Decision Support Analysis for a Renewable Energy System to Supply a Grid-connected Commercial Building

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Presentation

- Introduction to the project
  - Motivation & Context
  - Prior projects
- Project Breakdown
  - The Research Question
  - Characterizing the components
  - Analysis methods
  - Evaluation
- Conclusion, Contributions, Acknowledgements
- Q & A

Project Introduction

- Alternative energy
  - Particular interest: Using RES on-site in real time
    - Microgrid applications
    - Commercial vs. residential
- The Playas application
  - Unique situation: isolated town on its own branch (microgrid)
  - Desire to connect renewable energy sources (RES) to microgrid
    - Predict cost/benefit
    - Evaluate size/quantity of RES (particular source in mind)
  - Grid-connected building with high resolution data
- Decision support
  - Existing options
  - Custom solution

The Research Question

- How would a particular RES interact with the building's electrical load?
  - Command & Control Center
    - Diverse commercial load
    - Line-to-line 208 V_{RMS} 3Φ (120 V_{RMS} line-to neutral)
  - Emcore Concentrator Photovoltaic Array (CPV)
    - Alternate solar panel design
    - ~25 kW rating
- The key approach
  - Use limited known data to forecast source production, load consumption, and grid energy usage
  - Analyze power balance by the minute over a full year

Characterizing the Components

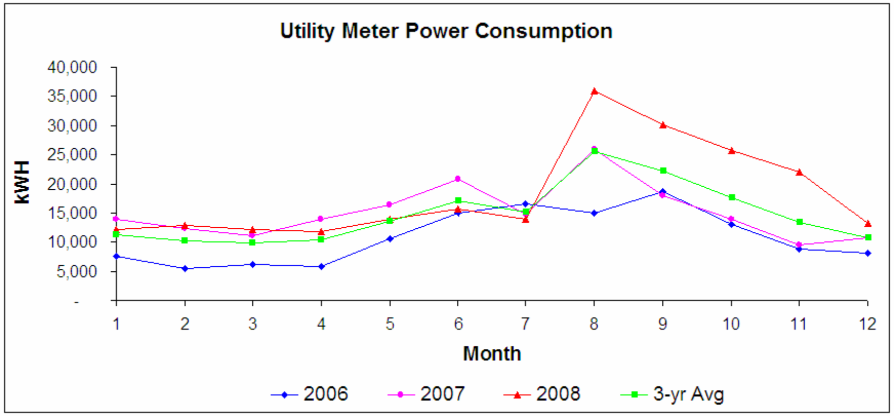
- Load
  - Preparing the data
    - Monthly billing history
    - One week of detailed real time data
    - Seasonal/weather considerations
  - Generating the annual load profile
- Source
  - Understanding the hardware
  - Preparing the data
    - One-day production test
    - Site data
  - Generating the annual source profile

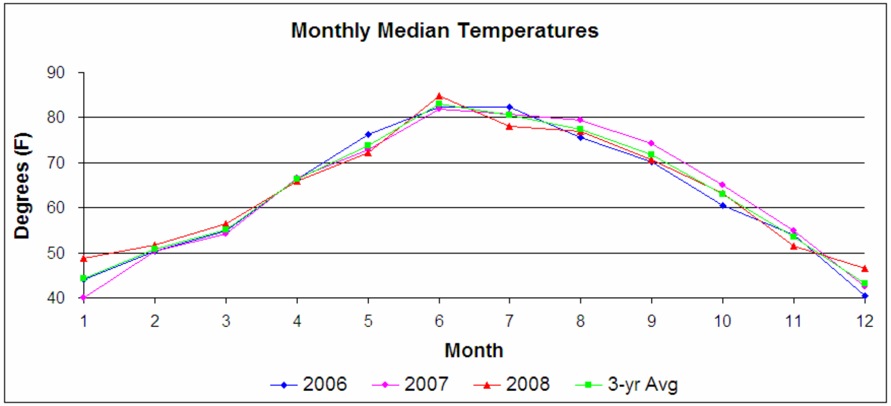
Characterizing the Load

- Monthly billing history
  - Three years of monthly bills (real power only)
- One week of detailed real time data
  - Per-minute resolution
  - Voltage, current, frequency, real power, reactive power, apparent power, power factor, PF angle
  - Measured with GE Sub meter
    - Uses combination of voltage probes and current transformers
- Other related data
  - Site usage
  - Weather trends

Load Monthly Data

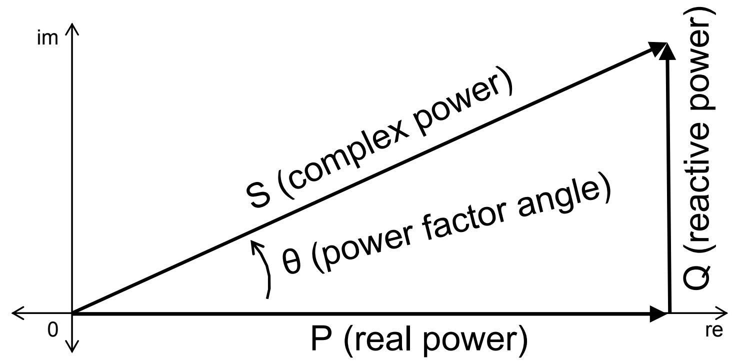
- Annual power usage trends.
  - Peak & decline in summer 2008
  - Unsure if this is a trend or not (more data needed)
  - 3-year per-month average used for analysis
- Weather trends
  - Seasonal impact
  - No direct correlation with year-to-year load



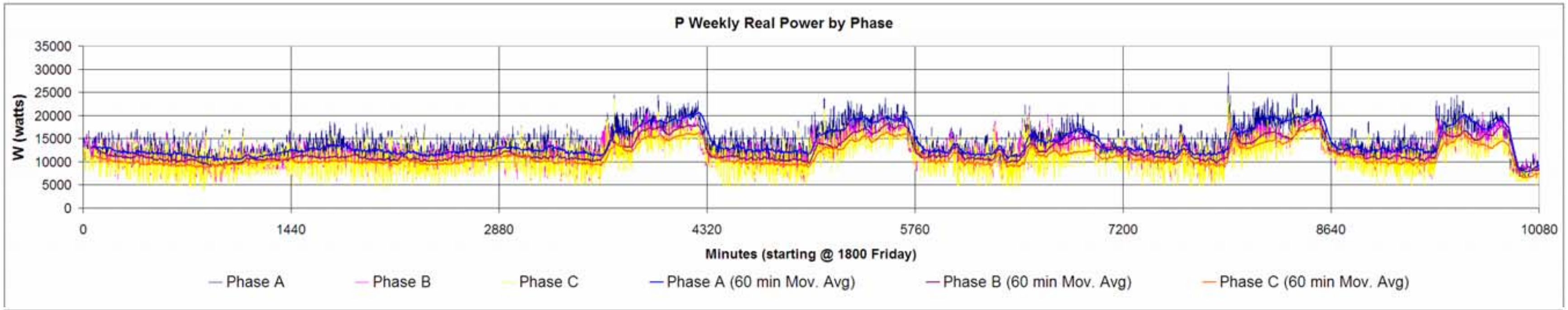


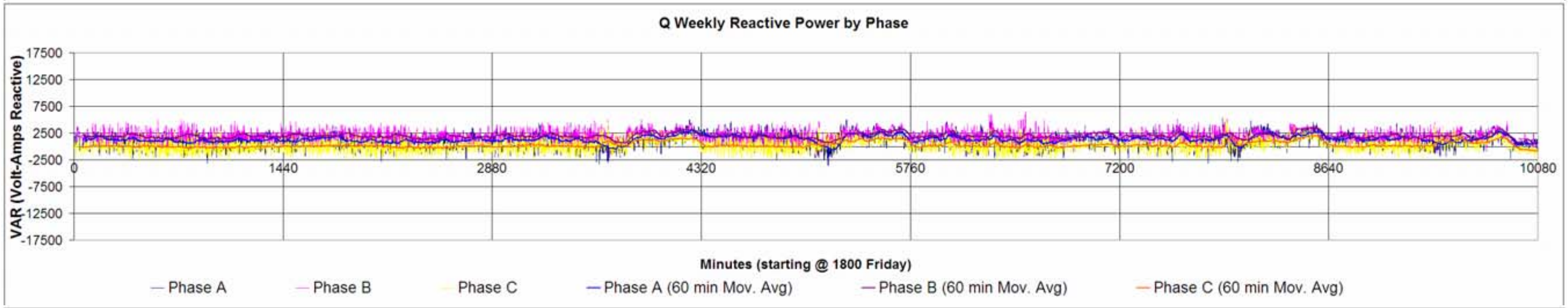
Power Relationships

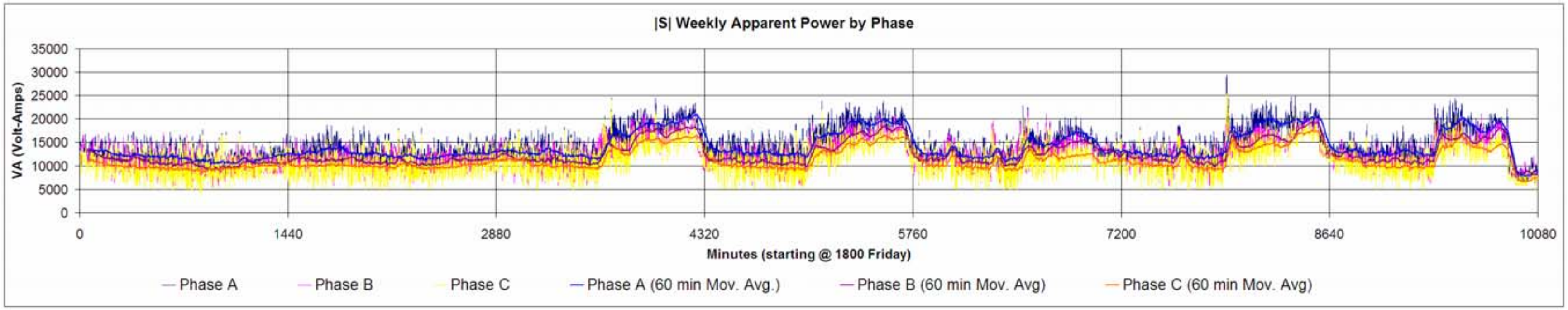
- P = real power
  - Electric utility meter measures P
  - Resistive component of load
- Q = reactive power
  - Not measured on utility meter
  - Inductive/capacitive component
- S = complex power
    - $S = P + jQ$
- |S| = apparent power
    - $|S| = \text{sqrt}(P^2 + Q^2)$
  - Represents magnitudes of real power plus reactive power exchanged
- θ = power factor angle
  - Represents phase shift between voltage and current
    - Power factor = cos θ
    - PF leading if θ < 0 (I leads V)
    - PF lagging if θ > 0 (I lags V)



Load Weekly Per-Minute Data: S, P, Q

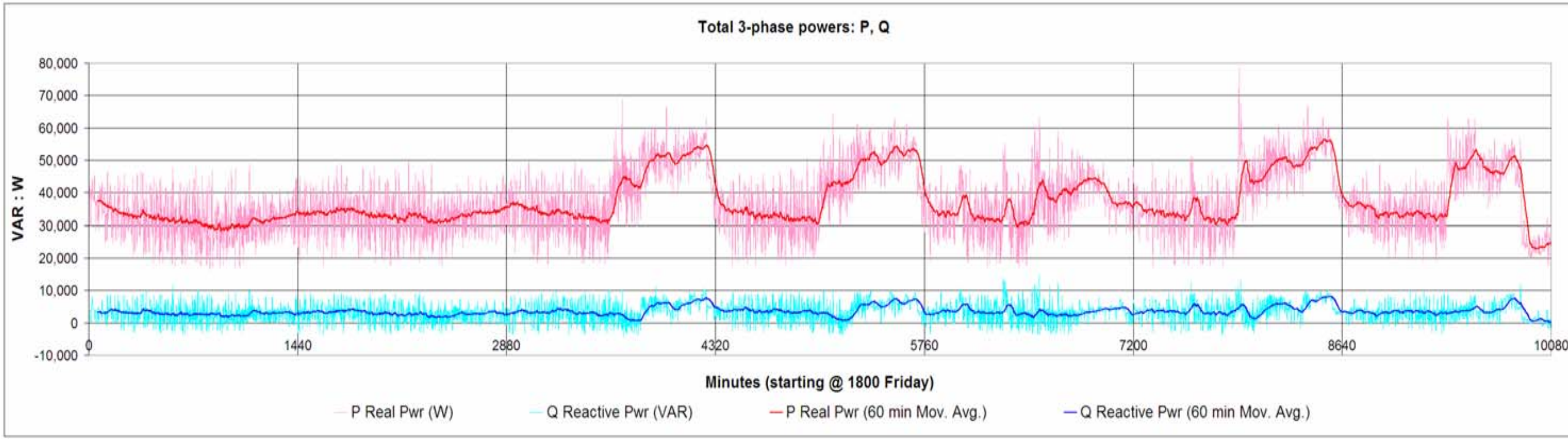






3-phase Total Real & Reactive Power

One week starting Fri 1800



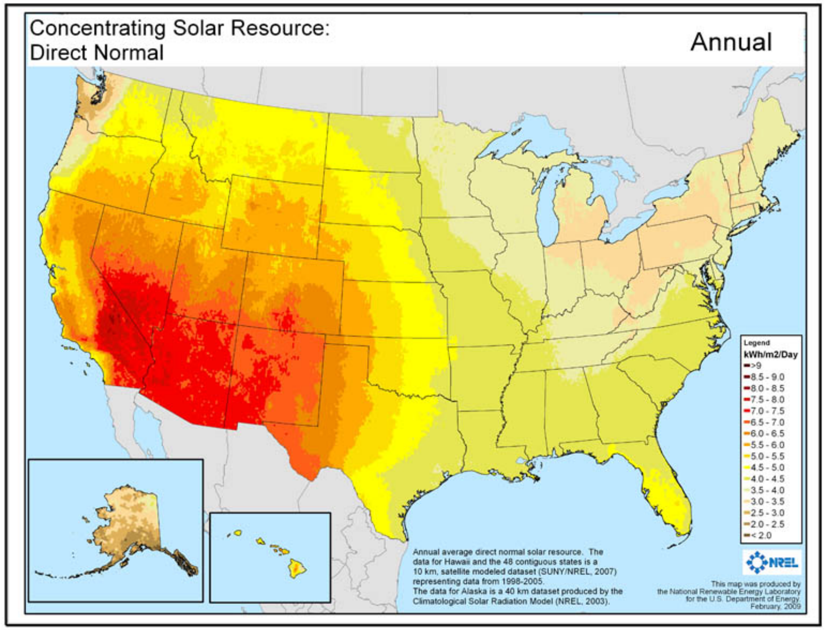
- P and Q both peak during weekday daylight hours
- Real power very large compared to Reactive P >> Q
  - Minimal power factor angle. $\theta \approx 0$ (Avg = 7.69°)
  - Close to ideal power factor PF ≈ 1 (Avg = 0.991)
  - Apparent power plot mimics Reactive almost exactly

Generating the Annual Load Profile

- Weekly per-minute profile normalized
  - Each minute's percentage of full week calculated
  - Week of minutes broken out into days
- Monthly profile generated for 2010
  - Constructed each month out of proper sequence of days
  - Averaged power bill into weekly portion
  - Each daily minute percentage multiplied by weekly power
  - Result is a minute-by-minute prediction of power usage for 2010

Characterizing the Source

- Understanding the hardware
  - CPV Specifications
- Characterizing the CPV
  - One-day performance test
  - Mathematical model
- Site Data for solar irradiation
  - Choosing the site
  - Preparing the data
- Generating the annual source profile



NREL: http://www.nrel.gov/gis/images/map_csp_us_10km_annual_feb2009.jpg

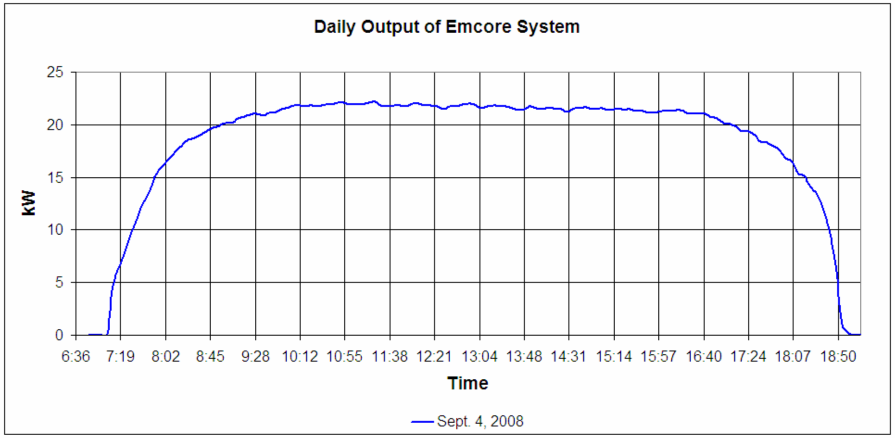
Hardware Specifications
Emcore Concentrator Photovoltaic Array (CPV)

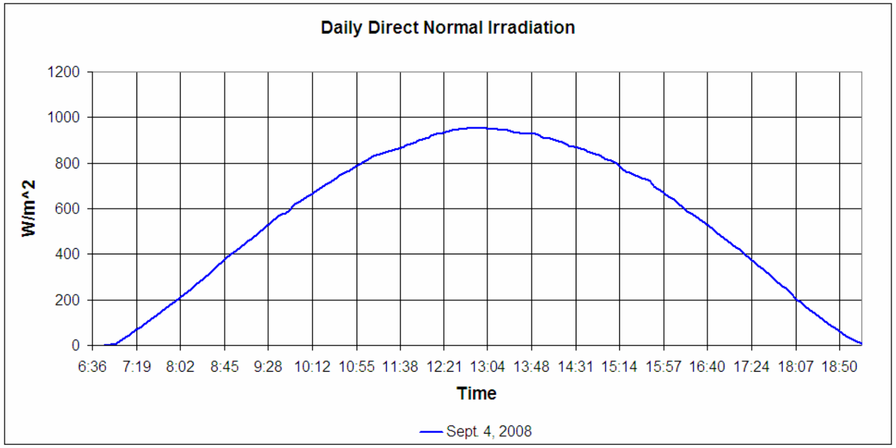
Emcore Corporation

- Specifications
  - 60 x 26 feet 19,000 pounds ~10 tons
  - Uses Fresnel lenses to concentrate light 500x
  - Electric current leaving PV cell keeps material cool
  - Rated for 25 kW, achieves ~22kW in test cond.
  - Temp dependence: ↑Temp ⇨ ↓ Production
    2% @ 122° F 1.2% @ 104° F 0.4% @ 50° F

Characterizing the CPV

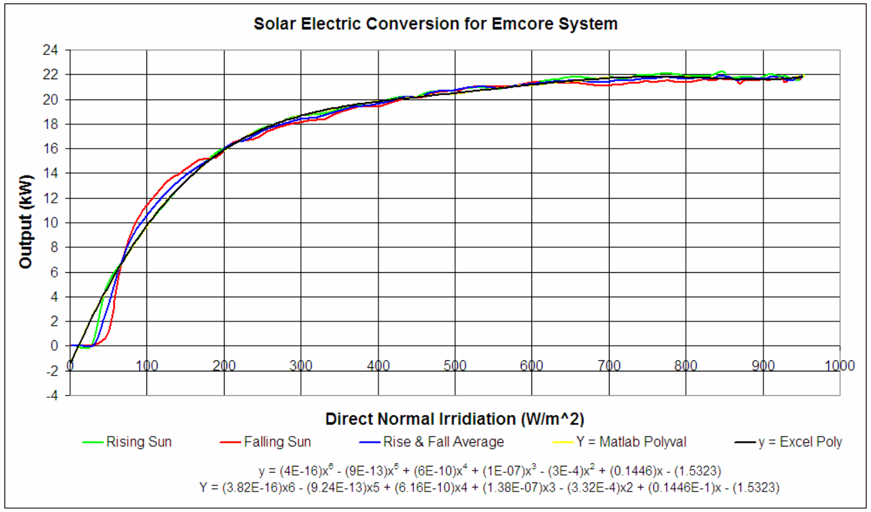
- One-day performance test
  - 22kw nominal output
  - Minimal output for indirect irradiation
- Solar data for test day
  - NWS @ Sunport
  - Direct irradiation



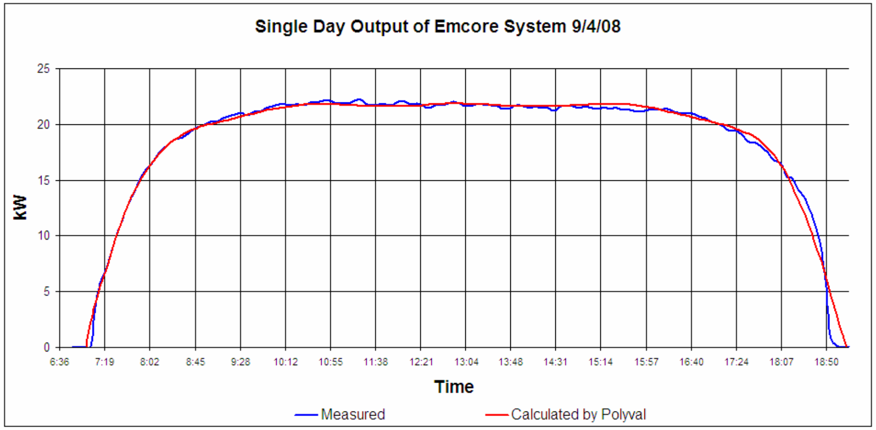


Characterizing the CPV

- Power output in kW as a function of solar irradiation
- Rising/falling sun averaged
- Least-squares polynomial fit
  - 6^{th} order MATLAB polyfit vs Excel polynomial
  - Problems with output < 0



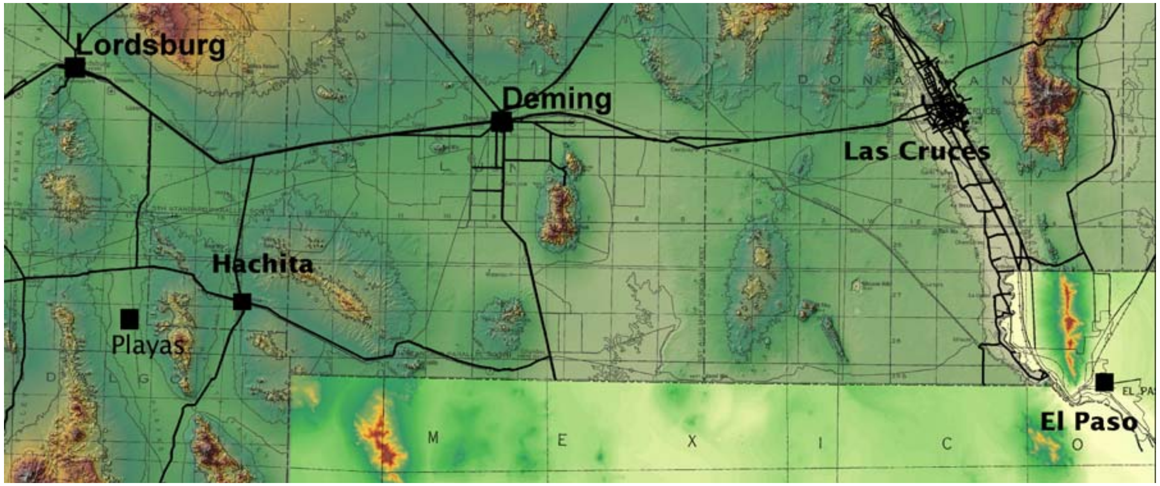
- Polyval used to re-construct daily output prediction based on test day solar data
- Mathematical model success
- Site solar data used for predictions



Site data for Source Characterization

- Predicting solar irradiation
  - Bird clear-sky model
  - Other hourly/monthly data sources
- Historical Data
  - Need high resolution
    - Most databases use hourly or daily averages
    - Prefer one-minute resolution
  - Nearby collection sites
    - Several sites offer close to required resolution
      - Las Cruces
      - El Paso
  - Site map next slide

Playas Area Geography



New Mexico Bureau of Geology and Mineral Resources

- Total Distance
  - Las Cruces: 108 mi El Paso: 125 mi Hachita: 12 mi
- Latitude: N/S displacement
  - Las Cruces: 20 mi El Paso: - 8 mi Hachita: 0 mi
- Elevation (Playas: 4498')
  - Las Cruces: 3940' El Paso: 3999' Hachita: 4524'

Site data for Source Characterization

- Las Cruces site chosen
  - Day length +/- 2 min on solstices, equal on equinoxes
  - Extra data for possible future use
- Complete year 1999 available
  - Daytime sun ~ 700-1000 W/m^2
  - Quantities close to Bird Clear Sky Model
    - Slightly lower, as expected, accounting for clouds and other atmospheric conditions
  - Source files at 5-minute resolution, expanded to 1-minute resolution using linear interpolation
  - Stored in months of minutes, match file size of load data exactly
- Data contains per-minute direct solar irradiation values

Generating the Annual Source Profile

- MATLAB used
  - Open monthly solar data file
  - Plug each minute's solar radiation value into polynomial using polyval function
  - Results are the expected CPV power output for each minute
  - Store resulting values into monthly production files
- Resulting files are the monthly predictions for minute-by-minute electric production from CPV
  - Negative values changed to zeros
    - Source is not consuming power, these are anomalies from polynomial error at low production

Analysis

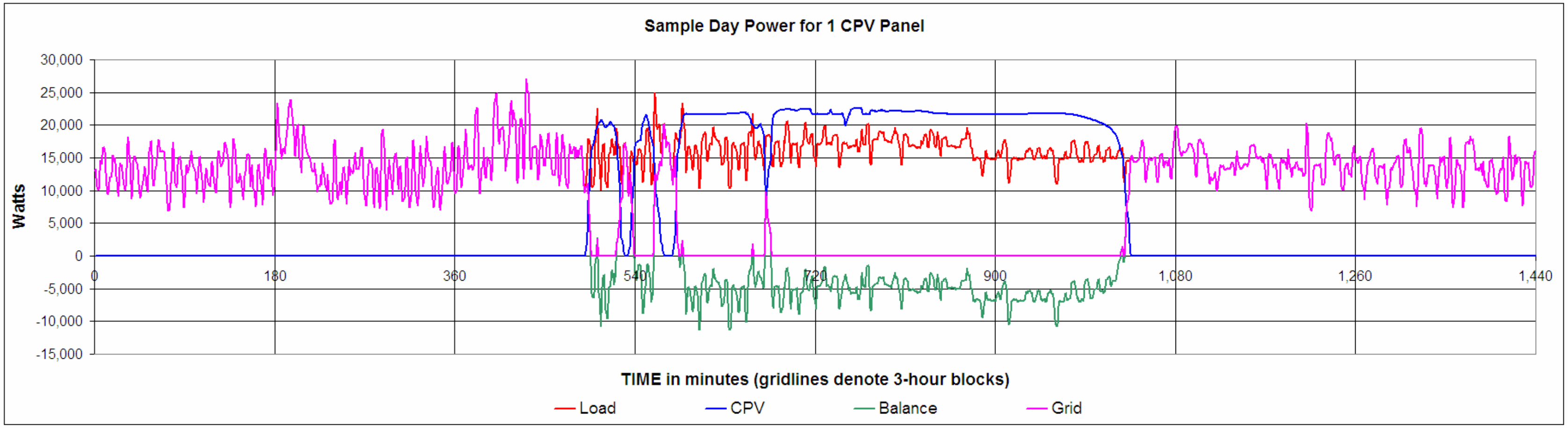
- Power balance
  - Compare load demand vs source production for every minute of a year
- Results
- Quantity of panels
- Evaluation spreadsheet

Analysis Computation

- Power balance
  - MATLAB used
    - Open each month's source and load data files
    - Perform mathematical power sum for each minute of the month.

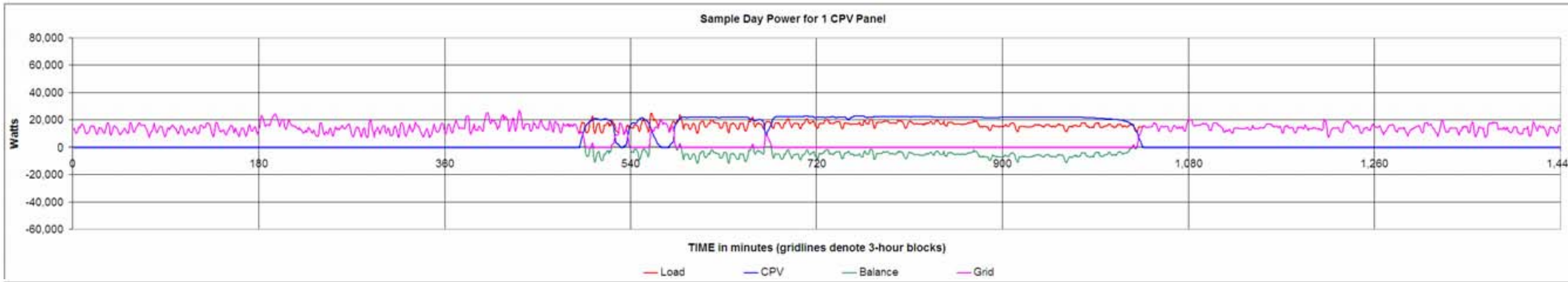
      (load power) – n(source power) = (balance)
    - Store balance figure into new monthly per-minute power balance file
    - Repeat for each value of n (n = number of panels)
  - Balance is a positive or negative number
    - Positive result represents grid power used
    - Negative result represents surplus power generated
      - Can be net-metered back to grid, sent to microgrid, or stored locally

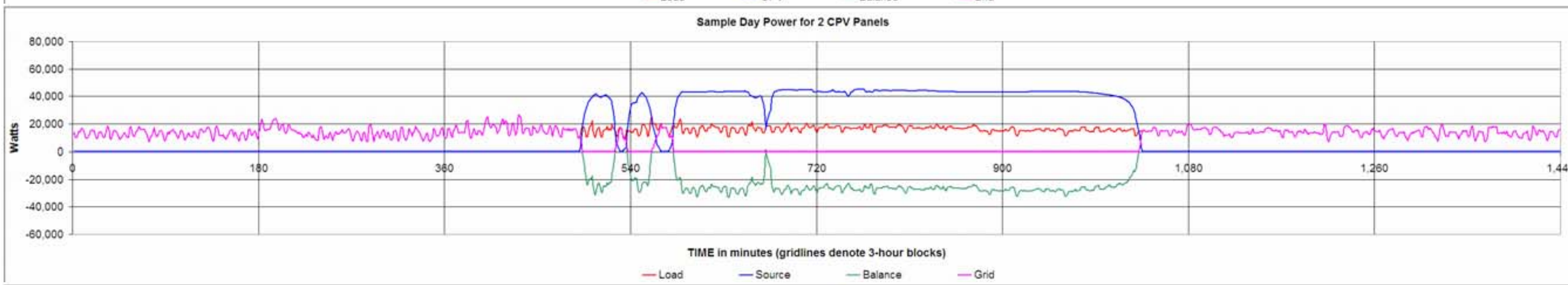
Power Balance for Sample Day (1 CPV)

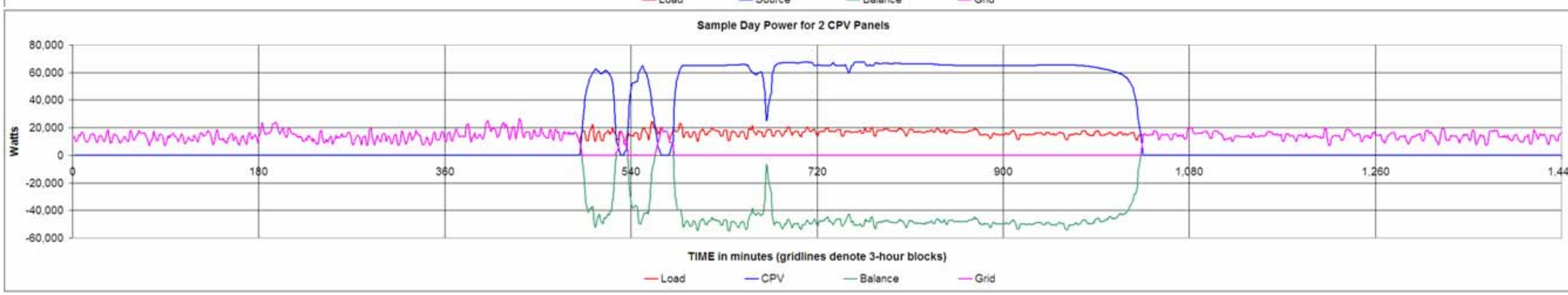


- Night: $P_{SOURCE} = 0$ $P_{LOAD} = P_{GRID}$
- Day: $P_{GRID} = P_{LOAD} - P_{SOURCE}$ for $P_{GRID} \geq 0$
- Per-minute resolution benefit can be seen
- Green notes surplus energy generated
  - Net metering, microgrid supply, and/or storage potential

Power Balance for Sample Day (Multiple CPV)







Evaluation

- Spreadsheet
  - Display results and computations
- Samples
- Evaluation of results
- Comparison to other RES options

Evaluation Spreadsheet

- Excel used to evaluate power balance results
- Retrieve data
  - Power balance data
    - Separate positive and negative power sum balances
    - Sum separately for each month
    - Provides surplus power and grid power usage figures
  - Other existing data
    - Original monthly power bills for comparison
- Perform error checks
  - Compare monthly summaries from results to original monthly bills
- Input user constants
  - Power buy/sell/REC rates, maintenance costs, emissions, financing options, project lifetime
- Calculate financial & environmental quantities
- Compute lifetime figures for cost, savings

Evaluation Spreadsheet

Master Summary ::: 1 Panel

W-min	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	W-min
Total Load Power	676,254,094	612,000,000	584,852,585	630,046,927	817,413,092	1,028,837,968	912,030,181	1,523,718,045	1,341,873,436	1,058,903,302	802,080,729	644,611,520	10,632,437,358	Total Load Power
Total RES Power	357,881,135	346,350,300	387,774,270	403,779,150	470,051,768	429,915,175	373,613,428	406,806,022	372,290,813	401,330,539	382,984,902	290,546,786	4,623,308,886	Total Source Power
Debt used from grid	395,403,926	341,596,737	320,718,496	328,134,173	401,490,235	614,929,505	564,792,291	1,117,934,607	972,280,202	673,089,483	463,327,957	423,842,159	6,617,409,815	Debt used from grid
Surplus RES	(77,030,977)	(75,947,068)	(123,640,434)	(101,864,445)	(54,118,851)	(16,008,735)	(26,375,592)	(1,024,403)	(2,877,823)	(15,516,728)	(44,089,077)	(69,779,413)	(608,281,347)	Surplus
Site-consumed RES	280,850,158	270,403,232	264,133,835	301,914,705	415,920,937	413,908,441	347,237,836	405,784,219	369,413,190	385,813,810	338,895,825	220,769,353		Site-consumed RES
Load check	676,254,088	611,999,969	584,852,331	630,048,876	817,413,172	1,028,838,005	912,030,127	1,523,718,028	1,341,873,392	1,058,903,274	802,080,782	644,611,512	10,632,437,354	Load check
source check	357,881,135	346,350,300	387,774,270	403,779,150	470,051,768	429,915,175	373,613,428	406,806,022	372,290,813	401,330,539	382,984,902	290,546,786	4,623,308,886	source check

kWH	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	kWH
	-	-	-	-	-	-	-	-	-	-	-	-		
Total Load Power	11,271	10,200	9,748	10,501	13,624	17,147	15,201	25,395	22,361	17,648	13,368	10,744	177,207	Total Load Power
Total RES Power	5,965	5,773	6,463	6,730	7,834	7,165	6,227	6,780	6,205	6,689	6,383	4,842	77,055	Total Source Power
3-yr avg billed power	11,240	10,200	9,800	10,480	13,640	17,160	15,120	25,600	22,240	17,600	13,480	10,694	177,254	3-yr avg billed power
% error	-0.27%	0.00%	0.54%	-0.20%	0.12%	0.07%	-0.53%	0.80%	-0.55%	-0.27%	0.83%	-0.46%	0.03%	% error
Debt used from grid	6,590	5,693	5,345	5,469	6,691	10,249	9,413	18,632	16,204	11,218	7,720	7,064	110,290	Debt used from grid
Surplus RES	(1,284)	(1,266)	(2,061)	(1,698)	(902)	(267)	(440)	(17)	(48)	(259)	(735)	(1,163)	(10,138)	Surplus
Site-consumed RES	4,681	4,507	4,402	5,032	6,932	6,898	5,787	6,763	6,157	6,430	5,648	3,679	66,917	Site-consumed RES
Load check	11,271	10,200	9,748	10,501	13,624	17,147	15,201	25,395	22,361	17,648	13,368	10,744	177,207	Power check
Source Check	5,965	5,773	6,463	6,730	7,834	7,165	6,227	6,780	6,205	6,689	6,383	4,842	77,055	Source Check
Net Metering														**Net Metering**
Net kWH	5,306	4,427	3,285	3,771	5,789	9,982	8,974	18,615	16,156	10,960	6,985	5,901	100,152	Net kWH
Savings kWH	5,965	5,773	6,463	6,730	7,834	7,165	6,227	6,780	6,205	6,689	6,383	4,842	77,055	Savings kWH
Savings %	53%	57%	66%	64%	58%	42%	41%	27%	28%	38%	48%	45%	43%	Savings %
Financial														**Financial**
Cost kWH	659	569	535	547	669	1,025	941	1,863	1,620	1,122	772	706	11,029	Cost kWH
Income kWH	(128)	(127)	(206)	(170)	(90)	(27)	(44)	(2)	(5)	(26)	(73)	(116)	(1,014)	Income kWH
Income RE Credits	-	-	-	-	-	-	-	-	-	-	-	-	-	Income RE Credits
Net	531	443	328	377	579	998	897	1,862	1,616	1,096	699	590	10,016	Net Annual Cost
Grid cost w/o RES	1,127	1,020	975	1,050	1,362	1,715	1,520	2,540	2,236	1,765	1,337	1,074	17,721	Grid cost w/o RES
Savings $	596	577	646	673	783	717	623	678	620	669	638	484	7,706	Savings $
Savings %	53%	57%	66%	64%	58%	42%	41%	27%	28%	38%	48%	45%	43%	Savings %
Emissions kg														**Emissions kg**
Carbon Dioxide	4,165	3,598	3,378	3,458	4,229	6,477	5,949	11,776	10,241	7,090	4,879	4,464	69,703	Carbon Dioxide
Sulfer Dioxide	18	16	15	15	18	28	26	51	44	31	21	19	302	Sulfer Dioxide
Nitrogen Oxides	9	8	7	7	9	14	13	25	22	15	10	9	148	Nitrogen Oxides
Emissions w/o RES kg														**Emissions w/o RES kg**
Carbon Dioxide	7,123	6,446	6,160	6,637	8,610	10,837	9,607	16,050	14,132	11,154	8,449	6,790	111,995	Carbon Dioxide
Sulfer Dioxide	31	28	27	29	37	47	42	70	61	48	37	29	486	Sulfer Dioxide
Nitrogen Oxides	15	14	13	14	18	23	20	34	30	24	18	14	237	Nitrogen Oxides
Savings kg														**Savings kg**
Carbon Dioxide	2,958	2,848	2,782	3,180	4,381	4,360	3,658	4,274	3,891	4,064	3,569	2,325	42,292	Carbon Dioxide
Sulfer Dioxide	13	12	12	14	19	19	16	19	17	18	15	10	183	Sulfer Dioxide
Nitrogen Oxides	6	6	6	7	9	9	8	9	8	9	8	5	90	Nitrogen Oxides
Emissions credits kg (all RES)														**Emissions credits kg (all RES)**
Carbon Dioxide	3,770	3,648	4,085	4,253	4,951	4,528	3,935	4,285	3,921	4,227	4,034	3,060	48,699	Carbon Dioxide
Sulfer Dioxide	16	16	18	18	21	20	17	19	17	18	17	13	211	Sulfer Dioxide
Nitrogen Oxides	8	8	9	9	10	10	8	9	8	9	9	6	103	Nitrogen Oxides
Savings %														**Savings %**
w/o considering surplus RES	42%	44%	45%	48%	51%	40%	39%	27%	28%	36%	42%	34%	38%	w/o considering surplus RES
considering all RES	53%	57%	66%	64%	58%	42%	41%	27%	28%	38%	48%	45%	43%	considering all RES

From data files

Error checking

Converted from W-min

User constants

User Constants

Energy cost

$/kWH	
0.1	Purchase electricity
0.1	Sell back electricity
0	Renewable Energy Credits

Emissions Released

g/kWH
632
2.74
1.34

Financial Analysis

$	50,000.00	RES Total cost
$	30,000.00	Principal Investment
$	20,000.00	Financed amount
	7%	Interest Rate (annual %)
	60	Term (months)
	$396.03	Monthly Payment
$	23,761.44	Financed cost
$	3,761.44	Interest expense
$	1,000.00	Annual maintenance cost
$	18,767.88	Annual total cost
$	53,761.44	Total Capital Cost
	7	Payback period (years)
	15	System lifespan
$	265,810.93	Total lifetime cost w/o RES
$	218,989.65	Total lifetime cost w/ RES
$	46,821.28	Total lifetime savings or (loss)
	18%	Total lifetime savings or (loss)

Evaluation results

- 1 panel
  - Can pay for itself with proper financing and advantageous renewable energy credit programs
  - Saves 50,000 kg of CO_2 per year (55 tons)
- 2 panels
  - Not likely to pay for itself unless load increases moderately
  - Saves 100,000 kg of CO_2 per year (110 tons)
- 3 panels
  - Couldn't possibly pay for itself unless load increases substantially
  - Saves 150,000 kg of CO_2 per year (165 tons)
- In general, producing more power than can be used on-site has limited payoff.

Source Comparison for Equal Footprint

- 3 CPV Panels
  - 14 w/ft^2 of panel, panel >> cell size
  - 75 kW rating (.075 MW)
  - ~66 kW actual output (.066 MW)
  - $750,000 ⇨ $11.36 per watt
- Traditional PV panels
  - 468 100w panels @ 10w/ft^2
  - ~46.8 kW (.046 mW)
  - $468,000 ⇨ $10.00 per watt
- Utility Wind Turbine
  - 1.6 MW rating
  - ~1.0 MW actual output
  - $1,500,000 ⇨ $1.50 per watt
- For twice the money WTG provides 10x power capacity of CPV.

Conclusion / Future direction

- Load predicted
  - Satisfactory results
  - More per-minute data will create better annual profile
- Effective mathematical model for source
- Means to evaluate lifetime cost/benefit
- Analysis
  - Automation would allow for simpler adaptation to new or alternate input data
- Evaluation
  - Automation for data input
  - Accommodating tiered rate structures
- Confirmation
  - Time will provide more data to evaluate how close the estimates came to actual values

Contributions

- Power quality analysis
- High resolution power balance
  - Per minute vs hourly or daily averages
- Characterization of unusual source type
  - CPV vs traditional PV
- Additional revenue programs
  - REC
- Environmental analysis

Acknowledgements

- Graduate/Thesis advisor
  - Dr. Kevin Wedeward
- Graduate Committee
  - Dr. Aly El-Osery, Dr. Bill Rison
- NMT EE Faculty
  - Thanks to all
  - Chair: Dr. Scott Teare
- Technical resources
  - Wes Helgeson, IERA
  - Mark Mansell, NM Bureau of Geology & Mineral Resources

Q & A

- Thank you
- Questions from general audience

- Closed session with committee