Small RE systems: performance versus prediction.

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Washington, DC.

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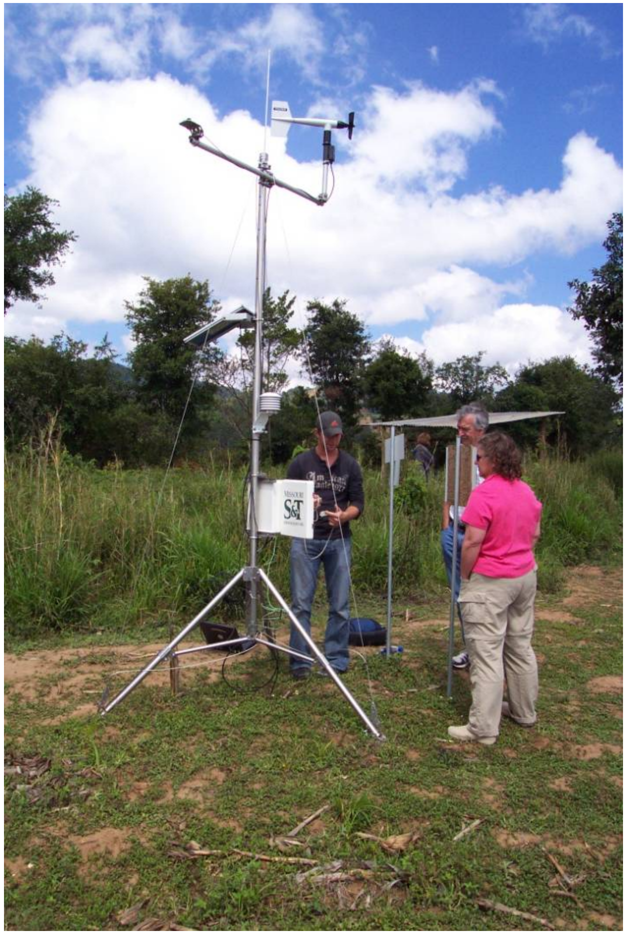
Outline

- What's a small RE?
- Wind
  - Regional
  - Site-specific
- PV/solar
  - Regional
  - Site-specific
- How well does it work?



Small RE systems

- Residential systems
  - – Typically 10 kW or smaller
  - – Grid inter-tie
    - Predictions for off-grid
  - – 240 VAC (single – phase)

Wind turbine model

- Turbine power curve
- Wind velocity at hub

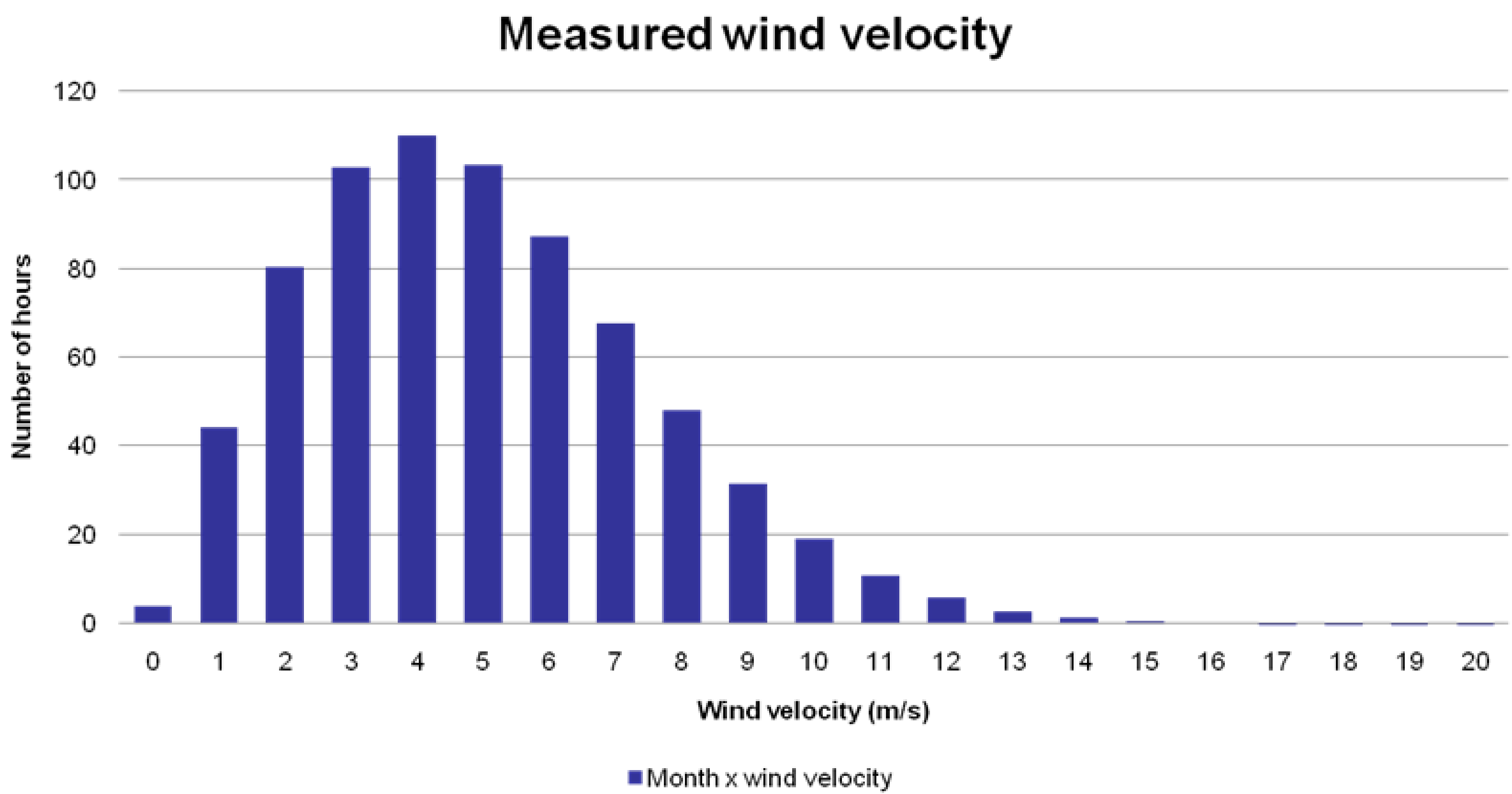
Power curve

System Power Curve

Wind Speed (m/s)	Power Out (W): Grid-tie
3	51
4	134
5	297
6	563
7	1000
8	1569
9	2233
10	3064
11	3500
12	3500

Source: Raum Energy

Wind velocity – perfect world



Product = energy

Wind Speed (m/s)	Power (kW) at sea level	Time (hr)	Energy (kWh)
0	0.00	3.8	0
1	0.00	44.2	0
2	0.00	80.4	0
3	0.14	102.9	14.40821266
4	0.43	109.9	47.26807999
5	0.88	103.3	90.91813408
6	1.51	87.5	132.1186068
7	2.35	67.6	158.898306
8	3.43	48.0	164.7914505
9	4.80	31.5	151.394866
10	6.42	19.2	123.2306923
11	8.21	10.9	89.11602135
12	10.02	5.7	57.25120445
13	11.37	2.8	31.87387155
14	11.76	1.3	15.09180992
15	12.06	0.5	6.616055375
16	12.14	0.2	2.660317411
17	12.15	0.1	0.994337542
18	12.10	0.0	0.345907509
19	11.92	0.0	0.111379452
20	11.44	0.0	0.032702727
		720.0	1,087.1

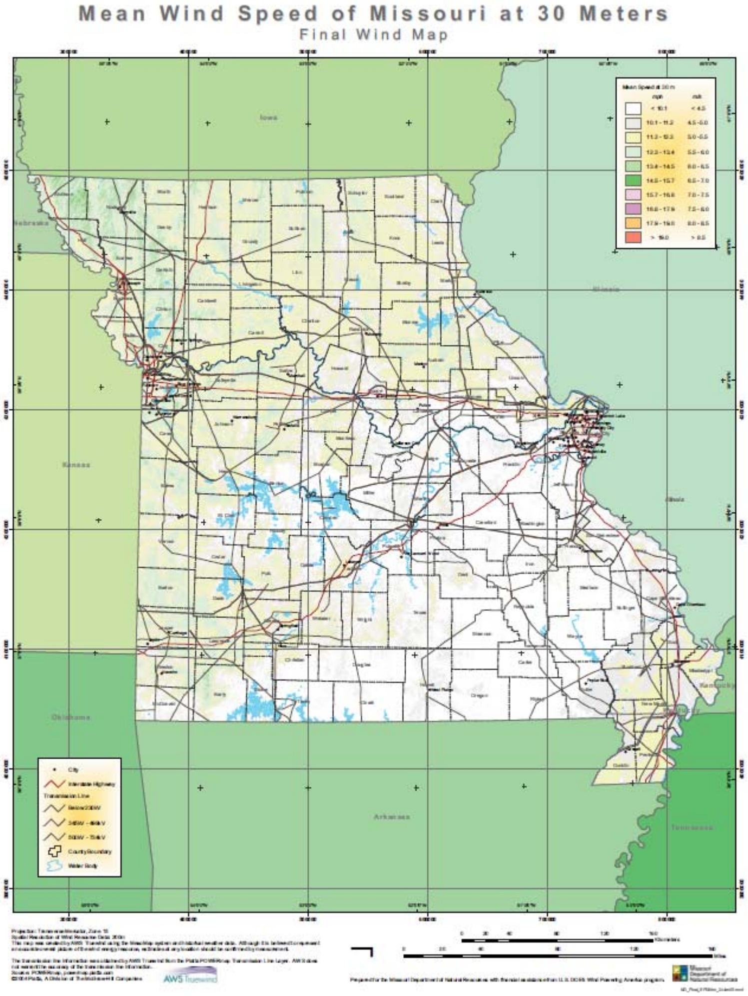
Reality

- Estimate wind velocity frequencies
- Estimate change in velocity from measurement height to hub height
- Estimate losses

INPUT VARIABLES	
Anemometer ave. vel. (m/s)	5
An. height above ground (m)	3
Hub height above grnd (m)	100
Site elevation ASL (m)	356
Weibull shape (K)	2
Wind shear exponent	0.142857
Turbulence factor	0.25
Time period (d)	30

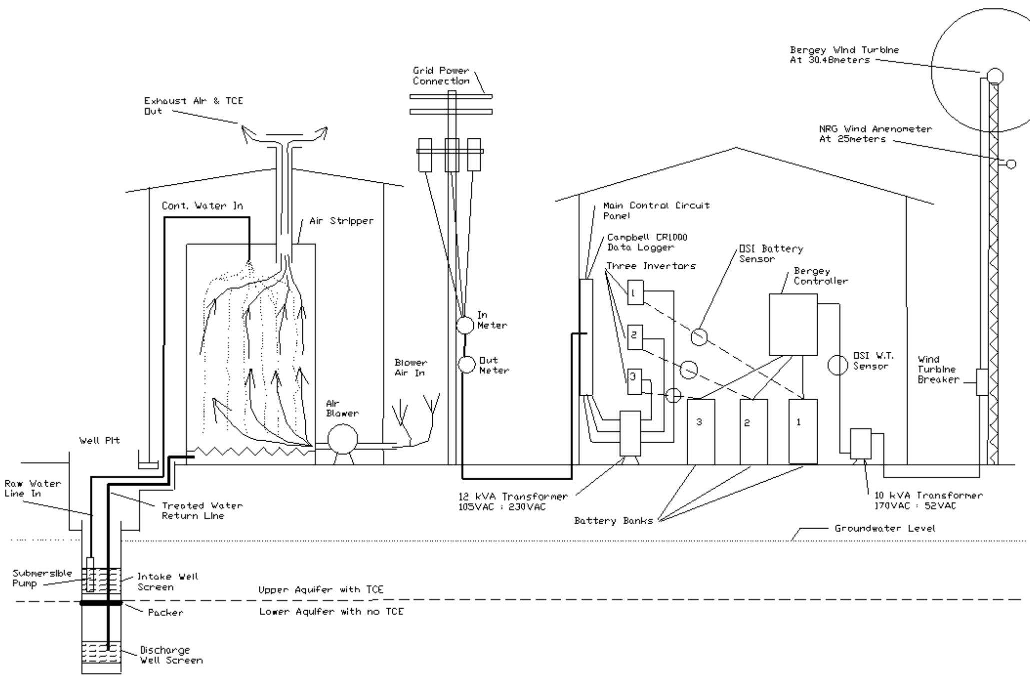
Where do we get wind velocity data?

- Maps
- Databases
- Measurement

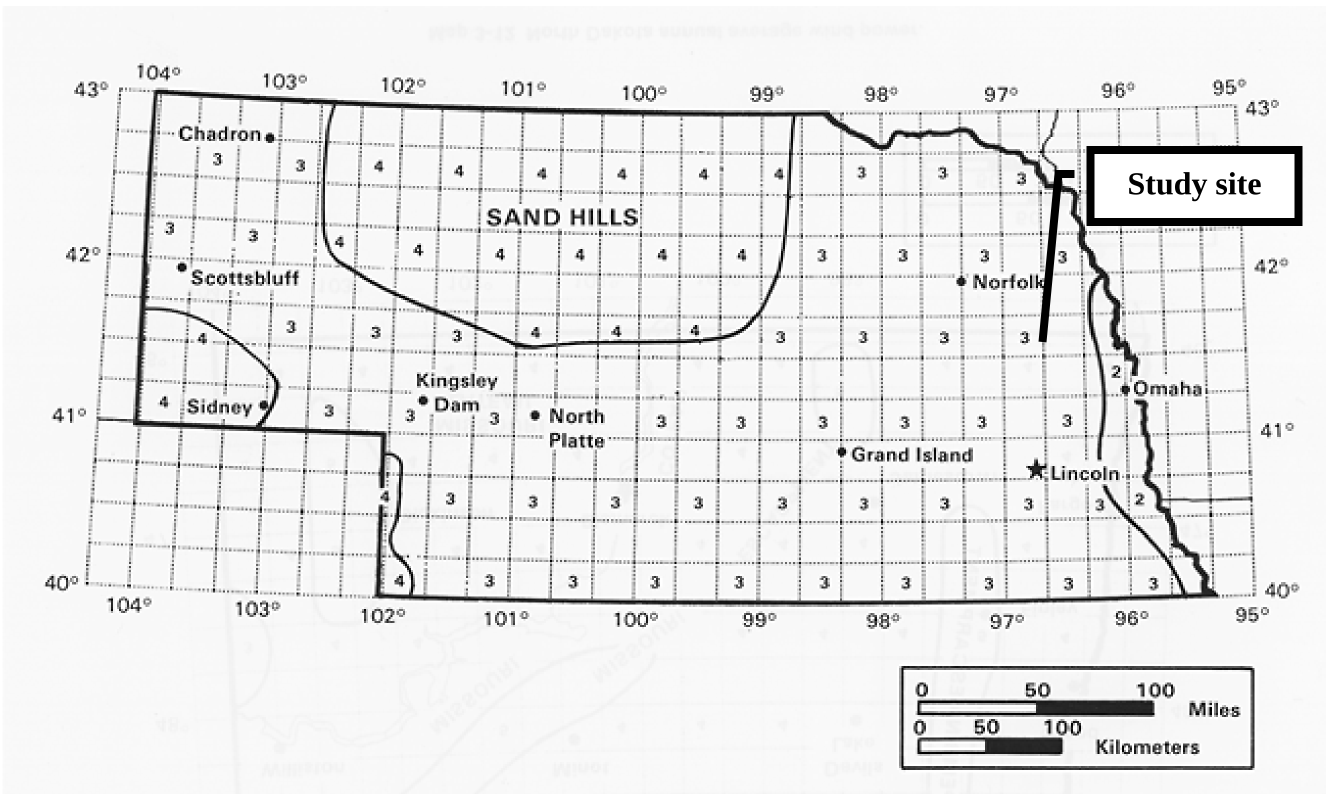


FNOP Case Study

- 10 kW Bergey XLS – January 7, 2004
- Converted to 7.5 kW battery charge – November 23, 2005
- Groundwater circulation well



Wind map for initial estimate



Source: Elmore et al. (2004)

Database for second estimate

Table 1. Regional Climate Databases

Name	States covered	Web address
High Plains Regional Climate Center	Colorado, Kansas, Nebraska, North Dakota, South Dakota, Wyoming	www.hprcc.unl.edu
Midwestern Regional Climate Center	Iowa, Illinois, Kentucky, Mississippi, Missouri, Minnesota, Ohio, Wisconsin	http://mcc.sws.uiuc.edu
Northeast Regional Climate Center	Connecticut, Washington, D.C., Massachusetts, Maryland, Maine, New Hampshire, New Jersey, New York, Rhode Island, Vermont, West Virginia	www.nrcc.cornell.edu
Southeast Regional Climate Center	Alabama, Florida, Georgia, North Carolina, South Carolina, Virginia	www.sercc.com
Southern Regional Climate Center	Alabama, Arkansas, Louisianna, Mississippi, Oklahoma, Tennessee, Texas	www.srcc.lsu.edu
Western Regional Climate Center	Arizona, California, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington	www.wrcc.dri.edu

Source: Elmore & Gallagher (2009)

Site-specific measurements

Comparison of predictions

	Wind map (Annual)	**Database (Annual from 12 yr of record)**	**Site specific monthly average (3/05 – 7/07)**
Velocity	5.35 m/s @ 10 m	3.73 m/s@ 3 m	5.36 m/s @ 25 m
Hub velocity at 30 m (m/s)	6.26	5.18	5.50
Predicted energy (kWh)	12,015	6,055	8,439
Actual annual energy average 1/04-7/05 (kWh)		8,439	

Lesson learned?

- Beware of variability!

Table 3. Wind Velocity Data

Month	Wind velocity measured at wind turbine		
	μ (m/s)	*k*	*c*
March 2005	6.27	2.15	7.05
April 2005	6.10	2.34	6.86
May 2005	5.83	2.20	6.59
June 2005	5.21	2.45	5.86
July 2005	4.68	2.19	5.28
August 2005	3.56	1.88	3.95
September 2005	5.26	2.19	5.92
October 2005	5.09	1.90	5.72
November 2005	6.04	1.80	6.78
December 2005	4.97	2.10	5.62
January 2006	5.91	2.02	6.67
February 2006	5.51	2.19	6.23
March 2006	6.32	2.27	7.15
May 2006	5.99	2.06	6.78
June 2006	5.07	2.05	5.74
August 2006	4.09	2.38	4.59
September 2006	4.74	2.01	5.33
October 2006	5.16	2.16	5.83
November 2006	5.18	1.84	5.82
December 2006	4.90	2.47	5.52
March 2007	5.86	2.39	6.60
April 2007	6.39	2.22	7.22
May 2007	5.70	2.27	6.43
June 2007	4.83	1.94	5.46

Source: Elmore & Gallagher 2009

Consider stochastic analysis!

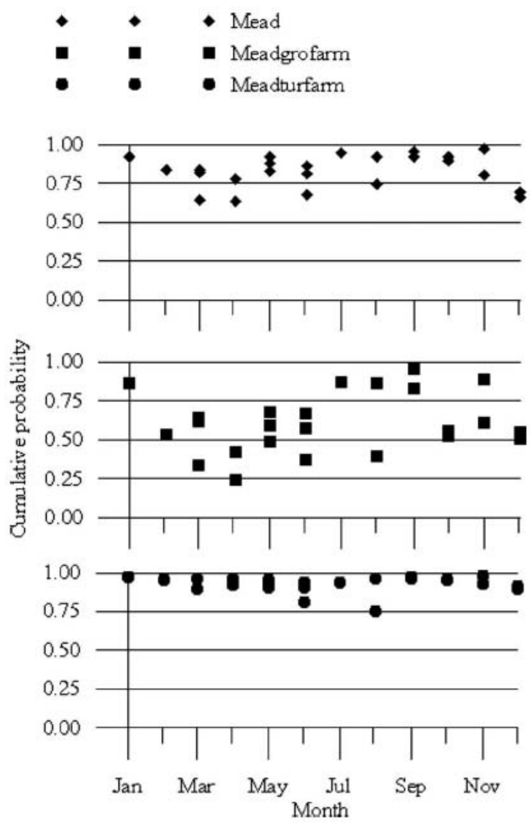


Fig. 4. Comparison of predicted and measured average wind velocities

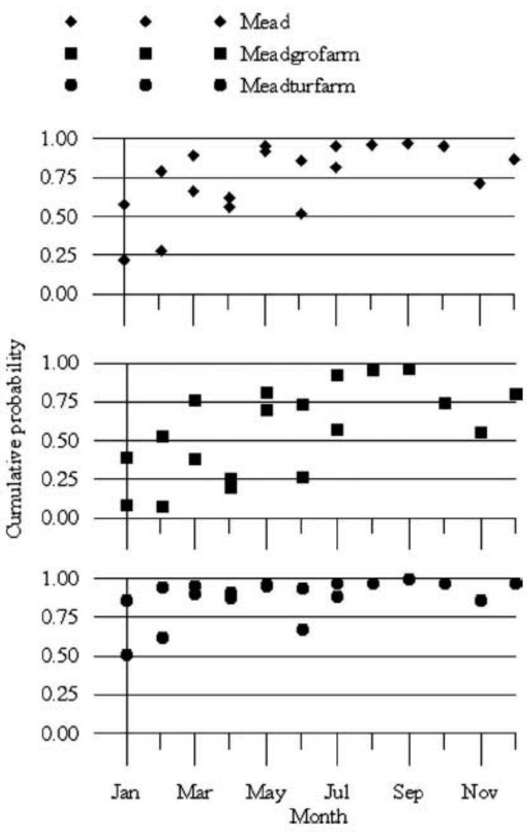


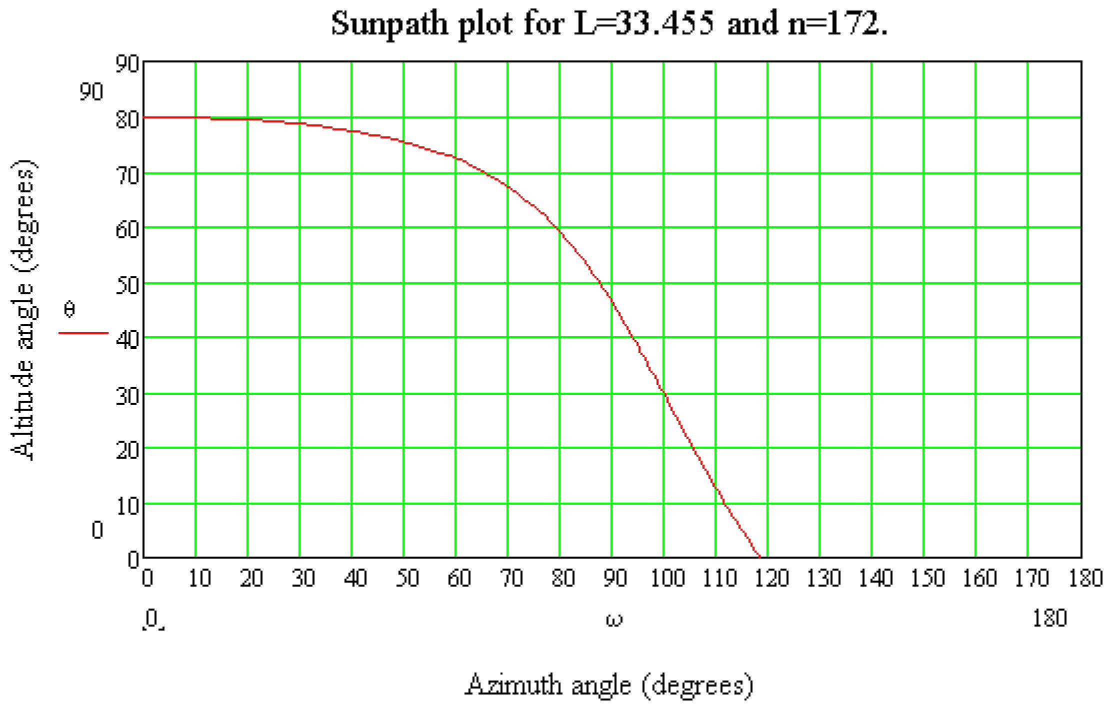
Fig. 5. Comparison of predicted and measured grid intertie monthly energy production values

Source: Elmore & Gallagher 2009

Solar!

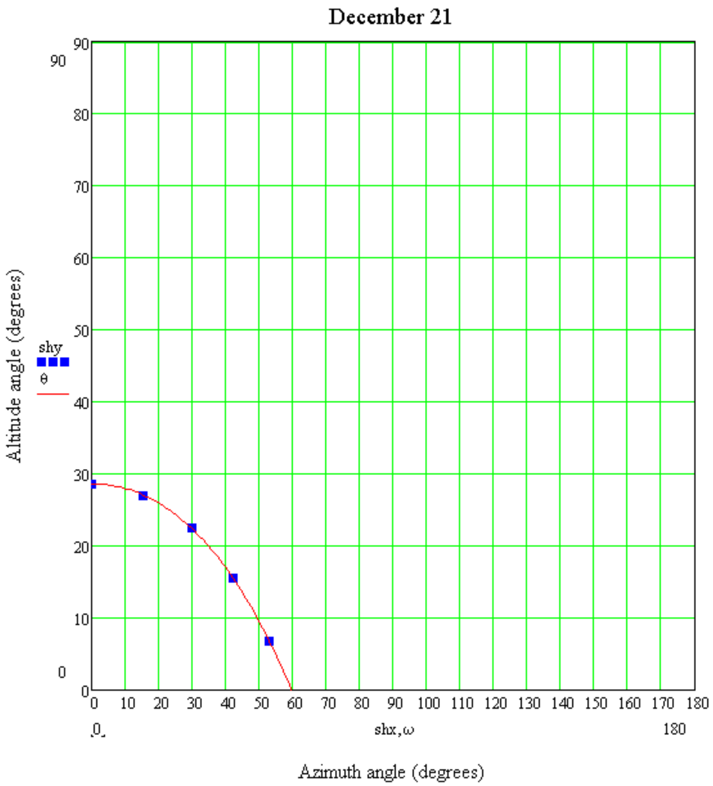
Solar geometry

- Function of position (latitude)
- Function of time (day, hour)
- Straight forward to calculate



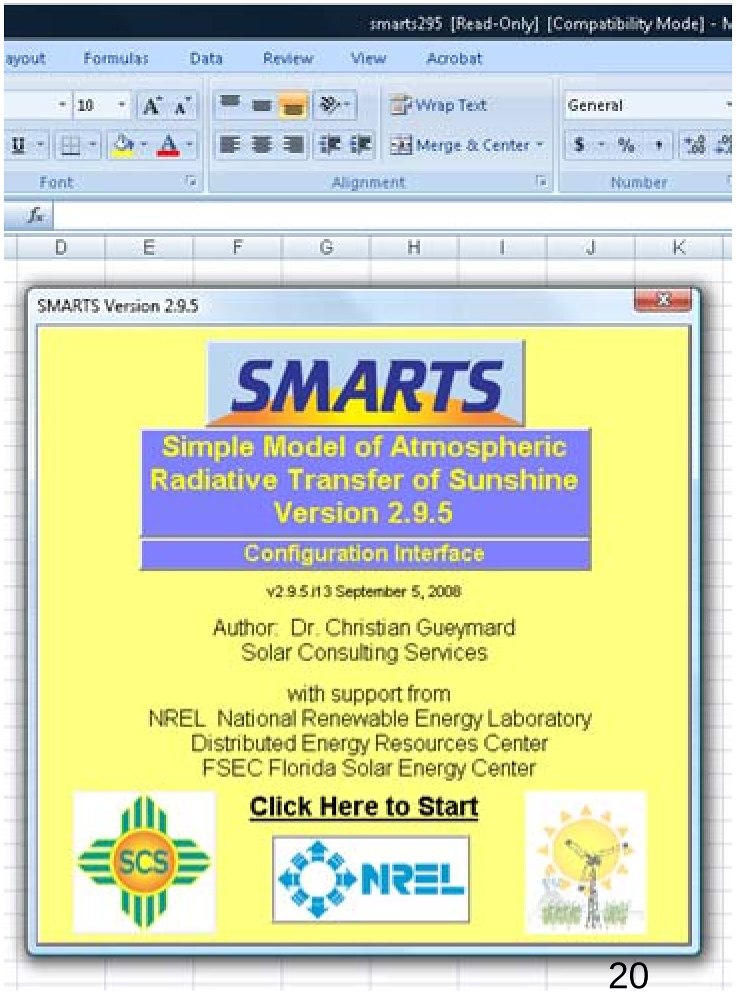
Basic design

- Where to locate?
- How many hours per day?



Simple Model of Atmospheric Radiative Transfer of Sunshine

- SMARTS
  http://www.nrel.gov/rredc/smarts/



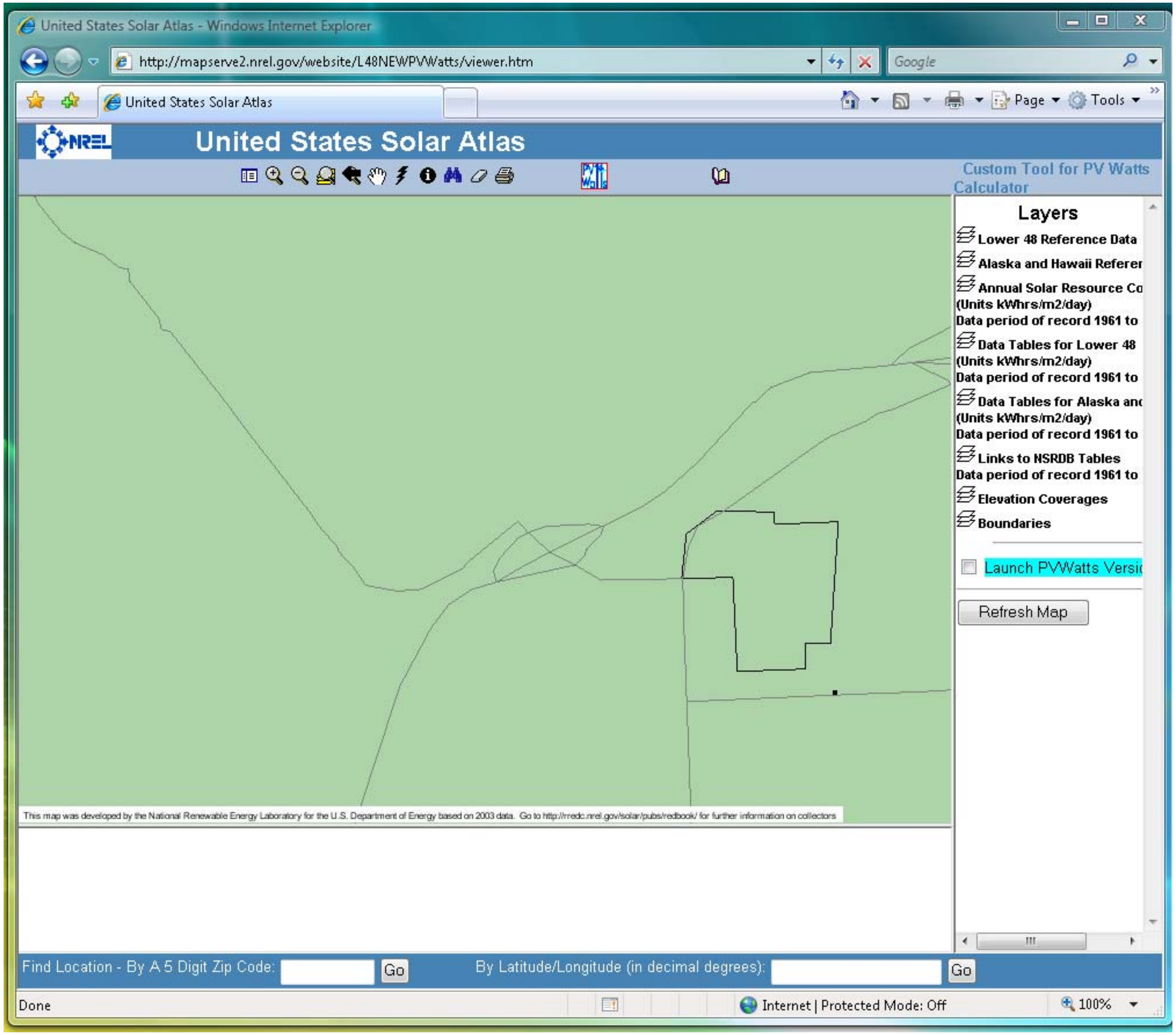
Output

```
* SOLAR POSITION (deg.):
    Zenith Angle (apparent) = 79.990  Azimuth (from North) =  103.23

      RELATIVE OPTICAL MASSES:
  - Rayleigh =  5.585
  - Water Vapor =  5.716
  - Ozone =  5.269
  - NO2 =  5.243
  - Aerosols =  5.694

  Results below are for this specific day:
 Year = 2001   Month = 10  Day =  3   Hour (LST) =  7.000   Day of Year = 276
   In Universal Time:
   Day (UT) =  3   Hour (UT) = 13.000
   Julian Day =  2452186.000  Declination =  -4.112 deg.  Radius vector = 1.00047   Equation of Time (min) =
11.049
   Local Apparent Time (or Solar Time):   7.066
```

PVWatts


United States Solar Atlas - Windows Internet Explorer
http://mapserve2.nrel.gov/website/L48NEWPVWatts/viewer.htm
United States Solar Atlas
United States Solar Atlas
Custom Tool for PV Watts Calculator
Layers
Lower 48 Reference Data
Alaska and Hawaii Referer
Annual Solar Resource Co
(Units kWhrs/m2/day)
Data period of record 1961 to
Data Tables for Lower 48
(Units kWhrs/m2/day)
Data period of record 1961 to
Data Tables for Alaska and
(Units kWhrs/m2/day)
Data period of record 1961 to
Links to NSRDB Tables
Data period of record 1961 to
Elevation Coverages
Boundaries
Launch PVWatts Versi
Refresh Map
Find Location - By A 5 Digit Zip Code:
Go
By Latitude/Longitude (in decimal degrees):
Go
Done
Internet | Protected Mode: Off
100%

Click on **Calculate** if default values are acceptable, or after selecting your system specifications. Click on **Help** for information about system specifications. To use a DC to AC derate factor other than the default, click on **Derate Factor Help** for information.

Site Location:

Cell ID:	0232376
State*:	Missouri
Latitude*:	37.915
Longitude*:	-91.586

PV System Specifications:

DC Rating (kW):	2.16	
DC to AC Derate Factor:	0.829526	DERATE FACTOR HELP
Array Type:	Fixed Tilt	

Fixed Tilt or 1-Axis Tracking System:

Array Tilt (degrees):	37.915	(Default = Latitude)
Array Azimuth (degrees):	180.0	(Default = South)

Energy Data:

Cost of Electricity (cents/kWh):	1

Calculate HELP Reset Form

PVWatts

AC Energy & Cost Savings

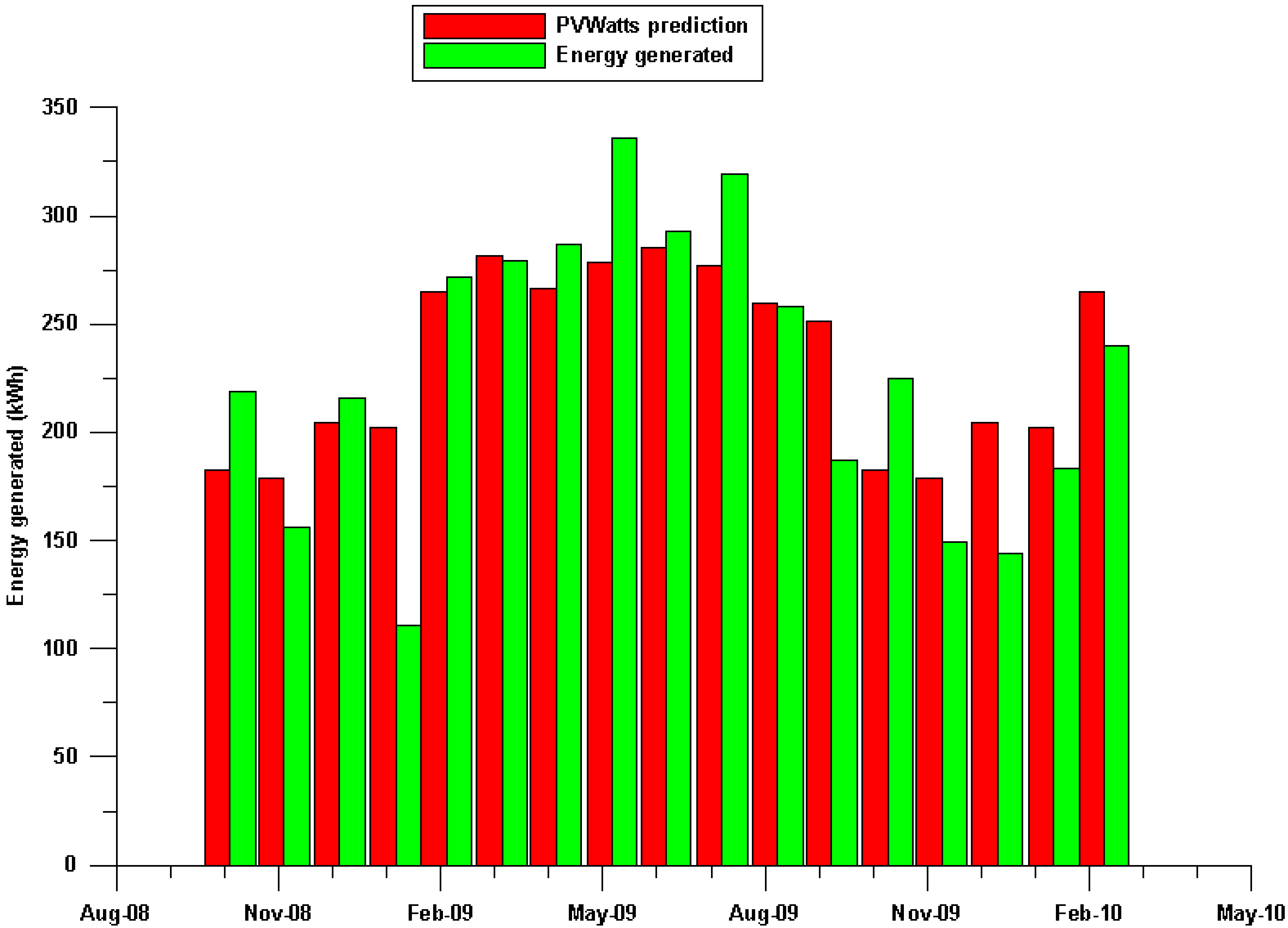
Cautions for Interpreting the Results

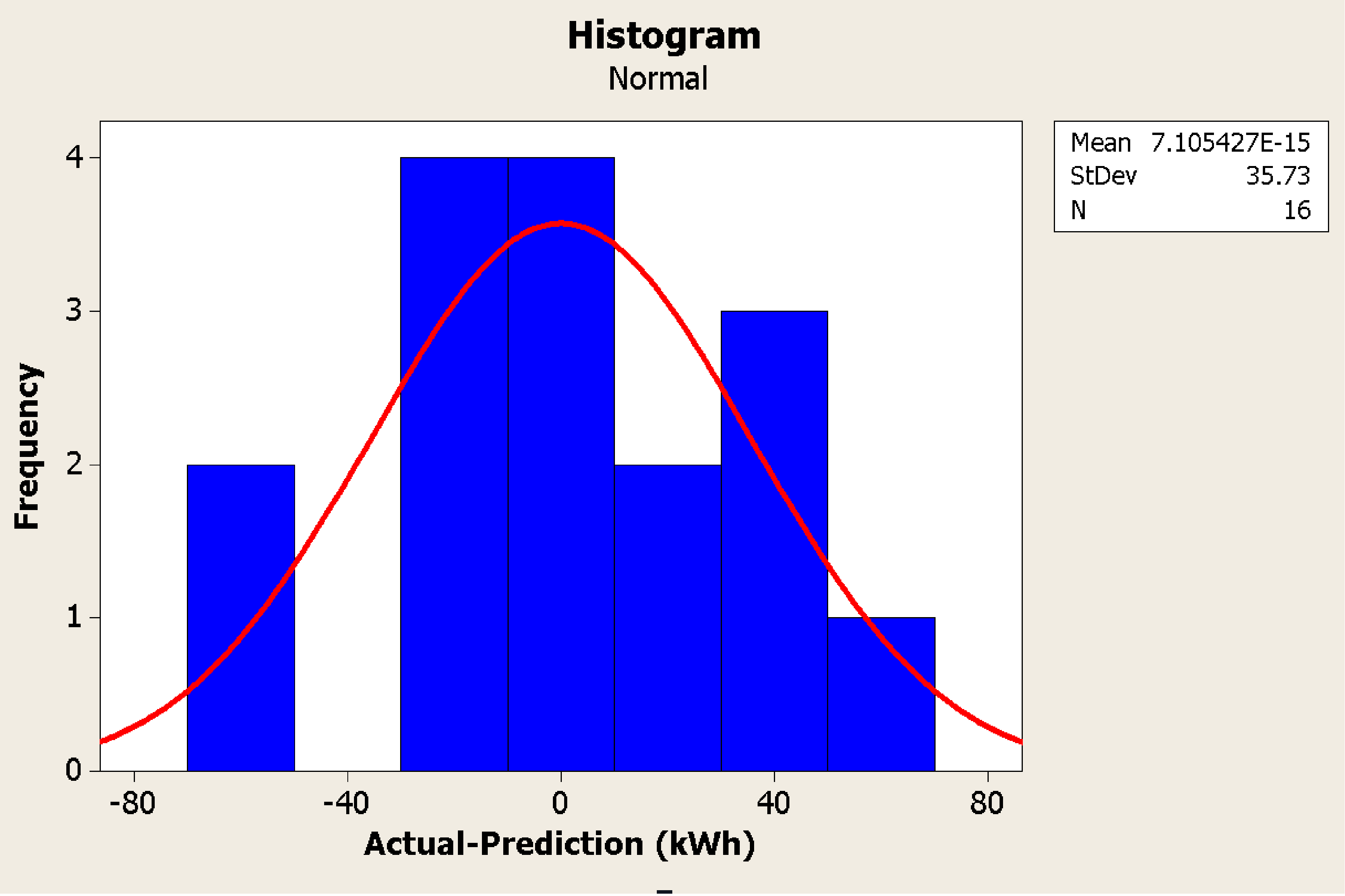
(Type comments here to appear on printout; maximum 1 row of 90 characters.)

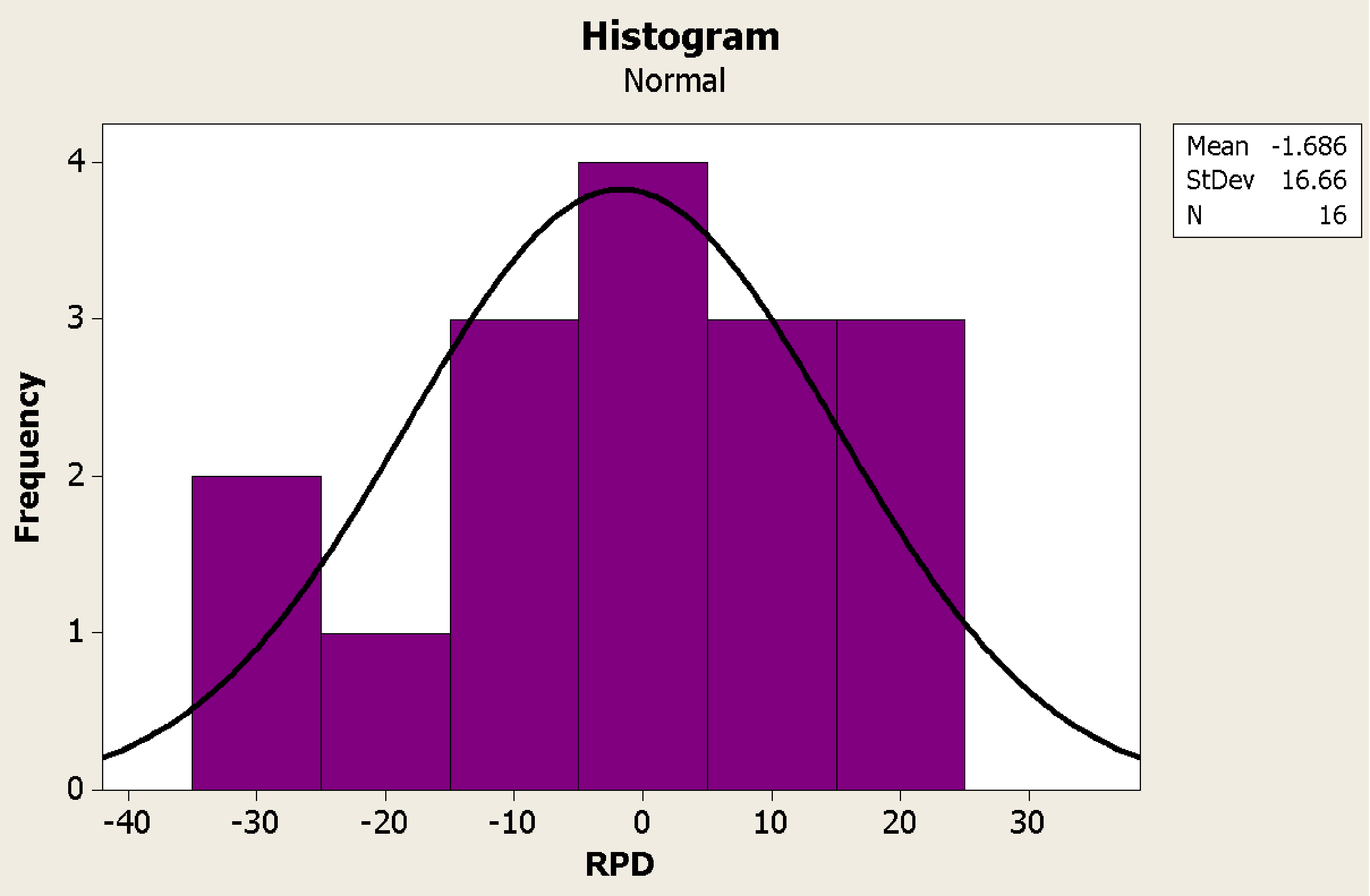
Station Identification	
Cell ID:	0232376
State:	Missouri
Latitude:	37.9 ° N
Longitude:	91.6 ° W
PV System Specifications	
DC Rating:	**2.16 kW**
DC to AC Derate Factor:	**0.830**
AC Rating:	1.79 kW
Array Type:	Fixed Tilt
Array Tilt:	37.9 °
Array Azimuth:	180.0 °
Energy Specifications	
Cost of Electricity:	1.0 ¢/kWh

Results			
Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value ($)
1	3.63	207	2.07
2	4.04	203	2.03
3	4.98	266	2.66
4	5.63	284	2.84
5	5.40	270	2.70
6	5.91	283	2.83
7	5.93	288	2.88
8	5.76	280	2.80
9	5.37	262	2.62
10	4.85	253	2.53
11	3.60	187	1.87
12	3.26	182	1.82
Year	4.87	2965	29.65

Output Results as Text

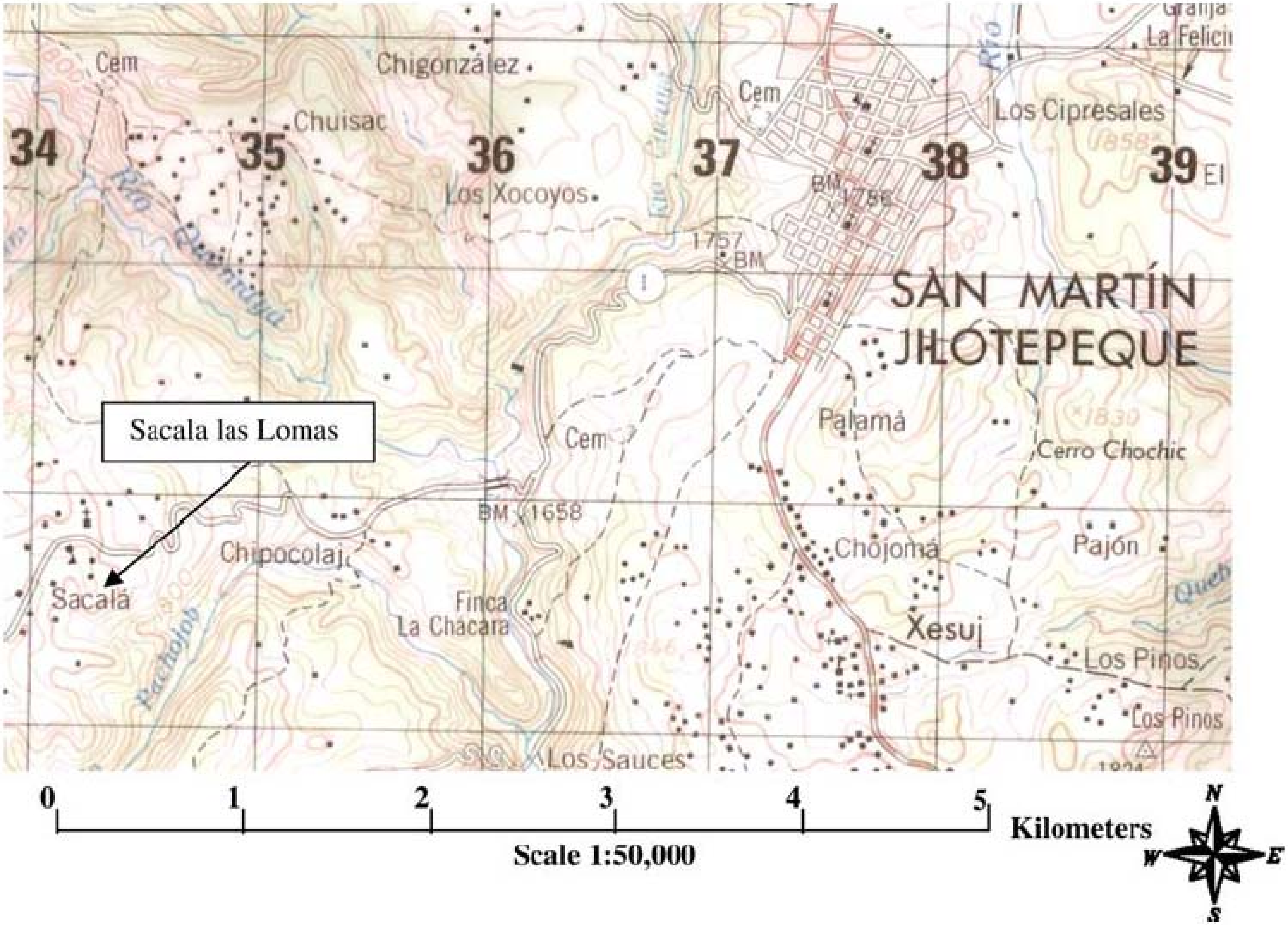

PVWatts prediction
Energy generated
Energy generated (kWh)
350
300
250
200
150
100
50
0
Aug-08
Nov-08
Feb-09
May-09
Aug-09
Nov-09
Feb-10
May-10


Histogram
Normal
Mean 7.105427E-15
StDev 35.73
N 16
Frequency
0
1
2
3
4
-80
-40
0
40
80
Actual-Prediction (kWh)


Histogram
Normal
Mean -1.686
StDev 16.66
N 16
Frequency
0
1
2
3
4
-40
-30
-20
-10
0
10
20
30
RPD

Expect variability!

Guatemala feasibility study



Source: Granich & Elmore (2009)

Environ Earth Sci

Table 1 Local groundwater well characteristics

Location	Ground elevation (m amsl)	Total depth (m)	Dynamic drawdown (m)	Yield (l/min)
San Martin 1	1,798	195	115	435
San Martin 2	1,808	196	90	1,518
Comalapa 1	2,112	189	NR[a]	435
Comalapa 2	2,080	215	115	757
Bola de Oro	1,776	244	164	651

NR Not reported

[a] Static water level recorded as 82 m

Source: Granich & Elmore (2009)


University of Science and Technology
Evaluating Renewable Energy Resources to Pump Water
Geological Engineering
Conducted with the support of the people of Sacala Las Lomas and their Canadian friends
Contact: Dr. Curt Elmore elmoreac@mst.edu
University of Science and Technology
Evaluación de la energía renovable para bombeado de agua subterránea
Ingeniería Geológica
Guiado porel apoyo de las personas de Las Lomas, Sacala y los amigos Canadienses
wagr38@mst.edu
Missouri
S&T
elmoreac@mst.edu

Fig. 2 Two alternative pumping designs for the water storage system in Sacala. *Alternative 1* three water storage tanks, *Alternative 2* two water storage tanks

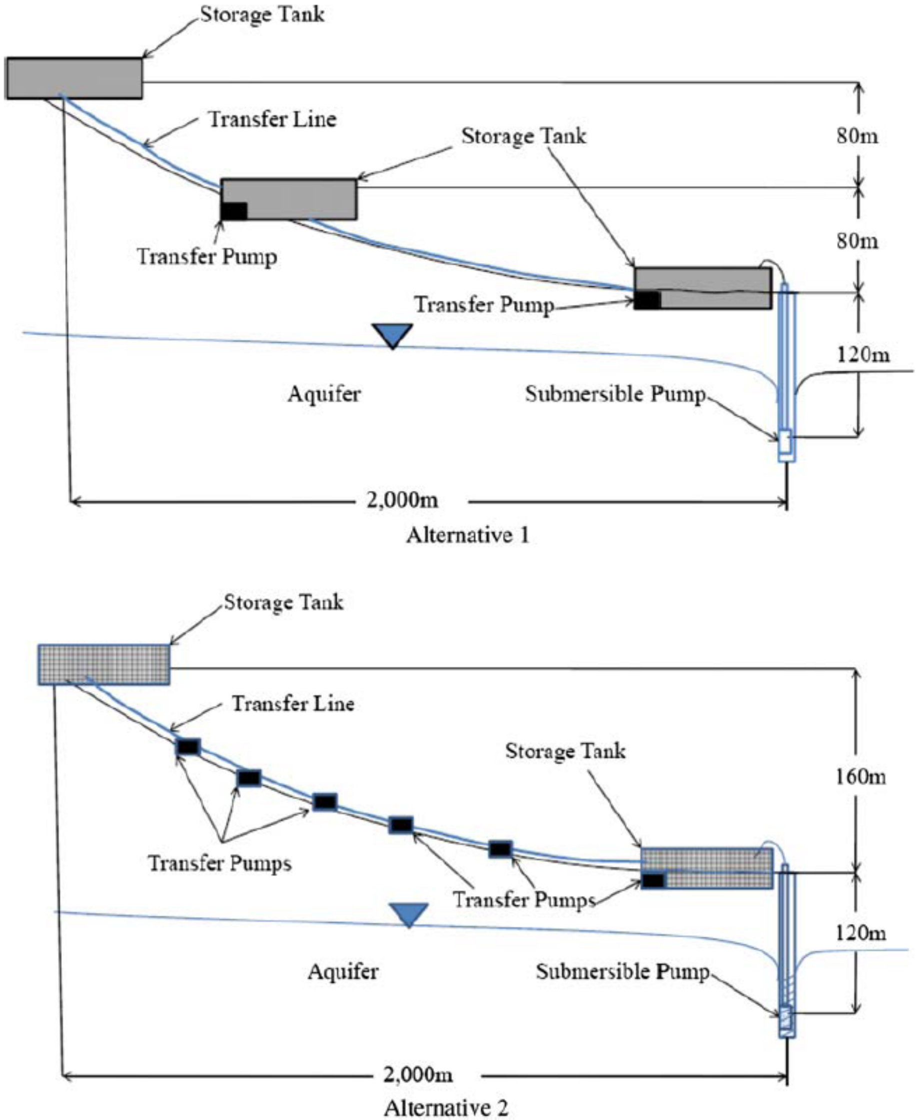


Table 4 Average solar insolation, ambient temperature, PSHs, and solar energy potential

Month[a]	Measured solar insolation (kW/m^2)	Ambient temperature (°C)	22-year average of PSHs (kWh/m^2/day)	Average of PSHs (kWh/m^2/day)	Precipitation (mm)	Energy/panel (kWh)
March 2008	0.210	15.80	6.02	5.20	5.1	8.38
April 2008	0.257	13.97	6.05	6.00	52.6	33.38
May 2008	0.226	15.10	5.48	4.54	98.8	28.11
June 2008	0.170	14.14	5.16	3.28	216.2	19.48
July 2008	0.167	13.99	5.45	3.30	292.4	17.52
August 2008	0.291	14.46	5.34	4.85	173.3	29.96
September 2008	0.170	14.70	4.73	4.00	221.8	24.63
October 2008	0.128	13.43	4.76	3.36	162.1	19.14
November 2008	0.175	13.53	4.90	4.88	<0.3	28.88
December 2008	0.149	13.89	4.95	4.28	2.3	26.15
January 2009	0.158	13.71	5.18	4.44	0.8	27.15
February 2009	0.181	13.92	5.73	4.84	1.3	26.82
March 2009	0.213	14.08	6.02	5.36	0.5	27.66

[a] Data collected from 24 March 2008 to 26 March 2009

Source: Granich & Elmore (2009)

Table 5 Average wind speeds, Weibull k values, and wind energy potential

Month[a]	Estimated wind velocity at 36.5 m (m/s)	22-year average of wind velocity at 36.5 m (m/s)	Weibull k	Energy/turbine (kWh)
March 2008	2.82	2.28	1.66	59
April 2008	2.60	2.10	1.30	230
May 2008	2.24	1.84	1.43	139
June 2008	2.26	1.76	1.61	128
July 2008	1.69	1.97	1.33	61
August 2008	1.91	1.89	1.61	62
September 2008	1.48	1.65	1.31	47
October 2008	1.94	2.07	2.29	47
November 2008	1.99	2.26	1.79	69
December 2008	2.11	2.51	2.23	65
January 2009	2.36	2.63	2.13	98
February 2009	2.98	2.47	2.22	195
March 2009	2.96	2.28	1.87	212

[a] Data collected from 24 March 2008 to 26 March 2009

Table 6 Energy demand, maximum solar panels (SPs) needed or maximum wind turbines (WTs) needed

Pump	Alternative 1			Alternative 2		
	Energy/pump (kWh/day)	SPs/pump	WTs/pump	Energy/pump (kWh/day)	SPs/pump	WTs/pump
16 SQF-10	9	16	28	NA	NA	NA
40 SQF-5	7.6	13	26	6.8	12	23
Total needed		97	186		108	207

“Technical” conclusion?

"Non-technical" benefit!

Conclusions

- Expect random variability!
- If the answer is too good to be true ….
- Have reasonable expectations
- Costs aren’t everything
  - Environmental remediation typically isn’t a revenue generator!