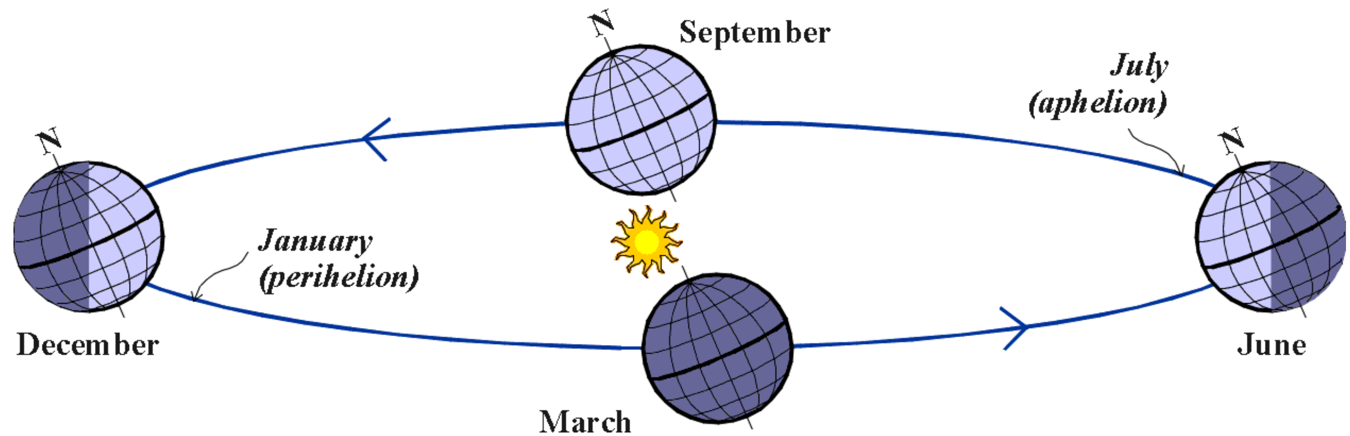


Not all Solar Energy is of Electricity

- Utilization of the heat from insolation
- Passive Solar House vs Active Solar House

Solar Information Needed

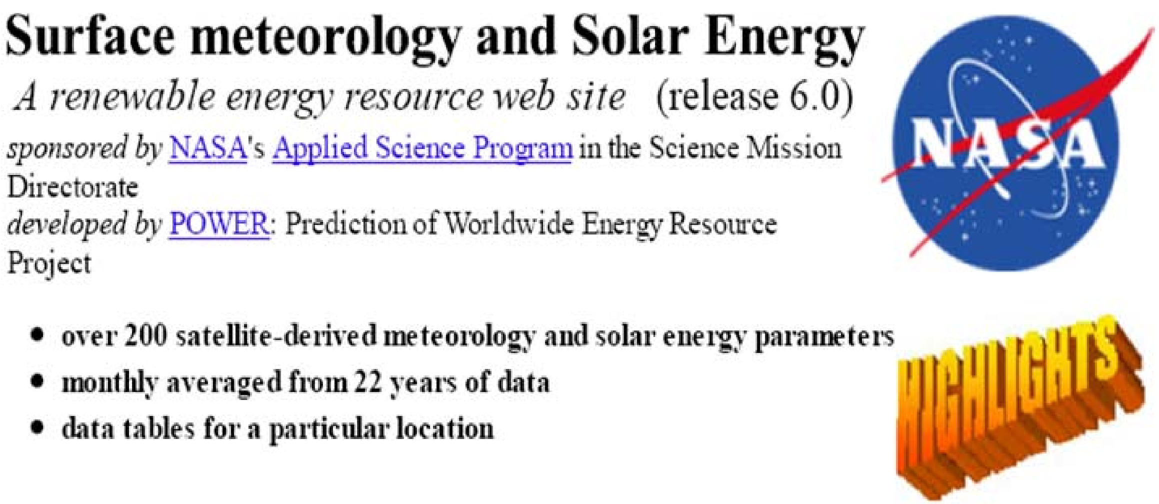
- Need to know how much sunlight is available
- Set of equations available to predict when the sun is in the sky at any time of day for any location on earth



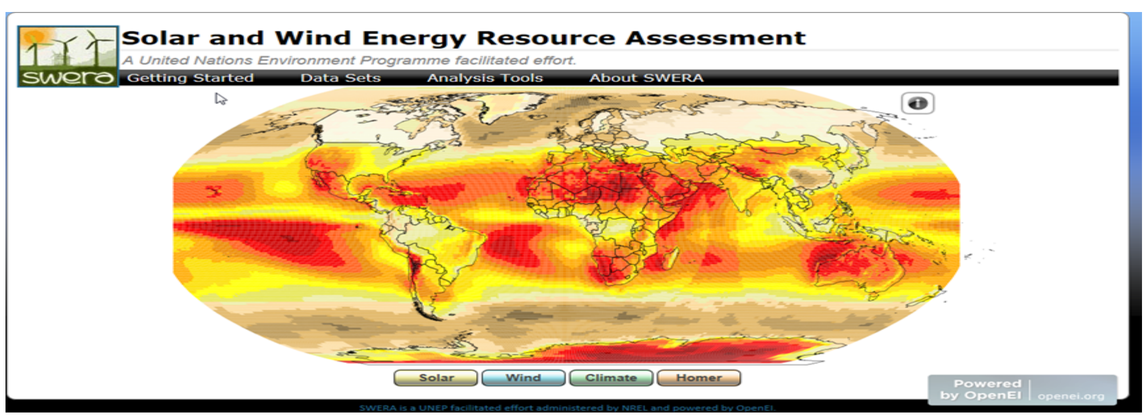
- Solar intensity ("Insolation": Incident Solar Radiation) on a clear day is also available for any location on earth
- Average daily insolation under the combination of clear and cloudy conditions → Need long-term measurements of sunlight hitting a horizontal surface

Solar Energy Resources

- http://eosweb.larc.nansa.org/cgi-bin/sse/sse.cgi
- NASA's Surface Meteorology and Solar Energy

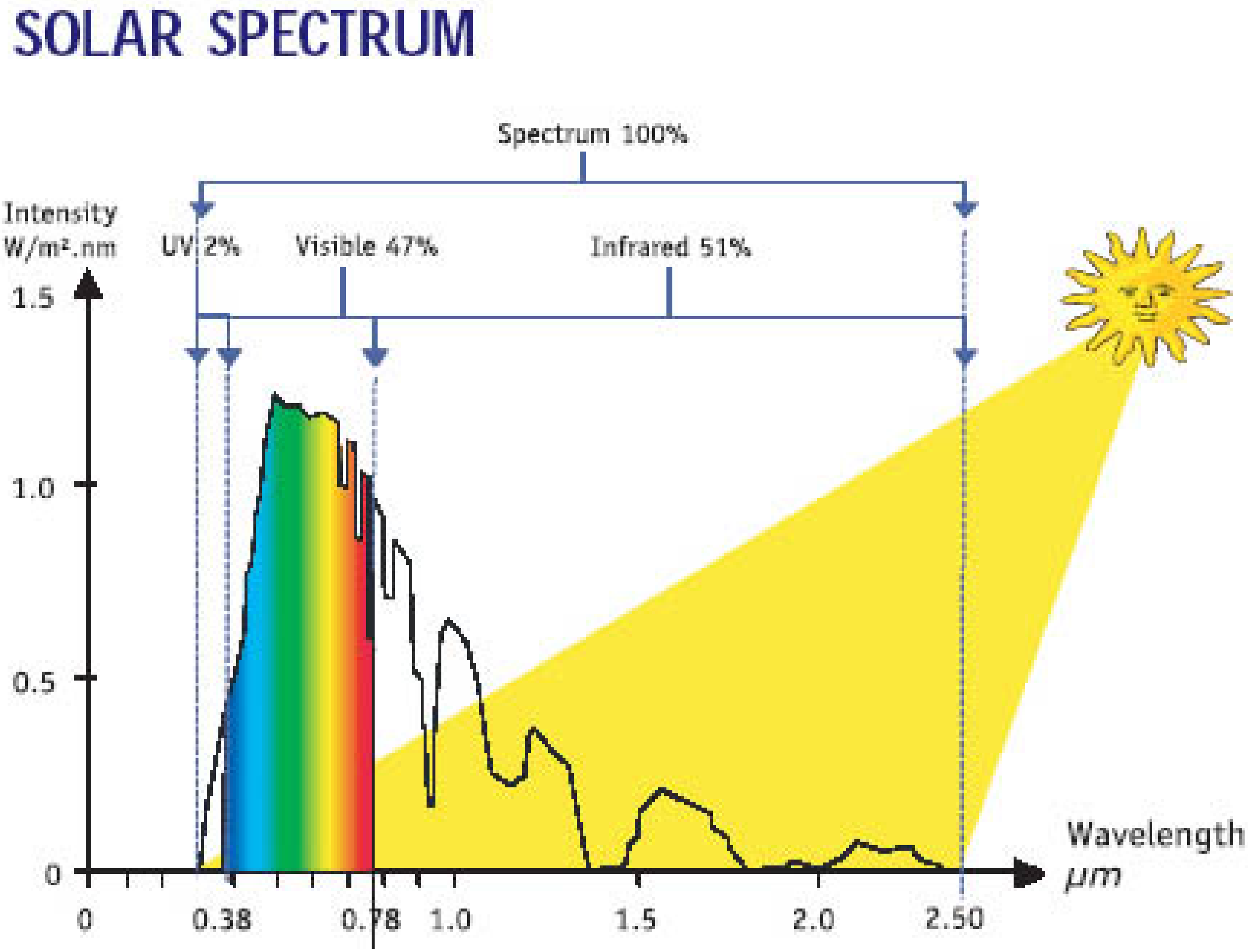


- SWERA



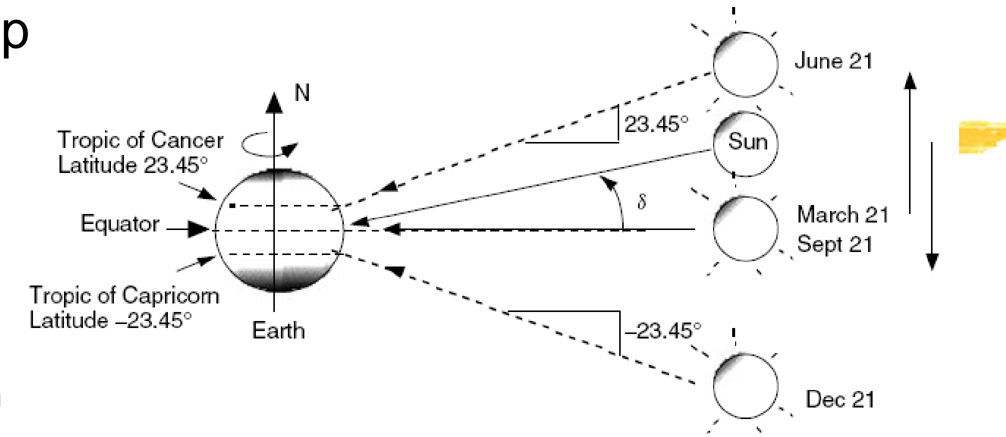
Solar Spectrum

- UV (2%); Visible (47%); IR (51%)



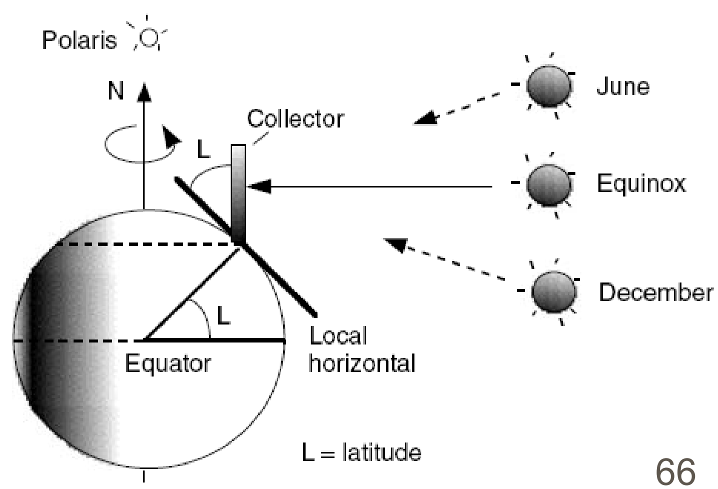
Solar Declination

- Fixed Earth and Sun Moving Up and Down View
- Solar Declination: Angle between the sun and the equator
- Solar declination: "angle between the sun's rays and the earth's equatorial plane, the latitude at which the sun is directly overhead at midday. Declination values are positive when the sun is north of the equator (March 21 to September 23) and negative when the sun is south of the equator. Maximum and minimum values of ds are +0.409 radians (+23.45 degrees) and -0.409 radians (-23.45 degrees)."
- A good rule of thumb of solar panel
  - Face it south
  - Tilt it up at an angle equal to the local latitude



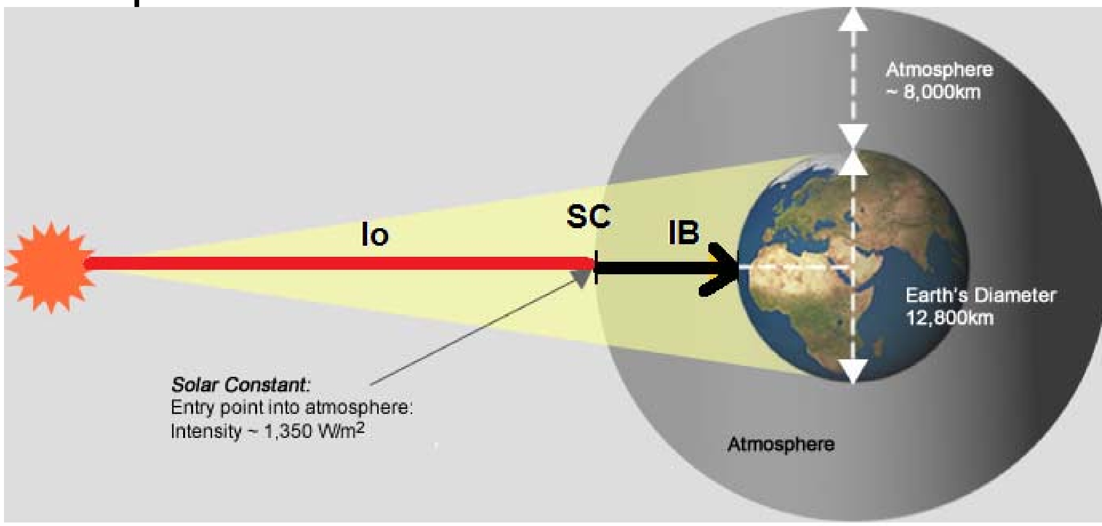
$$\delta = 23.45° \sin\left[\frac{360}{365}(n-81)\right]$$

$$\delta = \sin^{-1}\left\{\sin(23.45°)\sin\left[\frac{360}{365}(n-81)\right]\right\}$$



Solar Radiation in Space and on Earth Surface

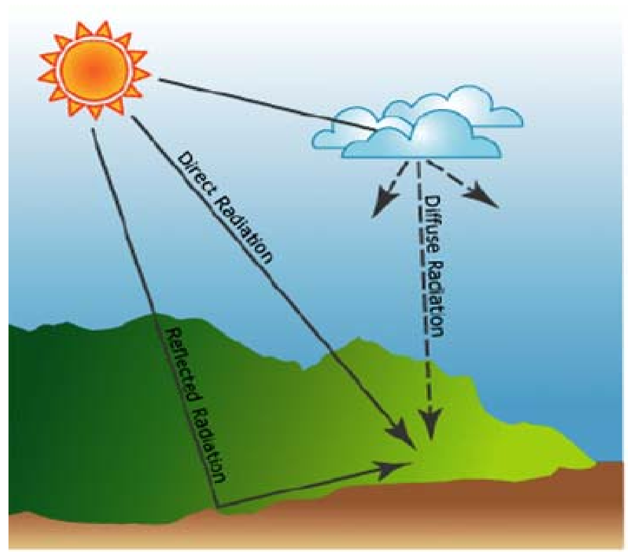
- Space



- Units:
  - ✓ kWh per square meter (preferred)
  - ✓ British Thermal Units
  - ✓ Kilocalories
  - ✓ Langleys

1 kW/m^2	=	316.95 $Btu/h\text{-}ft^2$
	=	1.433 langley/min
1 kWh/m^2	=	316.95 Btu/ft^2
	=	85.98 langleys
	=	3.60×10^6 $joules/m^2$
1 langley	=	1 cal/cm^2
	=	41.856 $kjoules/m^2$
	=	0.01163 kWh/m^2
	=	3.6878 Btu/ft^2

- Earth Surface - 3 components:
  - Beam Radiation: I_B
  - Diffuse Radiation: I_D
  - Reflected Radiation: I_R



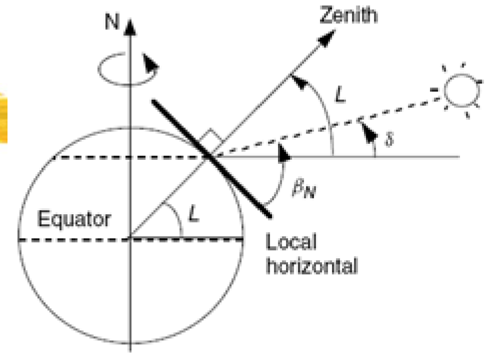
Source: esri.com

Clear Sky Beam Radiation

- Extraterrestrial Solar Insolation (I_o)

$$I_0 = \mathrm{SC} \cdot \left[1 + 0.034 \cos\left(\frac{360n}{365} \right) \right] \qquad (\mathrm{W/m^2})$$

degree^{o}



  - SC: Solar constant $1.377\ \mathrm{kW/m^2}$
  - n: day number

January	$n = 1$	July	$n = 182$
February	$n = 32$	August	$n = 213$
March	$n = 60$	September	$n = 244$
April	$n = 91$	October	$n = 274$
May	$n = 121$	November	$n = 305$
June	$n = 152$	December	$n = 335$

- Portion of the beam reaching the earth surface (I_B)

$$I_B = Ae^{-km}$$

  - A: Apparent extraterrestrial flux

$$A = 1160 + 75 \sin\left[\frac{360}{365}(n - 275) \right] \qquad (\mathrm{W/m^2})$$

  - k : optical depth

$$k = 0.174 + 0.035 \sin\left[\frac{360}{365}(n - 100) \right]$$

  - m: air mass ratio

$$m = \frac{1}{\sin\beta}$$

  - β: altitude angle of the sun

Beam on Earth Surface [Example Calculation]

- Question: Find the direct beam solar radiation normal to the sun's rays at solar noon on a clear day in Atlanta (latitude 33.7 degrees) on May 21. (solar declination table)

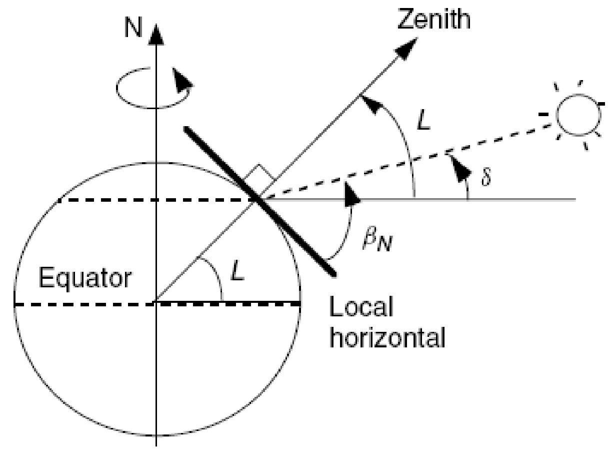
Month:	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
δ:	−20.1	−11.2	0.0	11.6	20.1	23.4	20.4	11.8	0.0	−11.8	−20.4	−23.4

$$I_B = Ae^{-km}$$

Air mass ratio $m = \dfrac{1}{\sin\beta}$

$$A = 1160 + 75\sin\left[\frac{360}{365}(n-275)\right] \qquad (\mathrm{W/m^2})$$

$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(n-100)\right]$$



altitude angle of the sun at solar noon.

$$\beta_N = 90^\circ - L + \delta$$

Solution

- Find the direct beam solar radiation normal to the sun's rays at solar noon on a clear day in Atlanta (latitude 33.7 degrees) on May 21.
- SOLUTION
  - n=141 for May 21

Month:	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
δ:	−20.1	−11.2	0.0	11.6	20.1	23.4	20.4	11.8	0.0	−11.8	−20.4	−23.4

January	$n = 1$	July	$n = 182$
February	$n = 32$	August	$n = 213$
March	$n = 60$	September	$n = 244$
April	$n = 91$	October	$n = 274$
May	$n = 121$	November	$n = 305$
June	$n = 152$	December	$n = 335$

$$A = 1160 + 75\sin\left[\frac{360}{365}(n-275)\right] = 1160 + 75\sin\left[\frac{360}{365}(141-275)\right]$$
$$= 1104\ \mathrm{W/m^2}$$

$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(n-100)\right]$$
$$= 0.174 + 0.035\sin\left[\frac{360}{365}(141-100)\right] = 0.197$$

  - Altitude angle of the sun at solar noon

$$\beta_N = 90^\circ - L + \delta = 90 - 33.7 + 20.1 = 76.4^\circ$$

  - Air mass ratio:

$$m = \frac{1}{\sin\beta} = \frac{1}{\sin(76.4^\circ)} = 1.029$$

  - Clear Sky Beam Radiation at the earth surface

$$I_B = Ae^{-km} = 1104\ e^{-0.197\times 1.029} = 902\ \mathrm{W/m^2}$$

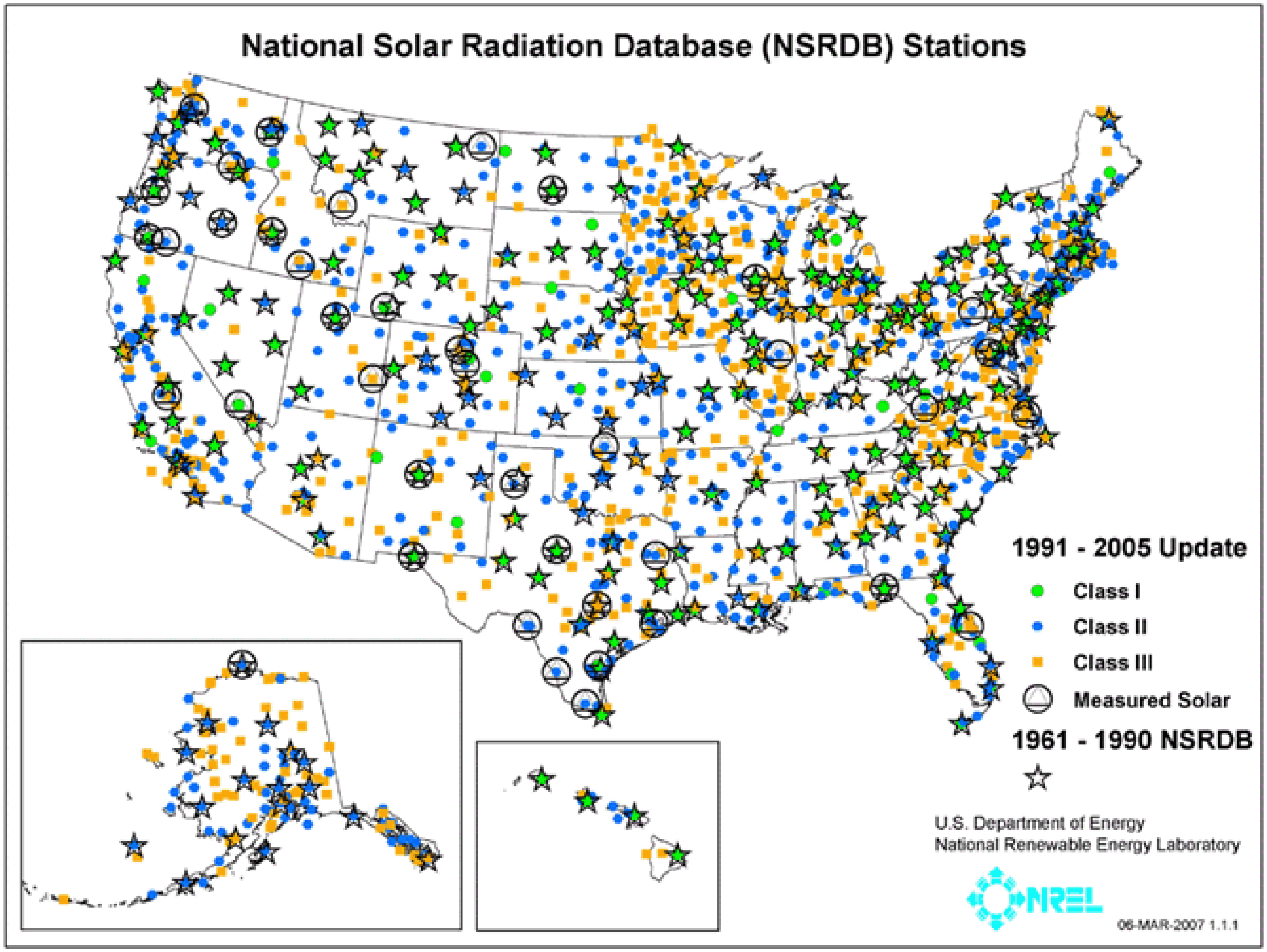
H2 =1160+75*SIN(E2*F2*3.14/180)

Solution p69 --- IB calculation.xlsx

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	n	Lat	delta	beta	360/365	n-275	n-100	A	k	m	IB		
2	141	33.7	20.1	76.4	0.986301	-134	41	1104.35	0.196693	1.029016	901.9977	21-May	Atlanta
3	22	33.7	-20.1	36.2	0.986301	-253	-78	1230.208	0.139912	1.693919	970.6241	22-Jan	Atlanta
4	22	37.5	-20.1	32.4	0.986301	-253	-78	1230.208	0.139912	1.867118	947.3859	22-Jan	Korea

Solar Radiation Measurement Stations

- 239 National Solar Radiation Database Stations

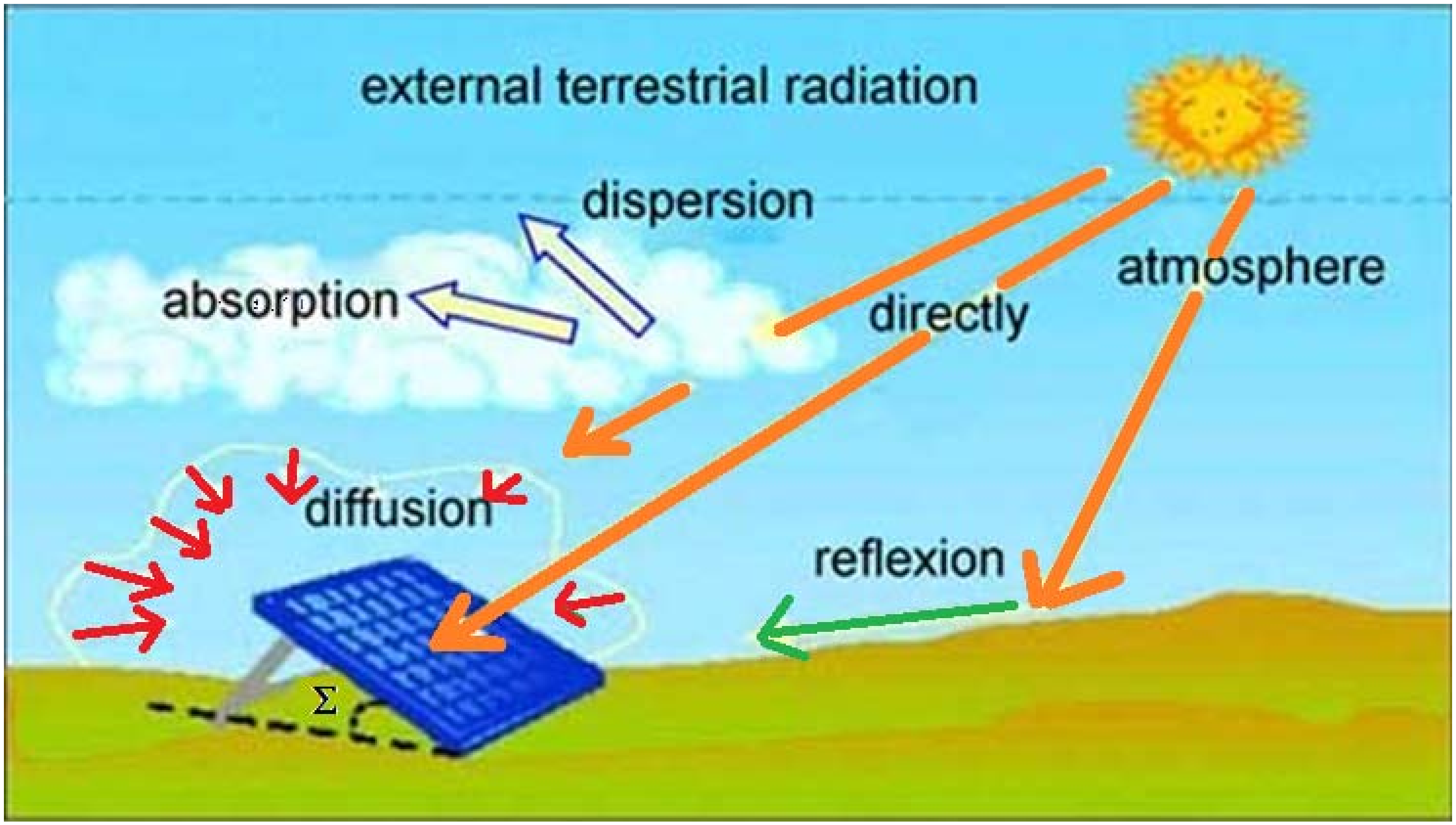


Pyranometer and Pyrheliometer

- Pyranometer: measures total radiation arriving from all directions, direct and diffuse compoenst
- Pyrheliometer: measures only direct radiation

Radiation on collector

- Collector Surface:
  - Beam radiation: I_{BC}
  - Diffuse radiation: I_{DC}
  - Reflected radiation: I_{RC}



Beam Radiation on **Collector**

incidence angle θ

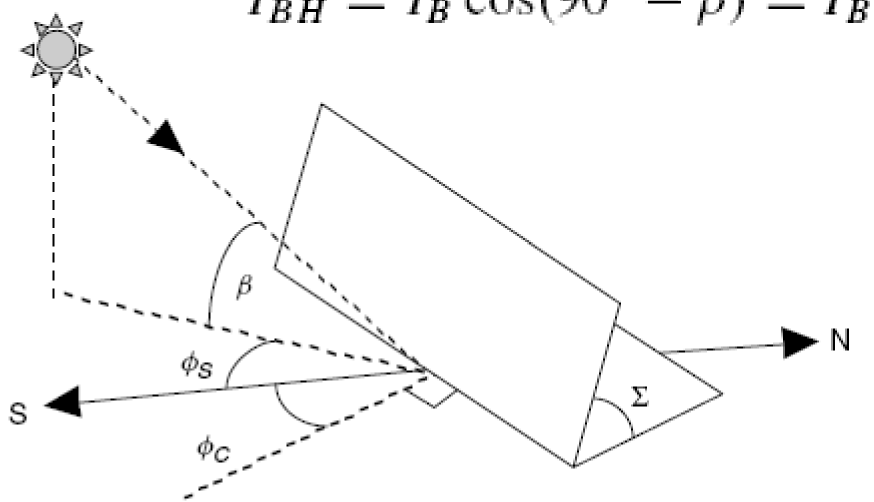
collector azimuth angle ϕ_C

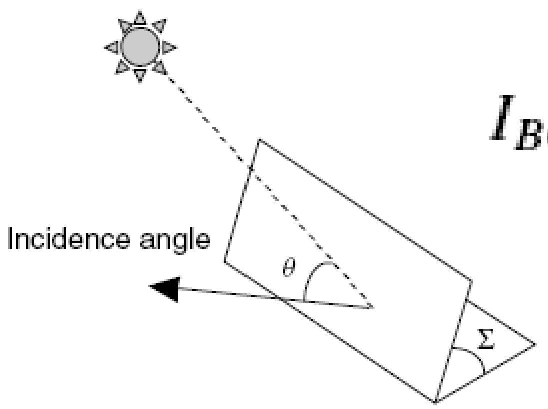
altitude angle β

solar azimuth angle ϕ_S

tilt angle Σ

$$I_{BH} = I_B \cos(90^\circ - \beta) = I_B \sin\beta$$





$$I_{BC} = I_B \cos\theta$$

$$\boxed{\cos\theta = \cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma}$$

Diffuse Radiation on Collector

- Sky diffuse factor (C)

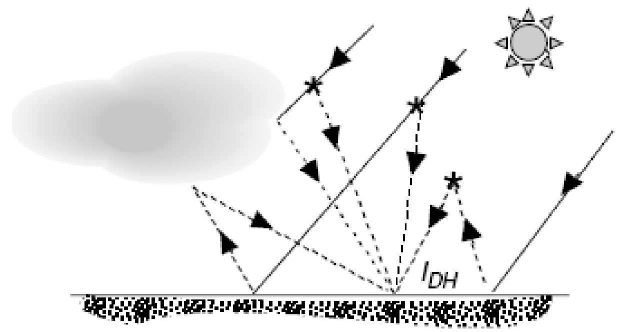
$$C = 0.095 + 0.04 \sin\left[\frac{360}{365}(n - 100)\right]$$

- n: day number

January	$n = 1$	July	$n = 182$
February	$n = 32$	August	$n = 213$
March	$n = 60$	September	$n = 244$
April	$n = 91$	October	$n = 274$
May	$n = 121$	November	$n = 305$
June	$n = 152$	December	$n = 335$

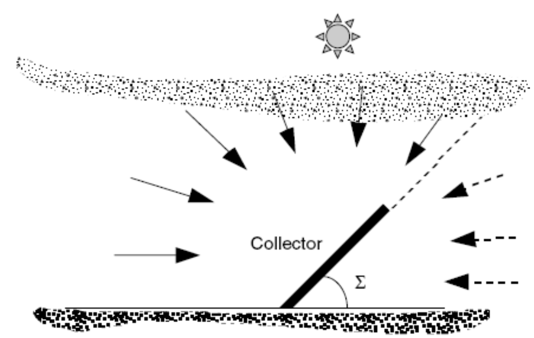
- Diffuse insolation on a Horizontal surface is proportional to the direct radiation

$$I_{DH} = C\ I_B$$



- Diffuse Radiation on collector

$$I_{DC} = I_{DH}\left(\frac{1 + \cos\Sigma}{2}\right) = C\ I_B\left(\frac{1 + \cos\Sigma}{2}\right)$$

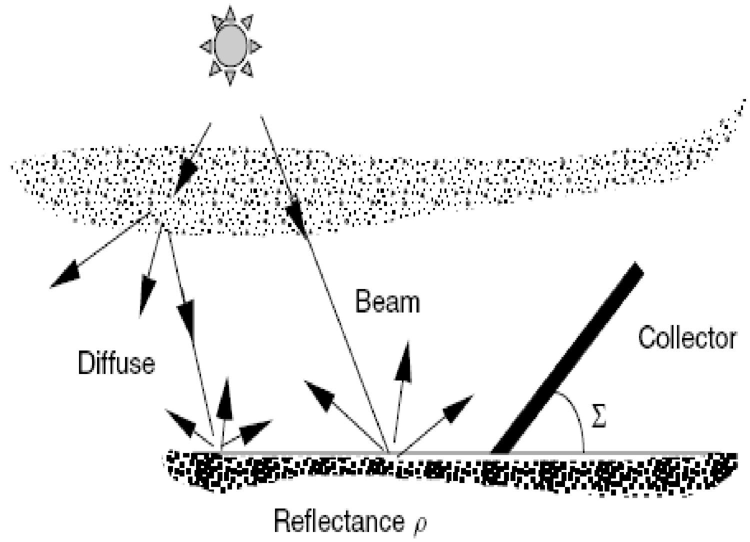


Reflected Radiation on Collector

- Reflection from ground with reflectance

$$I_{RC} = \rho(I_{BH} + I_{DH})\left(\frac{1-\cos\Sigma}{2}\right)$$

$$I_{RC} = \rho I_B(\sin\beta + C)\left(\frac{1-\cos\Sigma}{2}\right)$$



- **Combination** of all three: Radiation striking a collector on a clear day

$$\boxed{\cos\theta = \cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma}$$

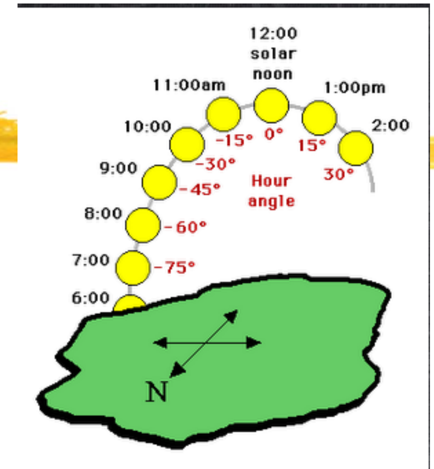
$$I_C = I_{BC} + I_{DC} + I_{RC}$$

$$I_C = Ae^{-km}\left[\cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma + C\left(\frac{1+\cos\Sigma}{2}\right) + \rho(\sin\beta + C)\left(\frac{1-\cos\Sigma}{2}\right)\right]$$

Average Monthly Insolation

- Estimate of average insolation that strikes a tilted collector under real conditions at a particular site
- $I_C = I_{BC} + I_{DC} + I_{RC}$ (direct + Diffuse + reflection) on collector surface
- Working on horizontal insolation first (since primary measurement data is on horizontal insolation I_H)
- $I_H = I_{DH} + I_{BH}$ (Horizontal Insolation = Horizontal Diffuse + Horizontal Beam)
- $I_{DC} \leftarrow I_{DH}$ & $I_{RC} \leftarrow I_H$ (already discussed)
- Question is how to get I_{BC} from I_H

Decomposition of Total Horizontal Insolation (I_H)



- **Clearness index** (K_T): Ratio of average horizontal insolation at a site (I_H) to the extraterrestrial insolation on a horizontal surface above the site and just outside the atmosphere (I_o)

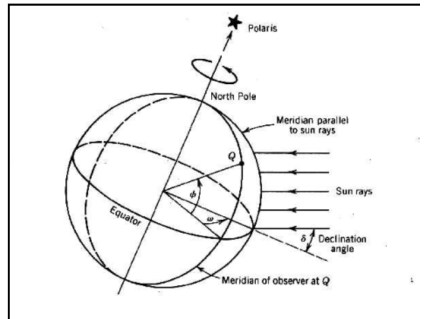
$$K_T = \frac{\overline{I}_H}{\overline{I}_0}$$

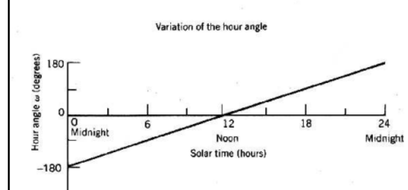
- Average value of I_o: averaging the product of normal radiation and the SIN of the solar hour angle from sunrise and sunset:

$$\overline{I}_0 = \left(\frac{24}{\pi}\right) SC \left[1 + 0.034 \cos\left(\frac{360n}{365}\right)\right] (\cos L \cos\delta \sin H_{SR} + H_{SR} \sin L \sin\delta)$$

- Correlation between Clearness Index and Diffuse Radiation:

$$\frac{\overline{I}_{DH}}{\overline{I}_H} = 1.390 - 4.027 K_T + 5.531 {K_T}^2 - 3.108 {K_T}^3$$





- Diffuse and Reflected Radiation on a tilted collector surface

$$\overline{I}_{DC} = \overline{I}_{DH}\left(\frac{1 + \cos\Sigma}{2}\right) \qquad \overline{I}_{RC} = \rho \overline{I}_H \left(\frac{1 - \cos\Sigma}{2}\right)$$

$$H_{SR} = \cos^{-1}(-\tan L \tan\delta)$$

SUNRISE HOUR ANGLE - The sunrise hour angle is the hour angle, expressed in degrees, when the sun's center reaches the horizon.

Conversion to Beam Radiation on Collector

- The average beam radiation on a horizontal surface (I_{BH}) can be found by subtracting the diffuse portion (I_{DH}) from the total (I_H):

$$\overline{I}_H = \overline{I}_{DH} + \overline{I}_{BH} \longrightarrow \overline{I}_{BH} = \overline{I}_H - \overline{I}_{DH}$$

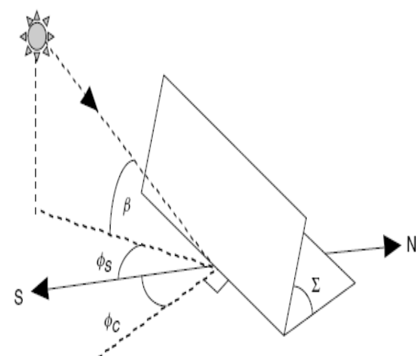
- Conversion of horizontal beam radiation (I_{BH}) to the beam radiation on collector (I_{BC}):

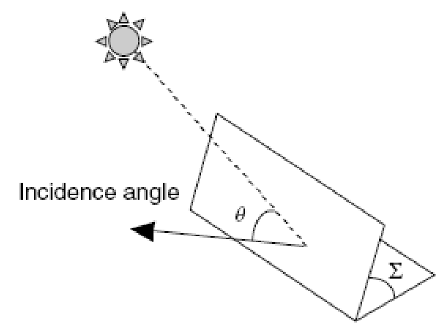
$$I_{BH} = I_B \sin\beta$$
$$I_{BC} = I_B \cos\theta \longrightarrow I_{BC} = I_{BH}\left(\frac{\cos\theta}{\sin\beta}\right) = I_{BH} R_B$$

θ is the incidence angle between the collector and beam

β is the sun's altitude angle

R_B is *beam tilt factor*





- Average value of Beam Tilt Factor (R_B):

Average value of Beam Tilt Factor (R_B)

- For South-Facing Collectors:

$$\overline{R}_B = \frac{\cos(L-\Sigma)\cos\delta\sin H_{SRC} + H_{SRC}\sin(L-\Sigma)\sin\delta}{\cos L\cos\delta\sin H_{SR} + H_{SR}\sin L\sin\delta}$$

$$H_{SR} = \cos^{-1}(-\tan L\tan\delta) \quad \text{sunrise hour angle (in radians)}$$

$$H_{SRC} = \min\{\cos^{-1}(-\tan L\tan\delta), \cos^{-1}[-\tan(L-\Sigma)\tan\delta]\}$$

sunrise hour angle for the collector

L is the latitude

Σ is the collector tilt angle.

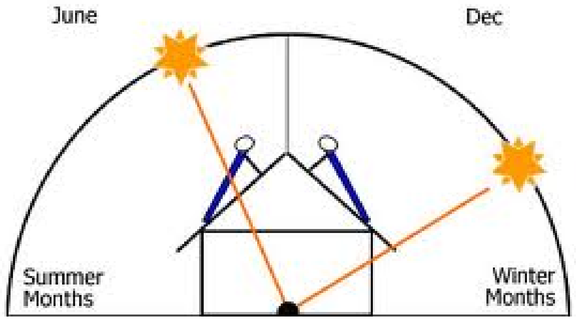
δ is the solar declination

- Final Equation for Insolation striking a collector

$$\overline{I}_C = \overline{I}_H\left(1 - \frac{\overline{I}_{DH}}{\overline{I}_H}\right)\cdot\overline{R}_B + \overline{I}_{DH}\left(\frac{1+\cos\Sigma}{2}\right) + \rho\overline{I}_H\left(\frac{1-\cos\Sigma}{2}\right)$$

Example Calculation

- Average Monthly Insolation on a Tilted Collector
- Average horizontal insolation (I_H) in Oakland, California (latitude 37.73∘N) in July is 7.32 kWh/m^2-day. Assume ground reflectivity of 0.2.
- **Question**: Estimate the insolation on a south-facing collector at a tilt angle of 30∘ with respect to the horizontal.



Solution Approach

- ⌘ 0. Target $$\overline{I}_C = \overline{I}_H\left(1-\frac{\overline{I}_{DH}}{\overline{I}_H}\right)\cdot\overline{R}_B + \overline{I}_{DH}\left(\frac{1+\cos\Sigma}{2}\right) + \rho\overline{I}_H\left(\frac{1-\cos\Sigma}{2}\right)$$
- ⌘ 1. Sun declination (δ) for July 16 (n=197)
- ⌘ 2. Sunrise Hour Angle (H_{SR}) using L=37.73^o
- ⌘ 3. Extraterrestrial Insolation (I_o) (with SC=1.37 kW/m^2)
- ⌘ 4. Clearness Index (K^T)
- ⌘ 5. Horizontal Diffuse Radiation (I_{DH})
- ⌘ 6. Diffuse Radiation on the Collector (I_{DC})
- ⌘ 7. Reflected Radiation on the Collector (I_{RC})
- ⌘ 8. Horizontal Beam Radiation (I_{BH})
- ⌘ 9. Sunrise Hour Angle on the Collector (H_{SRC})
- ⌘ 10. Beam Tilt Factor (R_B)
- ⌘ 11. Beam Radiation on the Collator (I_{BC})
- ⌘ 12. Total Insolation on the Collector (I_C)

Solution - Details

July 16 ($n = 197$):

$$\delta = 23.45 \sin\left[\frac{360}{365}(n-81)\right] = 23.45 \sin\left[\frac{360}{365}(197-81)\right]$$
$$= 21.35^\circ$$

$$H_{SR} = \cos^{-1}(-\tan L \tan \delta)$$
$$= \cos^{-1}(-\tan 37.73^\circ \tan 21.35^\circ) = 107.6^\circ = 1.878 \text{ radians}$$

$$\overline{I}_0 = \left(\frac{24}{\pi}\right) \mathrm{SC}\left[1 + 0.034 \cos\left(\frac{360n}{365}\right)\right](\cos L \cos\delta \sin H_{SR} + H_{SR} \sin L \sin\delta)$$
$$= \left(\frac{24}{\pi}\right) 1.37 \left[1 + 0.034 \cos\left(\frac{360 \cdot 197}{365}\right)^\circ\right](\cos 37.73 \cos 21.35^\circ \sin 107.6^\circ$$
$$+ 1.878 \sin 37.73^\circ \sin 21.35^\circ)$$
$$= 11.34 \text{ kWh/m}^2\text{-day}$$

$$K_T = \frac{\overline{I}_H}{\overline{I}_0} = \frac{7.32 \text{ kWh/m}^2 \cdot \text{day}}{11.34 \text{ kWh/m}^2 \cdot \text{day}} = 0.645$$

$$\frac{\overline{I}_{DH}}{\overline{I}_H} = 1.390 - 4.027 K_T + 5.531 {K_T}^2 - 3.108 {K_T}^3$$
$$= 1.390 - 4.027\ (0.645) + 5.531\ (0.645)^2 - 3.108\ (0.645)^3 = 0.258$$

Solution- Details (Continued)

$$\overline{I}_{DH} = 0.258 \cdot 7.32 = 1.89 \text{ kWh/m}^2\text{-day}$$

$$\overline{I}_{DC} = \overline{I}_{DH}\left(\frac{1+\cos\Sigma}{2}\right) = 1.89\left(\frac{1+\cos 30^\circ}{2}\right) = 1.76 \text{ kWh/m}^2\text{-day}$$

$$\overline{I}_{RC} = \rho\,\overline{I}_{H}\left(\frac{1-\cos\Sigma}{2}\right) = 0.2\cdot 7.32\left(\frac{1-\cos 30^\circ}{2}\right) = 0.10 \text{ kWh/m}^2\text{-day}$$

$$\overline{I}_{BH} = \overline{I}_{H} - \overline{I}_{DH} = 7.32 - 1.89 = 5.43 \text{ kWh/m}^2\text{-day}$$

$$\begin{aligned} H_{SRC} &= \min\{\cos^{-1}(-\tan L\tan\delta),\ \cos^{-1}[-\tan(L-\Sigma)\tan\delta]\} \\ &= \min\{\cos^{-1}(-\tan 37.73^\circ \tan 21.35^\circ),\ \cos^{-1}[-\tan(37.73-30)^\circ \tan 21.35^\circ]\} \\ &= \min\{107.6^\circ, 93.0^\circ\} = 93.0^\circ = 1.624 \text{ radians} \end{aligned}$$

$$\begin{aligned} \overline{R}_B &= \frac{\cos(L-\Sigma)\cos\delta\sin H_{SRC} + H_{SRC}\sin(L-\Sigma)\sin\delta}{\cos L\cos\delta\sin H_{SR} + H_{SR}\sin L\sin\delta} \\ &= \frac{\cos(37.73-30)^\circ\cos 21.35^\circ\sin 93^\circ + 1.624\sin(37.73-30)^\circ\sin 21.35^\circ}{\cos 37.73^\circ\cos 21.35^\circ\sin 107.6^\circ + 1.878\sin 37.73^\circ\sin 21.35^\circ} \\ &= 0.893 \end{aligned}$$

$$\overline{I}_{BC} = \overline{I}_{BH}\overline{R}_B = 5.43\cdot 0.893 = 4.85 \text{ kWh/m}^2\text{-day}$$

$$\overline{I}_{C} = \overline{I}_{BC} + \overline{I}_{DC} + \overline{I}_{RC} = 4.85 + 1.76 + 0.10 = 6.7 \text{ kWh/m}^2\text{-day}$$

Spreadsheet

I2 f_x =ACOS(-TAN(F2*3.14/180)*TAN(G2*3.14/180))

Insolation on a tilted collector.xlsx

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1		n	SC	IH	Σ	L	δ	ρ	HSR	Io	KT	IDH/IH	IDH	IDC	IRC	IBH	HSRC1	HSRC2	HSRC	RBn	RBd	RB	IBC	IC
2	Oakland	197	1.37	7.32	30	37.73	21.4	0.2	1.878	11.35	0.645	0.2596	1.8999	1.773	0.098	5.42	1.8779	1.6239	1.624	1.001	1.12	0.89	4.842	6.71292
3		22	1.37	2.3	30	37.73	-20.1	0.2	1.284	4.784	0.481	0.387	0.89	0.83	0.031	1.41	1.2841	1.5212	1.284	0.833	0.44	1.88	2.653	3.5145
4	Seoul	197	1.37	7.32	30	37.5	21.4	0.2	1.875	11.35	0.645	0.2596	1.8999	1.773	0.098	5.42	1.8753	1.6223	1.622	0.999	1.12	0.89	4.833	6.70394
5		22	1.37	2.3	30	37.5	-20.1	0.2	1.287	4.823	0.477	0.3903	0.8978	0.838	0.031	1.402	1.2865	1.5227	1.287	0.836	0.45	1.87	2.626	3.49448

S2 f_x =MIN(Q2,R2)

Insolation on a tilted collector.xlsx

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1		n	SC	IH	Σ	L	δ	ρ	HSR	Io	KT	IDH/IH	IDH	IDC	IRC	IBH	HSRC1	HSRC2	HSRC	RBn	RBd	RB	IBC	IC
2	Oakland	197	1.37	7.32	30	37.73	21.4	0.2	1.878	11.35	0.645	0.2596	1.8999	1.773	0.098	5.42	1.8779	1.6239	1.624	1.001	1.12	0.89	4.842	6.71292
3		22	1.37	2.3	30	37.73	-20.1	0.2	1.284	4.784	0.481	0.387	0.89	0.83	0.031	1.41	1.2841	1.5212	1.284	0.833	0.44	1.88	2.653	3.5145
4	Seoul	197	1.37	7.32	30	37.5	21.4	0.2	1.875	11.35	0.645	0.2596	1.8999	1.773	0.098	5.42	1.8753	1.6223	1.622	0.999	1.12	0.89	4.833	6.70394
5		22	1.37	2.3	30	37.5	-20.1	0.2	1.287	4.823	0.477	0.3903	0.8978	0.838	0.031	1.402	1.2865	1.5227	1.287	0.836	0.45	1.87	2.626	3.49448

Calculation is complex, so we need

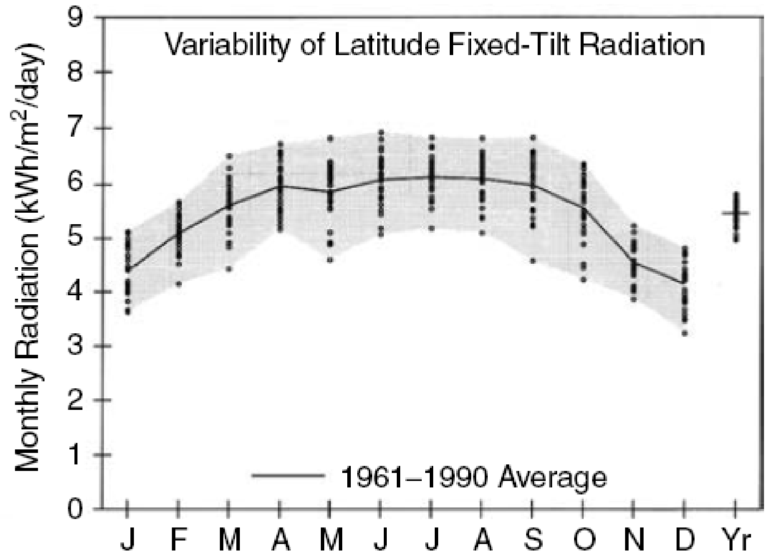
- Spreadsheet or Computer Analysis
- Pre-computed Data such as Solar Radiation Data Manual for Flat-Place and Concentrating Collectors (NREL, 1994)

Boulder, CO

WBAN NO. 94018

LATITUDE: 40.02° N
LONGITUDE: 105.25° W
ELEVATION: 1634 meters
MEAN PRESSURE: 836 millibars

STATION TYPE: Primary

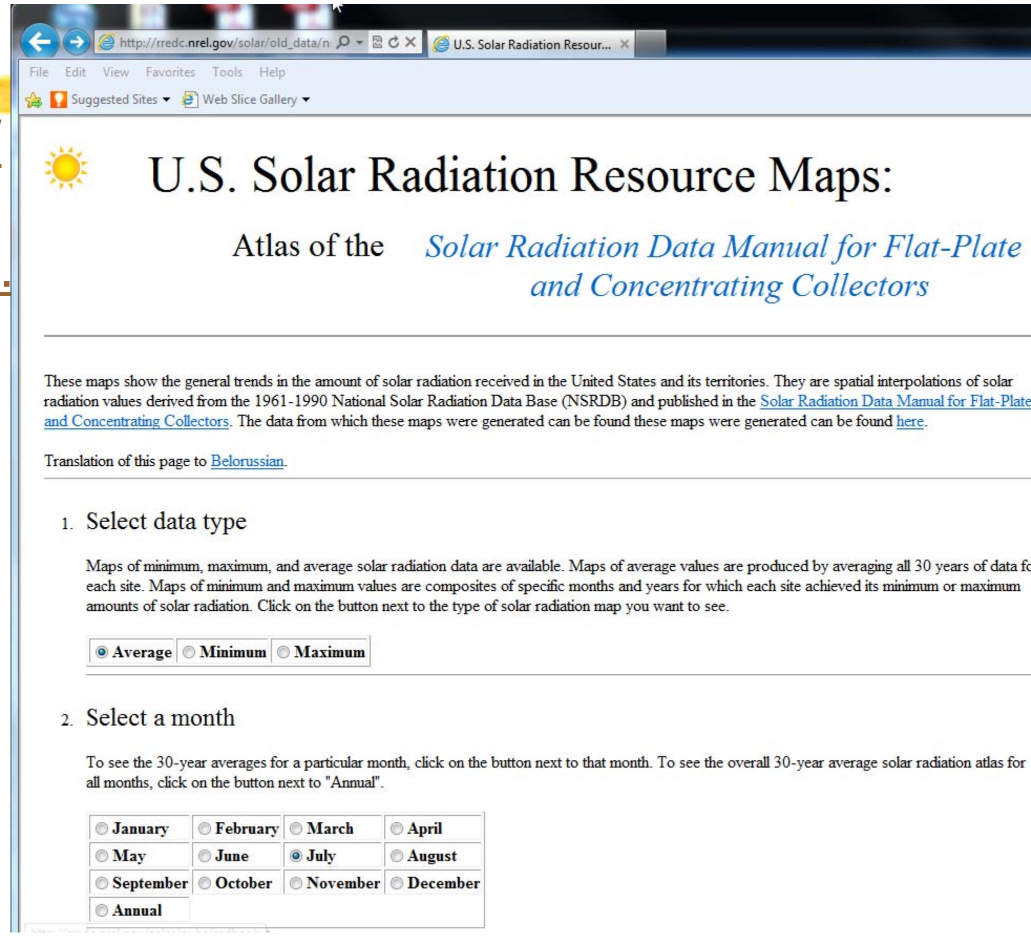


Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

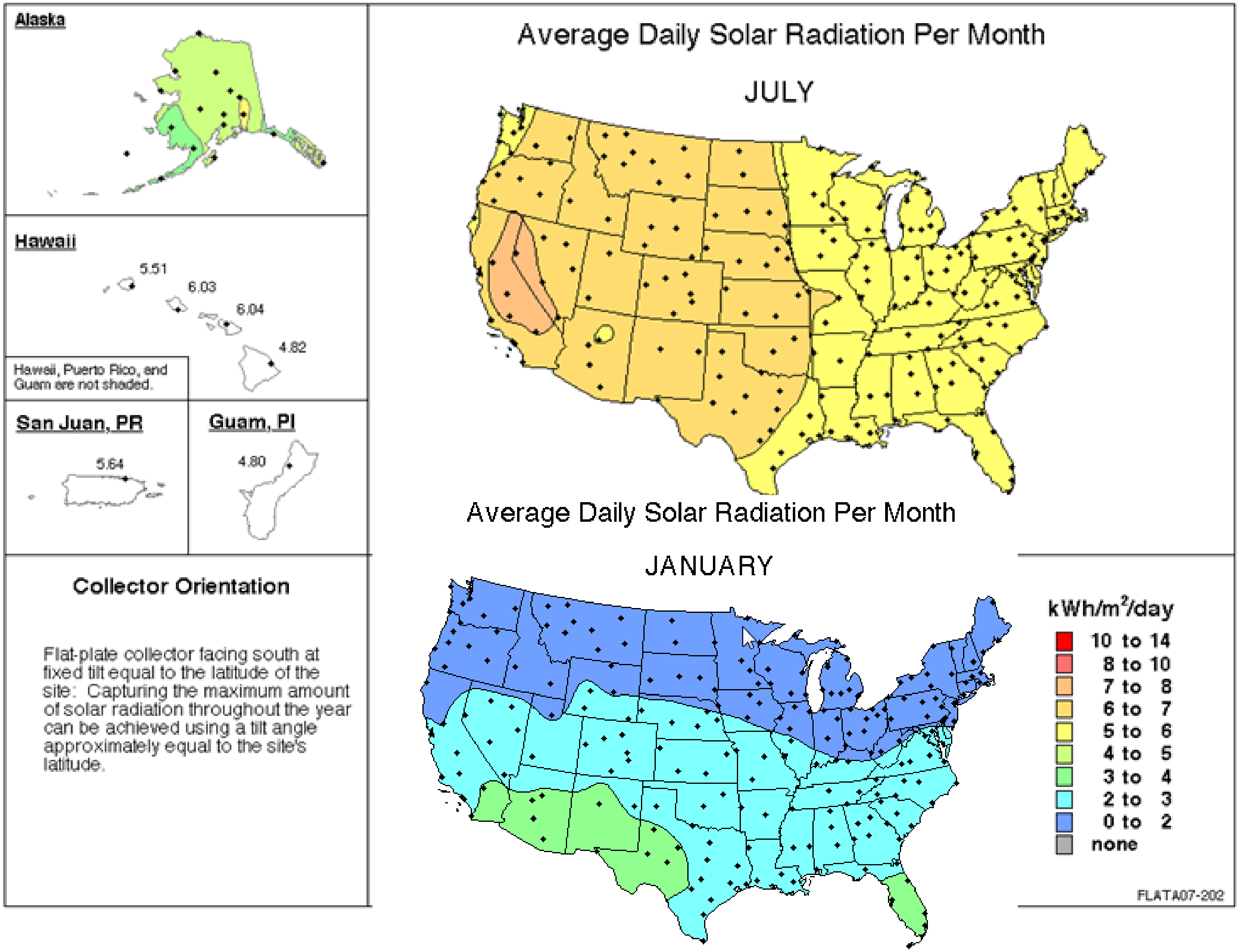
Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	2.4	3.3	4.4	5.6	6.2	6.9	6.7	6.0	5.0	3.8	2.6	2.1	4.6
	Min/Max	2.1/2.7	2.8/3.5	3.7/5.0	4.8/6.1	5.1/7.2	5.7/7.8	5.6/7.4	5.2/6.6	4.0/5.5	3.1/4.2	2.3/2.8	1.9/2.3	4.3/4.8
Latitude −15	Average	3.8	4.6	5.4	6.1	6.2	6.6	6.6	6.3	5.9	5.1	4.0	3.5	5.4
	Min/Max	3.2/4.4	3.8/5.1	4.3/6.2	5.3/6.8	4.9/7.3	5.5/7.6	5.6/7.4	5.3/7.1	4.6/6.7	4.0/5.8	3.4/4.6	2.8/4.1	4.9/5.7
Latitude	Average	4.4	5.1	5.6	6.0	5.9	6.1	6.1	6.1	6.0	5.6	4.6	4.2	5.5
	Min/Max	3.6/5.1	4.2/5.7	4.4/6.5	5.2/6.7	4.6/6.8	5.1/6.9	5.2/6.8	5.1/6.8	4.6/6.8	4.2/6.4	3.9/5.2	3.2/4.8	5.0/5.8
Latitude +15	Average	4.8	5.3	5.6	5.6	5.2	5.2	5.3	5.5	5.8	5.7	4.8	4.5	5.3
	Min/Max	3.9/5.6	4.3/5.9	4.4/6.5	4.8/6.2	4.1/6.0	4.4/5.9	4.5/5.9	4.6/6.2	4.4/6.6	4.2/6.5	4.1/5.6	3.5/5.3	4.8/5.6
90	Average	4.5	4.6	4.3	3.6	2.8	2.6	2.7	3.2	4.0	4.6	4.4	4.3	3.8
	Min/Max	3.6/5.4	3.7/5.2	3.5/5.0	3.0/4.0	2.3/3.1	2.2/2.8	2.3/2.9	2.7/3.6	3.1/4.6	3.4/5.3	3.7/5.1	3.4/5.2	3.4/4.1

Daily Total Radiation incident on a tilted surface [kWh/m^2/day]

- U. S. Solar Radiation Resource Maps:
- http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/Table.html
- Data Types
  - Average
  - Minimum
  - Maximum
- Month Selection
- Orientation
  - Flat latitude
  - Flat latitude-15
  - Flat latitude+15
  - Etc
- View Map

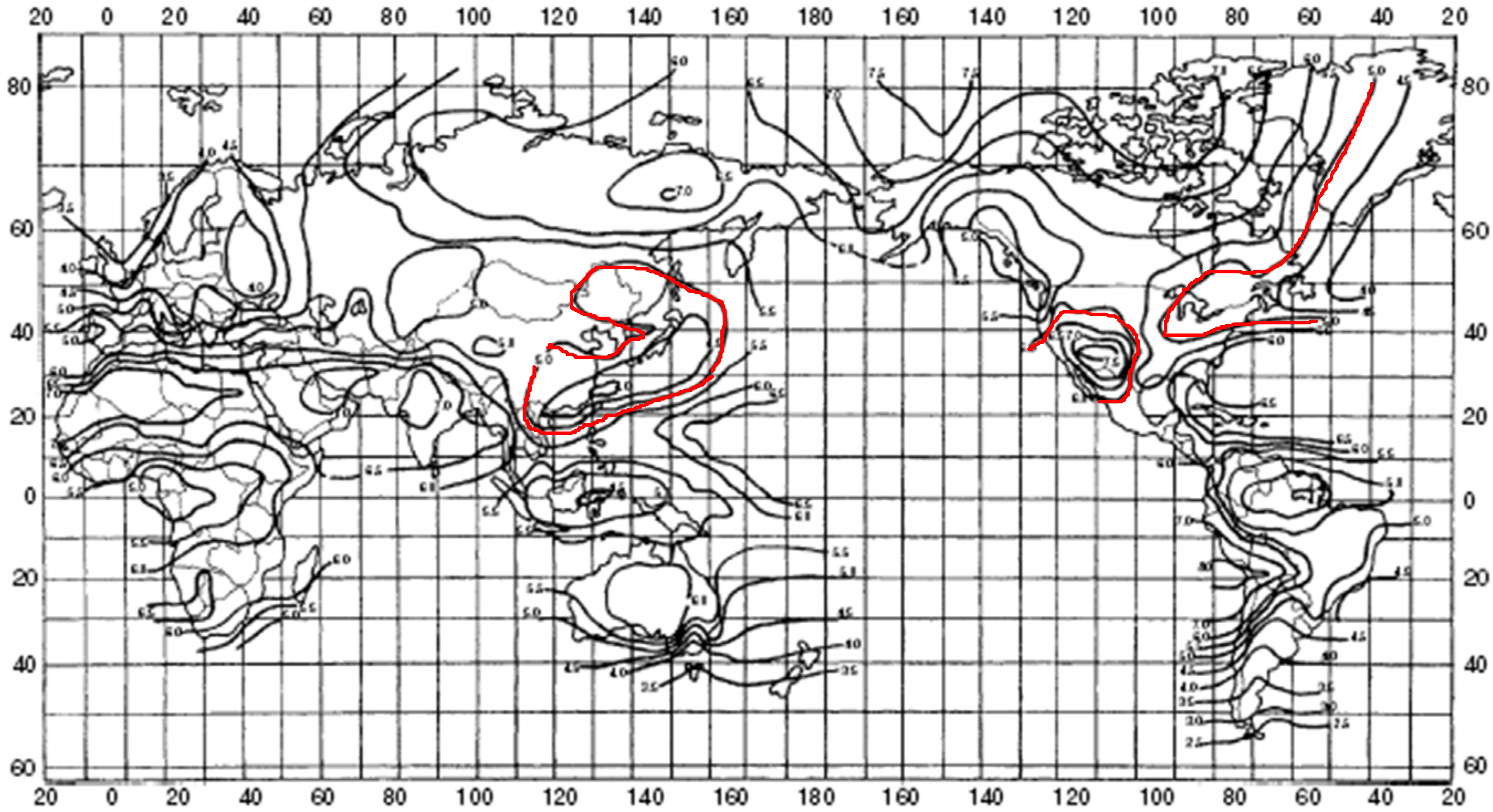


Average Solar Radiation, Jan/July, Flat, South Facing, Tilted Latitude



Daily Total Radiation incident on a tilted surface [kWh/m^2/day]

- Spring

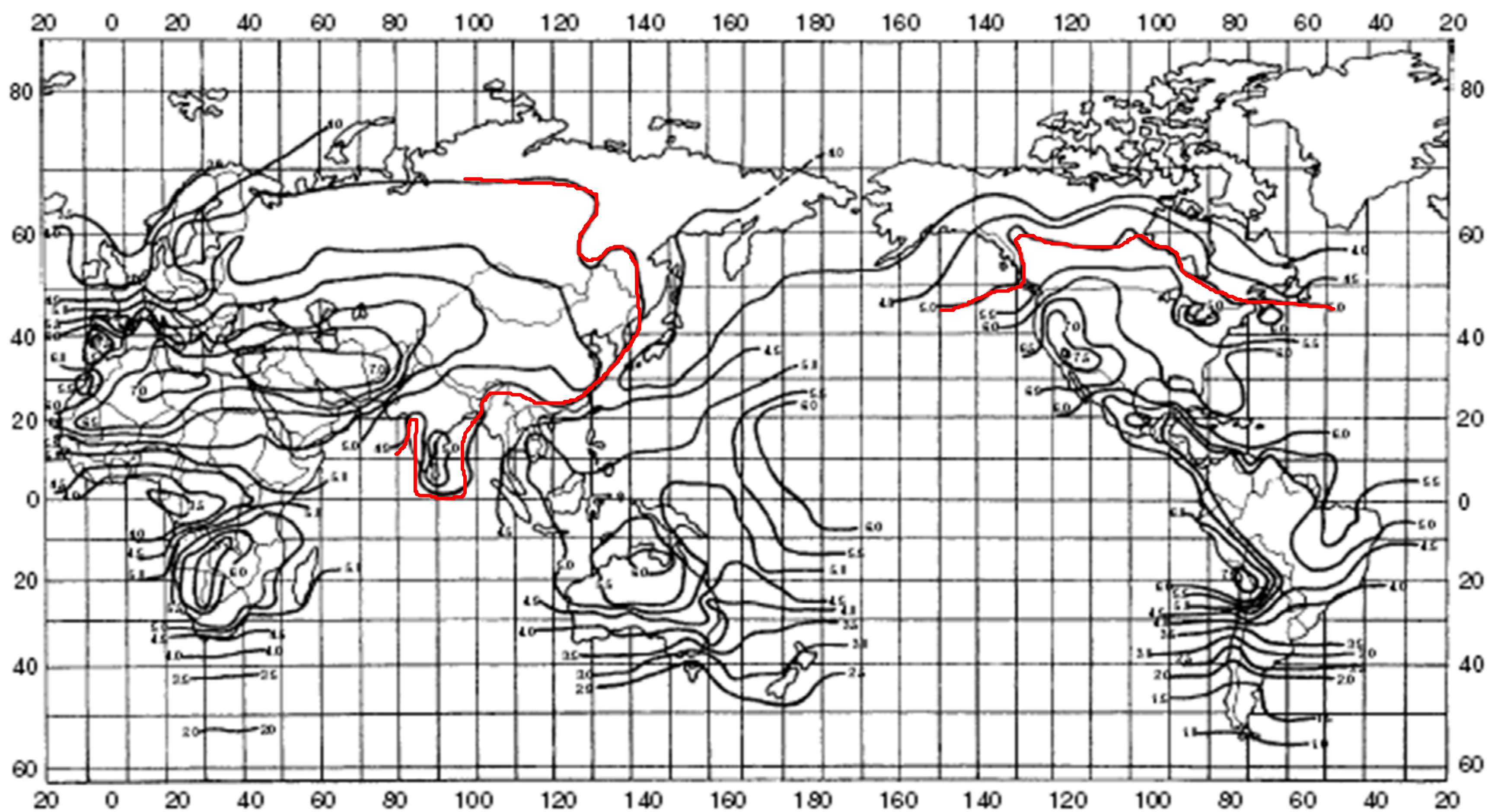


SPRING - Tilt angle equals the latitude angle

Daily total solar radiation incident on a tilted surface in kWH/m^2/day

Daily Total Radiation incident on a tilted surface [kWh/m^2/day]

- Summer

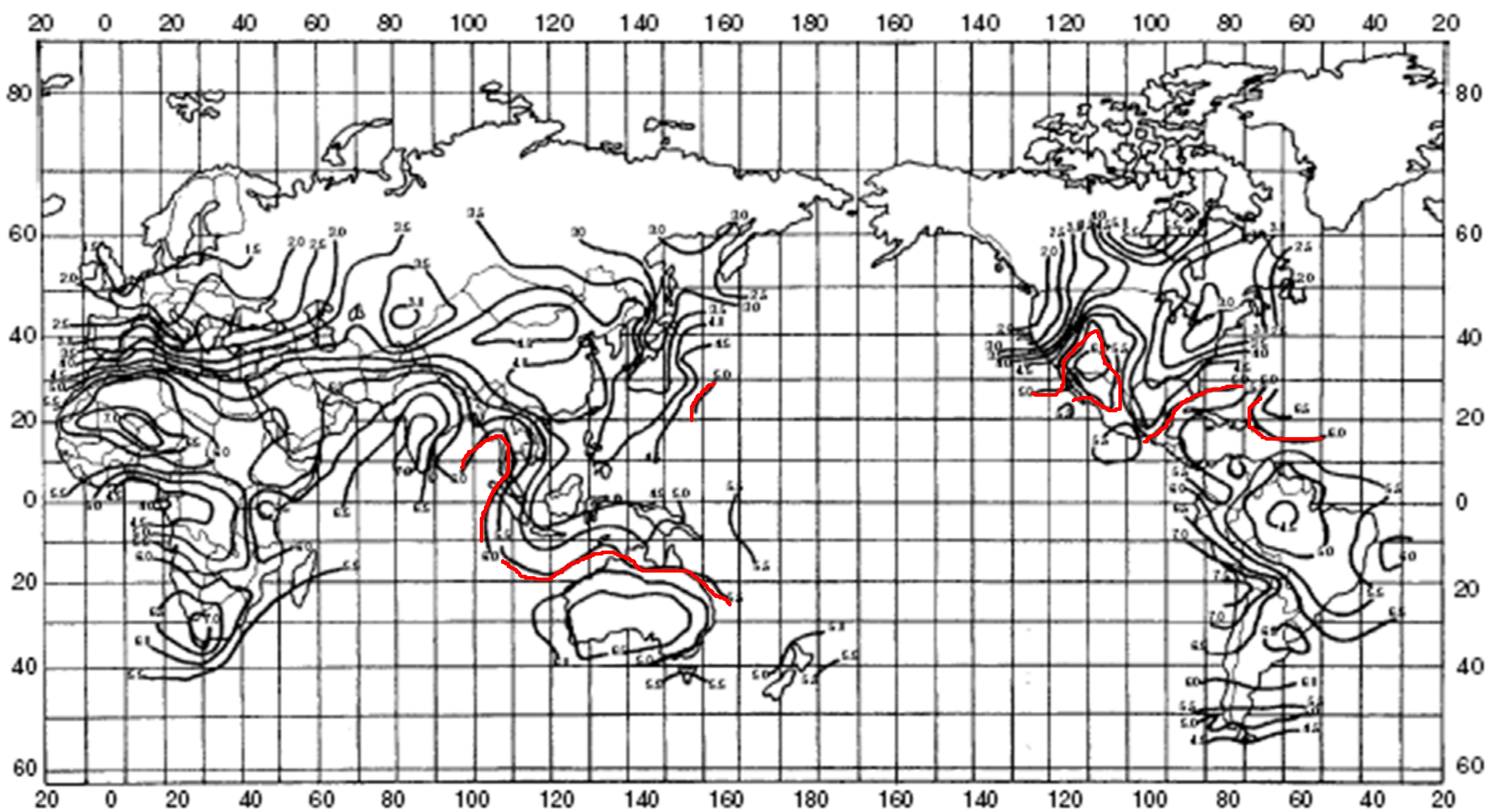


SUMMER - Tilt angle equals the latitude angle

Daily total solar radiation incident on a tilted surface in kWH/m^2/day

Daily Total Radiation incident on a tilted surface [kWh/m^2/day]

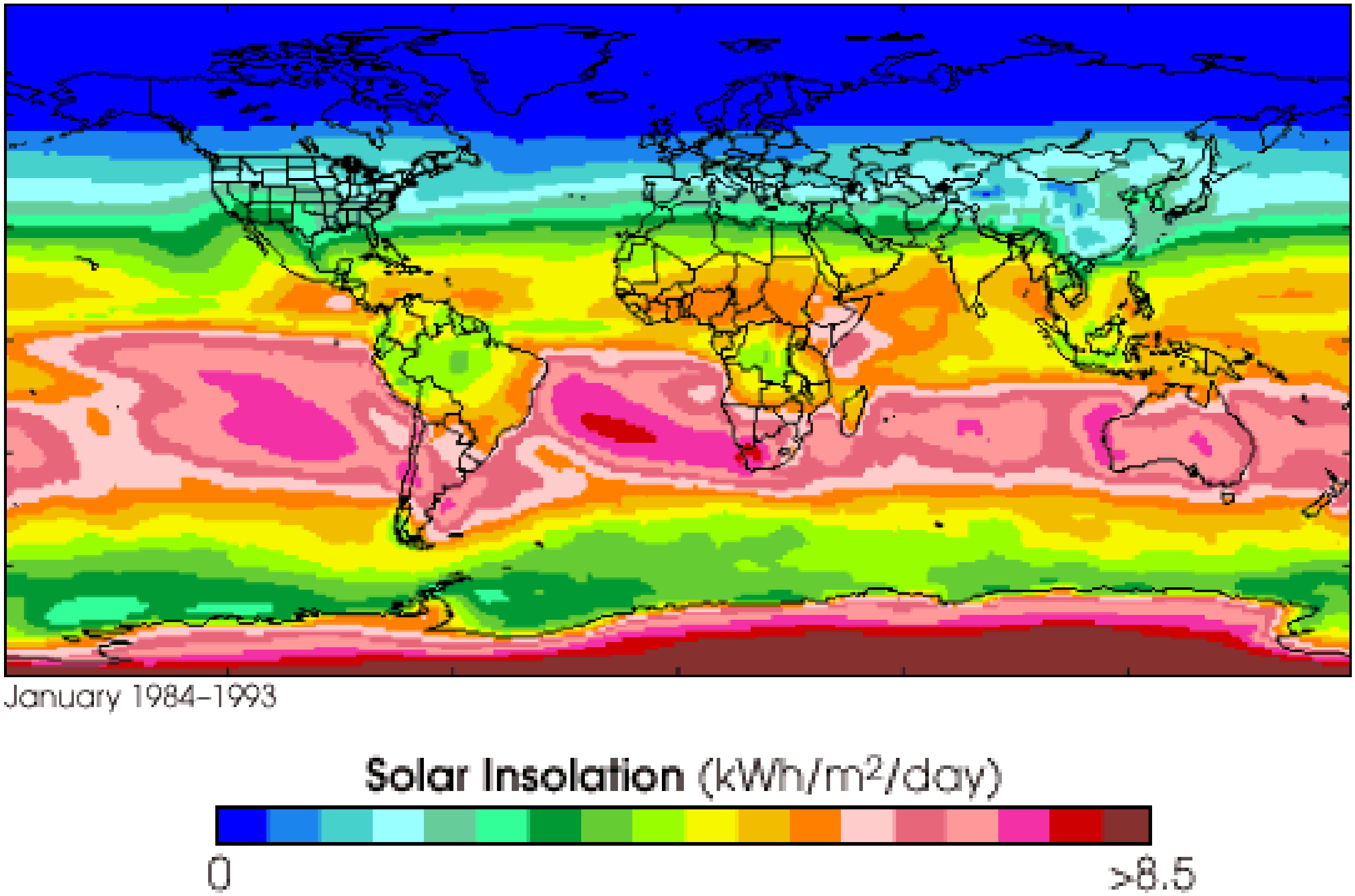
- Winter



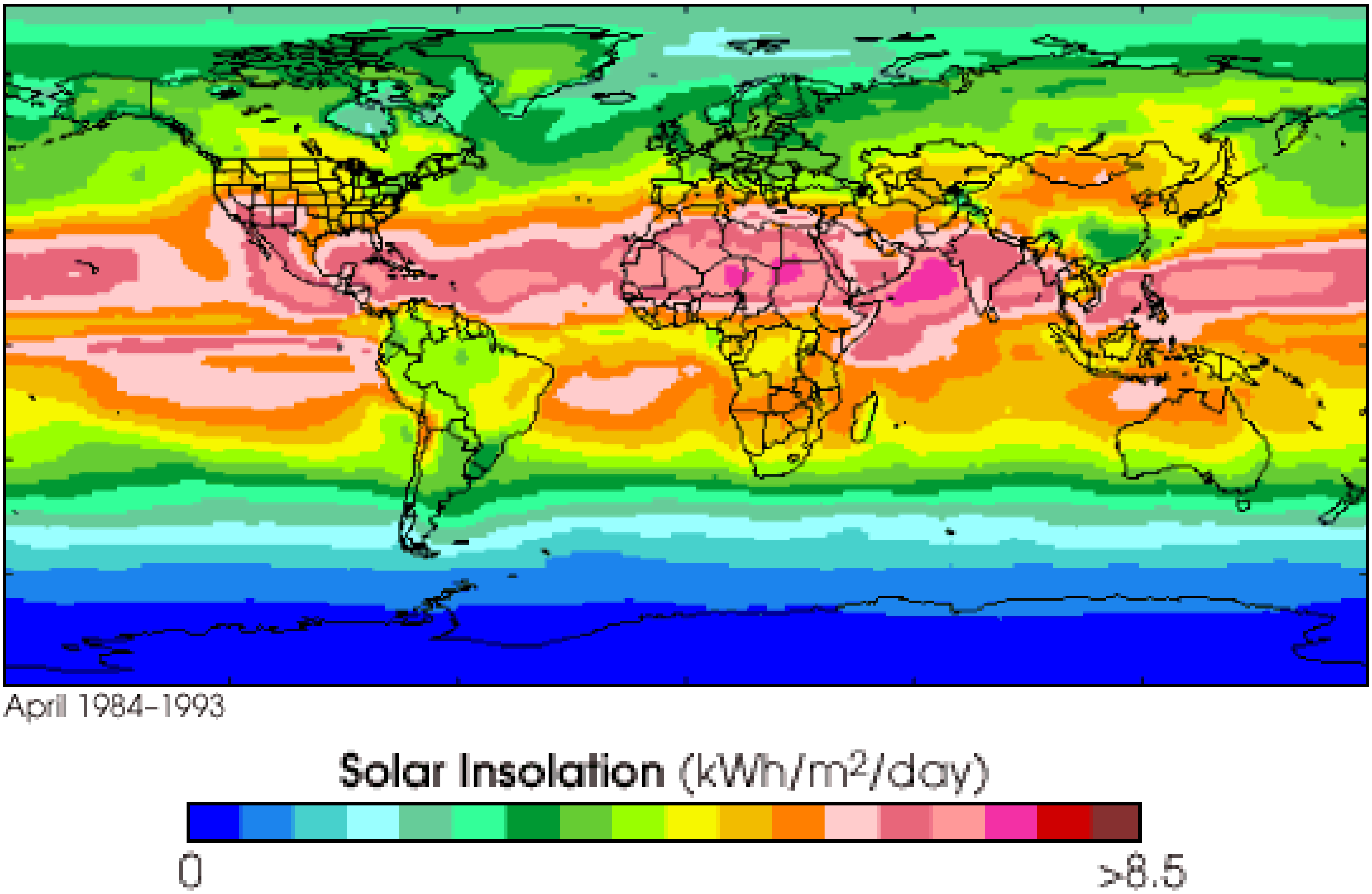
WINTER - Tilt angle equals the latitude angle

Daily total solar radiation incident on a tilted surface in kWH/m^2/day

Solar Insolation Map - January

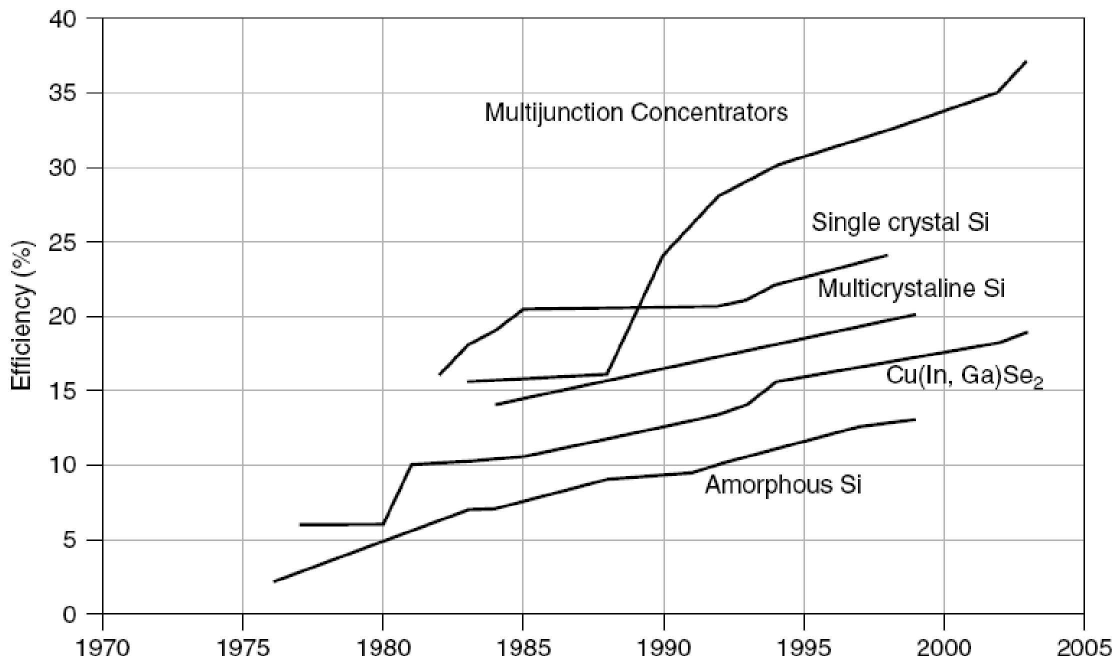


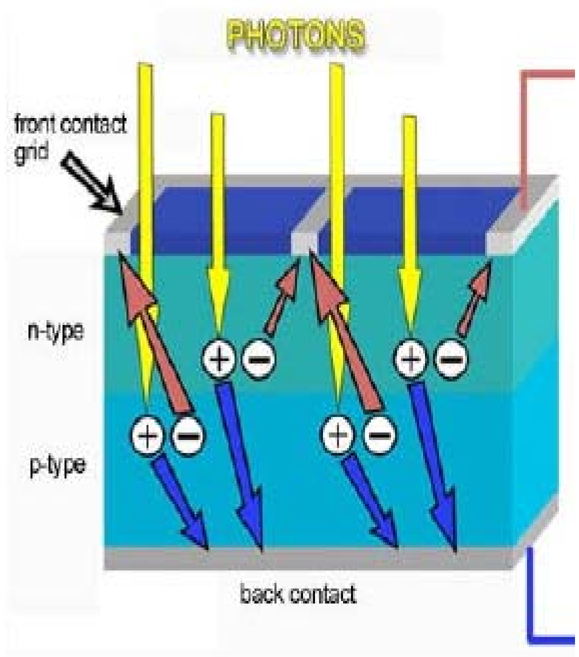
Solar Insolation Map - April



Photovoltaic Material and Electrical Characteristics

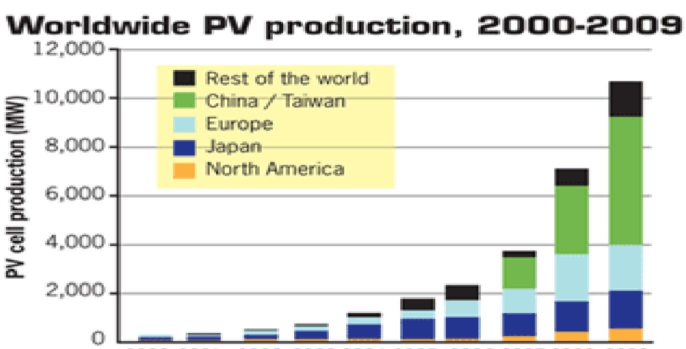
- Photovoltaic (PV): a device that is capable of converting the energy contained in photons of light into an electrical voltage or current
- A photon (short wavelength and high energy) break free electrons from the atoms in the photovoltaic material.
- **“The surface of the earth receives 6000 times as much solar energy as our total energy demand”**
- PV Cell Efficiency



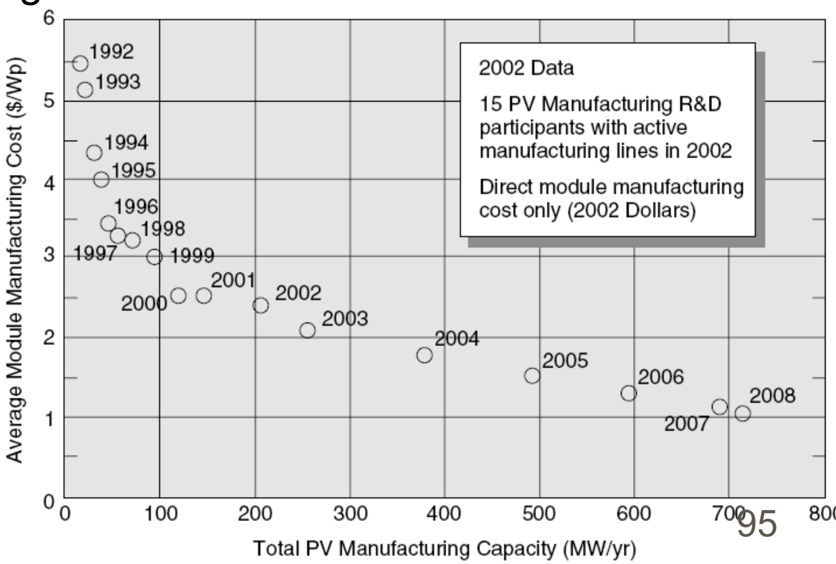


PV History

- 1829: Edmund Becquerel – voltage development on an metal electrode under illumination
- 1876: Adams and Day - PV effect on solid – built a cell made of Selenium with 1- 2 % efficiency
- 1904: Albert Einstein – Theoretical explanation of PV effect
- 1904: Czochralski (Polish Scientist) developed a method to grow perfect crystals of silicon →which later in 1940s and 1950s were adopted to make the first generation of single-crystal silicon PV cells, which continues to dominate the PV industry today
- Before 1958: Cost prohibitive
- 1958: Practical PV, used is space for Vanguard I satellite
- 1970s: Oil shock spurred the commercial PV development
- 1980s: High efficiency and low cost PV emerged
- 2002: Worldwide PV production
  - 600MW/year and increasing by 40% per year

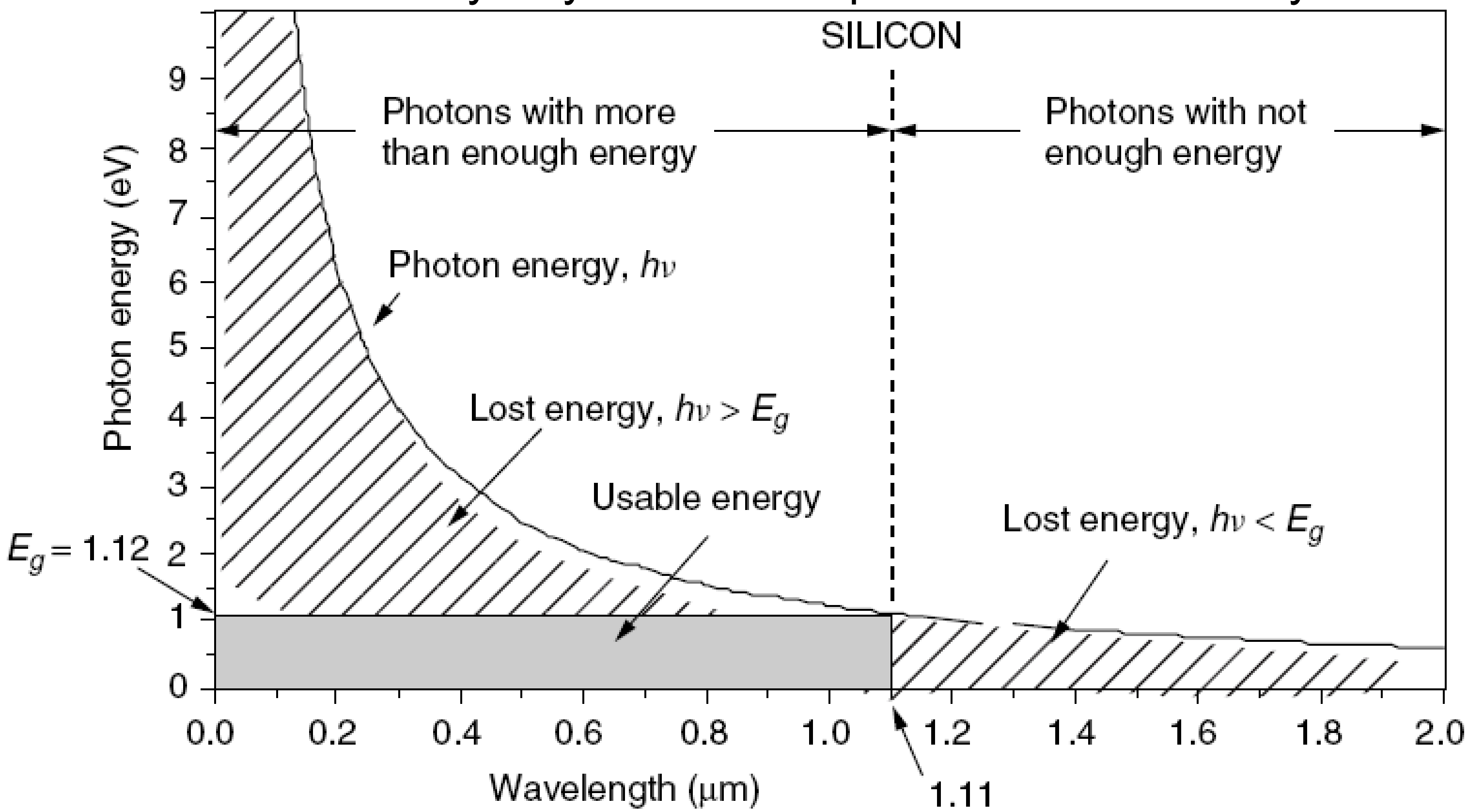


Source: Photovoltaic Technologies for the 21st Century, December 2010



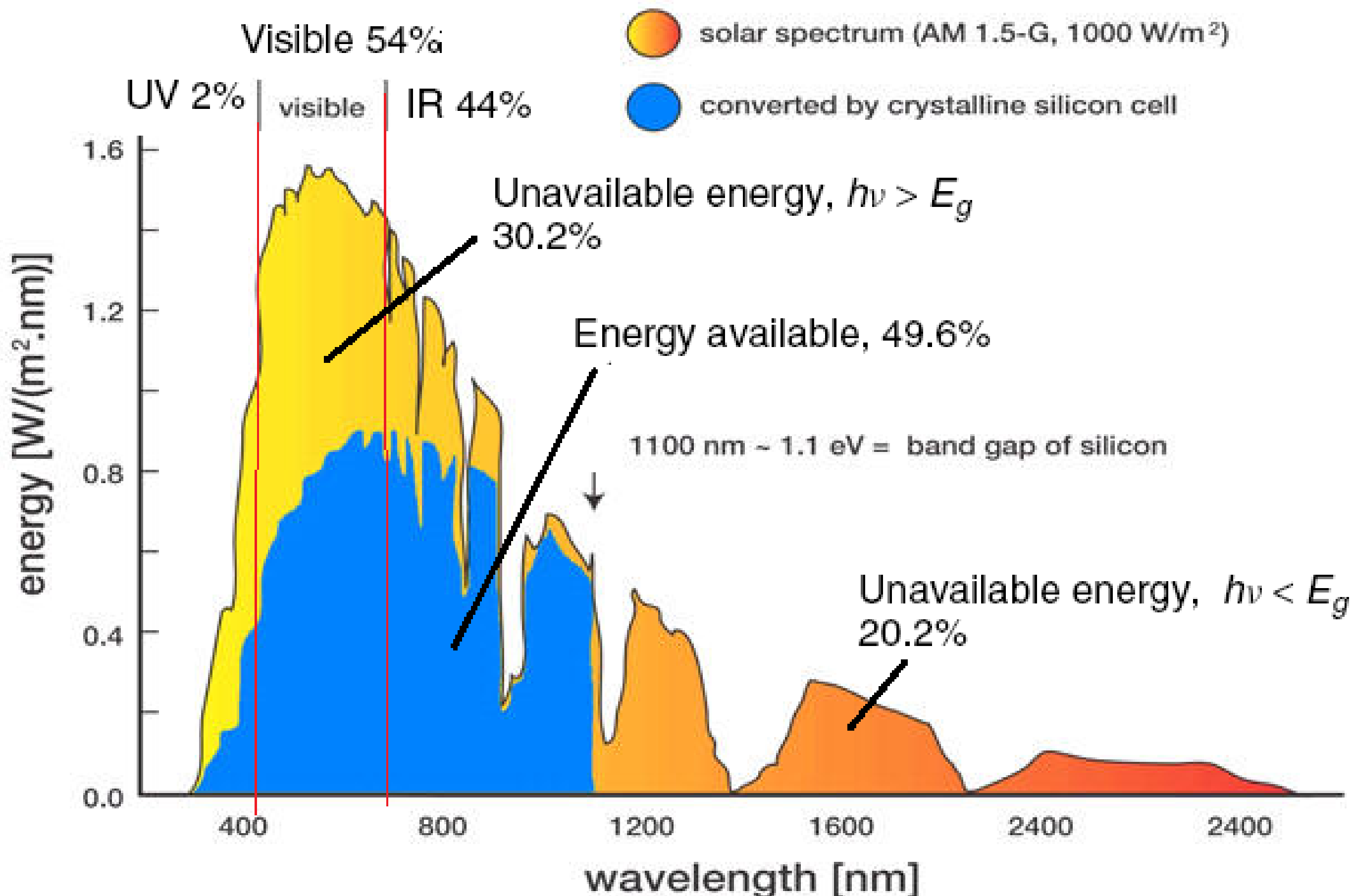
PV Semiconductor Physics

- For Si PV cells, photons with wavelength above **1.11 um** don't have the **1.12 eV** needed to excite an electron, and this energy is lost. Photons with shorter wavelengths have more than enough energy, but any energy above 1.12 eV is wasted any way – since one photon can excite only one electron.



- h – Planck's constant = 6.626^(-34) [J-s]
- v – frequency [Hertz[

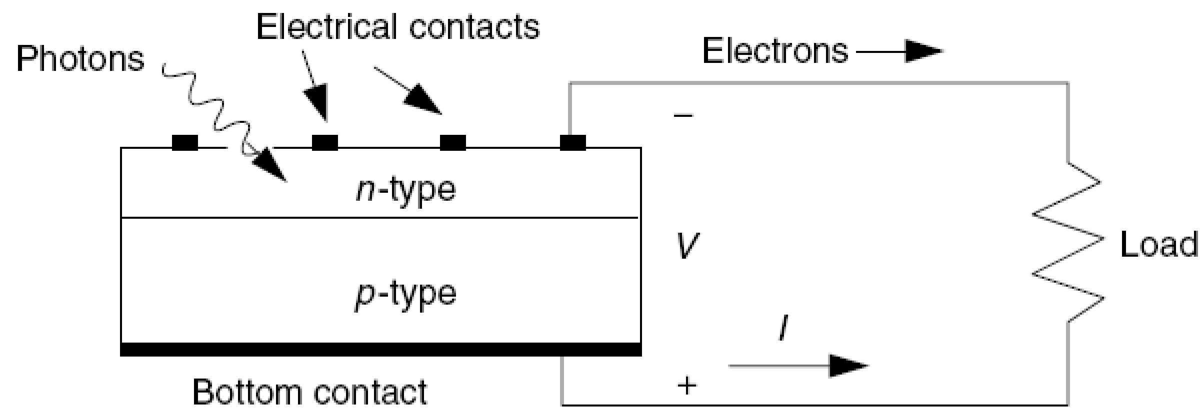
Solar Spectrum



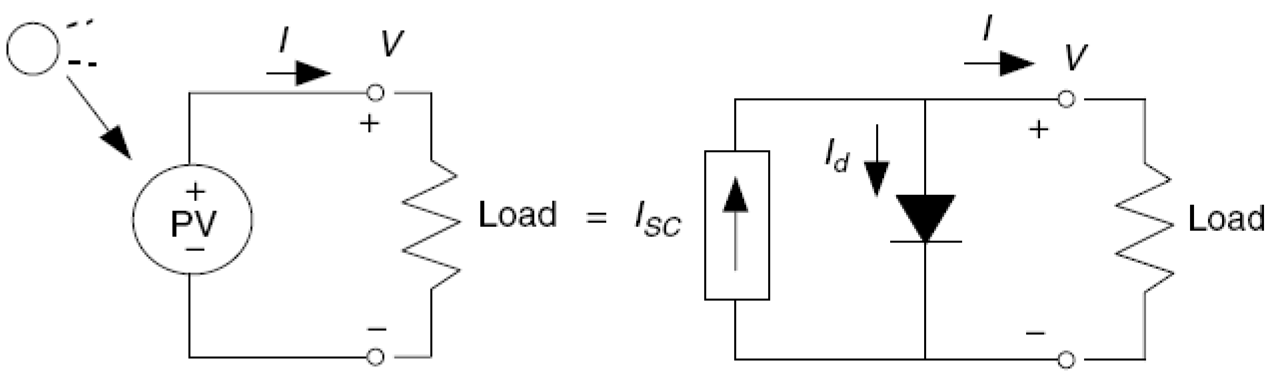
- AM (Air Mass) Ratio
  - AM0: Sun in space (no atmosphere0
  - AM1: Sun is directly overhead
  - AM1.5: Sun is 42 degrees above the horizon (standard condition)

PV Cell Circuit

- Electron flow

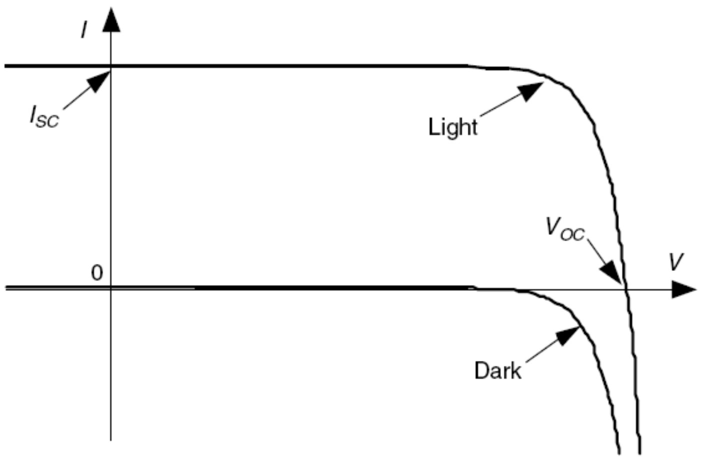


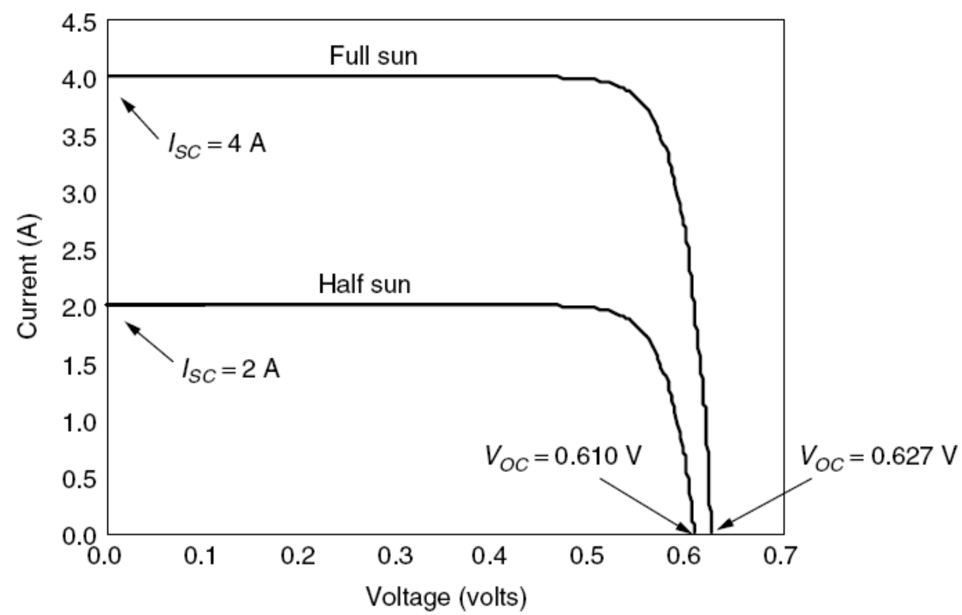
- Equivalent Circuit
  - Current source driven by sunlight in parallel with a real diode



I-V Curve

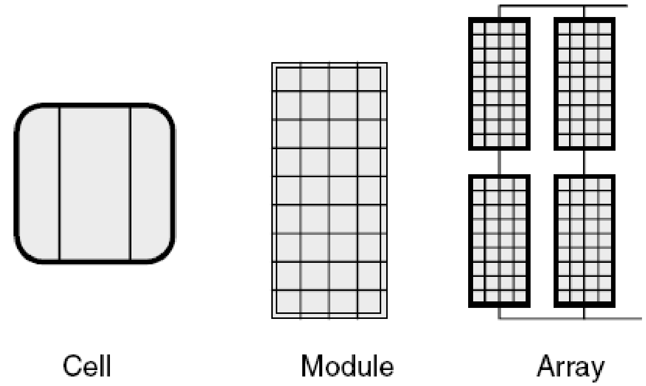
- Isc: Short Circuit Current
- Voc: Open Circuit Voltage

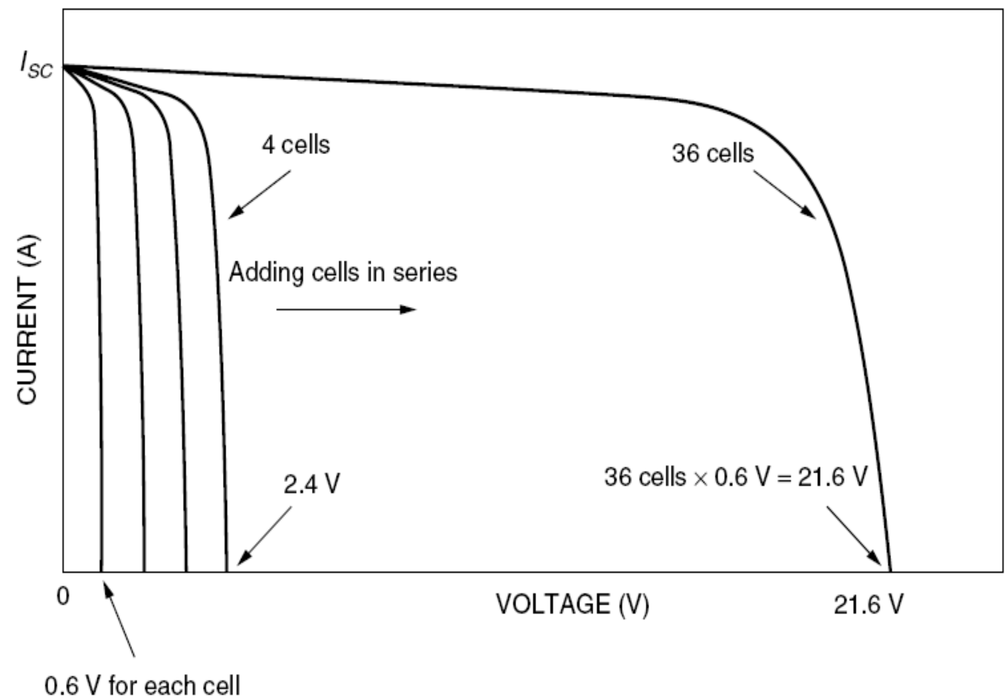




PV Cells, Modules, and Arrays

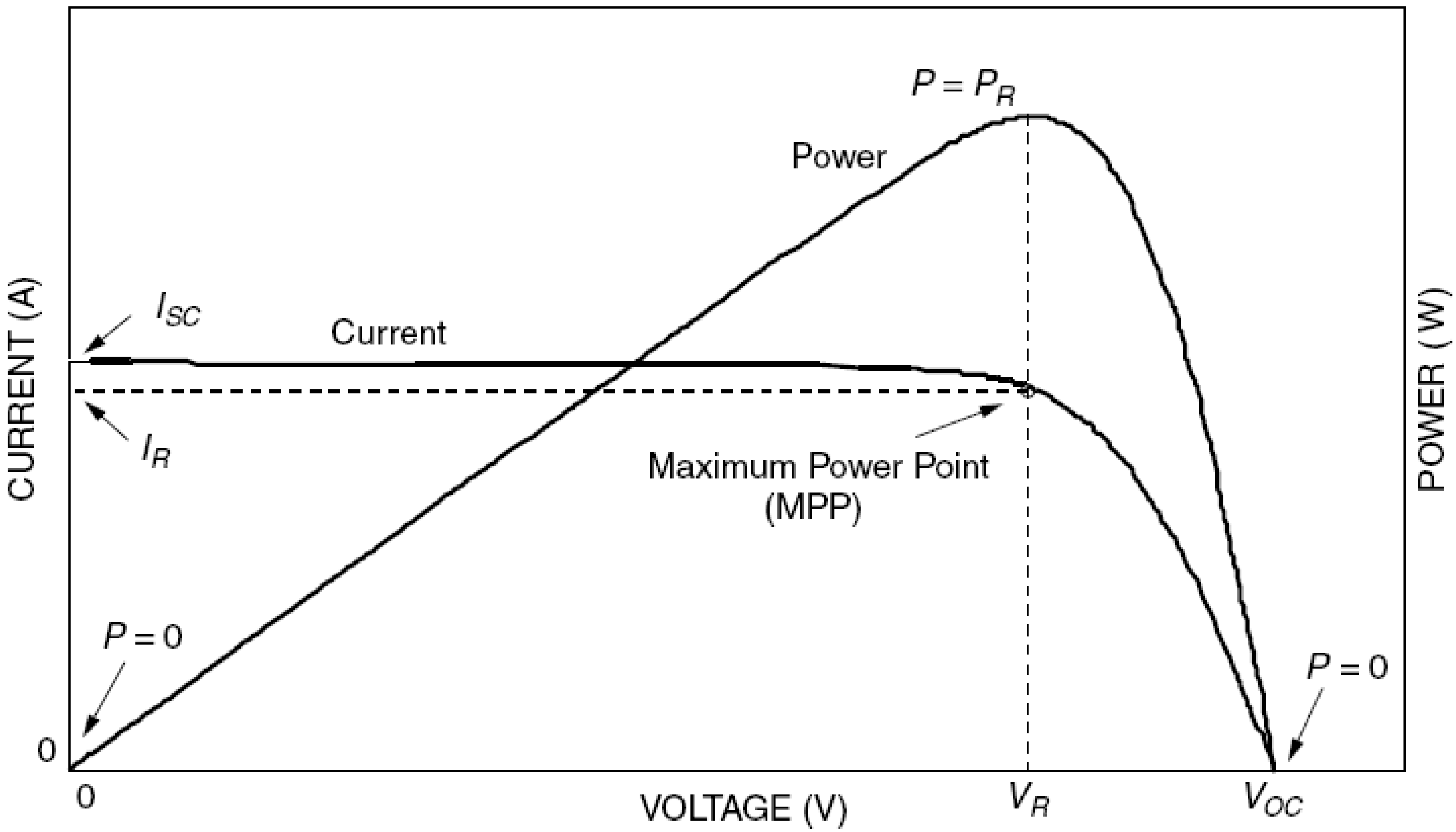
- Individual cell: 0.5V
- Module:
  - 36 cells in series – 12V module
  - 72 cells in series – 24V module
- Parallel – increase current
- Series- increase voltage





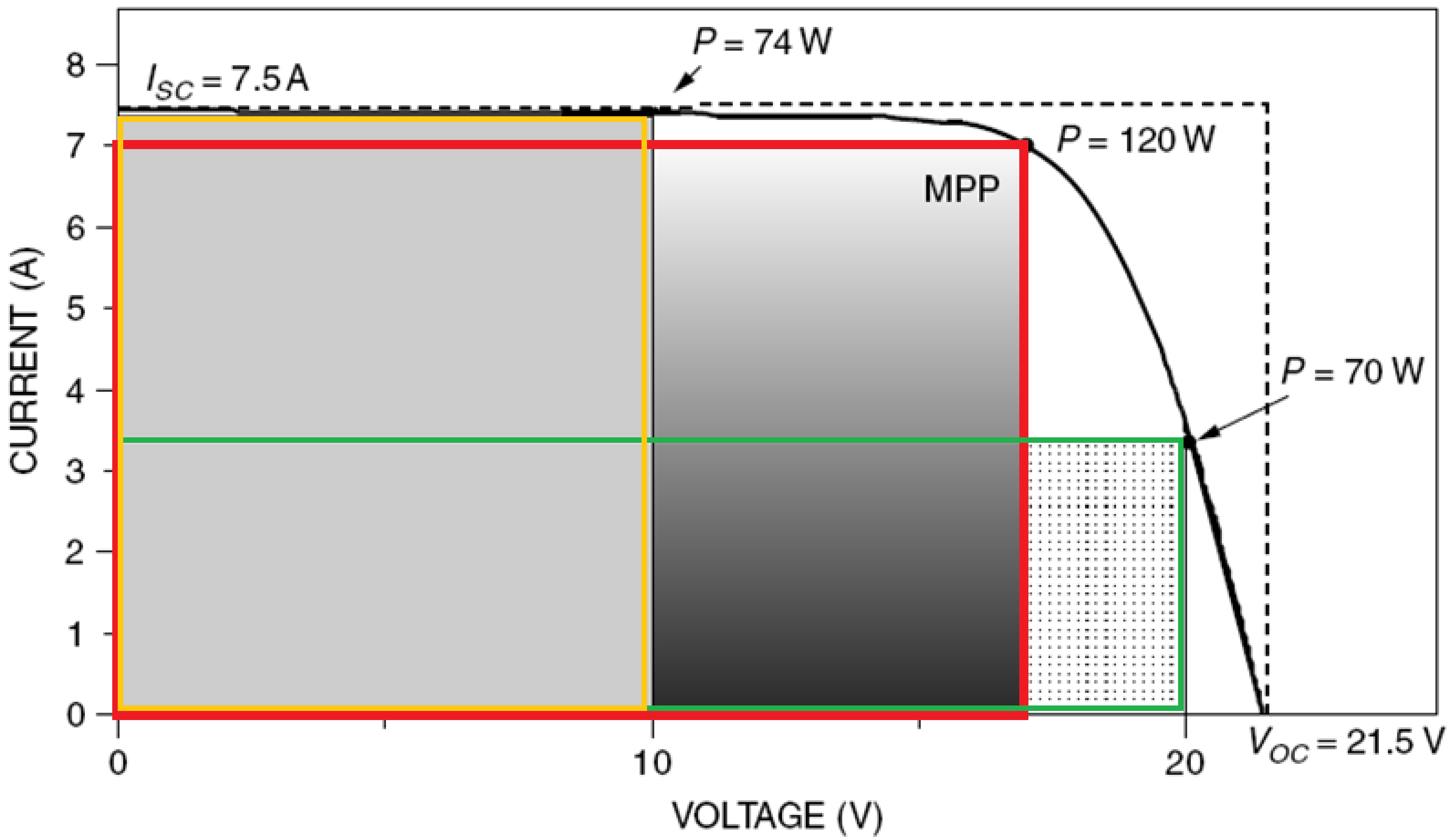
I-V Curve and Power Output

- Maximum Power Point (MPP)
- I_R: Rated Current
- V_R: Rated Voltage



Maximum Power Point

- The biggest possible rectangle – the area is power
- Fill Factor (FF): performance measure: ratio of the power at MPP to the product of V_{oc} and I_{sc}. (solid_rectangle/dotted_rectangle)

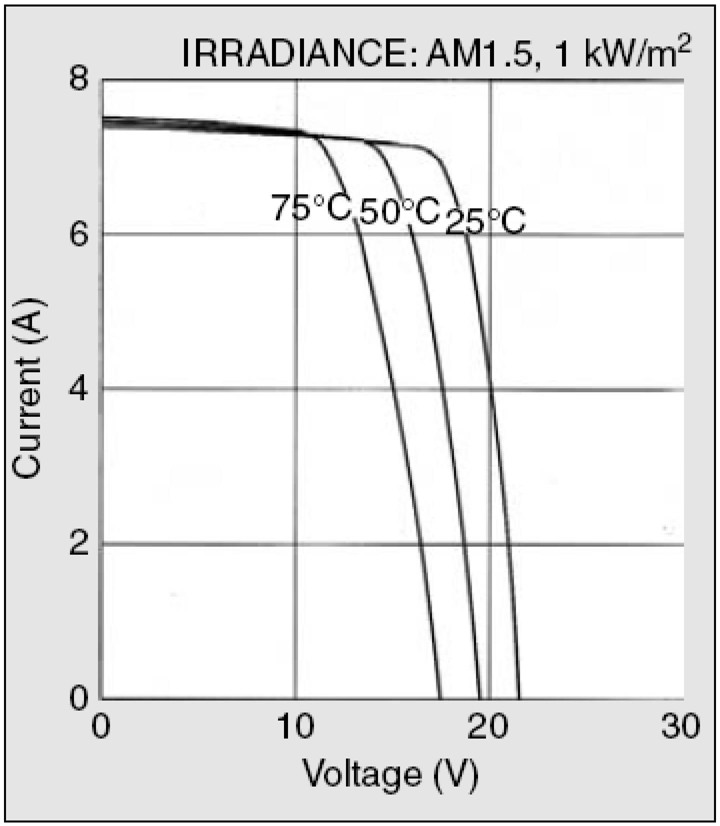


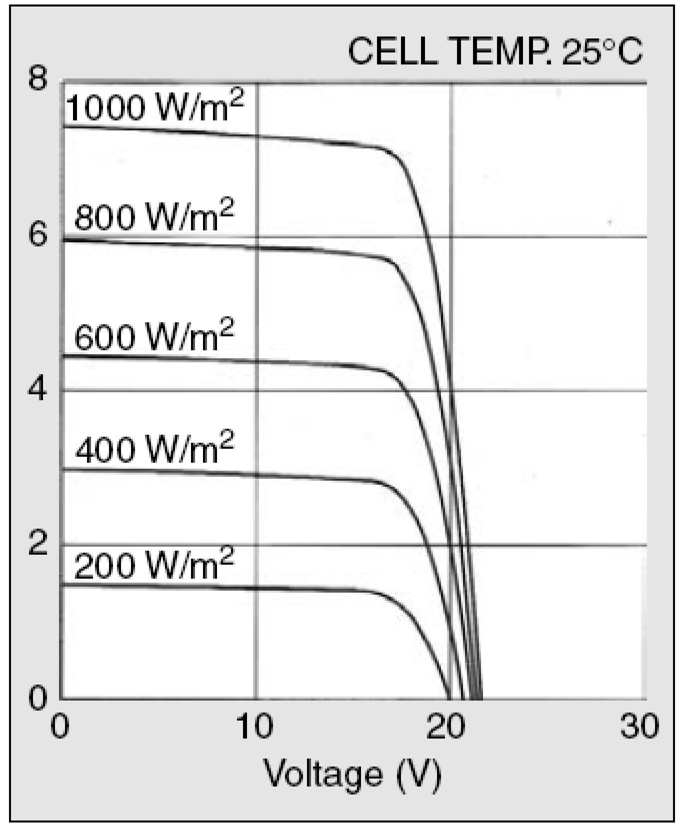
PV Module Performance Examples

Manufacturer	Kyocera	Sharp	BP	Uni-Solar	Shell
Model	KC-120-1	NE-Q5E2U	2150S	US-64	ST40
Material	Multicrystal	Polycrystal	Monocrystal	Triple junction a-Si	CIS-thin film
Number of cells n	36	72	72		42
Rated Power $P_{DC,STC}$ (W)	120	165	150	64	40
Voltage at max power (V)	16.9	34.6	34	16.5	16.6
Current at rated power (A)	7.1	4.77	4.45	3.88	2.41
Open-circuit voltage V_{OC} (V)	21.5	43.1	42.8	23.8	23.3
Short-circuit current I_{SC} (A)	7.45	5.46	4.75	4.80	2.68
Length (mm/in.)	1425/56.1	1575/62.05	1587/62.5	1366/53.78	1293/50.9
Width (mm/in.)	652/25.7	826/32.44	790/31.1	741/29.18	329/12.9
Depth (mm/in.)	52/2.0	46/1.81	50/1.97	31.8/1.25	54/2.1
Weight (kg/lb)	11.9/26.3	17/37.5	15.4/34	9.2/20.2	14.8/32.6
Module efficiency	12.9%	12.7%	12.0%	6.3%	9.4%

Insolation and Temperature Effect

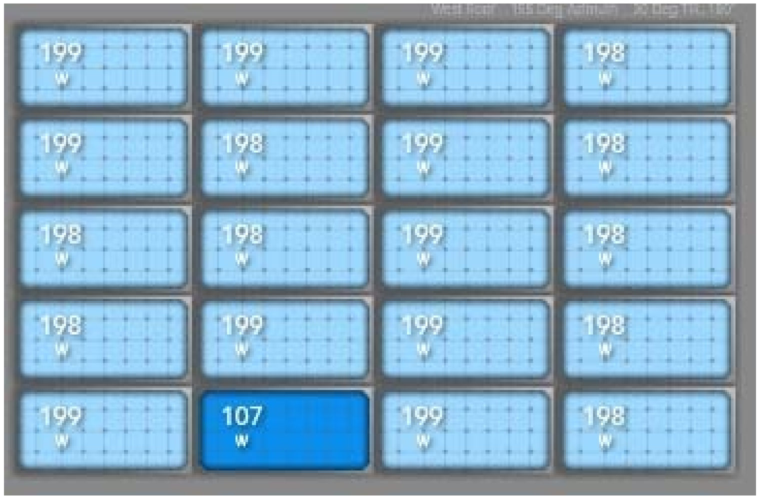
- Decrease in insolation, decrease in short-circuit current
- Increase in cell temperature, substantial decrease in open-circuit voltage, and slight decrease in short-circuit current
- Kyocera 120-W multicrystal-Si module example





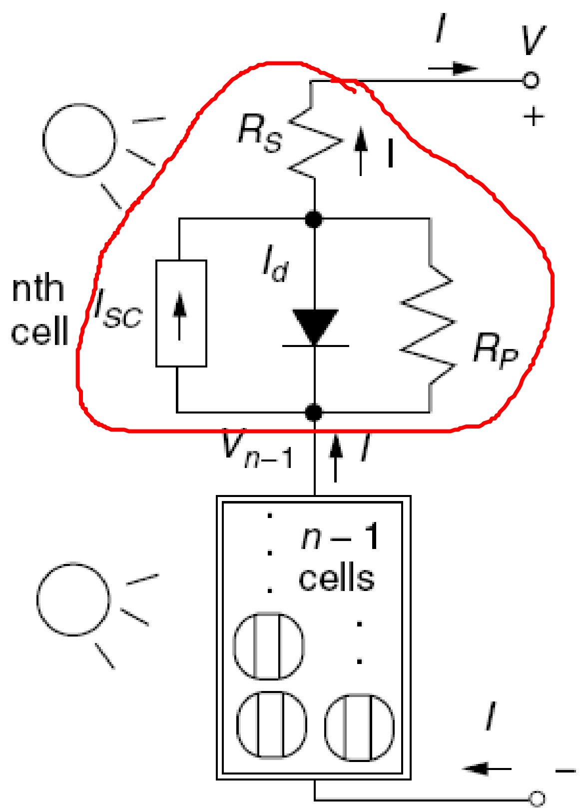
Shading Effect and Bypass Diode

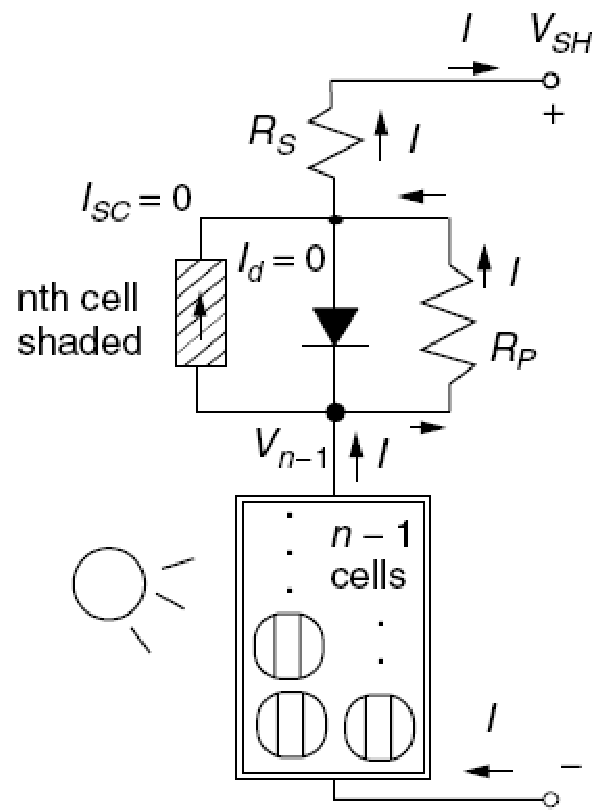
- Output of a PV module can be reduced dramatically when even a small portion of it is shaded.
- Even a single cell under shade in a long string of cells can easily cut output power by more than half.
- External diodes mitigate the impacts of shading



Physics of Shading

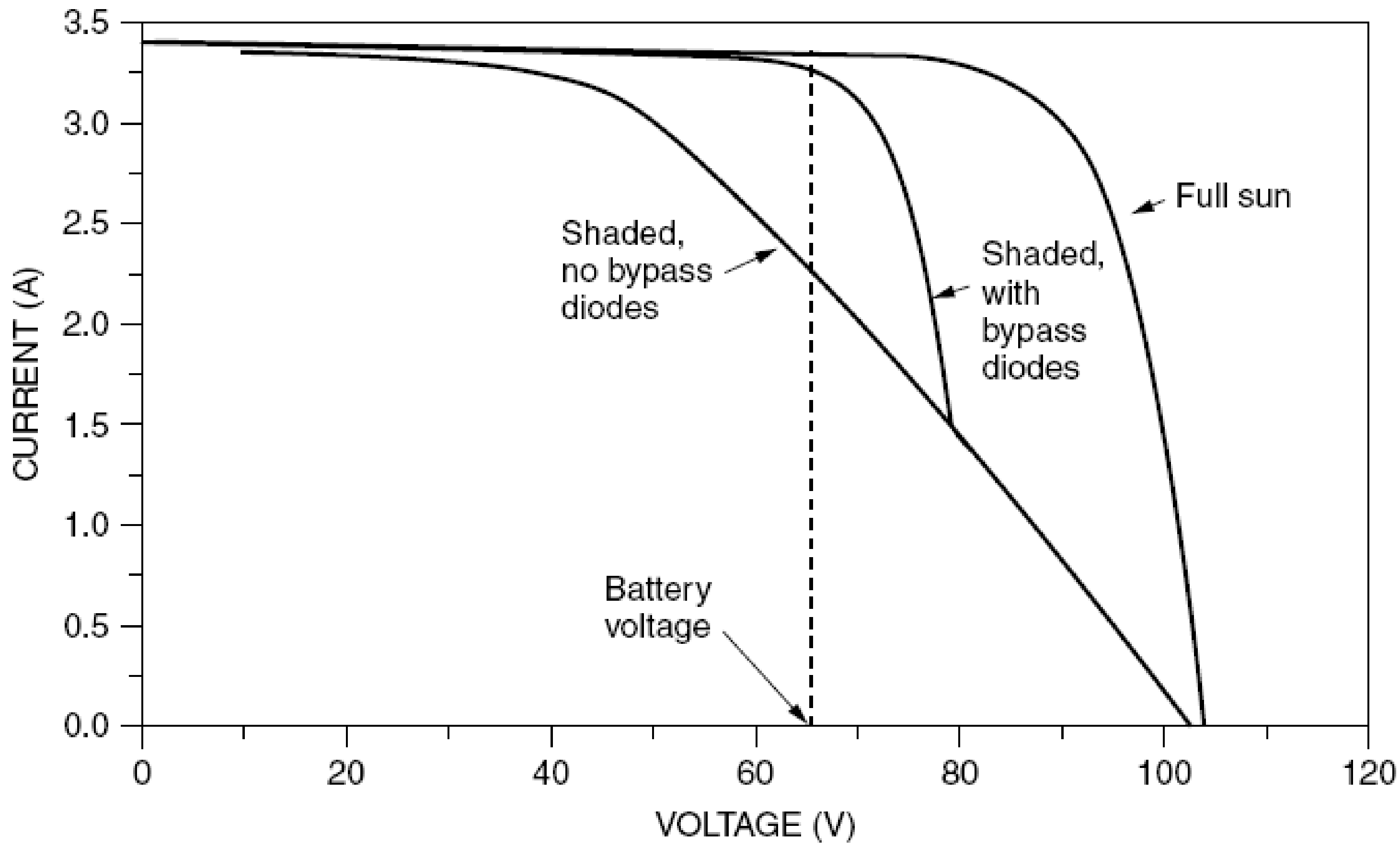
- All cells under sun
  - The same current flows through each cell
- Top cell under shade
  - The current source is reduced to zero for the cell
  - Now the current from other cells must flow through Rp, which drop the voltage, instead of adding voltage.



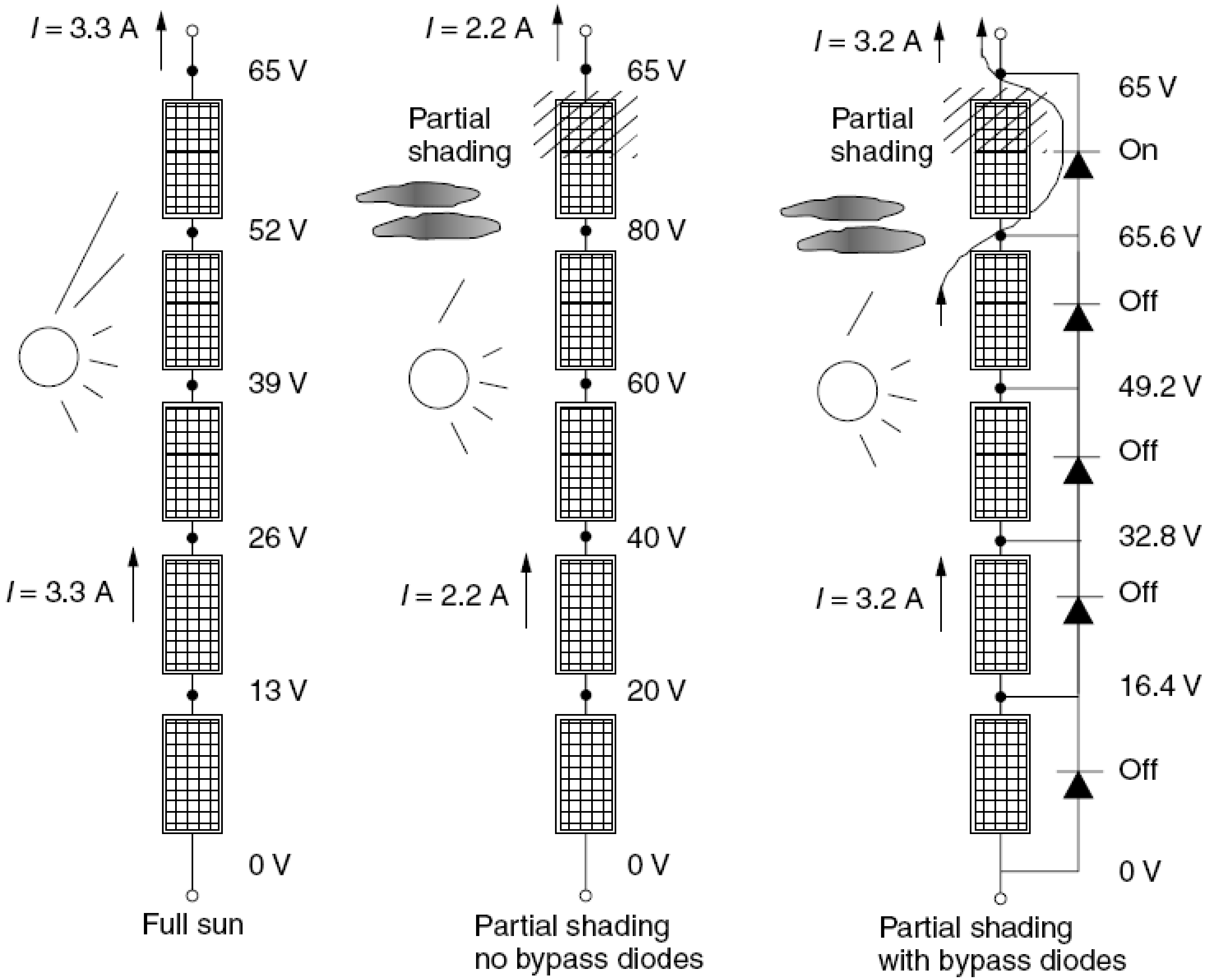


Impact of Bypass Diode

- For a 5 PV modules in series delivering 65V to a battery bank – one module has 2 shaded cells.
- Charging current drops to 2.2A from 3.3A
- With a bypass diode, the current is recovered to 3,2 A

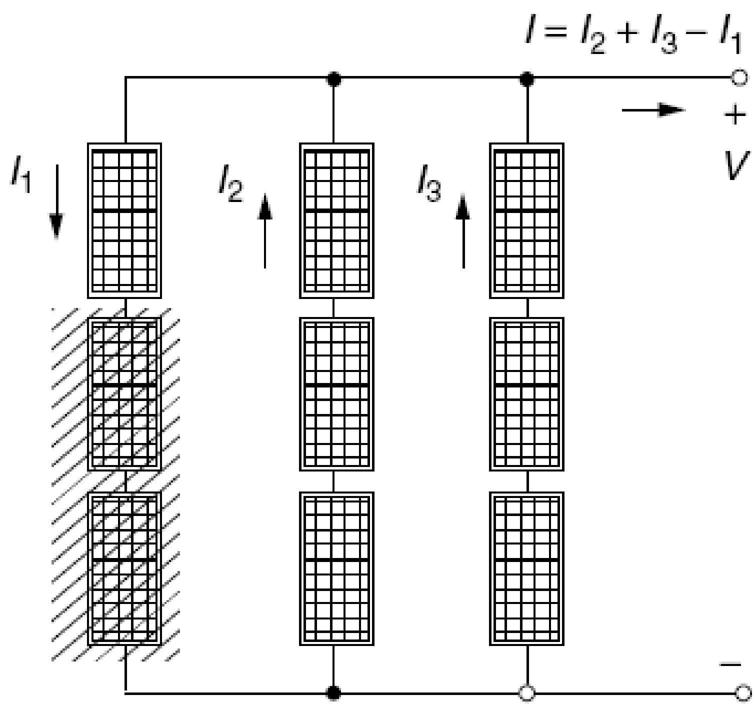


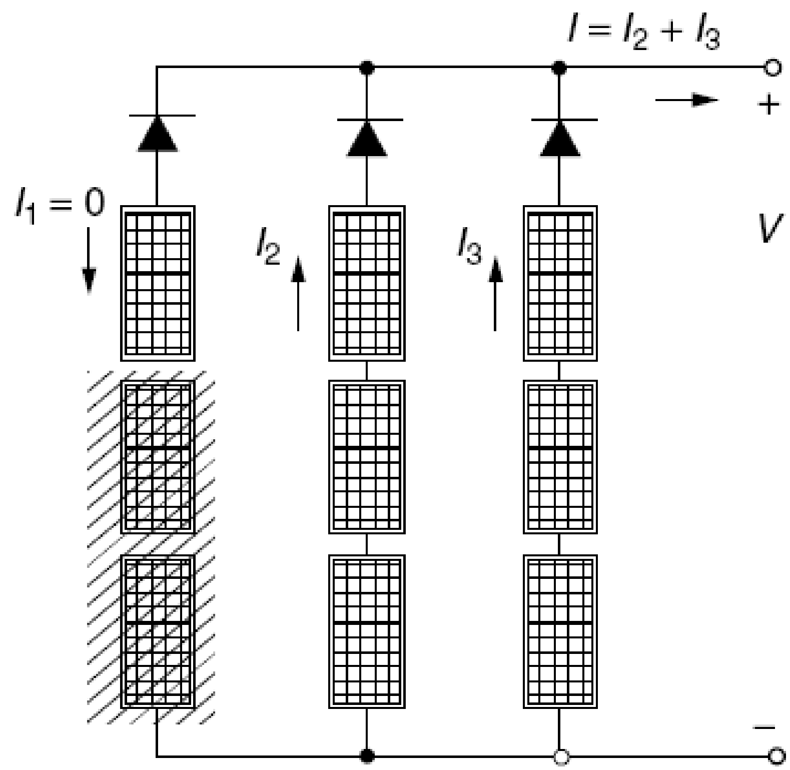
Mitigation by Bypass Diode



Partial Cell under Performance – Blocking Diode

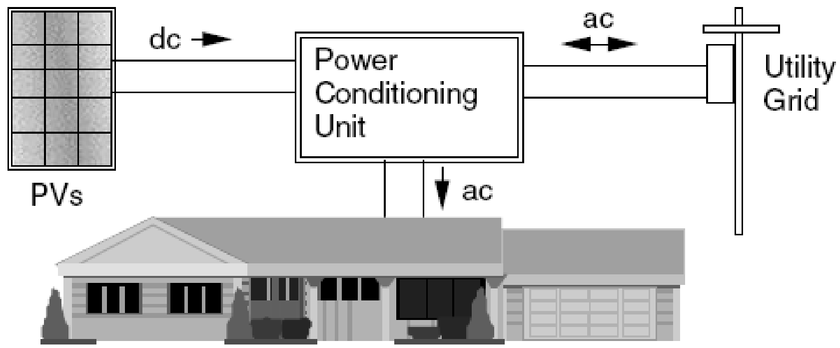
- In Parallel Combination of strings of cells: Separate the malfunctioning or shaded string of cells by blocking (or "Isolation") diode at the top of each string



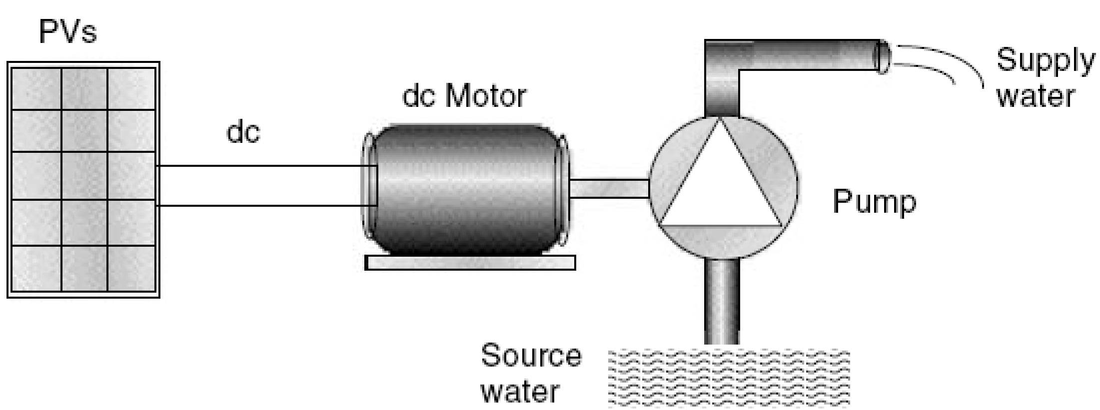


PV System Configurations

- Utility connected PV System: Feed/get power directly from/to the utility grid and PV

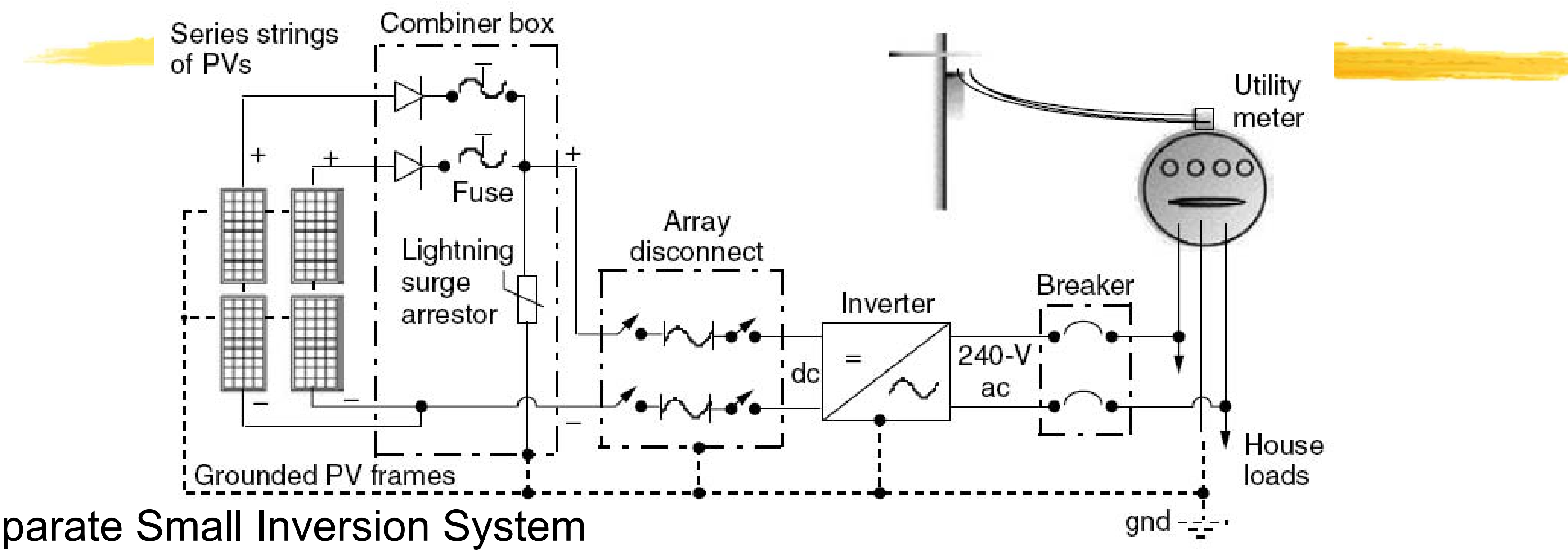


- Stand-alone system: Charge batteries (with or without Generator backup) and serves load

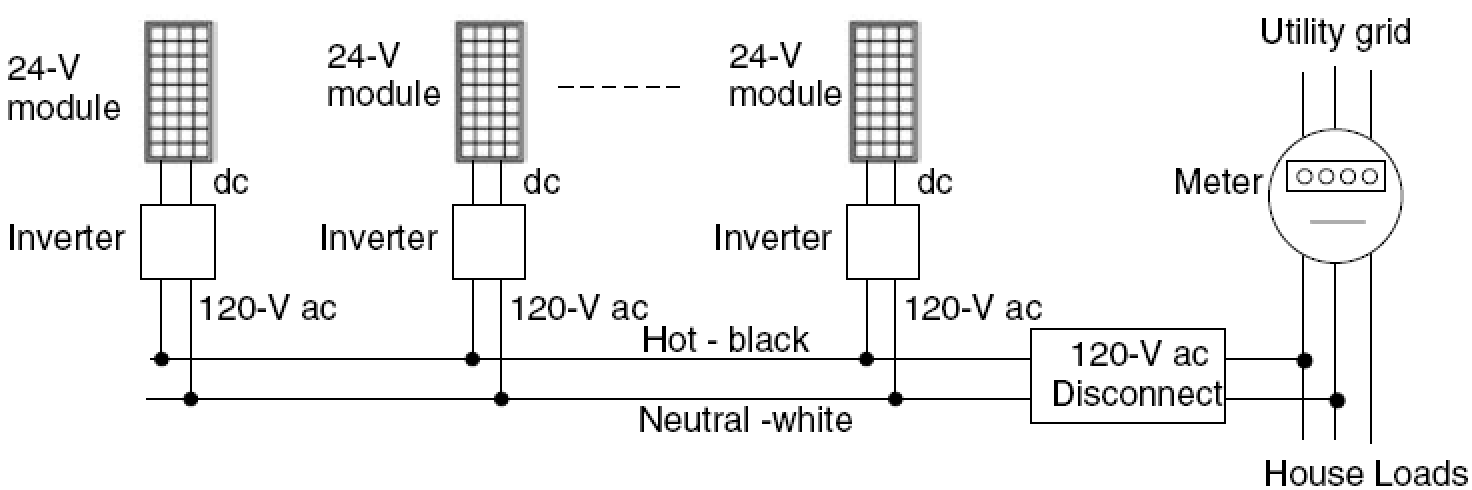


Grid-Connected PV System

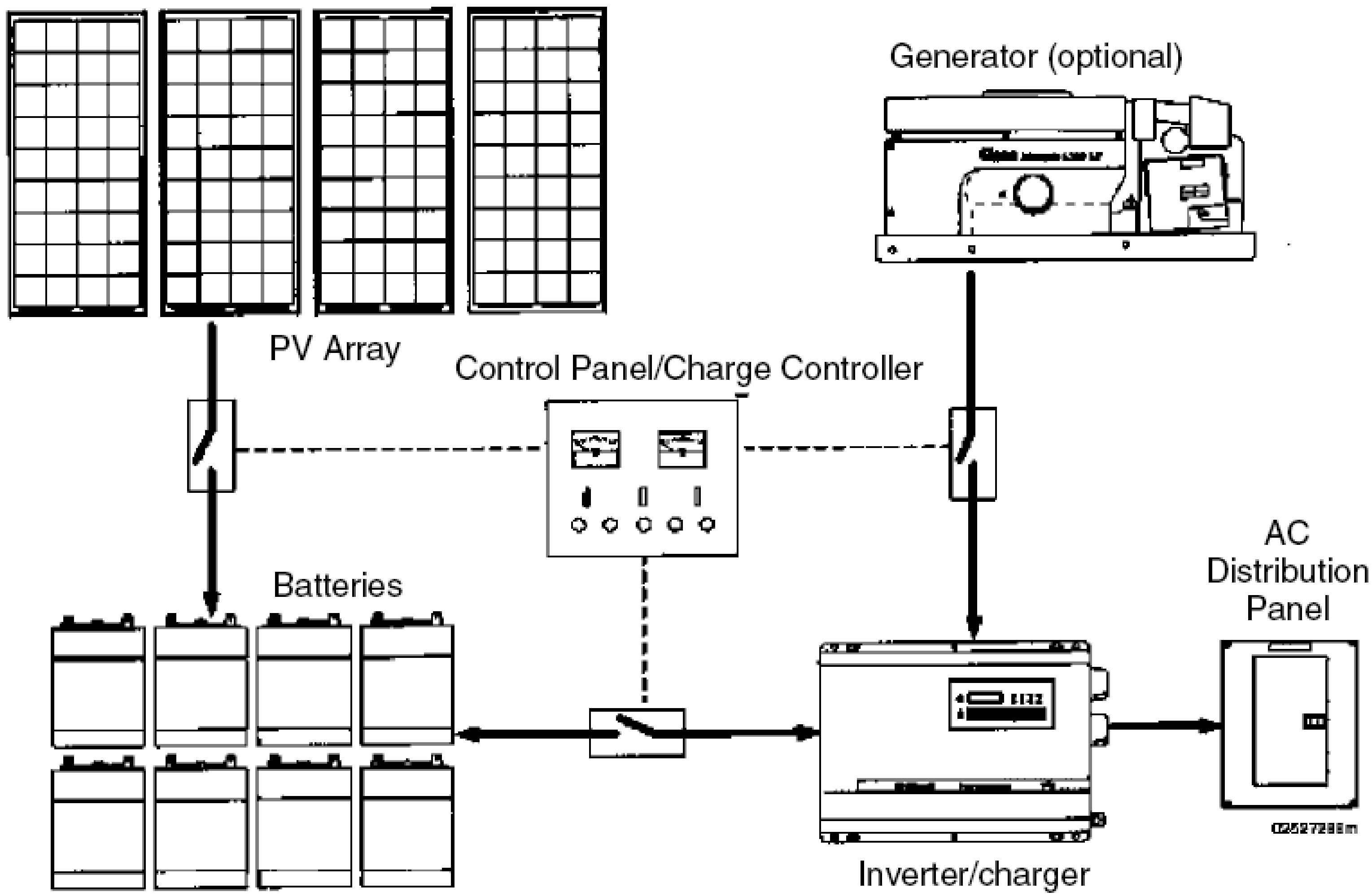
- Combined Inversion system



- Separate Small Inversion System

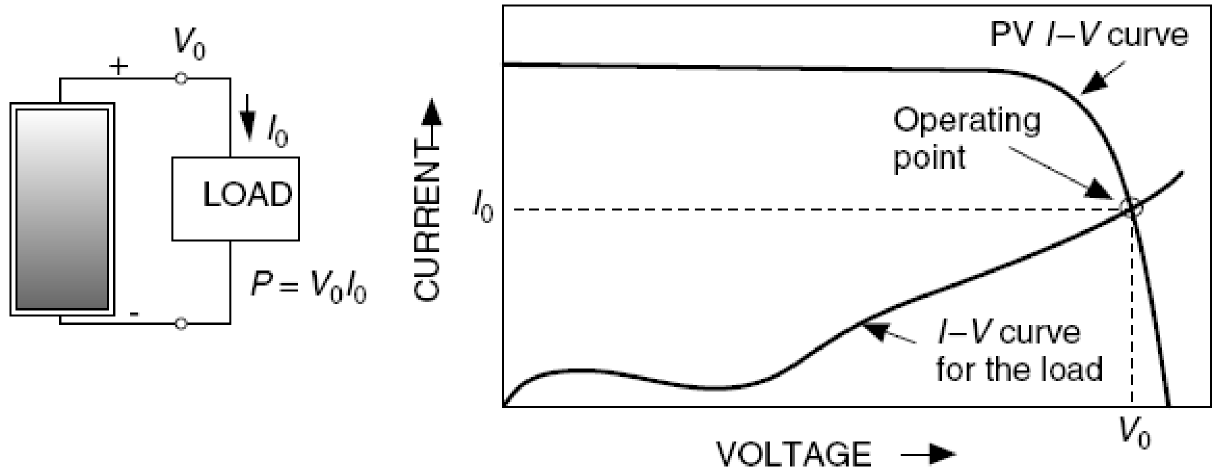


Example Stand-Alone PV System

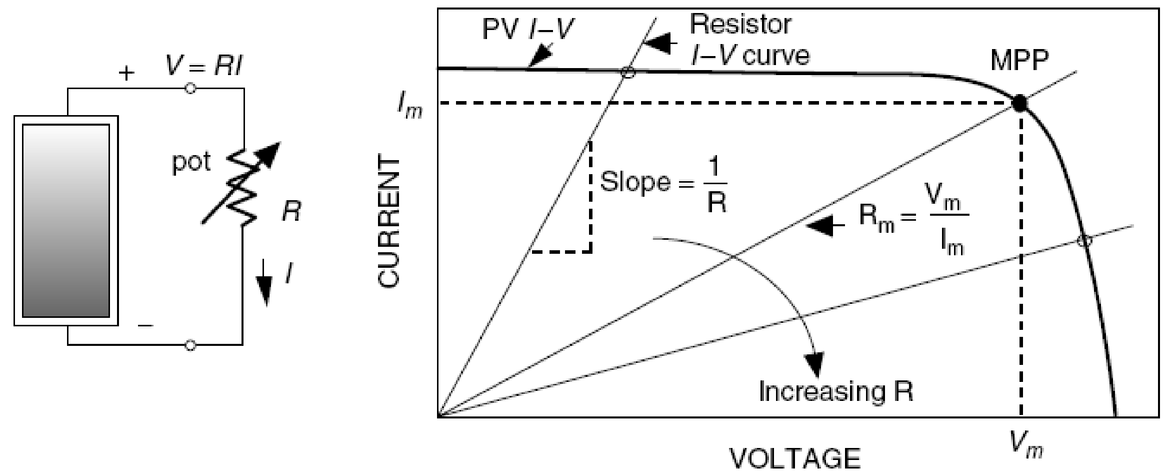


Operating Point

- PV Cell's I-V Curve
- Load's I-V Curve
- The intersection point is the operating point.

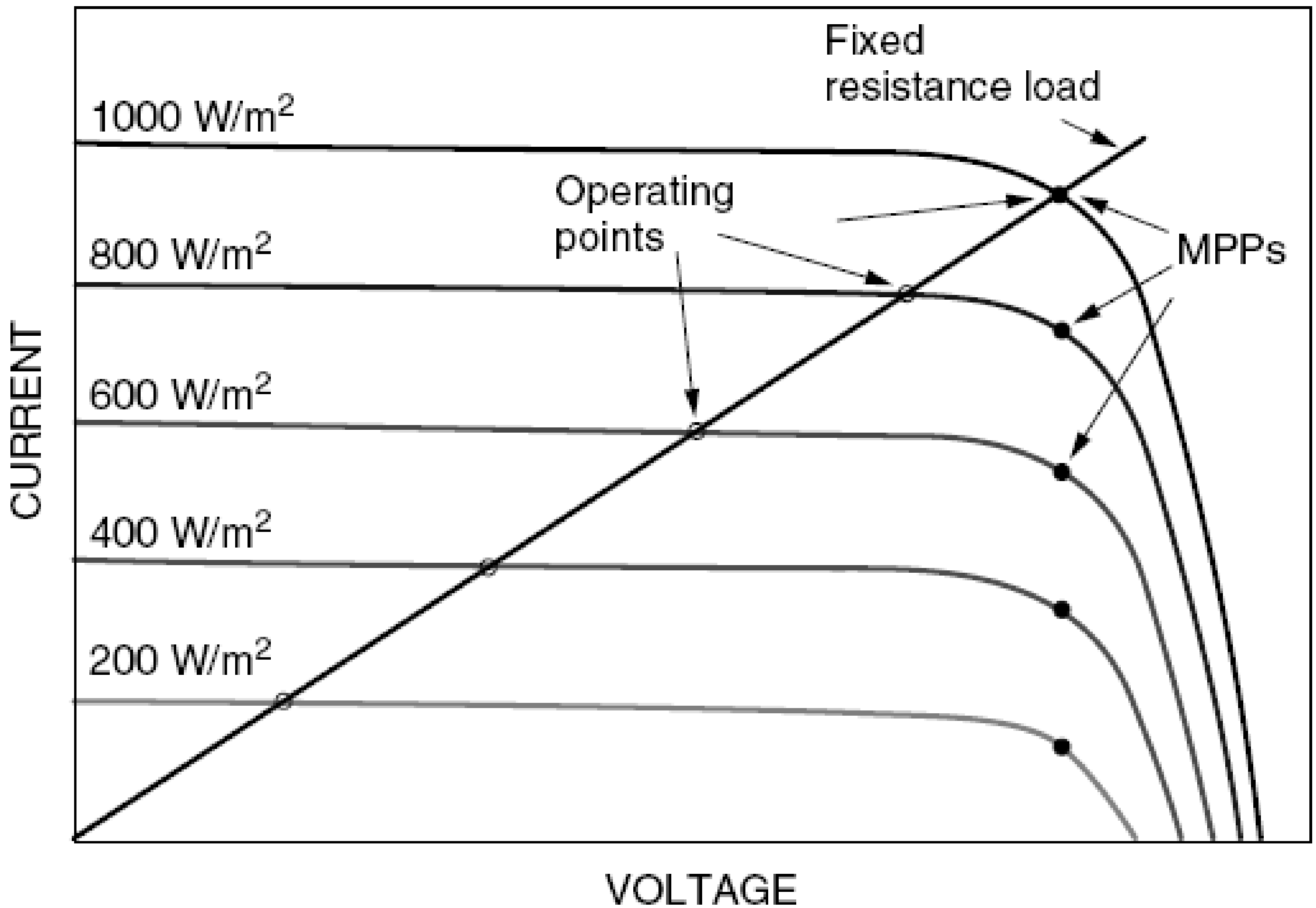


- Changes in Operating Points by the changes in resistance



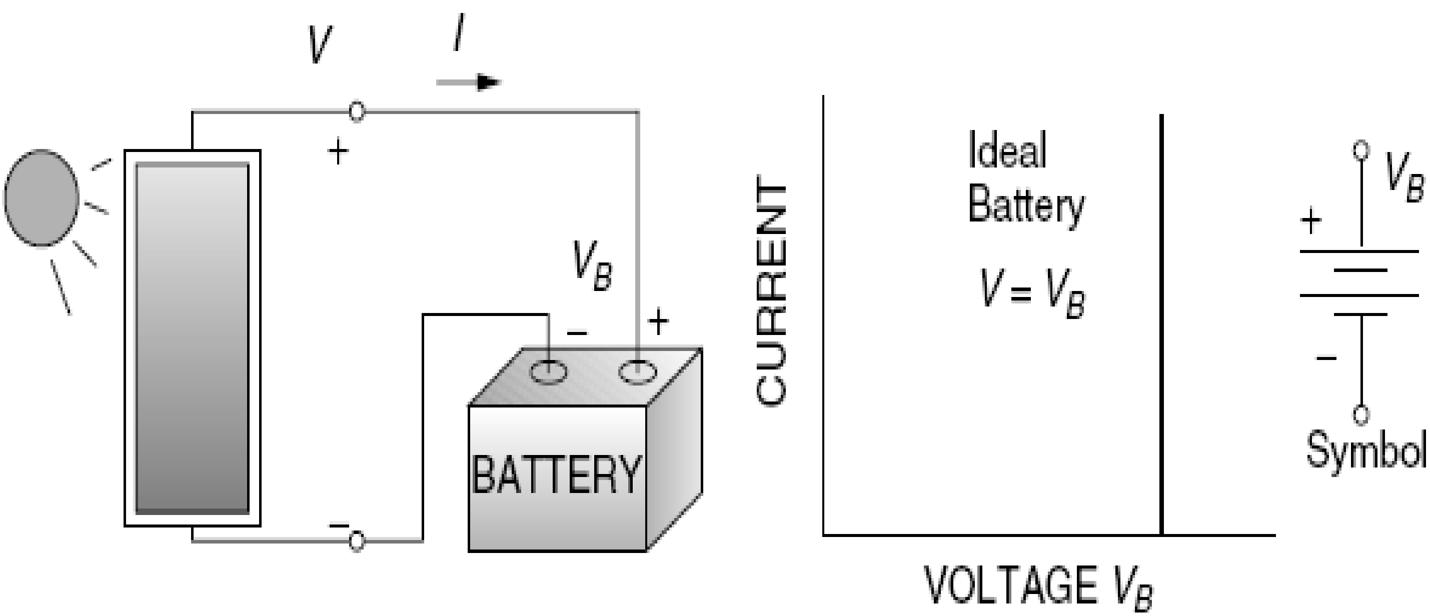
Operating Point Change over Insolation

⌘ With fixed resistance, the operating point moves down off the MPP as the Insolation condition changes and the PV is less efficient



Battery I-V Curve

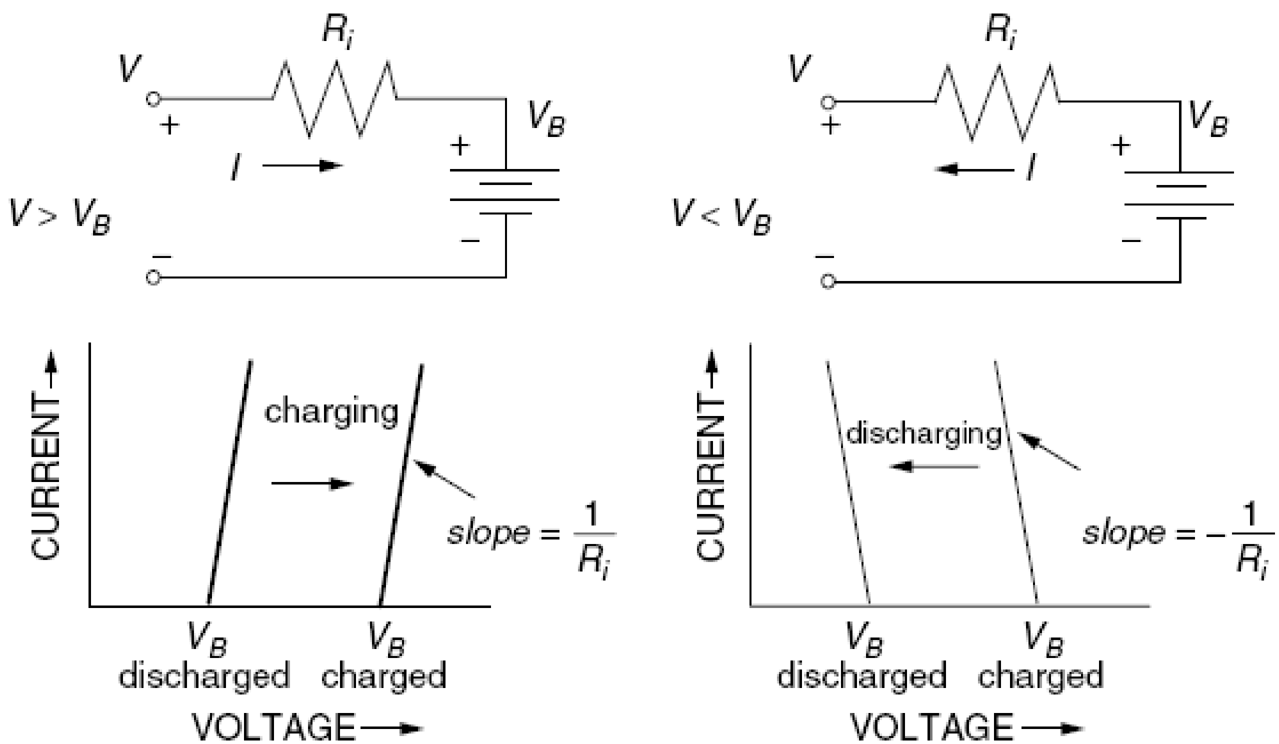
- Ideal: Voltage remains constant no matter how much current is drawn
- I-V Curve: Straight up-and-down line



Battery I-V Curve

⌘Real Battery

- ⌘ Real battery has internal resistance: $V = V_B + R_i * I$
  - Charging: Applied voltage must be bigger than V_B
  - Discharging: Output Voltage is less than V_B.

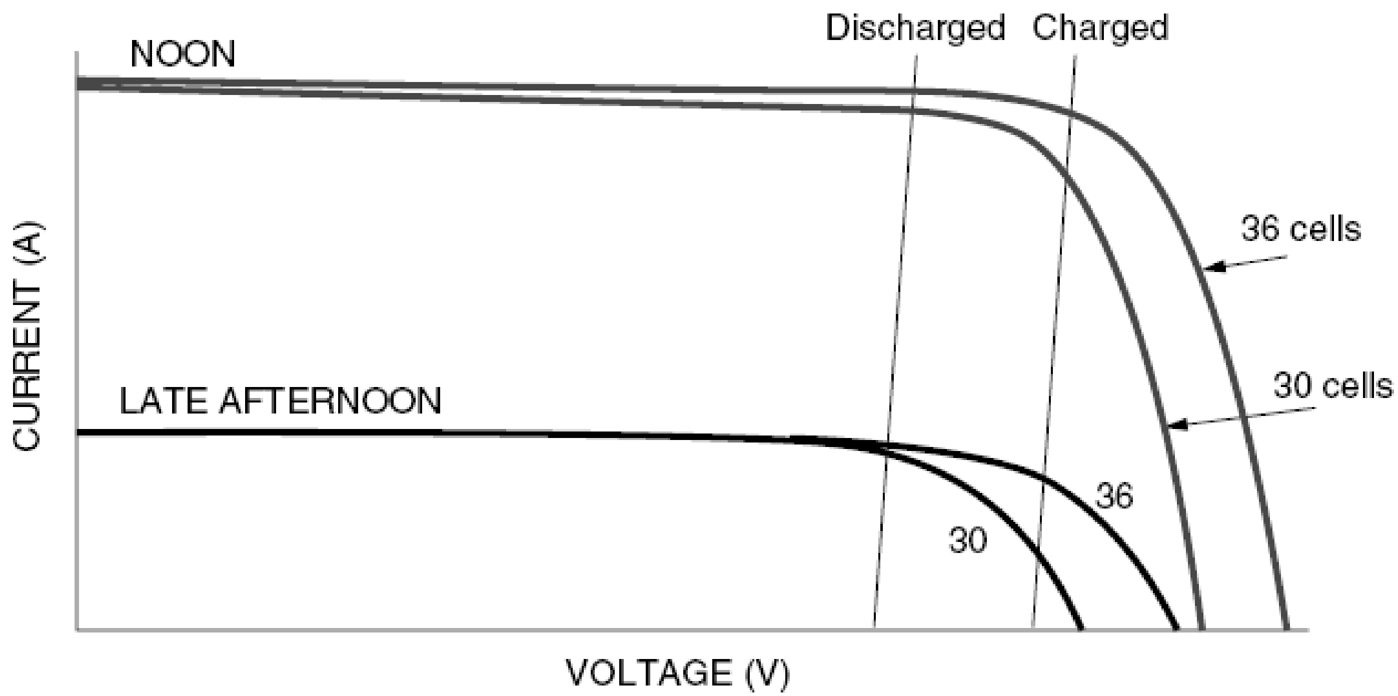


(a) Charging

(b) Discharging

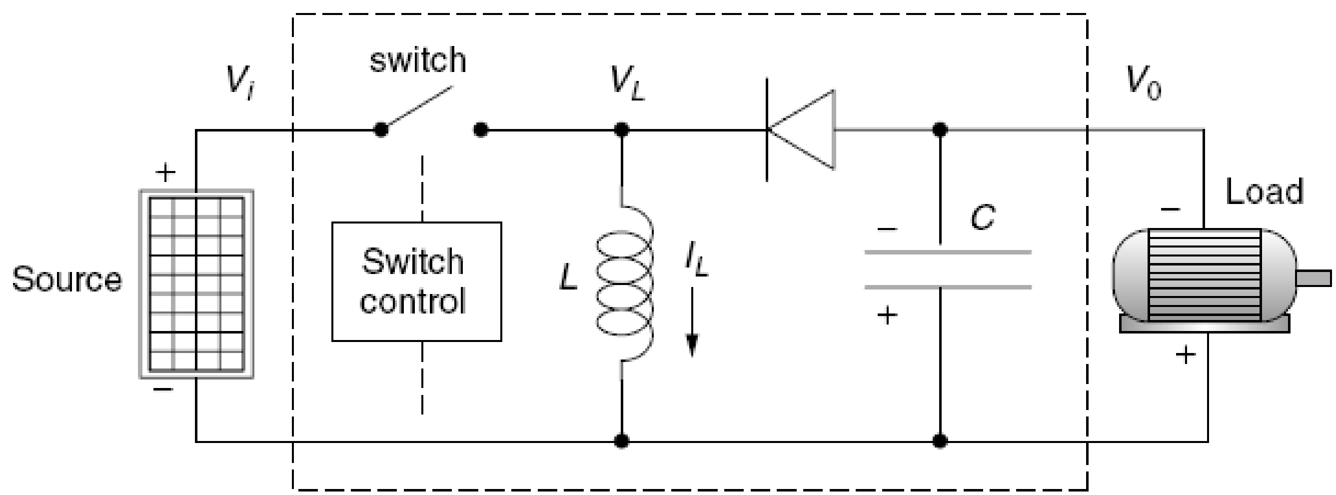
Charging and Discharing

- Charging moves I-V curve toward the right during the day (from PV) → So current lowers and prevents overcharging
- Discharging moves I-V curve toward left during late afternoon (from PV)



Voltage Control

- Benefit of operating PV near the knee (MPP) of the I-V Curve throughout the ever-changing daily conditions
- Conversion of DC voltages → Switched mode dc-to-dc converter {on-off switch to allow current to pass or block}
- Boost Converter: Step-up
- Buck Converter: Step-Down
- Buck-Booster Converter: Combination



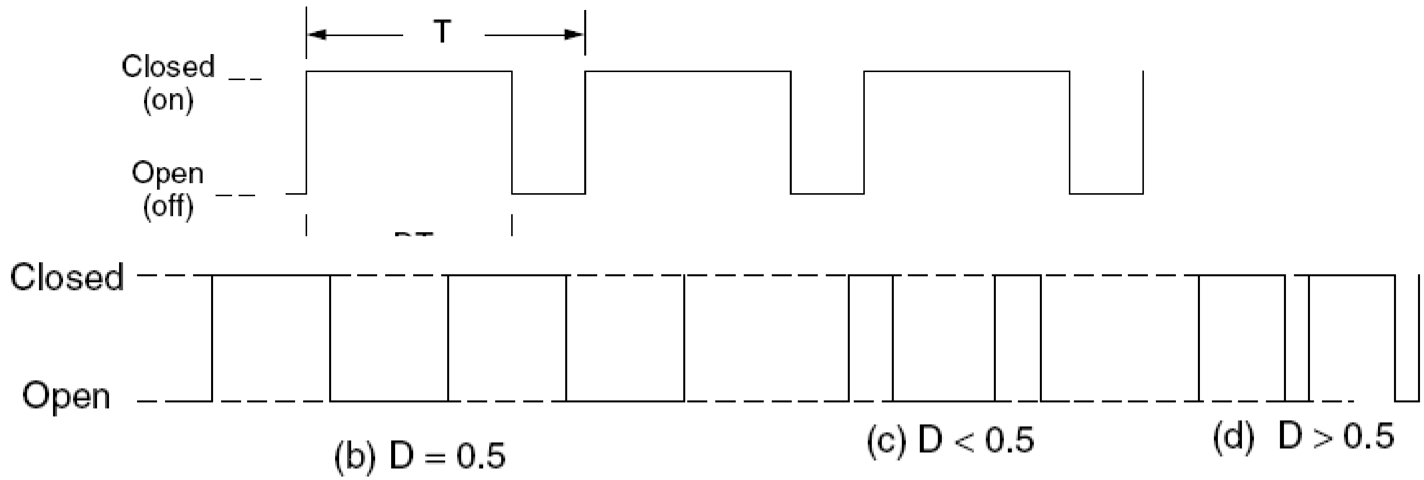
Buck-boost converter

Circuit Operational Principle

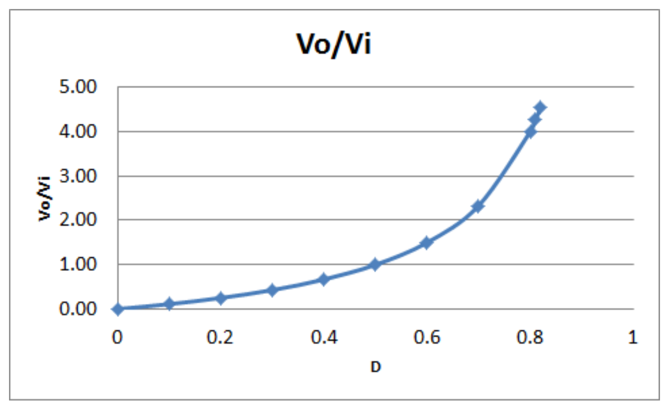
- When the switch is closed, the input voltage V_i is applied across the inductor, driving current I_L through the inductor. All of the source current goes through the inductor since the diode blocks any flow to the rest of the circuit. During this portion of the cycle, energy is being added to the magnetic field in the inductor as current builds up. If the switch stayed closed, the inductor would eventually act like a short-circuit and the PVs would deliver short-circuit current at zero volts.
- When the switch is opened, current in the inductor continues to flow as the magnetic field begins to collapse (remember that current through an inductor cannot be changed instantaneously—to do so would require infinite power). Inductor current now flows through the capacitor, the load, and the diode. Inductor current charging the capacitor provides a voltage (with a polarity reversal) across the load that will help keep the load powered after the switch closes again.
- If the switch is cycled quickly enough, the current through the inductor doesn't have a chance to drop much while the switch is open before the next jolt of current from the source. With a fast enough switch and a large enough inductor, the circuit can be designed to have nearly constant inductor current. That's our first important insight into how this circuit works: Inductor current is essentially constant.
- If the switch is cycled quickly enough, the voltage across the capacitor doesn't have a chance to drop much while the switch is closed before the next jolt of current from the inductor charges it back up again. Capacitors, recall, can't have their voltage change instantaneously so if the switch is cycling fast enough and the capacitor is sized large enough, the output voltage across the capacitor and load is nearly constant. We now have our second insight into this circuit: Output voltage Vo is essentially constant (and opposite in sign to Vi).

Input – Output Voltage by Duty Cycle

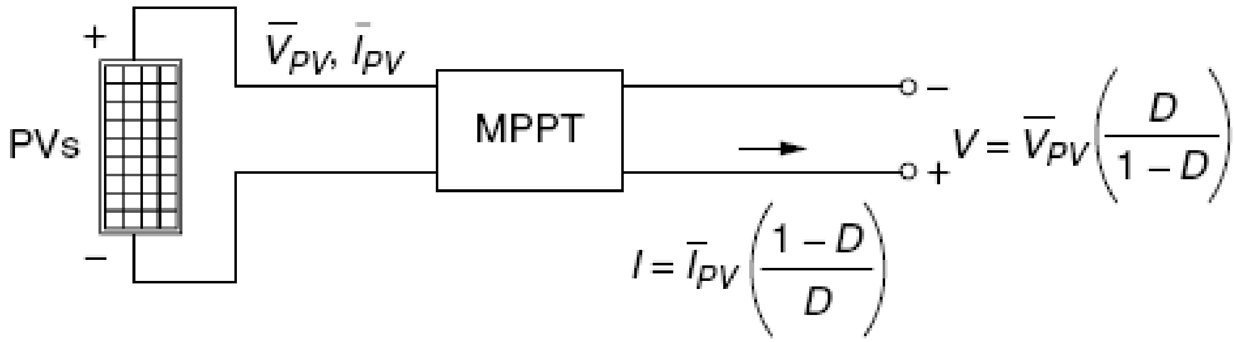
- The duty cycle of the switch itself controls the relationship between the input and output voltages of the converter.
- The duty cycle D ($0 < D < 1$) is the fraction of the time that the switch is closed. This variation in the fraction of time the switch is in one state or the other is referred to as *pulse-width modulation* (PWM).

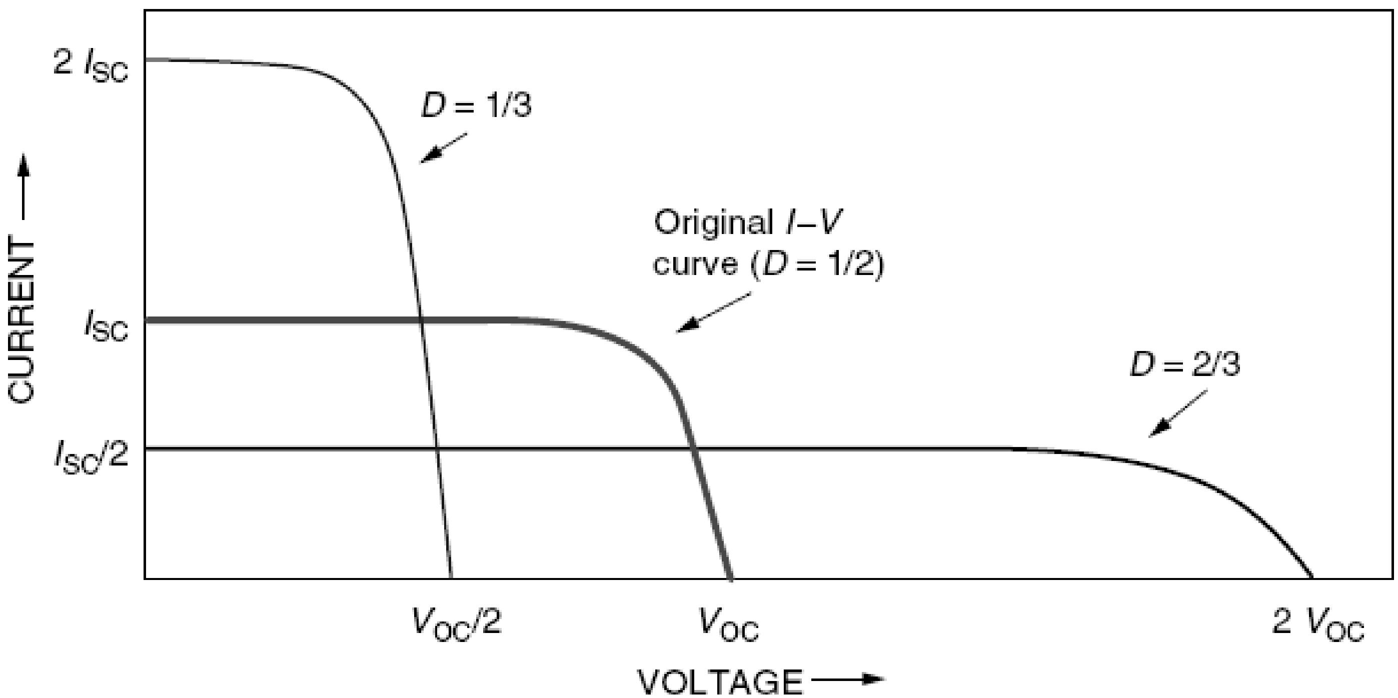


$$\frac{V_0}{V_i} = -\left(\frac{D}{1-D}\right)$$



MPPT and PV I-V with Duty Cycle





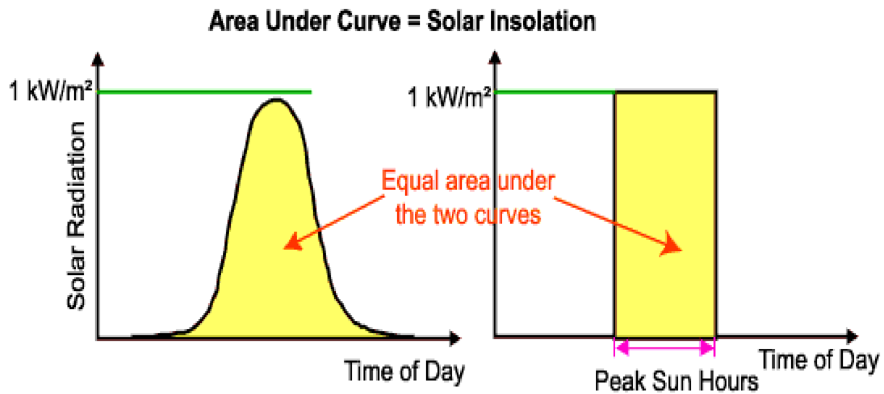
Estimation of PV Performance

- "1-sun" of insolation is defined as 1 kW/m^2
- (EX)5.6 kWh/m^2-day = 5.6 h/day of 1-sun = 5.6 h of "peak sun"
- P_{ac} =AC power delivered by an array under 1-sun insolation.
- Daily kWh delivered = [rated power]*[number of hours of peak sun]

$$\text{Energy (kWh/day)} = \text{Insolation}\left(\frac{\text{kWh/m}^2}{\text{day}}\right)\cdot A\ (\text{m}^2)\cdot\overline{\eta}$$

A is the area of the PV array

$\overline{\eta}$ is the average system efficiency over the day.



DC power from the system 1-sun of insolation,

$$P_{dc}\ (\text{kW}) = \left(\frac{1\ \text{kW}}{\text{m}^2}\right)\cdot A\ (\text{m}^2)\cdot\eta_{1-\text{sun}}$$

η_{1-sun} is the system efficiency at 1-sun.

$$P_{ac}(\text{kW}) = P_{dc}\ (\text{kW})\ \cdot \textbf{[Dc-AC Conversion Efficiency]}$$

$$\text{Energy (kWh/day)} = P_{ac}(\text{kW})\cdot(\text{h/day of "peak sun"})$$

PVUSA test conditions (PTC)
standard test conditions (STC)

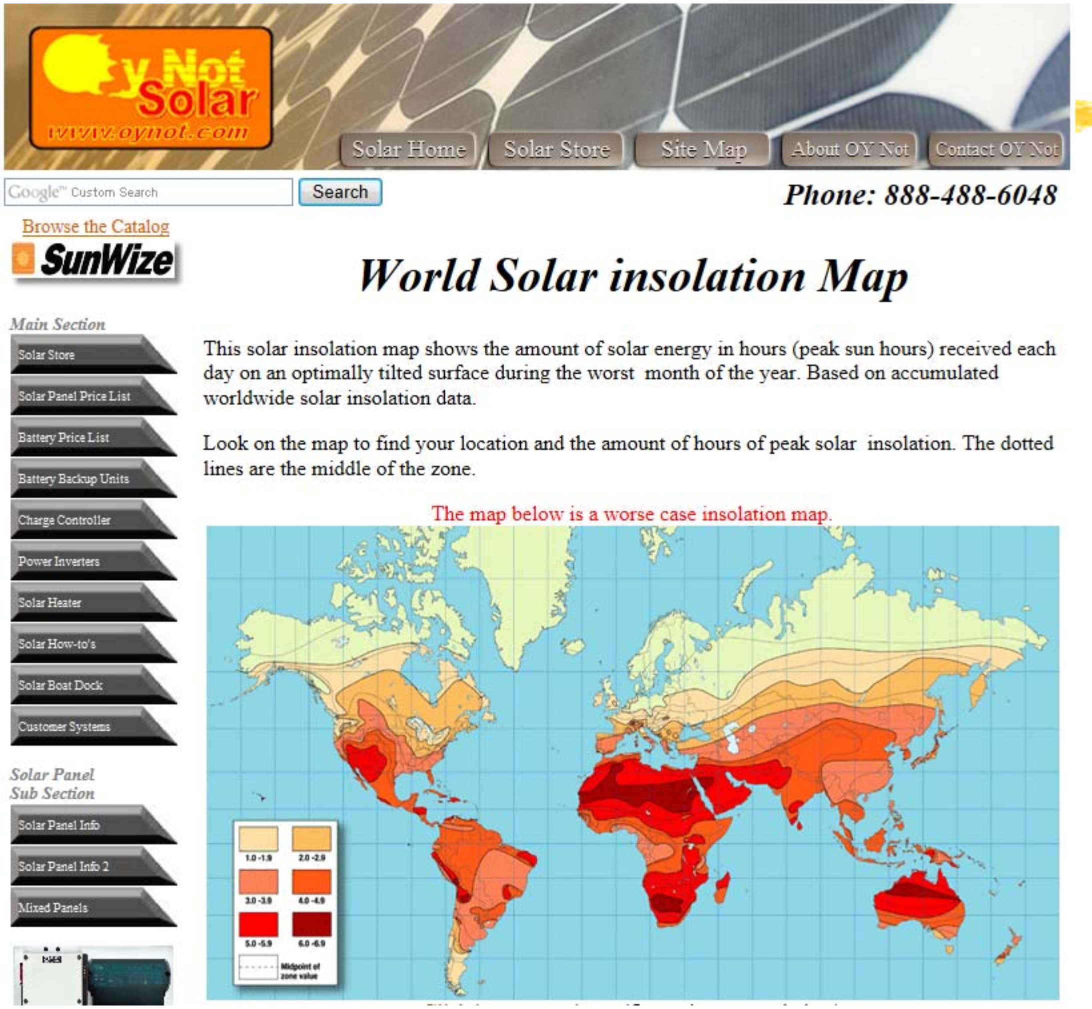
$$P_{ac} = P_{dc,STC}\times\ (\text{Conversion Efficiency})$$

$P_{dc(STC)}$ is the dc power of the array

53% and 70%

Peak Sun Map

- ⌘ http://www.oynot.com/solar-insolation-map.html
- ⌘ The amount of solar energy in hours ("**peak sun**" hours) received each day on an optimally tilted surface during the **worst month** ("design month") of the year.



PV Energy Delivery Calculation

- Estimate the annual energy delivered by the 1-kW (dc, STC) array in Madison, WI, which south-facing, and has a tilt angle equal to its latitude minus 15°. Assume the dc-to-ac conversion efficiency at 72%.

- Insolation Table for Madison

Tilt	Madison, WI						Latitude 43.13°N						
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Year
Lat − 15	3.0	3.9	4.5	5.1	5.8	6.2	6.2	5.7	4.8	3.8	2.5	2.3	4.5
Lat	3.4	4.3	4.7	5.0	5.5	5.7	5.8	5.5	4.8	4.0	2.8	2.6	4.5
Lat + 15	3.6	4.4	4.6	4.6	4.8	4.9	5.0	5.0	4.6	4.0	2.9	2.8	4.3
90	3.5	4.0	3.7	3.2	2.9	2.8	2.9	3.2	3.4	3.3	2.6	2.7	3.2
1-Axis (Lat)	3.9	5.0	5.8	6.4	7.3	7.8	7.7	7.1	6.0	4.8	3.2	3.0	5.7
Temp. (°C)	−4.0	−1.1	5.3	13.7	20.5	25.7	28.0	26.4	21.9	15.5	6.7	−1.2	13.1

Solution

- From 72% Conversion efficiency
  - P_{ac}=1.kW*0.72 = 0.72kW
- From the Insolation Table, the annual average insolation is 4.5 kWh/m^2-day
  - Same as 4.5 h “peak sun”/day
- Energy Calculation

$$\text{Energy} = 0.72\ \text{kW} \times 4.5\ \text{h/day} \times 365\ \text{day/yr} = 1183\ \text{kWh/yr}$$

Detailed Monthly Analysis

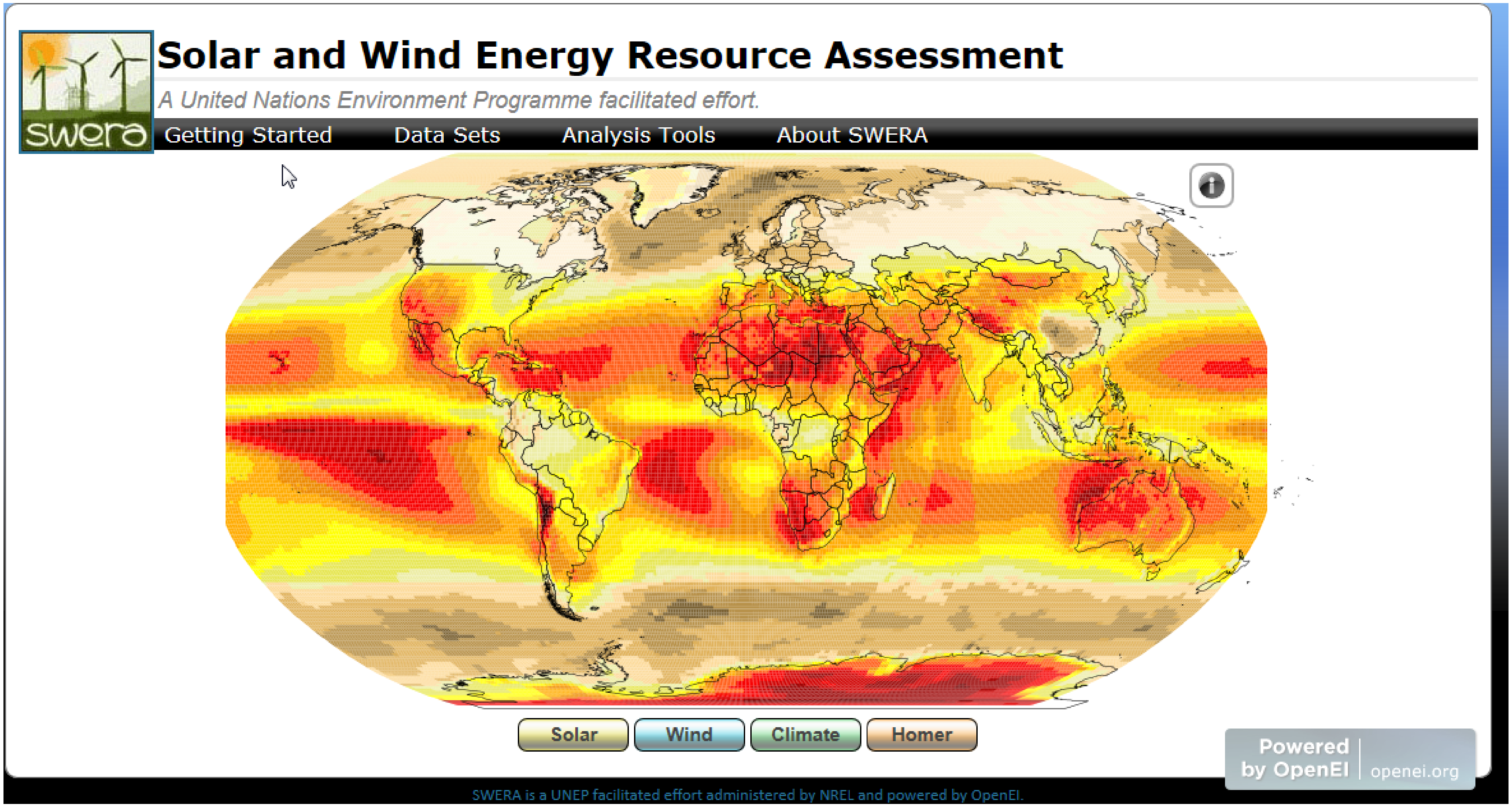
Madison, WI, South L-15

dc Power	1 kW at STC
Temp. coef.	0.5%/°C
Mismatch	0.03
Dirt	0.04
Inverter	0.90
NOCT	47°C

Month	Insolation (kWh/m^2-day)	Avg Max Temp. (°C)	Cell Temp. (°C)	Array dc Power (kW)	Array ac Power (kW)	Energy (kWh/mo)
Jan	3.0	−4.0	29.8	0.98	0.82	76
Feb	3.9	−1.1	32.7	0.96	0.81	88
Mar	4.5	5.3	39.1	0.93	0.78	109
Apr	5.1	13.7	47.5	0.89	0.74	114
May	5.8	20.5	54.3	0.85	0.72	129
Jun	6.2	25.7	59.5	0.83	0.69	129
July	6.2	28.0	61.8	0.82	0.68	131
Aug	5.7	26.4	60.2	0.82	0.69	122
Sept	4.8	21.9	55.7	0.85	0.71	102
Oct	3.8	15.5	49.3	0.88	0.74	87
Nov	2.5	6.7	40.5	0.92	0.77	58
Dec	2.3	−1.2	32.6	0.96	0.81	57
Avg:	4.5	13.2			kWh/yr =	1202

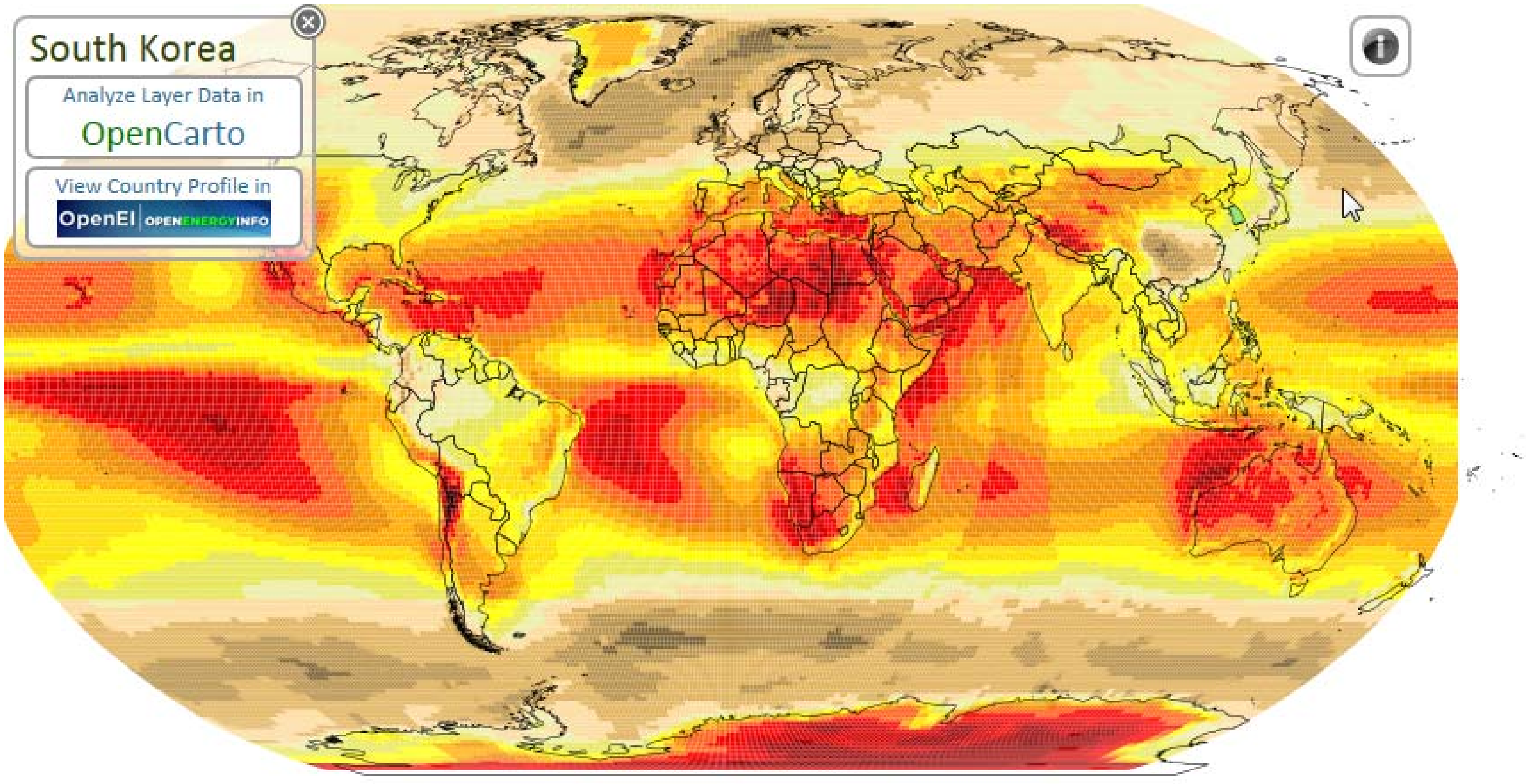
SWERA

- Solar and Wind Energy Resource Assessment
- http://en.openei.org/apps/SWERA/



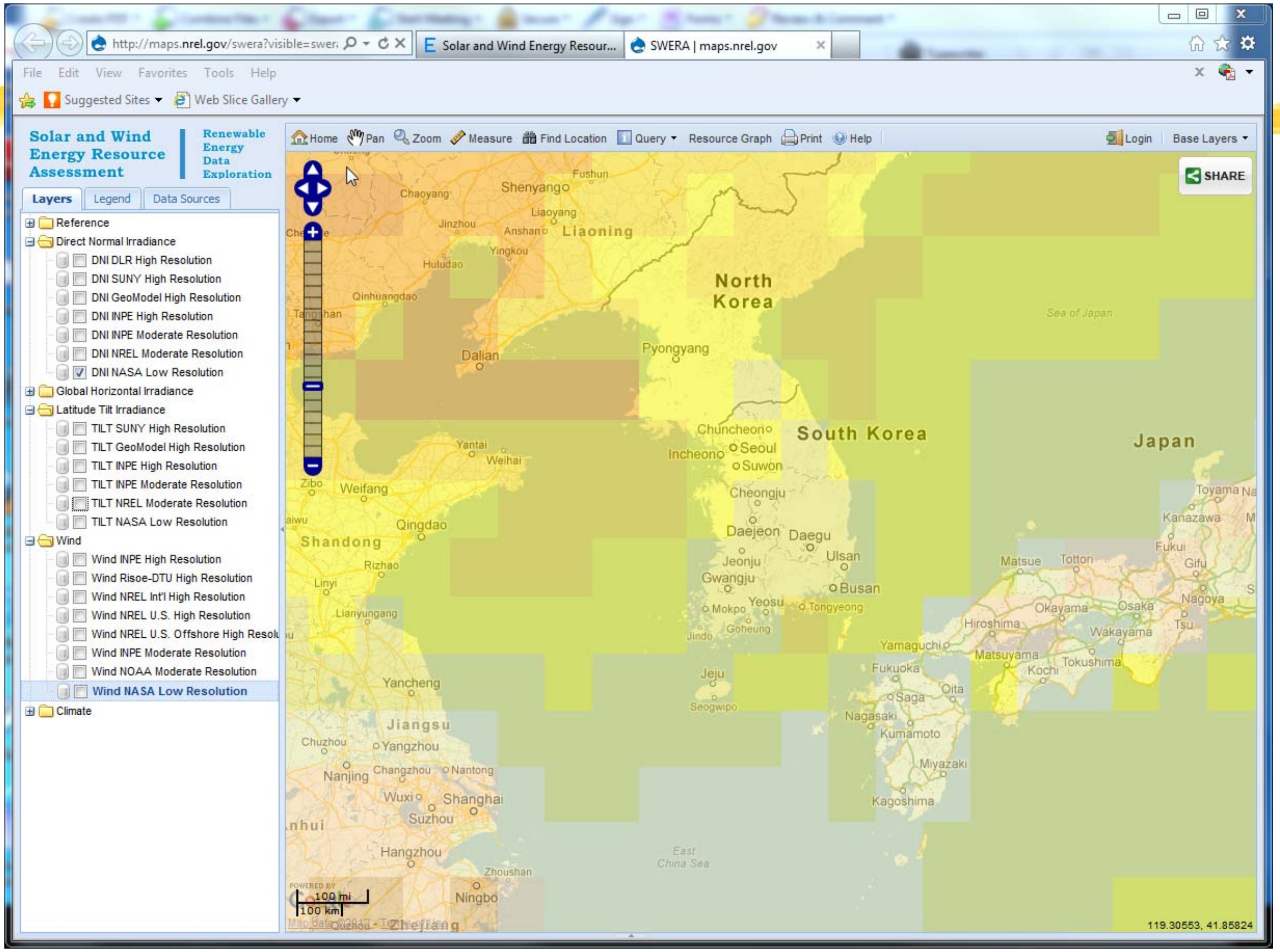
Getting data for Insolation and Wind speed

⌘Select Korea



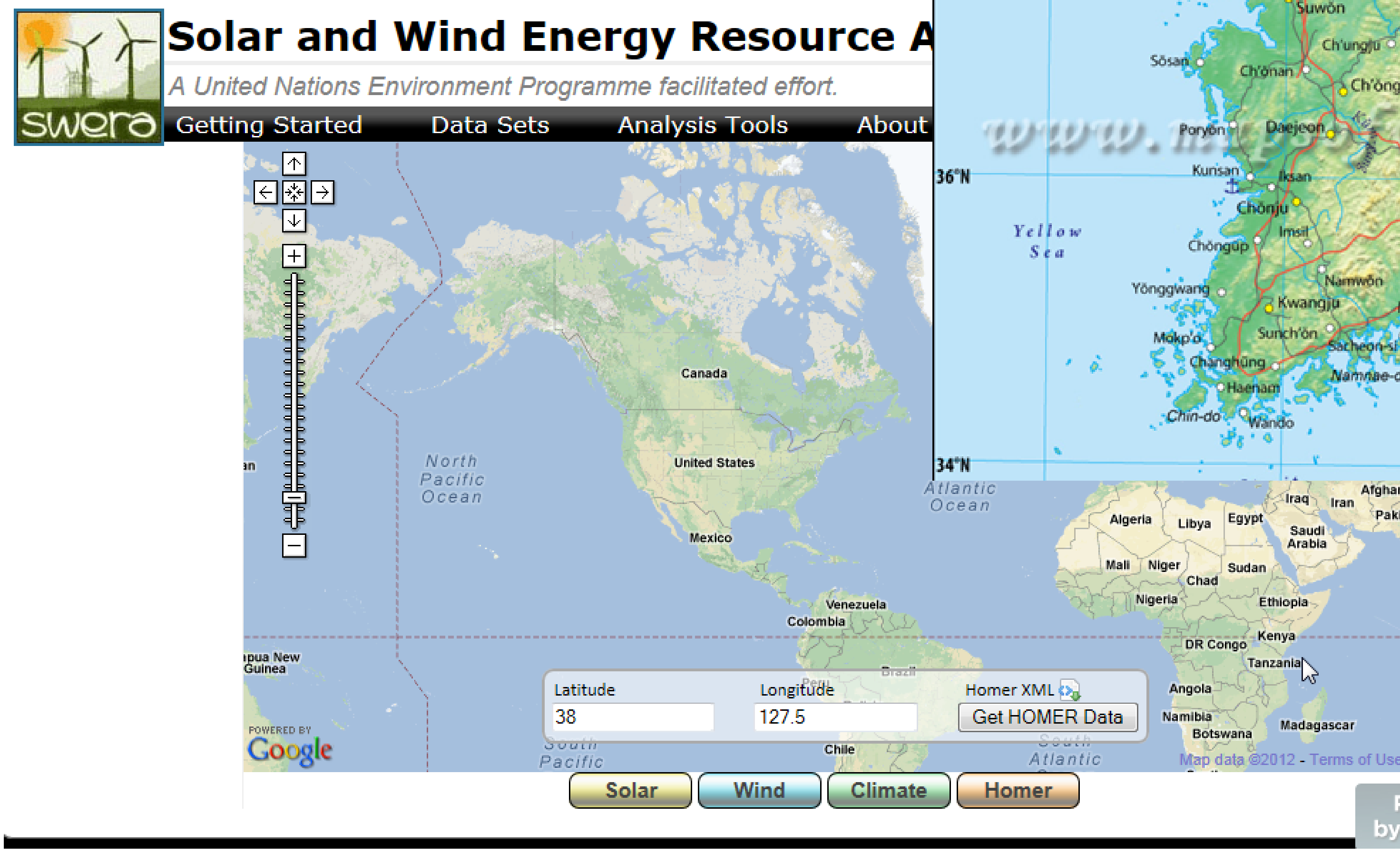
Layers of Data

- Solar
  - DNI: Direct Normal Irradiance
  - GHI: Global Horizontal Irradiance
  - TLT: Tilted Flat Plate Collector
- Wind
  - Hub height: 50m
  - Speed in m/s



Getting data for Insolation and Wind speed

- 1 Click HOMER
- 2 Input: Latitude and Longitude
- 3 Click GET Homer Data



Data for Homer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     </monthly>

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        - <values>
            <float> 50 </float>
          </values>
```

Capacity Factor

- Capacitor Factor (CF): Ratio with Rated Power
- CF of 0.4 means:
  - the system delivers full-rated power 40% of the time and no power at all the rest of the time, or
  - the system deliver 40% of rated power all of the time.

$$\text{Energy (kWh/yr)} = P_{ac}\text{(kW)} \cdot \text{CF} \cdot 8760\text{(h/yr)}$$

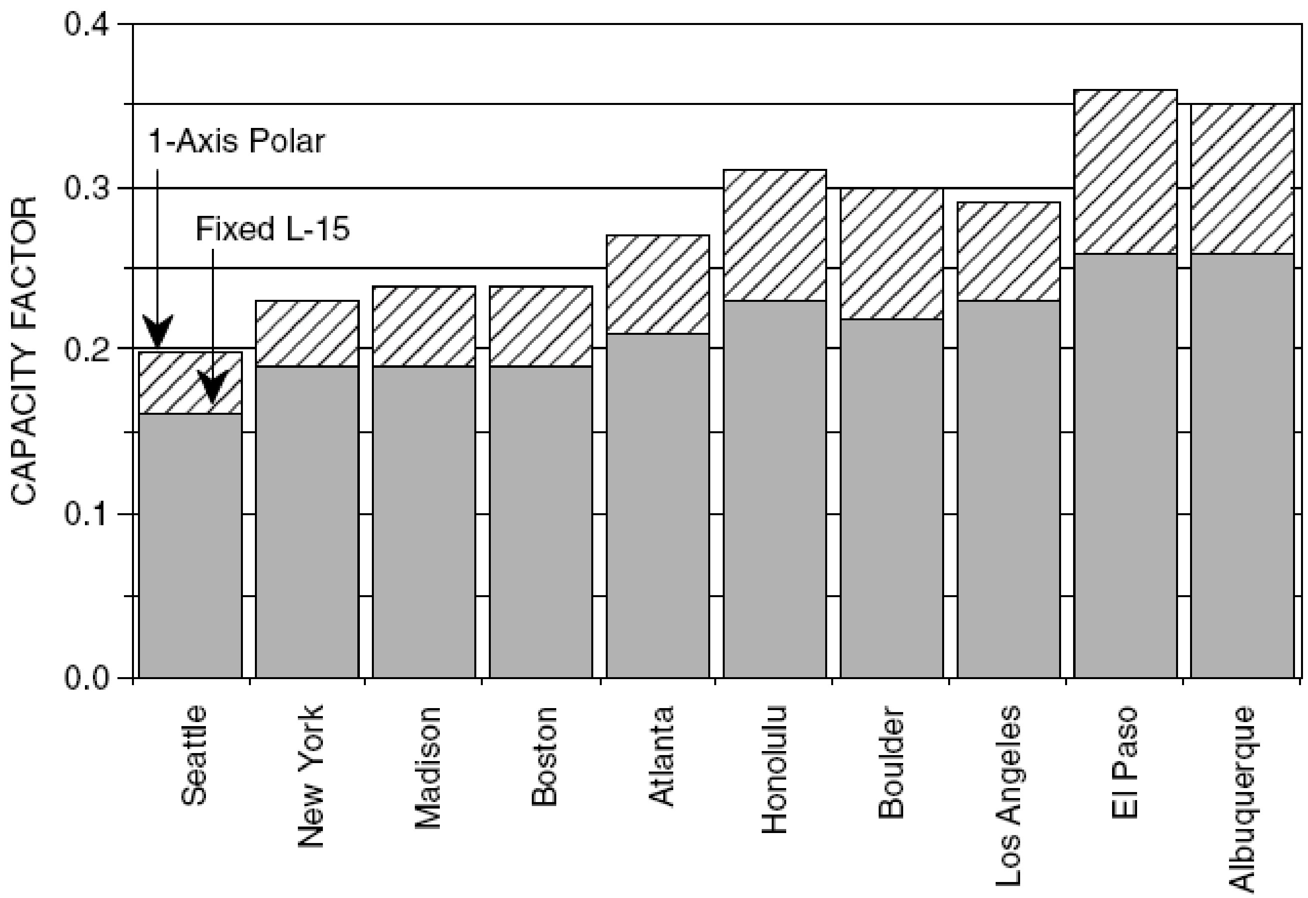
$$\text{Energy (kWh/day)} = P_{ac}\text{(kW)} \cdot \text{(h/day of ``peak sun'')}$$

- CF for Grid-Connected PV:

$$\text{Capacity factor (CF)} = \frac{\text{(h/day of ``peak sun'')}}{\text{24 h/day}}$$

CFs for a number of U.S. cities

- CF: 0.16 – 0.26 for fixed south-facing panel at tilt L-15
- CF: 0.20 – 0.36 for single axis polar mount tracker



Grid-Connect PV System Sizing

- Questions
  - How many kWh/yr are required?
  - How many peak watts of dc PV power are needed to provide that amount?
  - How much area will that system require?
  - What real components are available ?
- Example
  - An energy efficient house in Fresno (Latitude at 22^o) is to be fitted with a rooftop PV array that will annually displace all of the 3600 kWh/yr of electricity that the home uses.
  - Question: How many kW (dc, STC) of panels will be required and what area will be needed?
  - Assumptions:
    - Roof is south-facing with a moderate tilt angle
    - Annual insolation for L-15 is 5.7kWh/m^2-day
    - Dc-to-ac conversion efficiency at 75%
    - Solar system average 1-sun efficiency at 12.5%

Sizing Solution

- Roof is south-facing with a moderate tilt angle
- Annual insolation for L-15 is 5.7kWh/m^2-day
- DC-to-AC conversion efficiency at 75%
- Solar Cell efficiency at 12.5%
- 1. Annual Energy Equation

$$\text{Energy (kWh/yr)} = P_{ac}(\text{kW}) \cdot (\text{h/day @1-sun}) \cdot 365 \text{ days/yr}$$

- 2. AC Power

$$P_{ac} = \frac{3600 \text{ kWh/yr}}{5.7 \text{ h/day} \times 365 \text{ days/yr}} = 1.73 \text{ kW}$$

- 3. DC Power

$$P_{dc,STC} = \frac{P_{ac}}{\text{Conversion efficiency}} = \frac{1.73 \text{ kW}}{0.75} = 2.3 \text{ kW}$$

- 4. Area Calculation

$$P_{dc,STC} = 1 \text{ kW/m}^2 \text{ insolation} \cdot A \ (\text{m}^2) \cdot \eta$$

$$A = \frac{2.3 \text{ kW}}{1 \text{ kW/m}^2 \cdot 0.125} = 18.4 \text{ m}^2 \ (198 \text{ ft}^2)$$

PV and Inverter Modules

Module:	Sharp NE-K125U2	Kyocera KC158G	Shell SP150	Uni-Solar SSR256
Material:	Poly Crystal	Multicrystal	Monocrystal	Triple junction a-Si
Rated power $P_{dc,STC}$:	125 W	158 W	150 W	256 W
Voltage at max power:	26.0 V	23.2 V	34 V	66.0 V
Current at max power:	4.80 A	6.82 A	4.40 A	3.9
Open-circuit voltage V_{OC}:	32.3 V	28.9 V	43.4 V	95.2
Short-circuit current I_{SC}:	5.46 A	7.58 A	4.8 A	4.8
Length:	1.190 m	1.290 m	1.619 m	11.124 m
Width:	0.792 m	0.990 m	0.814 m	0.420 m
Efficiency:	13.3%	12.4%	11.4%	5.5%

Manufacturer:	Xantrex	Xantrex	Xantrex	Sunny Boy	Sunny Boy
Model:	STXR1500	STXR2500	PV 10	SB2000	SB2500
AC power:	1500 W	2500 W	10,000 W	2000 W	2500 W
AC voltage:	211–264 V	211–264 V	208 V, 3Φ	198–251 V	198–251 V
PV voltage range MPPT:	44–85 V	44–85 V	330–600 V	125–500 V	250–550 V
Max input voltage:	120 V	120 V	600 V	500 V	600 V
Max input current:	—	—	31.9 A	10 A	11 A
Maximum efficiency:	92%	94%	95%	96%	94%

Sizing Solution -- Continued

- PV Module selection
  - Kyocera KC158G 158-W module: 23.2V
  - Number of modules?
  - From DC Power = 2300W→ 2300/158=14.6
    - 2-string: 23.2x2=46.4V
    - 3-string: 23.2x3=69.6V --- Pick this. Open Circuit voltage (28.9x3=86.7V) is still below 120V max of the STXR2500 inverter
  - 3x5 (15 modules)
- Inverter Module
  - Xantrex STXR2500 Inverter:
    - MPPT Input voltage 44-85V
    - Max input voltage: 120V
- Check if the energy requirement is met

$$\text{Area} = 15 \text{ modules} \times 1.29 \text{ m} \times 0.99 \text{ m} = 19.1 \text{ m}^2 \ (206 \text{ ft}^2)$$

$$P_{dc,STC} = 158 \text{ W/module} \times 15 \text{ modules} = 2370 \text{ W}$$

$$\text{Energy} = 2.37 \text{ kW} \times 0.75 \times 5.7 \text{ h/day} \times 365 \text{ day/yr} = 3698 \text{ kWh/yr}$$

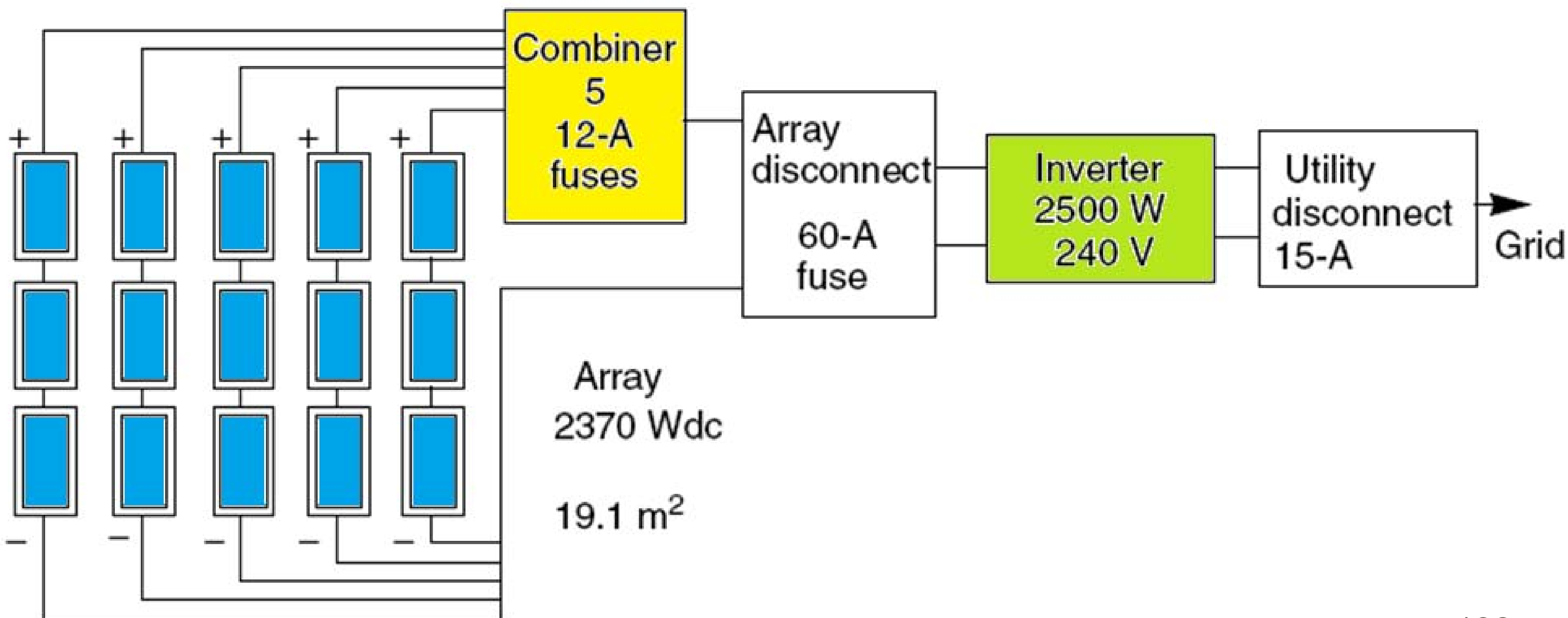
Module:	Kyocera KC158G
Material:	Multicrystal
Rated power $P_{dc,STC}$:	158 W
Voltage at max power:	23.2 V
Current at max power:	6.82 A
Open-circuit voltage V_{OC}:	28.9 V
Short-circuit current I_{SC}:	7.58 A
Length:	1.290 m
Width:	0.990 m
Efficiency:	12.4%

Manufacturer:	Xantrex
Model:	STXR2500
AC power:	2500 W
AC voltage:	211–264 V
PV voltage range MPPT:	44–85 V
Max input voltage:	120 V
Max input current:	—
Maximum efficiency:	94%

Final Design

NEC Article 690

- Other requirements
  - NEC – 600V max voltage limit
  - Fuse and disconnect switch: withstand 125% of expected dc voltage
  - Consider potential exceeded solar insolation: give 125%
  - Combiner fuse rating: (7.58 PV short circuit current)x(1.25)x(1.25) =11.8A
  - Array disconnect switch rating: 11.8Ax 5 = 59.2A
  - Inverter fuse rating (125%): 1.25x[2500W/240V]=13A



Grid-Connected PV System Economics

- Estimation of the cost of electricity generated by PV
  - Amortizing cost of **Principal** (**P** $) over a **period** (***n*** year) with **interest rate of *i*** for Loan payment.
  - **Annual Payment** (**A** $/yr) divided by **Annual kWh** → $/kWh
- **CRF** (Capital Recovery Factor):

$$\mathrm{CRF}(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

- Annual Loan Payment (A):

$$A = P \cdot \mathrm{CRF}(i,n)$$

- **Example**: A PV system costs $16,850 to deliver 4000 kWh/yr. If the system is paid for with a 6% 30-year loan, what would be the cost of electricity, ignoring income tax benefit, loan tax deduction, etc?

$$\mathrm{CRF}(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{0.06(1.06)^{30}}{(1.06)^{30} - 1} = 0.07265/\mathrm{yr}$$

$$\mathrm{A} = \mathrm{P}\ \mathrm{CRF}(i,n) = \$16{,}850 \times 0.07265/\mathrm{yr} = \$1224/\mathrm{yr}$$

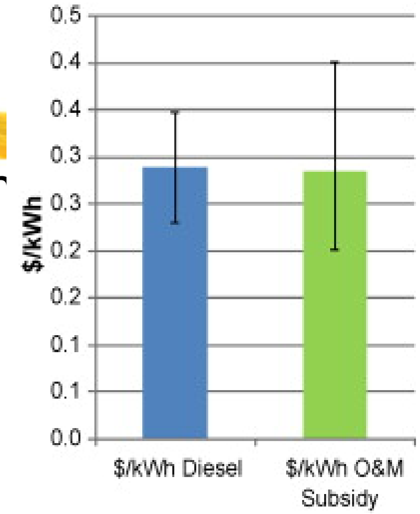
$$\text{Cost of electricity} = \frac{\$1224/\mathrm{yr}}{4000\ \mathrm{kWh/yr}} = \$0.306/\mathrm{kWh}$$

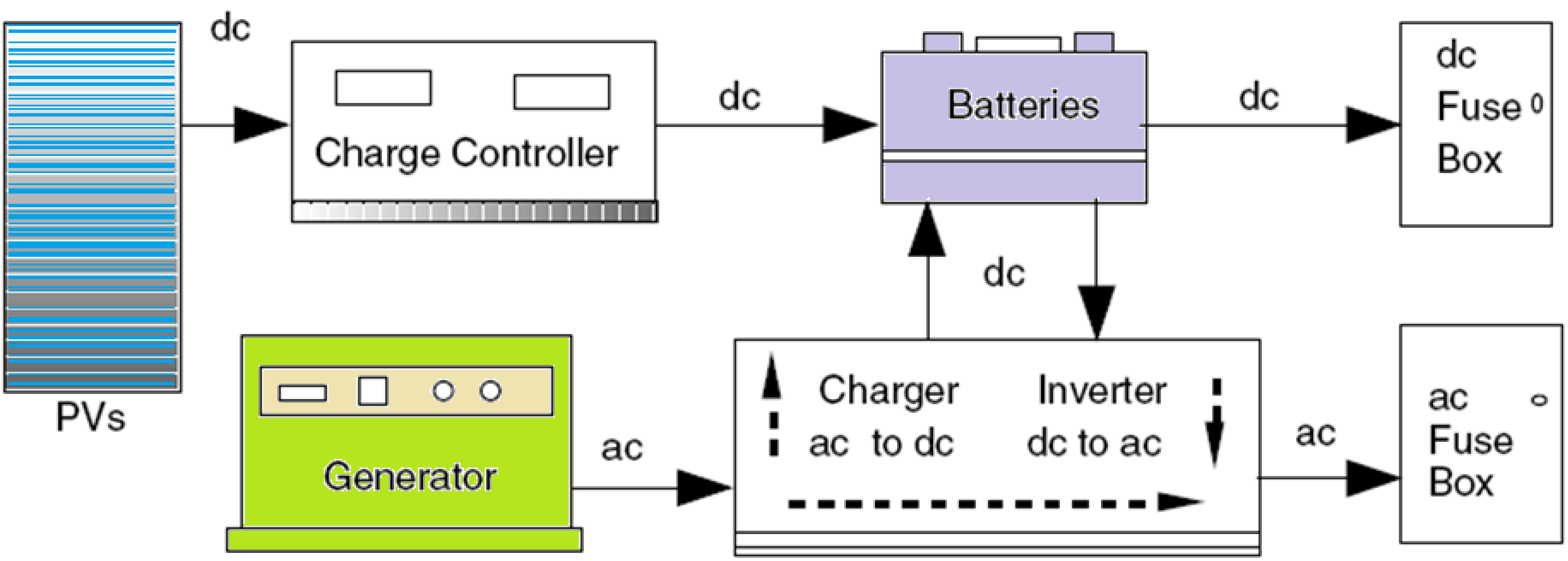
D2 =(B2*(1+B2)^C2)/((B2+1)^C2-1)

	A	B	C	D	E	F	G	H
1	P [$]	i	n	CRF	A [$/yr]	kWh	COE [$/kWh]	
2	16850	0.06	30	0.072649	1224.13	4000	0.31	
3	16850	0.05	30	0.065051	1096.12	4000	0.27	
4	16850	0.04	30	0.05783	974.44	4000	0.24	
5	16850	0.03	30	0.051019	859.67	4000	0.21	
6	16850	0.02	30	0.04465	752.35	4000	0.19	
7	16850	0.01	30	0.038748	652.91	4000	0.16	
8								

Stand-Alone PV Systems

- When grid is not nearby, electricity becomes more valuable, and stand-alone power system can provide enormous benefit, and complete, instead of $0.1/kWh utility power, with $0.5/kWh gasoline or diesel generators.
- A general stand-alone PV system with back-up generator and separate outputs for AC and DC loads.





Design Process for Stand-Alone System

- Load study
  - Know your object and (future) target : P_{ac}
- Inverter and System Voltage (12, 24, or 48V)
  - Relevant to PV output voltage
- PV Sizing
  - P_{dc}, efficiency, Area, V_{oc}, and I_{sc}.
- Battery Sizing
- Hybrid PV System (Generator Sizing)
- System Cost Analysis
  - COE ($/kWh)

Load Study

Kitchen Appliances	*Power*
Refrigerator: ac EnergyStar, 14 cu. ft	300 W, 1080 Wh/day
Refrigerator: ac EnergyStar, 19 cu. ft	300 W, 1140 Wh/day
Refrigerator: ac EnergyStar, 22 cu. ft	300 W, 1250 Wh/day
Refrigerator: dc Sun Frost, 12 cu. ft	58 W, 560 Wh/day
Freezer: ac 7.5 cu. ft	300 W, 540 Wh/day
Freezer: dc Sun Frost, 10 cu. ft	88 W, 880 Wh/day
Electric range (small burner)	1250 W
Electric range (large burner)	2100 W
Dishwasher: cool dry	700 W
Dishwasher: hot dry	1450 W
Microwave oven	750–1100 W
Coffeemaker (brewing)	1200 W
Coffeemaker (warming)	600 W
Toaster	800–1400 W

- TV: 100 W Vacuum Cleaner: 1000 W Ceiling Fan: 100 W
- Computer: 125 W Laptop: 20 W Clothes Washer: 250 W
- Window A/C: 1200 W Iron: 1000 W Component Stereo: 40 W
- Clock Radio: 2 W Electric Blanket: 60 W Microwave: 1000 W

Example Electricity Demand

- A modest household monthly energy demand for a cabin:
  - 19-cu ft refrigerator
  - 6 30W compact fluorescent lamp (5h/day)
  - 19 in TV (3h/day) connected to a satellite
  - Cordless phone
  - 1000W Microwave (6 min/day)
  - 250W Washing machine (30 min/day)
  - 100W pump for 100ft deep well that supplies 120 gallons/day (1.25 h/day)
- Power and Energy Demand (3.11kWh/day)

Appliance	Power (W)	Hours	Watt-hours/day	Percentage
Refrigerator, 19 cu. ft	300		1140	37%
Lights (6 @ 30 W)	180	5	900	29%
TV, 19-in., active mode	68	3	204	7%
TV, 19-in., standby mode	5.1	21	107	3%
Satellite, active mode	17	3	51	2%
Satellite, standby mode	16	21	336	11%
Cordless phone	4	24	96	3%
Microwave	1000	0.1	100	3%
Washing machine	250	0.2	50	2%
Well pump, 100 ft, 1.6 gpm	100	1.25	125	4%
Total			3109	100%

System Voltage

- System voltage: Inverter dc input voltage = **battery bank voltage** = PV array voltage
- High voltage:
  - low current → minimize wire loss
  - More batteries in series
- A guideline:
  - Keep the maximum steady-state current drawn below around 100A → readily available electrical hardware and wire size can be used
  - Suggest system voltage

Maximum ac Power	System dc Voltage
<1200 W	12 V
1200–2400 W	24 V
2400–4800 W	48 V

- **BOS (Balance of System):** Balance of equipment necessary to integrate PV array with site load, which includes the array circuit wiring, fusing, disconnects, and inverter

Batteries

- Comparison of Battery Characteristics
- SLI: engine **S**tarting, vehicle **L**ighting, and engine **I**gnition

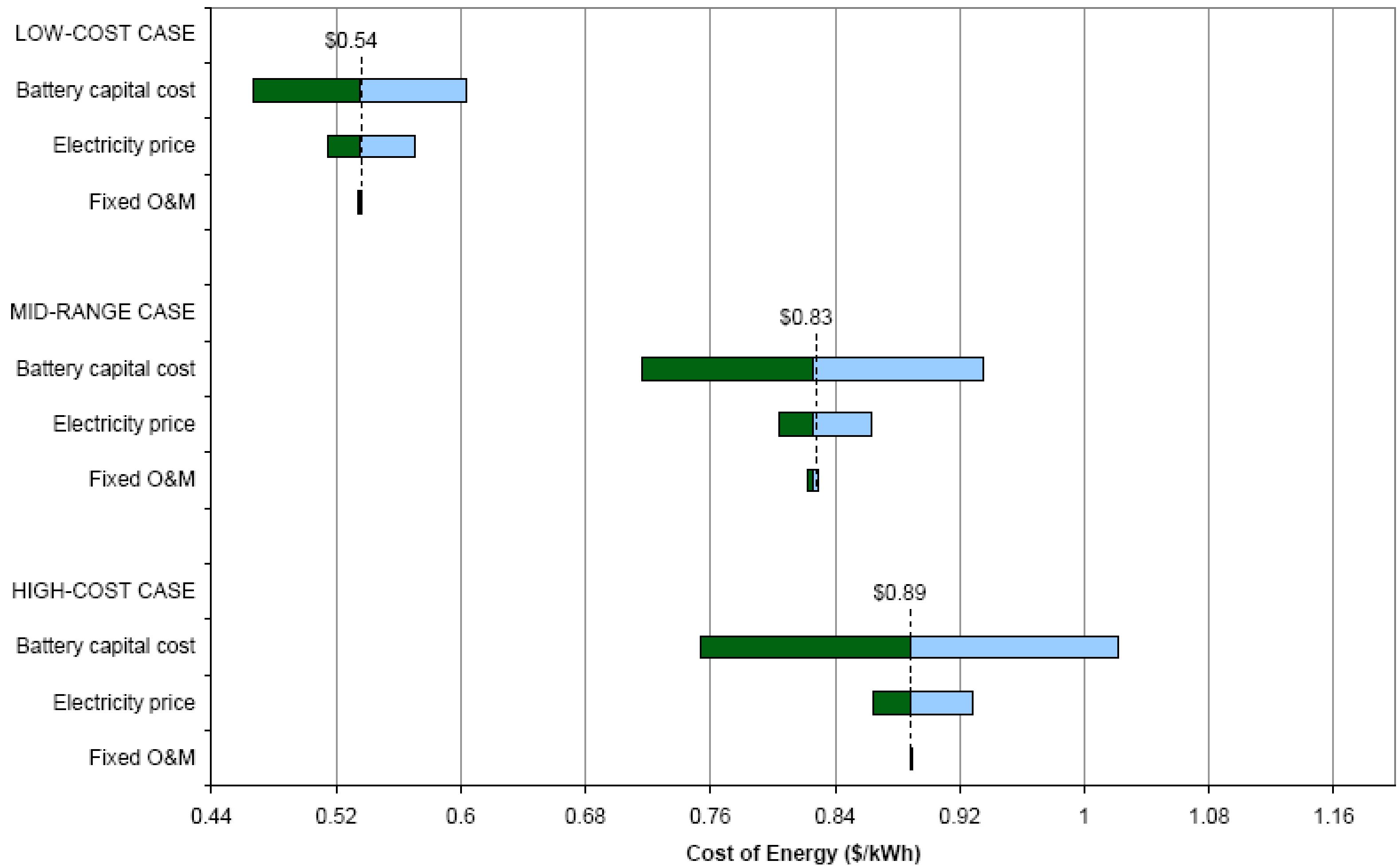
Battery	Max Depth Discharge	Energy Density (Wh/kg)	Cycle Life (cycles)	Calendar Life (years)	Efficiencies Ah %	Efficiencies Wh %	Cost ($/kWh)
Lead-acid, SLI	20%	50	500	1–2	90	75	50
Lead-acid, golf cart	80%	45	1000	3–5	90	75	60
Lead-acid, deep-cycle	80%	35	2000	7–10	90	75	100
Nickel–cadmium	100%	20	1000–2000	10–15	70	60	1000
Nickel–metal hydride	100%	50	1000–2000	8–10	70	65	1200

[a] Actual performance depends greatly on how they are used.

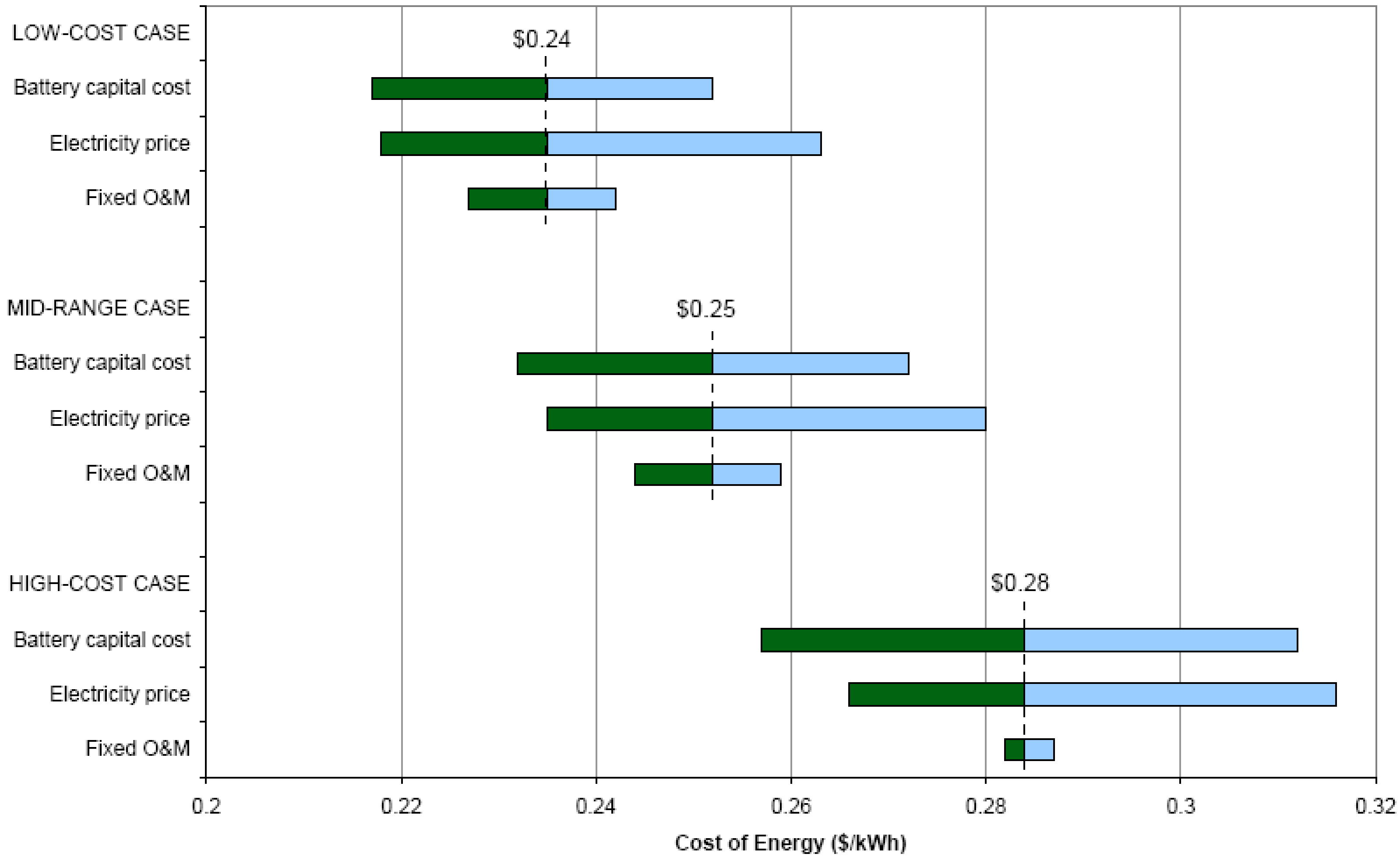
Source: Linden (1995) and Patel (1999).

- Lead-Acid: Cheapest, highest efficiency
- NiCd: Expensive, longer life cycle, dischargeable 100% without damage, more forgivable when abused

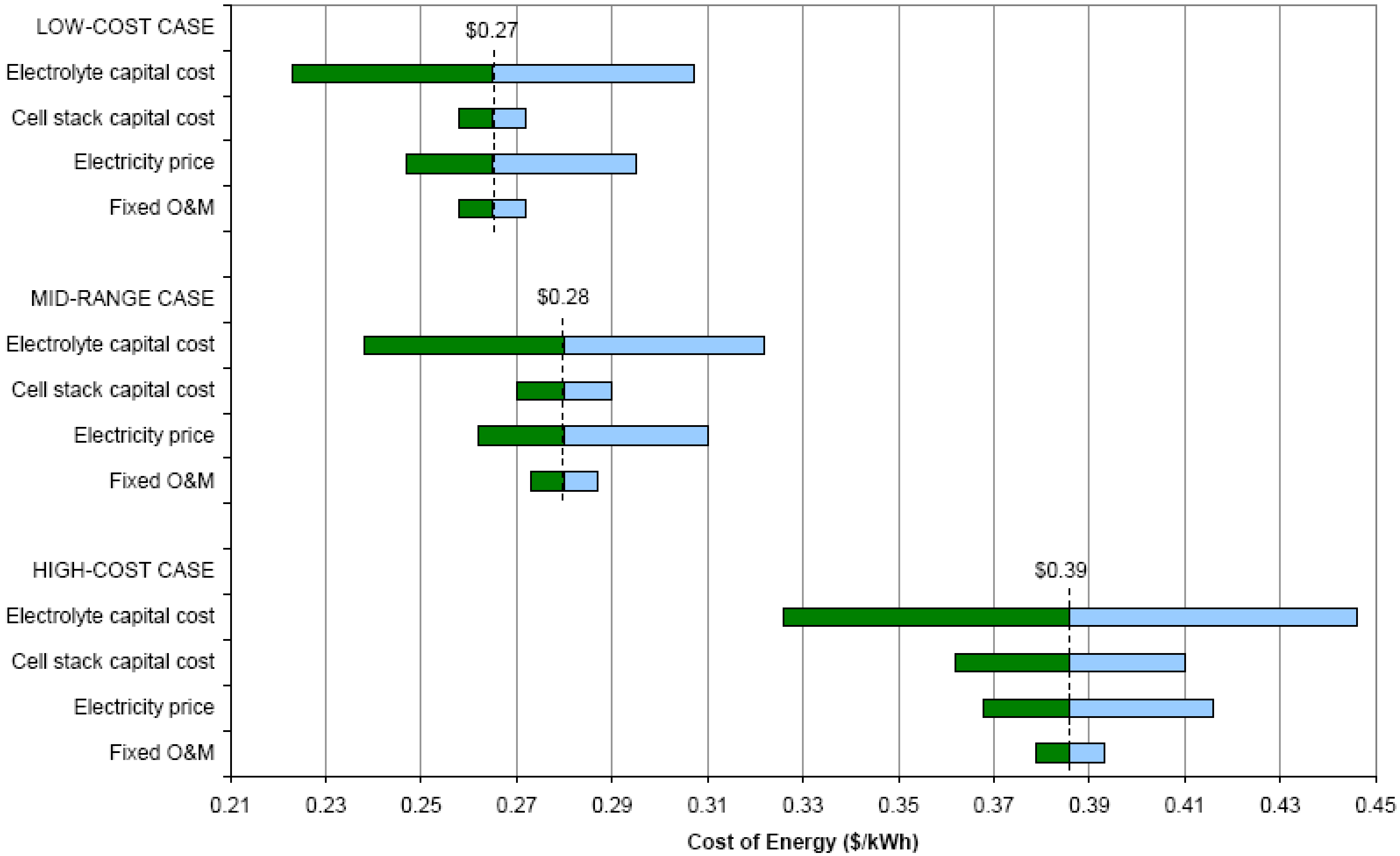
Nickel Cadmium Battery



Sodium Sulfur Battery



Vanadium Redox (Reduction-Oxidation) Battery



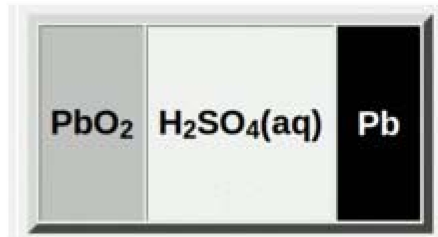
Lead-Acid Batteries

- 1860s: Raymond Gaston Plante first fabricated battery cells with corroded lead-foil electrodes and a dilute solution of sulfuric acid and water
- Chemical reaction in discharge

$$\text{Positive plate :} \quad PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$$

$$\text{Negative plate :} \quad Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$

Fully Discharged



Fully Charged

Compound State Symbols
(s): Solid
(l): liquid
(g): gaseous
(aq): aquaeius - solution

- ¾ of the \$30 B global market are for automobile SLI (400 – 600 A for starting, after that alternator quickly recharges the battery. Not for deep discharge)
- 2 V per cell
- Deep Discharge type: thicker plates, greater space around the plates, big and heavy, can be discharged by 80%
- Biggest utility battery bank: 10MW (5000A at 2kV) for 4 hours in to grid (Chino, CA)

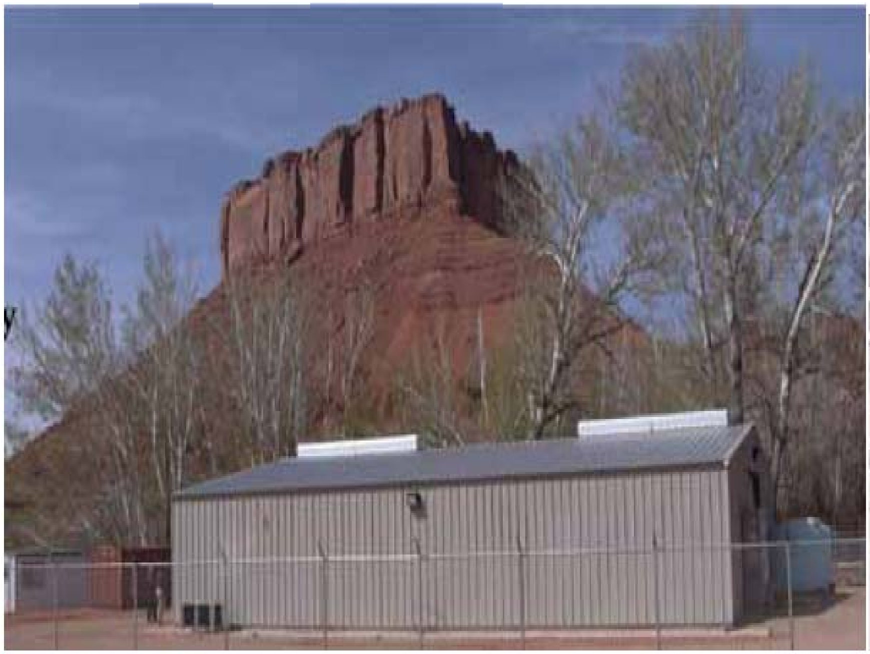
Installed Large Scale Battery Energy Storage

Table I. Examples of installed large scale battery energy storage systems.

Name	Application	Operational Dates	Power	Energy	Battery Type	Cell Size & Configuration	Battery Manufacturer
Crescent Electric Membership Cooperative (now Energy United) BESS, Statesville, NC, USA	Peak Shaving	1987-May, 2002	500 kW	500 kWh	Lead-acid, flooded cell	2,080 Ah @ C/5; 324 cells	GNB Industrial Battery, now Exide Battery
Berliner Kraft- und Licht (BEWAG) Battery System, Berlin, Germany	Frequency Regulation and Spinning Reserve	1987-1995	8.5 MW in 60 min of frequency regulation; 17 MW for 20 min. of spinning reserve	14 MWh	Lead-acid, flooded cell	7,080 cells in 12 parallel strings of 590 cells each; Cell size: 1,000 Ah	Hagen OCSM cells
Southern California Edison Chino Battery Storage Project, CA, USA	Several "demo" modes including load-leveling, transmission line stability, local VAR control, black start.	1988-1997	Energy: 14 MW	40 MWh	Lead-acid, flooded cells	8,256 cells in 8 parallel strings of 1032 cells each; Cell size: 2,600 Ah	Exide Batteries GL-35 cells
Puerto Rico Electric Power Authority (PREPA) Battery System, Puerto Rico	Frequency control and spinning reserve	11/1994-12/1999	20 MW	14 MWh	Lead-acid, flooded cell	6,000 cells in 6 parallel strings of 1000 cells each; Cell size: 1,600 Ah	C&D Battery
PQ2000 installation at the Brockway Standard Lithography Plant in Homerville, Georgia, USA	Power Quality, Uninterruptable Power Supply	1996-2001	2 MW	55 kWh	Lead-acid	2000 Low-Maintenance, Truck-Starting Batteries, 48 per 250 kW module, 8 modules per 2 MW PQ2000 system	AC Battery, acquired by Omnion Power Engineering in 1997, in turn acquired by S&C Electric in 1999
Metlakatla Power and Light (MP&L), Alaska, Battery System, Alaska, USA	Voltage regulation and displacing diesel generation	1997-present	1 MW	1.4 MWh	Valve regulated lead-acid Absolyte IIP	1,134 cells/378 ea., 100A75 modules in 1 string	GNB Industrial Battery, now Exide Technologies, and General Electric
Golden Valley Electric Association (GVEA) Fairbanks, Alaska, USA	VAR Support, spinning reserve, power system stabilization	9/19/2003-present	27 MW	14.6 MWh	Nickel/cadmium type SBH920 cells	4 strings of 3,440 cells each, for a total of 13,760 cells	ABB and Saft

Installed Large Scale Battery - Continued

AEP Sodium Sulfur Distributed Energy Storage System at Chemical Station, N. Charleston, WV, USA	Substation upgrade deferral	2006-present	1.0 MW	7.2 MWh	Sodium/Sulfur	50 kW NAS battery modules, 20 ea	NGK Insulators LTD (battery)/ S & C Electric Co. (balance of system)
Long Island, New York Bus Terminal Energy Storage System, NY, USA	Load Shifting	2008-present	1.2 MW	6.5 MWh	Sodium/Sulfur	20 ea. 50 kW (60kW peak) NAS battery modules	NGK Insulators LTD (battery)/ABB Inc. (integration and balance of system)
Vanadium-Redox Battery at the Sumitomo Densetsu Office, Osaka, Japan	Peak Shaving	2000-present	3 MW	800 kWh	Vanadium-Redox Flow Battery	50 kW Sumitomo battery modules	Sumitomo Electric Industries (SEI) of Osaka, Japan
Pacificorp *Castle Valley*, Utah Vanadium-Redox Battery (VRB) System, Utah, USA	Distribution line upgrade deferral, voltage support	March 2004-present	250 kW	2 MWh	Vanadium-Redox Flow Battery	50 kW Sumitomo battery modules, 250 kW for 8 hours	VRB Power Systems (purchased by Prudent Energy Co., Beijing, China in 2009)



- *Exterior and interior views of the 2MWh VRB system at Castle Valley, UT.*

NaS Battery Project

Table II. Na/S battery projects as of december 2009. (Courtesy of NGK.)

Name of Developer	Country	Location	KW	Start of Operation/Status
TEPCO (Tokyo Electric Power Company)	Japan	Many locations around Tokyo	200,000 (approx.)	As of the end of 2008
HEPCO (Hokkaidou Electric Power Company)	Japan	Wakkanai City, Hokkaido	1,500	Feb. 2008
Other Japanese Electric Companies	Japan	Many locations other than Tokyo area	60,000 (approx.)	As of the end of 2008
JWD (Japan Wind Development Co., Ltd.)	Japan	Rokkasho Village, Aomori	34,000	Aug. 2008
AEP (American Electric Power)	USA	Charleston WV, Bluffton OH, Milton WV, Churubusco IN, Presidio, TX	11,000	4 sites except for Presidio: July 2006–Jan. 2009; Presidio: Shipped in Nov. 2009
NYPA (New York Power Authority)	USA	Long Island, NY	1,000	April 2008
PG&E (Pacific Gas and Electric Company)	USA	Not decided	6,000	Shipped in 2008
Xcel	USA	Luverne, MN	1,000	Nov. 2008
Younicos	Germany	Berlin	1,000	July 2009
Enercon	Germany	Emden, Lower Saxony	800	July 2009
EDF	France	Reunion Island	1,000	Dec. 2009
ADWEA (Abu Dhabi Water & Electricity Authority)	UAE	Abu Dhabi	48,000	Partially operated
Total			365,300	

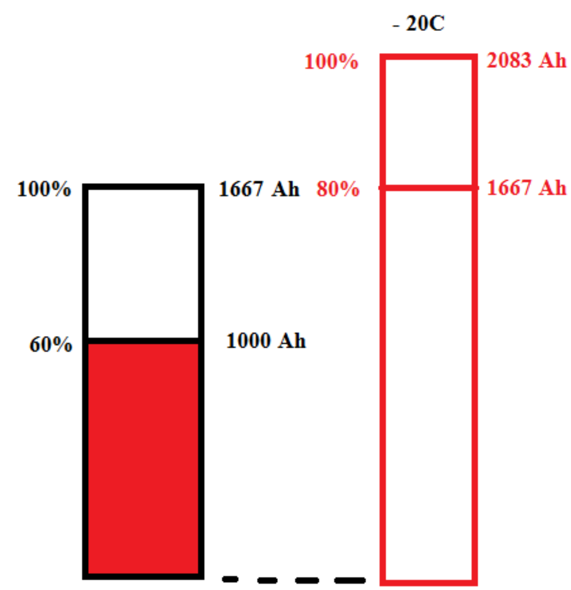
Battery Storage Capacity

- Energy Storage: Amp-hour (Ah) at **a nominal voltage** and at a specified **discharge rate**
- Ah capacity [C] that would drain from **2V** {full charge} to **1.75V** {full discharge}
- 12-V 10-h 200-Ah: delivers 20A for 10 h, then the voltage drops to 6x1.75=**10.5** V, considered as **fully discharged**.
- Discharging rate: C/h ←delivering current
- **C/20 rate** is standard in PV system
- Example of Deep-Cycle Lead-Acid Battery Characteristics

BATTERY	Voltage	Weight (lbs)	Ah @ $C/20$	Ah @ $C/100$
Concorde PVX 5040T	2	57	495	580
Trojan T-105	6	62	225	250
Trojan L16	6	121	360	400
Concorde PVX 1080	12	70	105	124
Surette 12CS11PS	12	272	357	503

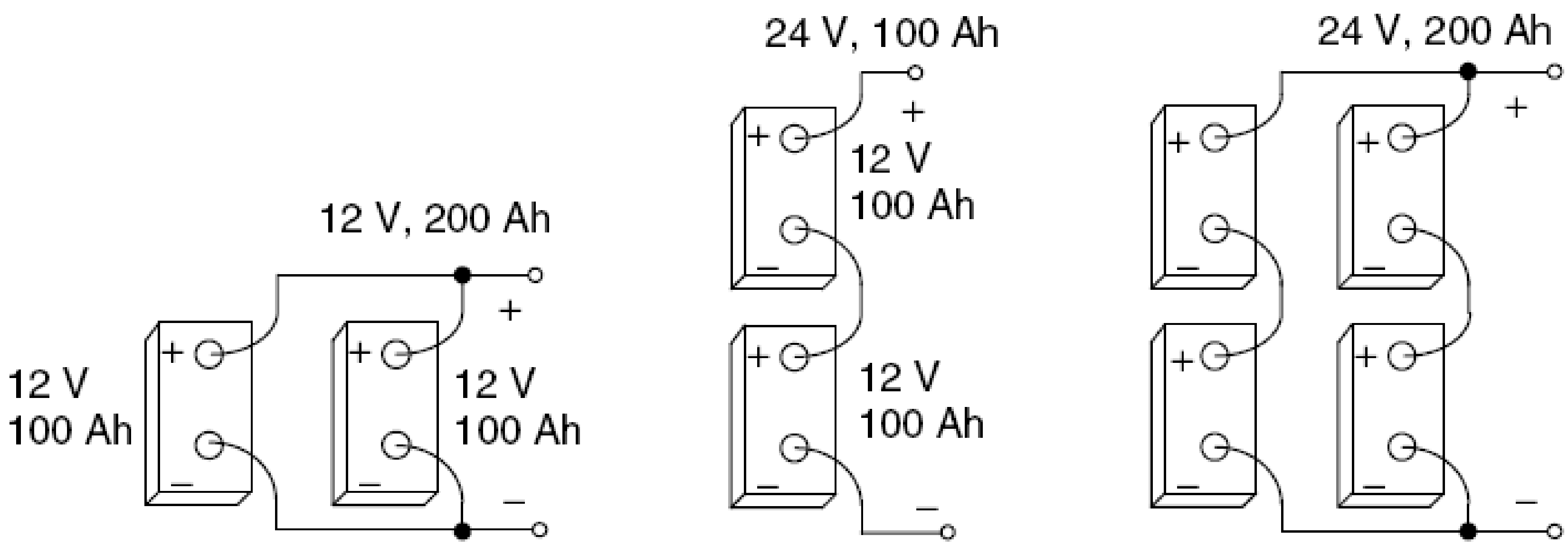
Battery Storage Calculation

- Example
  - Suppose that batteries located at a remote telecommunications site may drop to −20◦C. If they must provide 2 days of storage for a load that needs 500 Ah/day at 12 V, how many amp-hours of storage should be specified for the battery bank?
  - Assume that, to avoid freezing, the maximum depth of discharge at −20◦C is 60%.
  - Also, assume that the actual capacity of the battery at −20◦C discharged over a 48-h period is about 80% of the rated capacity.
- Solution:
  - 1. Energy need for 2 days: 500x2 = 1000 Ah
  - 2. Battery storage for 2 days with discharge no more than 60% (which means that 60% of the stored energy must be able to cover the energy need): Battery storage= 1000Ah/0.6 = 1667 Ah
  - 3. Since the actual capacity is only 80%: Battery storage = 1667 Ah/0.8 = 2083 Ah



Battery Wiring

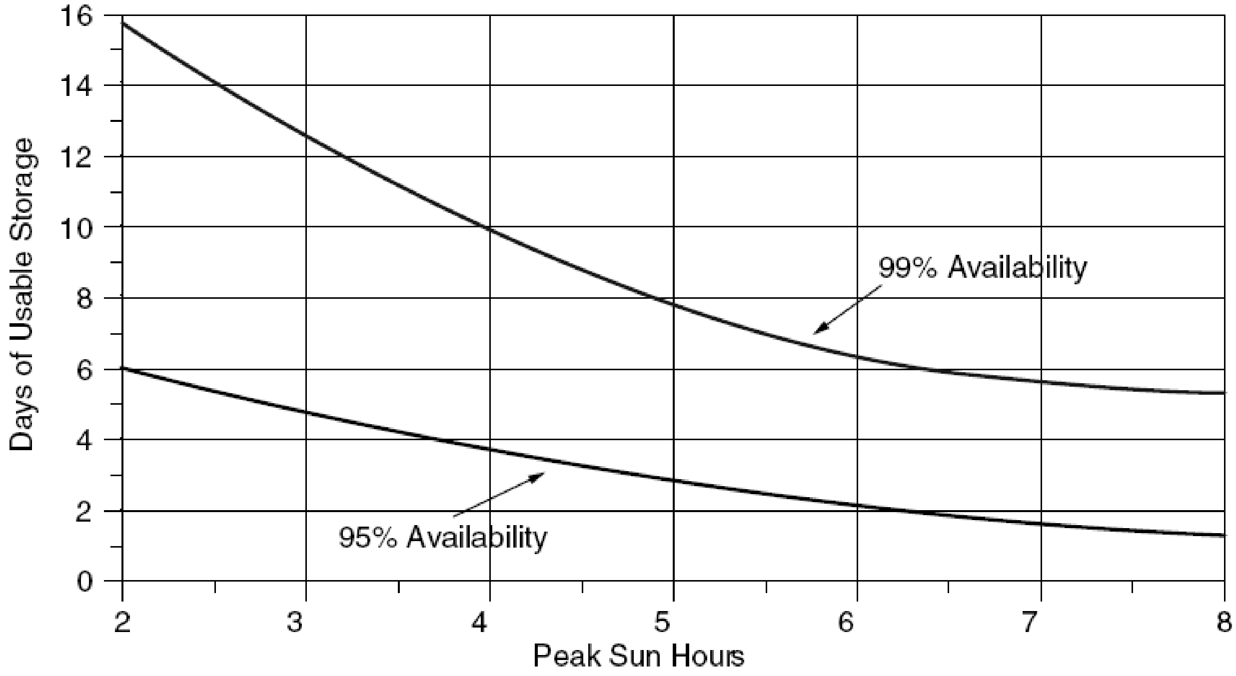
- Series: Voltages add → Ah remains the same
- Parallel: Currents add → Ah adds



(a) Parallel, Amp-Hrs add (b) Series, Voltages add (c) Series/Parallel

Battery Sizing

- Statistical nature of weather
- No set rules about how best to size battery storage except the cost trade-off
- Battery system of meeting demand 99% of the time may be 3 times higher than that of meeting 95% of the time.
- The number of days of storage to supply a load in the design month [the month with the worst combination of insolation and load]
- **Days of "usable battery storage**" needed for a stand-alone system

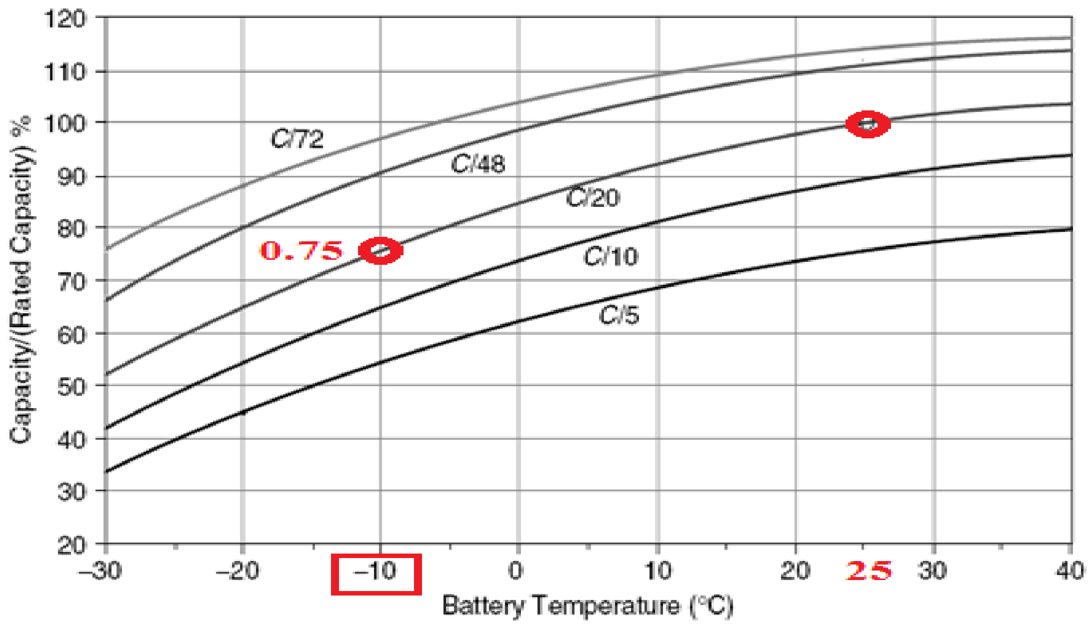


Battery Sizing

- Nominal rated storage vs. usable storage:

$$\text{Nominal }(C/20, 25^{\circ}\text{C})\text{ battery capacity} = \frac{\text{Usable battery capacity}}{(\text{MDOD})(\text{T, DR})}$$

- Variables:
  - MDOD (maximum depth of discharge): 0.8 for lead-acid; 0.25 for auto SLI
  - (T,DR): **Discharge Rate Factor** under a given Temperature



Battery Sizing Example

- A cabin near Salt Lake City, Utah, has an ac demand of 3000 Wh/day in the winter months. A decision has been made to size the batteries such that a 95% system availability will be provided, and a back-up generator will be kept in reserve to cover the other 5%. The batteries will be kept in a ventilated shed whose temperature may reach as low as −10◦C. The system voltage is to be 24 V, and an inverter with overall efficiency of 85% will be used.
- SOLUTION APPROACH
  - 1. AC load → DC load demand (with 85% inverted efficiency)
  - 2. Battery Capacity (Ah)
  - 3. Usable storage (Ah)
  - 4. Nominal capacity (Ah)
    - Assumption: 80% deep discharge ←MDOD
    - Assumption: 95% discharge rate ← (T,DR)
  - 5. Battery Bank Design

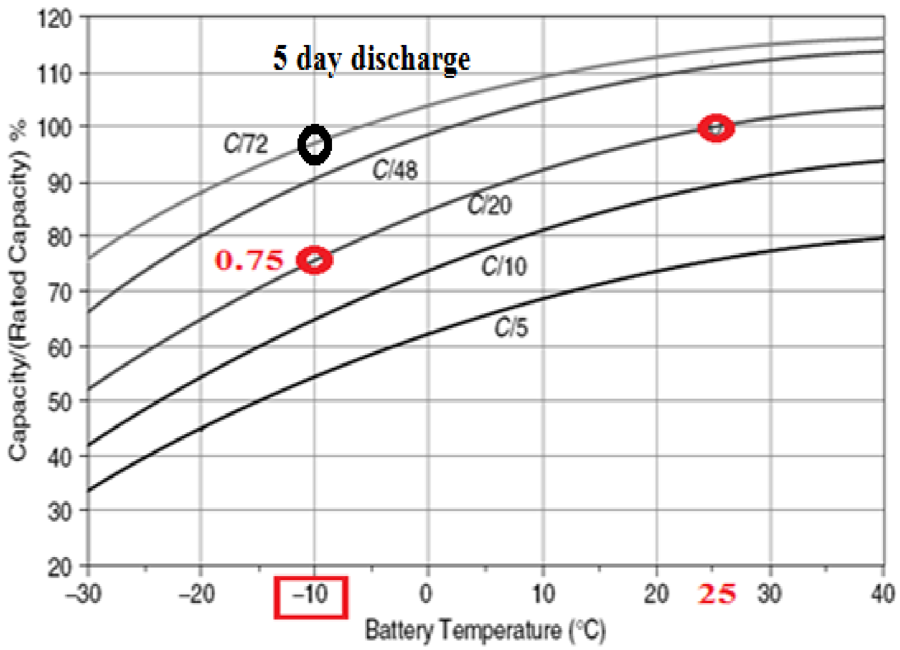
SOLUTION - details

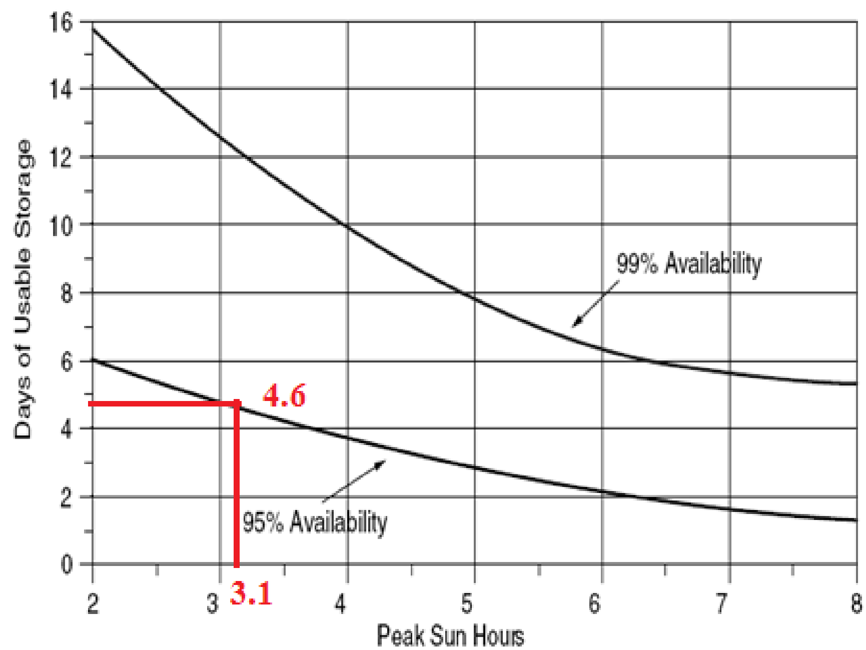
$$\text{DC load} = \frac{\text{AC load}}{\text{Inverter efficiency}} = \frac{3000\ \text{Wh/day}}{0.85} = 3529\ \text{Wh/day}$$

$$\text{Load} = \frac{3529\ \text{Wh/day}}{24\ V} = 147\ \text{Ah/day @ 24 V}$$

peak-sun

Tilt	Jan	Feb	Nov	Dec	Year
Lat − 15	2.9	4.0	3.3	2.5	5.2
Lat	3.2	4.3	3.7	2.9	5.3
Lat + 15	3.4	4.4	3.9	$\boxed{3.1}$	5.0





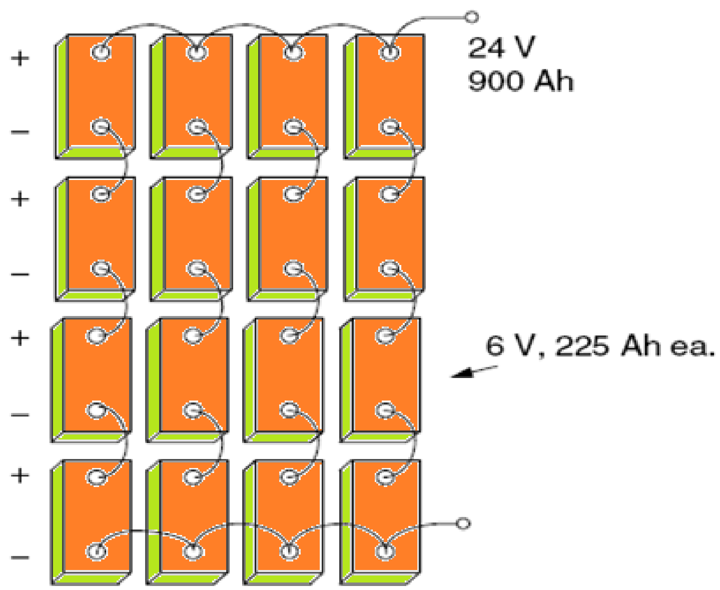
$$\text{Usable storage} = 147\ \text{Ah/day} \times 4.6\ \text{day} = 676\ \text{Ah}$$

$$\text{Nominal } (C/20, 25^\circ\text{C}) \text{ battery capacity} = \frac{676\ \text{Ah}}{0.80 \times 0.97} = 871\ \text{Ah (at 24 V)}$$

Battery Selection - Example

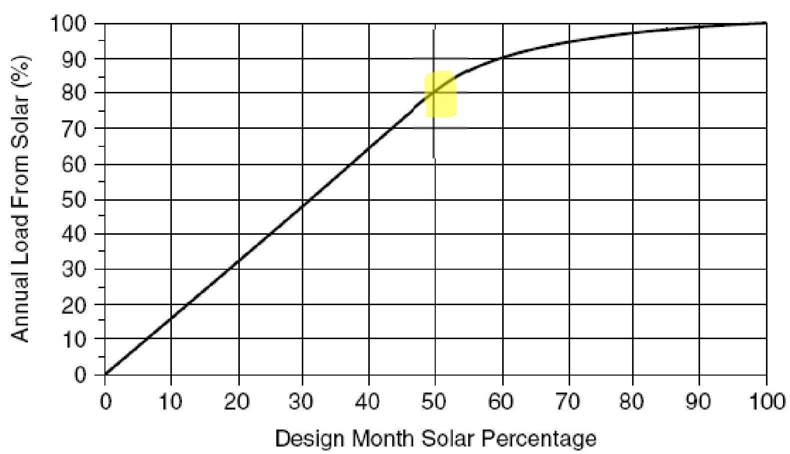
⌘ 871 Ah @ 24V

BATTERY	Voltage	Weight (lbs)	Ah @ $C/20$	Ah @ $C/100$
Concorde PVX 5040T	2	57	495	580
Trojan T-105	6	62	225	250
Trojan L16	6	121	360	400
Concorde PVX 1080	12	70	105	124
Surette 12CS11PS	12	272	357	503



Hybrid PV Systems

- Supplying load in the worst month ("design month") is much more demanding than the rest of the year
- Hybrid system option: Most of the load covered by PV and the remainder supplied by a **generator**
- Key decision: relationship between **shrinking the PV system** and **increasing the fraction of the load carried by the generator**
- Example (Salt Lake City case) of significant reduction in PV size while covering high fraction of the annual load.



- PV system designed to deliver only 50% of the load in the design month will still cover about 80% of the annual load

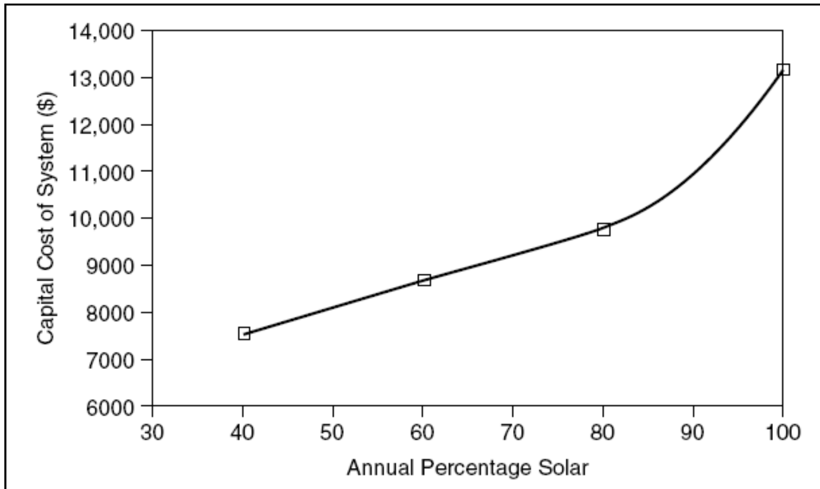
Batteries and Generators for Hybrid PV Systems

- Battery Storage Bank:
  - can be smaller since the generator can charge during the poor weather condition
  - nominal 3-day storage system is often recommended
- Generators: 5 kWh/gallon

Type	Size Range (kW)	Applications	Cost ($/W)	Maintenance Intervals (hours)		
				Oil Change	Tune-up	Engine Rebuild
Gasoline (3600 rpm)	1–20	Cabin Light use	$0.50	25	300	2000–5000
Gasoline (1800 rpm)	5–20	Residence Heavy use	$0.75	50	300	2000–5000
Diesel	3–100	Industrial	$1.00	125–750	500–1500	6000

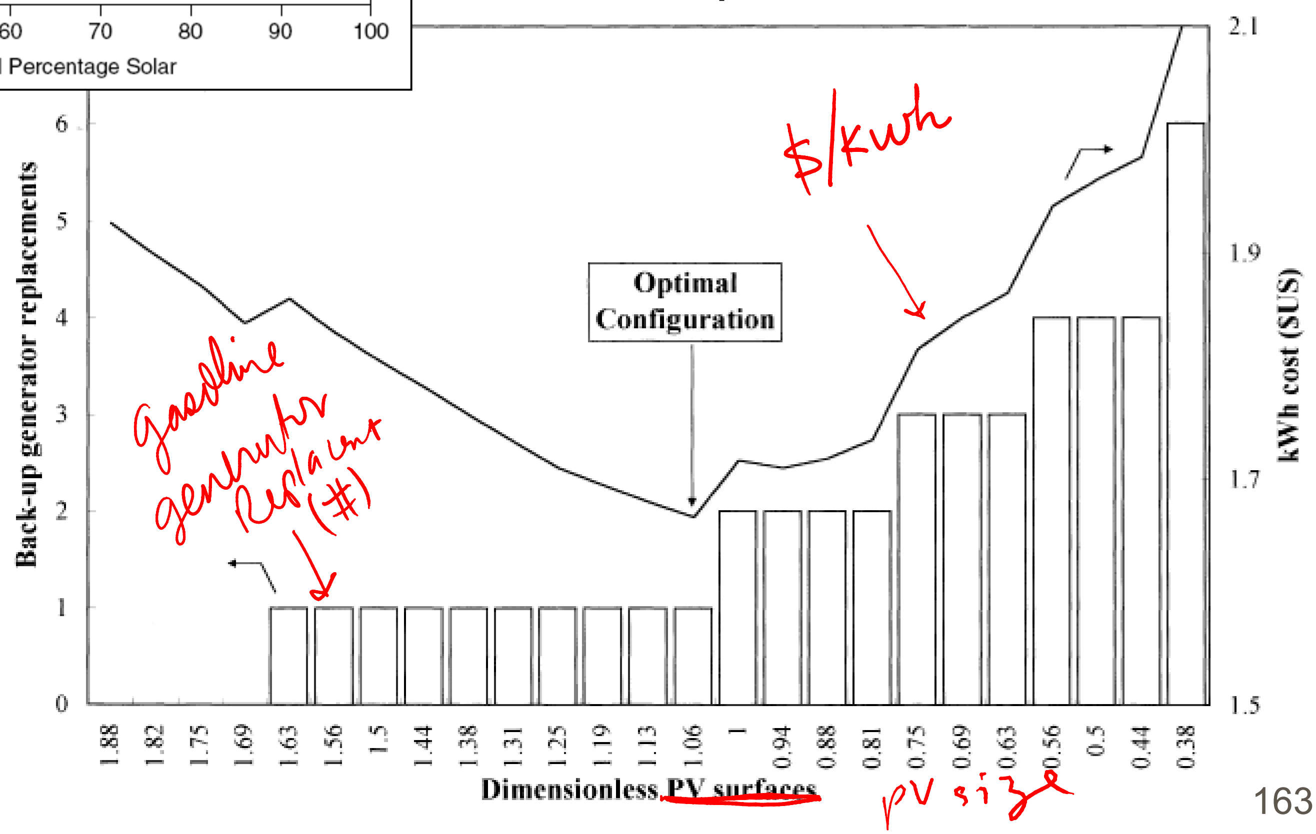
Source: Sandia National Laboratories (1995).

Capital Cost Reduction in Hybrid PV



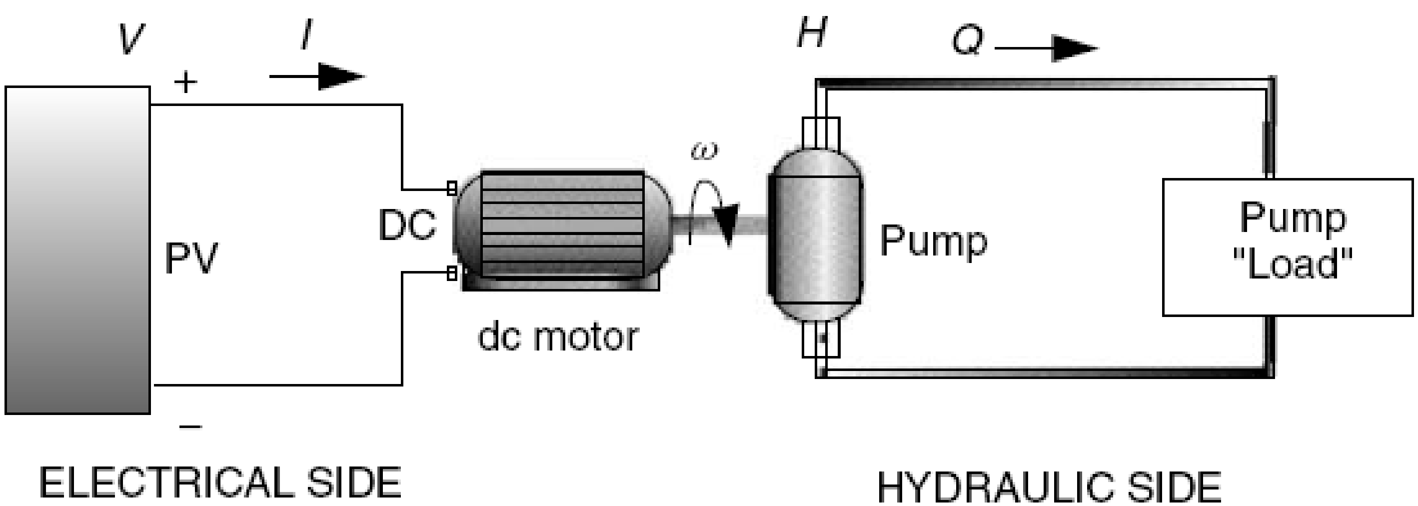
Capital Cost Impact

COE Impact

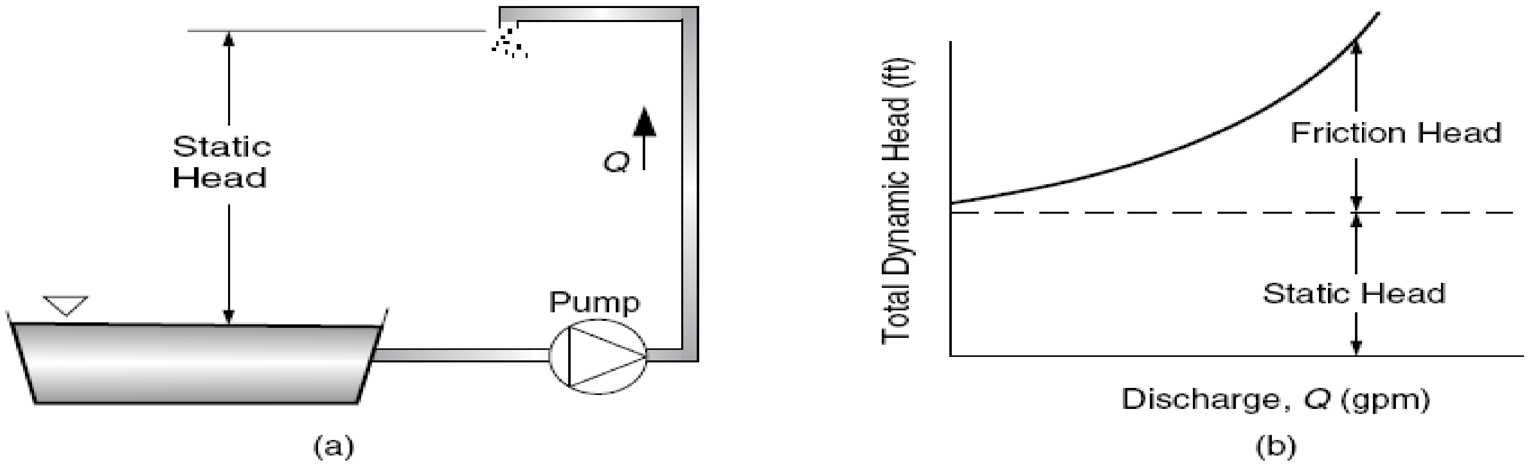


PV-Powered Water Pumping

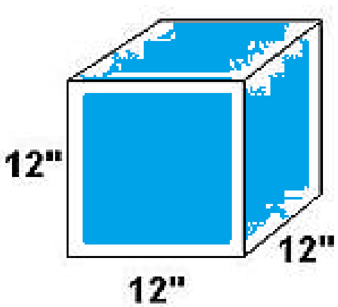
- Most economically viable PV application
- Water pumping in remote areas: raise water from a well or spring and store it in a tank → irrigation, cattle watering, village water supply
- PV Array directly attached to a DC pump
- No battery is required
- Simple, low cost, and reliable



Hydraulic System Curves



- Static Head ("feet of water")



1-ft cube weighing 62.4 lb would exert on its 144 square inches

$$1 \text{ ft of head} = 62.4 \text{ lb}/144 \text{ in.}^2 = 0.433 \text{ psi}$$

pounds per square inch (psi)

$$1 \text{ psi} = 2.31 \text{ ft of water.}$$

  - **Typical city water pressure = 60 psi = 140 feet of water**

- Friction in the Pipe system (roughness inside the pipes, # of bends, valves, etc)

Pressure Loss due to Friction

- Plastic Pipe
- Feet of Water per 100ft of Tube for various tube diameters

gpm	0.5 in.	0.75 in.	1 in.	1.5 in.	2 in.	3 in.
1	1.4	0.4	0.1	0.0	0.0	0.0
2	4.8	1.2	0.4	0.0	0.0	0.0
3	10.0	2.5	0.8	0.1	0.0	0.0
4	17.1	4.2	1.3	0.2	0.0	0.0
5	25.8	6.3	1.9	0.2	0.0	0.0
6	36.3	8.8	2.7	0.3	0.1	0.0
8	63.7	15.2	4.6	0.6	0.2	0.0
10	97.5	26.0	6.9	0.8	0.3	0.0
15		49.7	14.6	1.7	0.5	0.0
20		86.9	25.1	2.9	0.9	0.1

- gpm: Gallons per minute

Friction Loss in Elbows and Valves

- Friction loss expressed as equivalent lengths of tube

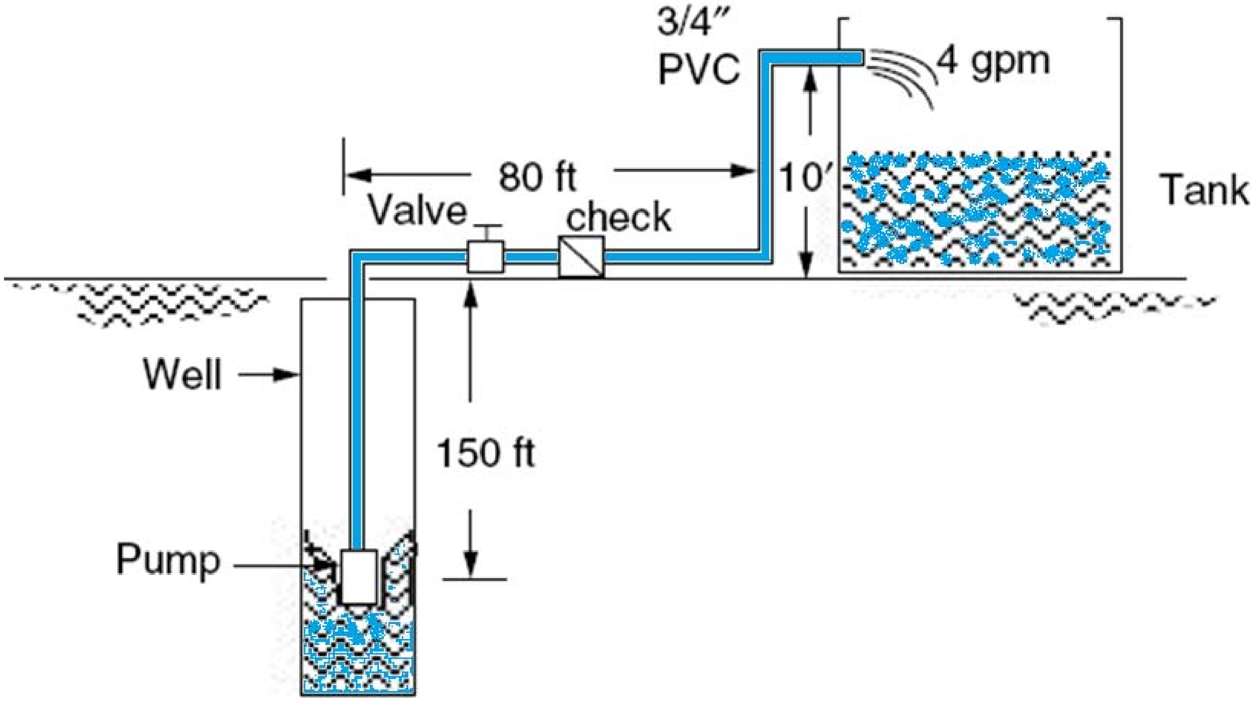
Fitting	0.5 in.	0.75 in.	1 in.	1.5 in.	2 in.	3 in.
90-degree ell	1.5	2.0	2.7	4.3	5.5	8.0
45-degree ell	0.8	1.0	1.3	2.0	2.5	3.8
Long sweep ell	1.0	1.4	1.7	2.7	3.5	5.2
Close return bend	3.6	5.0	6.0	10.0	13.0	18.0
Tee—straight run	1.0	2.0	2.0	3.0	4.0	
Tee—side inlet or outlet	3.3	4.5	5.7	9.0	12.0	17.0
Globe valve, open	17.0	22.0	27.0	43.0	55.0	82.0
Gate valve, open	0.4	0.5	0.6	1.0	1.2	1.7
Check valve, swing	4.0	5.0	7.0	11.0	13.0	20.0

[a] Units are feet of pipe for various nominal pipe diameters.

- Interpretation: 0.75in 90-degree elbow adds to the pressure drop of the same amount as would 2.0ft of straight pipe.
- Static Head + Friction Head = Total Dynamic Head (H)

Pumping Head Calculation Example

- A pump is required to deliver 4 gpm from a depth of 150 ft. The well is 80 ft from the storage tank, and the delivery pipe rises another 10 ft. The piping is 3/4-in.diameter plastic, and there are three 90◦ elbows, one swing-type check valve, and one gate valve in the line.
- Q: What is the pumping head?



Solution

- Length of pipe = 150+80+10=240 ft
- Equivalent pipe length for 3 elbows: 3x2.0=6 ft
- Eq. pipe length for check valve: 5.0 ft
- Eq. pipe length for the gate valve (open): 0.5 ft
- Total Eq. Pipe Length: 240+6+5+0.5=251.5 ft

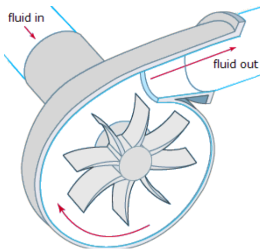
Fitting	0.5 in.	0.75 in.
90-degree ell	1.5	2.0
45-degree ell	0.8	1.0
Long sweep ell	1.0	1.4
Close return bend	3.6	5.0
Tee—straight run	1.0	2.0
Tee—side inlet or outlet	3.3	4.5
Globe valve, open	17.0	22.0
Gate valve, open	0.4	0.5
Check valve, swing	4.0	5.0

- Pressure drop at 4 gpm per 100ft pipe: 4.2 ft
- Therefore, the Friction head = [4.2 x 251.5] / [100] = 10.5 ft
- Static Head = 150+10 = 160 ft
- Total Head = 160 + 10.5 = 170.5 ft of water pressure

gpm	0.5 in.	0.75 in.
1	1.4	0.4
2	4.8	1.2
3	10.0	2.5
4	17.1	4.2
5	25.8	6.3
6	36.3	8.8
8	63.7	15.2
10	97.5	26.0
15		49.7
20		86.9

Hydraulic Pumps

- Different flow rate will results in different pump head
- To determine the actual flow for a given pump, we need to know the characteristics of the pump
- 2 types of pump for PV-power system

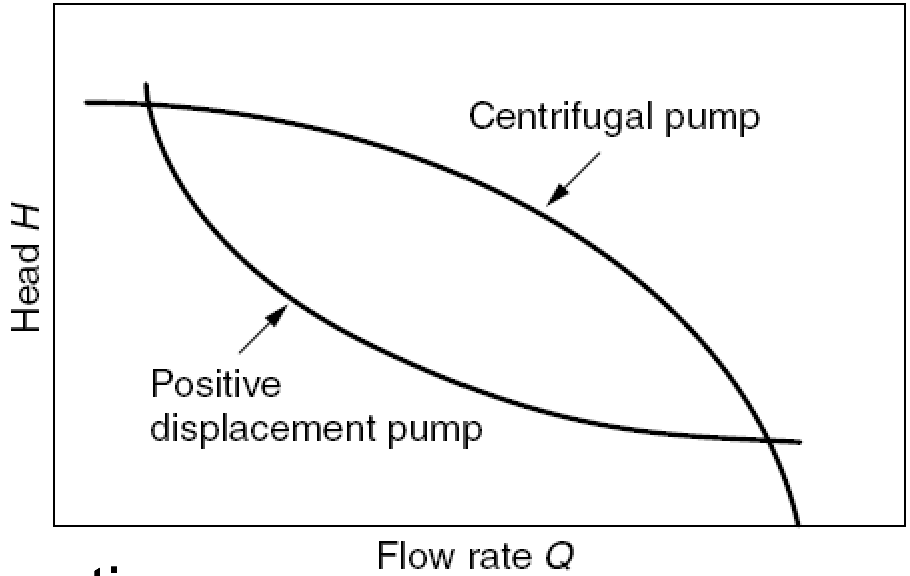


  - Centrifugal pump
    - Fast spinning impellers create suction input side of the pump and create pressure on the delivery side, which throw water out of the pump
    - Limited by the ability of atmosphere pressure to push up water into the suction side of the pump – theoretical max is 32 ft.
  - Positive displacement pump
    - Helical pumps: rotating shaft to push water up a cavity
    - Jack pumps: oscillating arm drives shaft up and down (like the classic oil-rig pumper)
    - Diaphragm pumps: rotating cam opens and closes valves
    - Most useful in low volume applications

Centrifugal	Positive Displacement
High-speed impellers	Volumetric movement
Large flow rates	Lower flow rates
Loss of flow with higher heads	Flow rate less affected by head
Low irradiance reduces ability to achieve head	Low irradiance has little effect on head
Potential grit abrasion	Unaffected by grit

Hydraulic Pump Curve

- Graphical relationship between head (H) and flow (Q)



- Observations
  - Centrifugal pump: Raising the open end of the hose higher and higher (increasing the head) will result in less and less flow until a point is reached at which there is no flow at all.
  - Flapper valve, diaphragm, or rotating screw in a positive displacement pump holds up the water column mechanically, so their flow rates are much less affected by increasing head.

Power delivered by pump

$$P = \rho H Q \qquad \rho \text{ is fluid density}$$

conversion factors...
453.54 g = 1 lb
1000 mL = 1L
1000 L = 264.17 gal

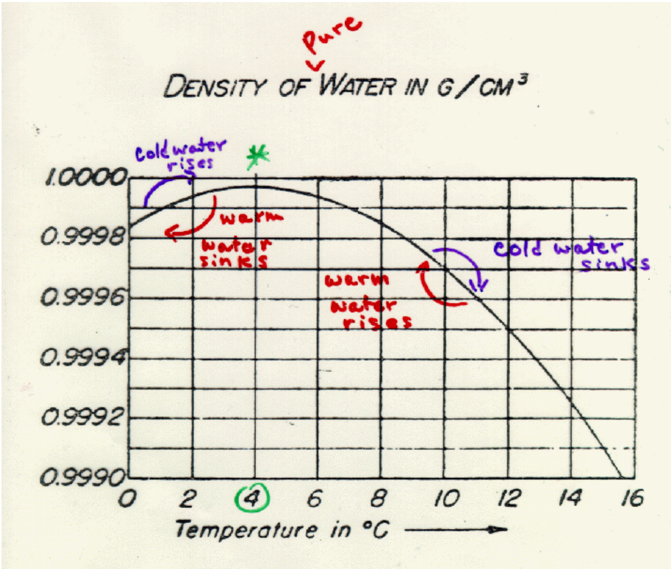
conversion equation...
(1.00g/mL) x (1lb / 453.54g) x (1000 mL / 1L) x (1000 L / 264.17 gal)
= 8.35 lbs/gal

In American units

$$P(\text{watts}) = 8.34 \text{ lb/gal} \times H(\text{ft}) \times Q(\text{gal/ min}) \times (1 \text{ min}/60 \text{ s}) \times 1.356 \text{ W}/(\text{ft-lb/s})$$

$$\boxed{P(\text{watts}) = 0.1885 \times H(\text{ft}) \times Q(\text{gpm})}$$

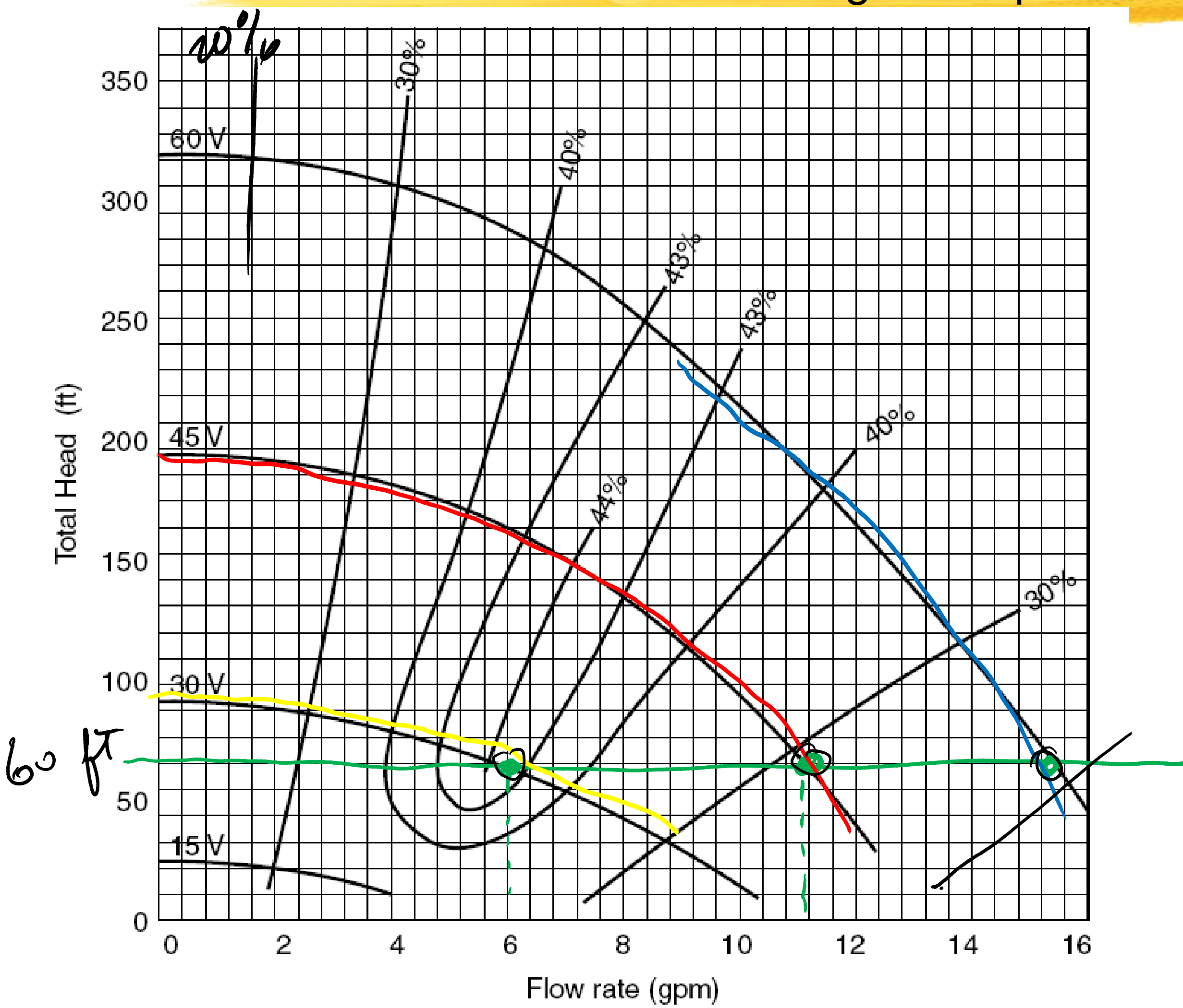
In SI units, $\boxed{P(\text{watts}) = 9.81 \times H(\text{m}) \times Q(\text{L/s})}$



Pump curves under different input voltages

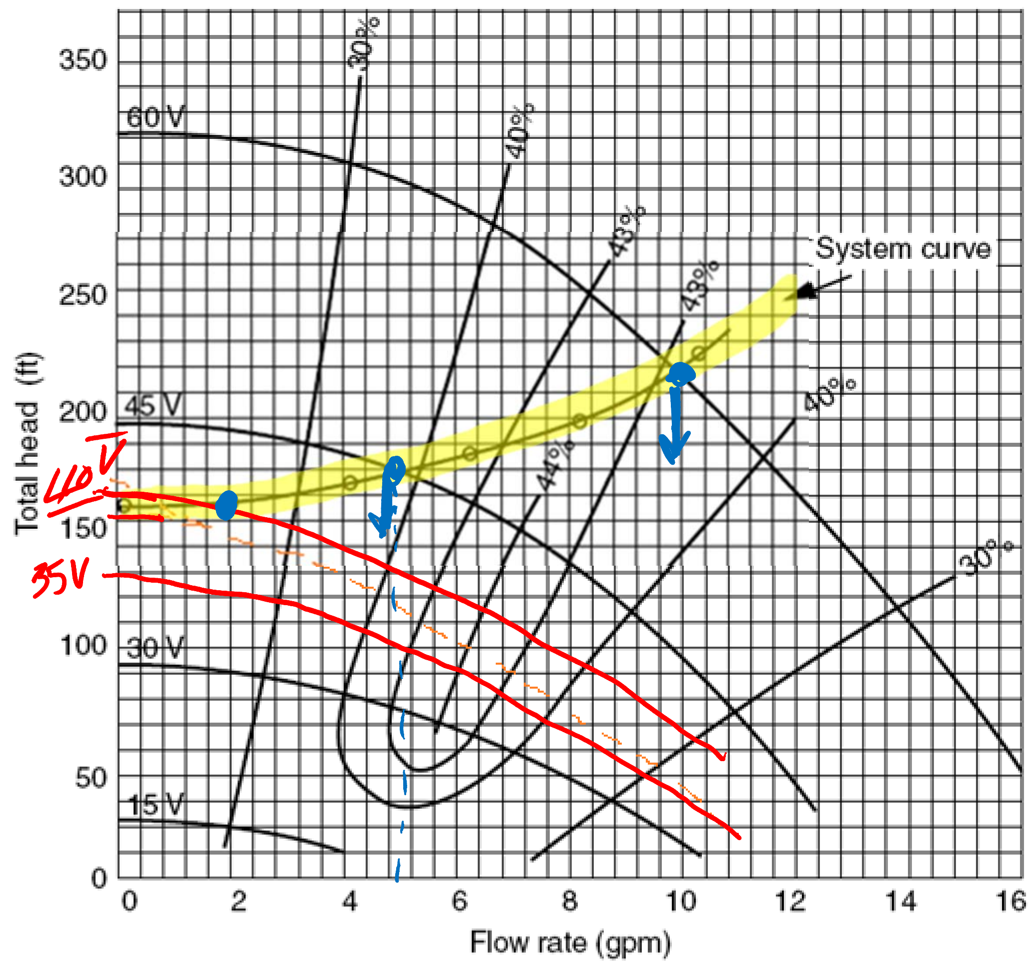
⌘ Example gpm and pump efficiency

- Jacuzzi SJ1C11 DC Centrifugal Pump for PV application



Combination of Hydraulic System Curve and Pump Curve

- Q-H System curve
  - Well System (Situation)
- Q-H pump curve
  - Pump Capability
- Determine the hydraulic operating point
- Observation
  - Pump will not deliver any water unless the voltage applied to the pump is at least 36V
  - At 45V, about 5 gpm would pumped
  - At 60V, the flow would be 9.5 gpm
  - **Which one is better? Higher Efficiency?**



PV-Pump Design Process

- 1. Determine the water production goal (gallons/day) in the design month (highest water need and lowest insolation)
- 2. Use the design month insolation (hours at 1-sun) as the hours of pumping, and find the pumping rate Q (gpm):

$$Q(\text{gpm}) = \frac{\text{Daily demand (gal/day)}}{\text{Insolation(h/day@1-sun)} \times 60 \ \text{min/h}}$$

- 3. Find the total dynamic head H at Q. Friction head may be assumed to be 5% of the static head
- 4. Find a pump capable of delivering the desired head and flow Q. Note the input power and the nominal voltage. Pump efficiency for suction pumps is 25% and submersible pumps 35%.

$$P_{\text{in}} \text{ (W) to pump} = \frac{\text{Power to fluid}}{\text{Pump efficiency}} = \frac{0.1885 \times H(\text{ft}) \times Q(\text{gpm})}{\eta_p}$$

- 5. The number of PV modules in series (15V PV module) from the pump voltage

$$\text{Modules in series} = \frac{\text{Pump voltage(V)}}{15 \text{ V/module}}$$

- 6. The number of PV strings in parallel using pump input power, and PV rated current (IR), and de-rating factor (for dirt and temperature effect) with 0.80.

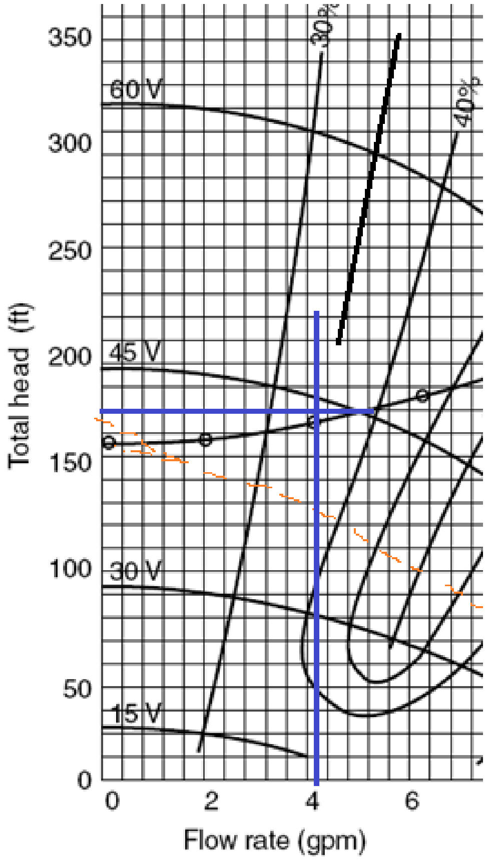
$$\text{\# strings} = \frac{\text{Pump input power } P_{\text{in}}(\text{W})}{\text{\# mods in series} \times 15 \text{ V/mod} \times I_R(\text{A}) \times \text{de-rating}}$$

- 7. Estimate the water pumped.

$$Q(\text{gal/day}) = 15 \text{ V/mod} \times I_R \text{ (A)} \times (\text{\# mods}) \times (\text{Peak h/day}) \times 60 \ \text{min/h}$$
$$\times \text{ de-rating} \times \eta_P/[0.1885 \times H(\text{ft})]$$

PV-Pump System Design Example

- **Sizing an Array for a 150-ft Well in Santa Maria, California.**
  - Goal: pump at least 1200 gallons per day from the 150-ft well.
  - Directions
    - Use Jacuzzi SJ1C11 pump
    - **Use Siemens SR100 15-V PV modules with rated current 5.9 A**
    - The worst month (December) insolation is 4.9 kWh/m^2-day
  - Question: Size the PV array



- **Sol.**
  - 1. $$Q = \frac{1200 \text{ gal/day}}{4.9 \text{ (h/day @1-sun)} \times 60 \text{ min /h}} = 4.1 \text{ gpm}$$
  - 2. @4.1 gpm, the hydraulic curve shows that about 170 ft of head is needed and at the operating point the pump efficiency is about 34% → estimated pump input power

$$P_{\text{in}}(\text{W}) = \frac{0.1885 \times H(\text{ft}) \times Q(\text{gpm})}{\text{Pump efficiency}} = \frac{0.1885 \times 170 \times 4.1}{0.34} = 386 \text{ W}$$

Example-Solution (continued)

- 3. At the above operating point, the pump voltage required is a little under 45V → 3 15-V modules in series
- 4. Number of Parallel Strings (de-rating at 80%) (5.9A – rated current)

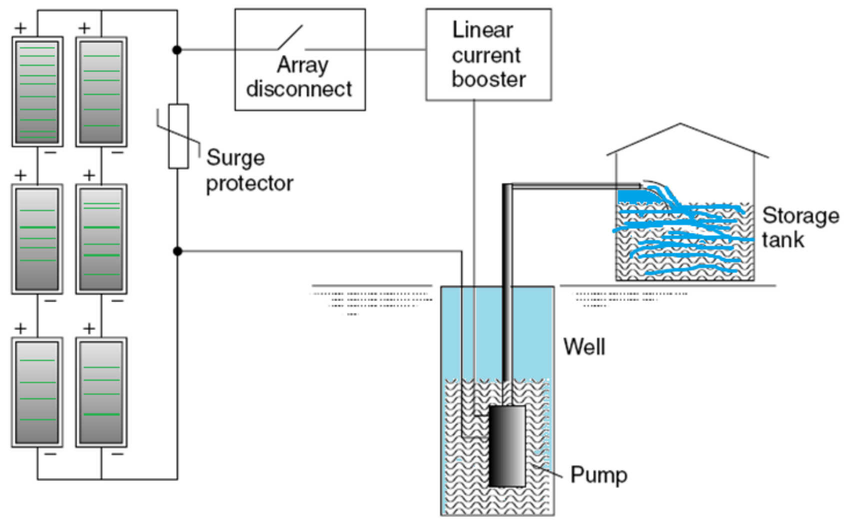
$$\# \text{ strings} = \frac{386 \text{ W}}{3 \text{ modules string} \times 15 \text{ V/module} \times 5.9 \ A \times 0.80} = 1.8$$

So 2 parallel strings.

- 5. Estimated water delivery in December

$$Q \approx \frac{15 \text{ V} \times 5.9 \text{ A} \times 6 \text{ modules} \times 4.9 \text{ h/day} \times 60 \ \min/\text{h} \times 0.80 \times 0.34}{0.1885 \times 170 \text{ ft}}$$

$$= 1325 \text{ gal/day}$$



Buck Converter as Linear Current Booster

- Low sun → not enough torque to pump
- Lower voltage and increase current → lower speed pumping, but pumping anyway