IOWA STATE UNIVERSITY
Electrical Power and Energy Systems (EPES)
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MW Resource Assessment Model for a Hybrid Energy Conversion System With Wind and Solar Resources

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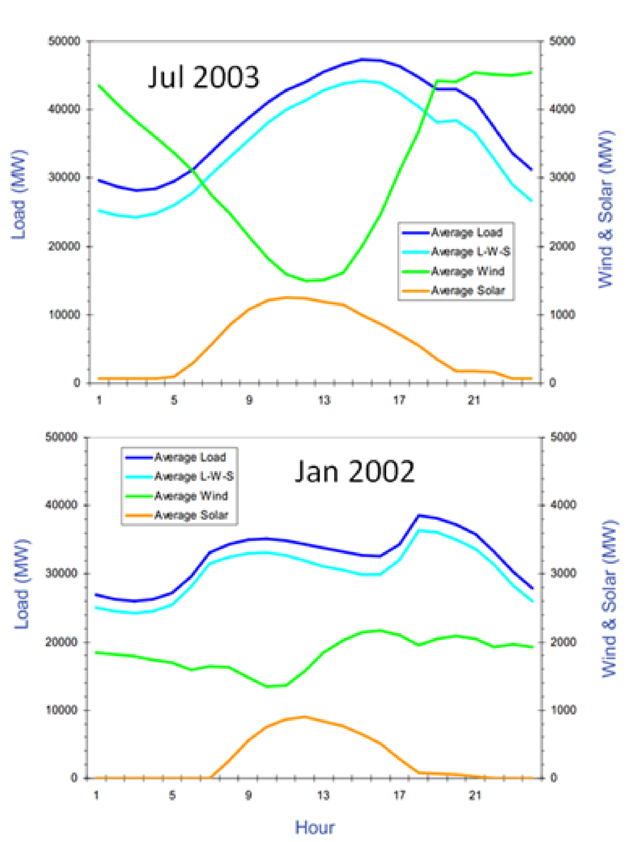
Challenges in Grid Integration of Renewable Energy

- Dealing with intermittency of Power output from renewable energy sources.
- Increasing the renewable energy penetration without hampering grid stability and reliability.
- Addressing adverse effect of output fluctuations on power grid frequencies, voltages & transient performance.

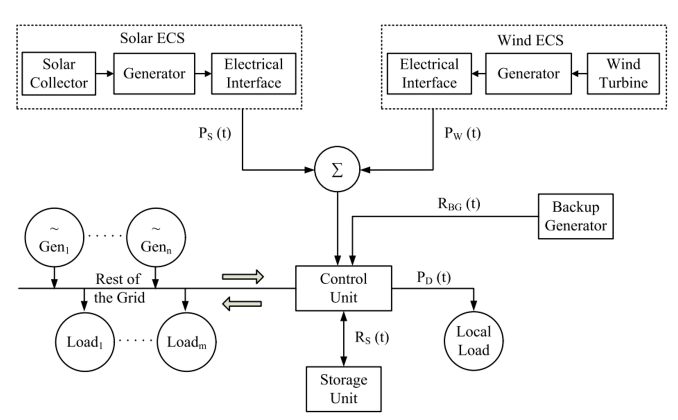


• California Average wind and solar output, along with net demand – July 2003 & Jan 2002 (scaled to 2010 levels)[2]

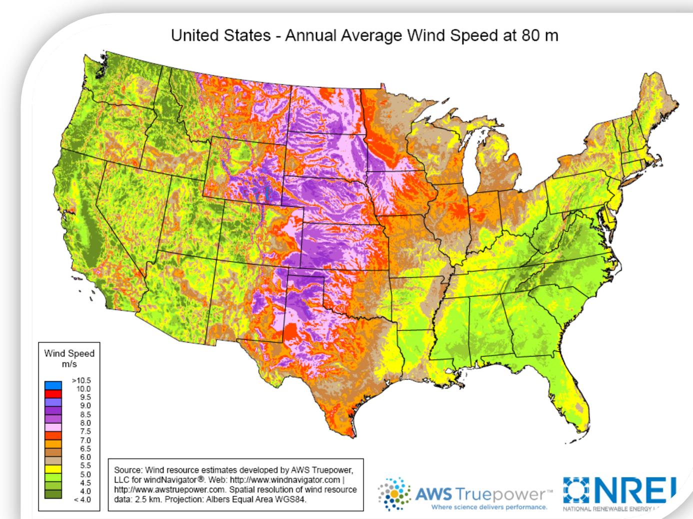
Taking Advantage of Hybrid Wind-Solar Generation:

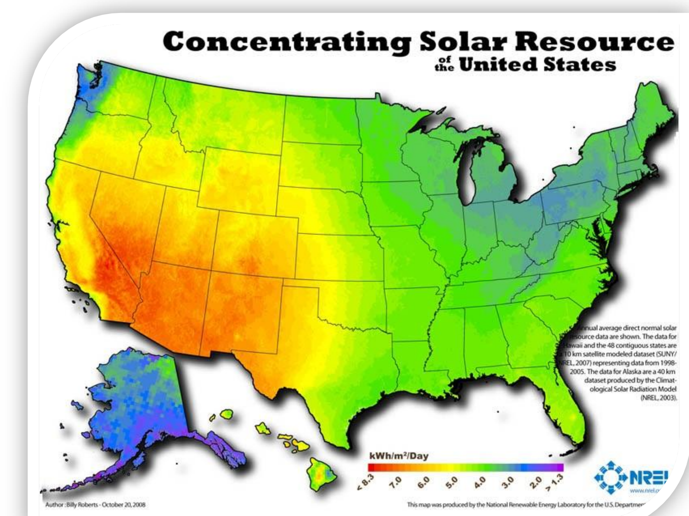
- Complementary solar and wind plant profiles when considered in aggregate can be a good match to the load profile.
- As compared to stand-alone plants, the hybrid plant would require less storage or reserve capacity.
- Reduction in emissions, generation of additional jobs, security of supply etc.

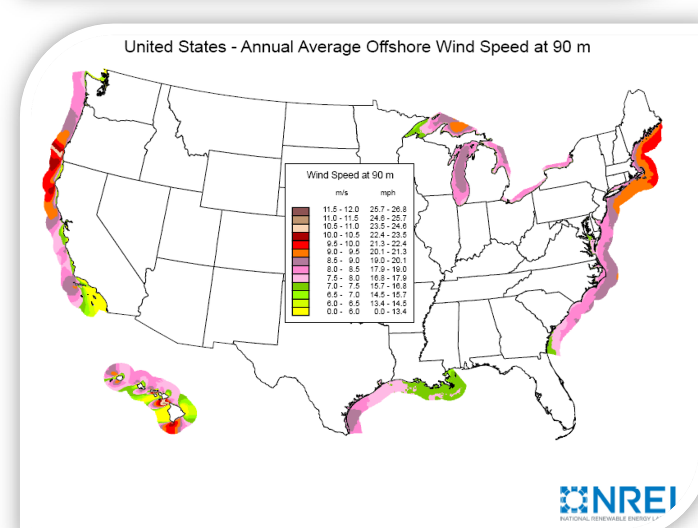
Schematic of Wind & Solar Hybrid Energy Conversion System (HECS)

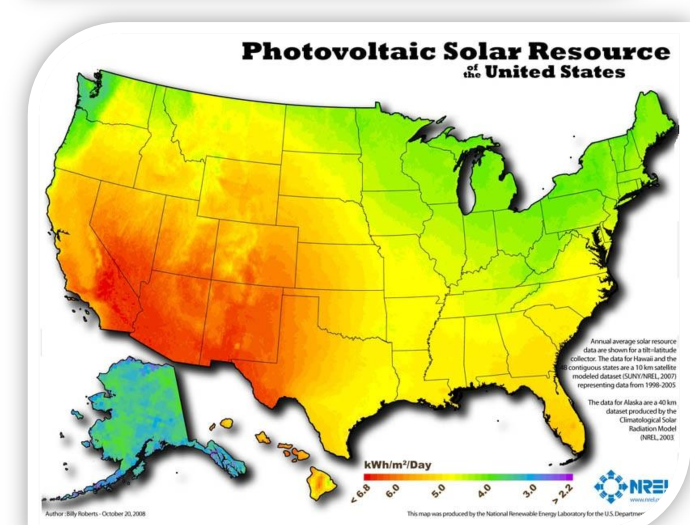


Wind (*Onshore & Offshore*) & Solar (*Concentrating & Photovoltaic*) Resource of USA









Identification of Candidate Wind-Solar Sites, HECS ID Tool

- Desired Locations should have
  - Highest complementarity
  - Least distance
- HECS ID Tool automatically computes & creates a pairing of sites locations to form hybrid locations.

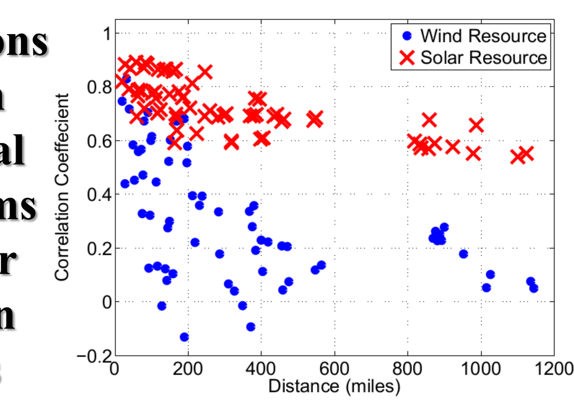
Wind Speed Data			
Serial #	ID	Latitude	Longitude
W1	3579°	35.08	-116.96
W2	709°	32.71	-116.27
W3	1169°	33.94	-116.76
W4	1481°	34.11	-101.17
W5	1551°	34.16	-116.37
W6	5606°	35.56	-116.61
W7	2832°	34.86	-116.74
W8	2935°	34.92	-118.99
W9	6172°	35.89	-117.87
W10	9039°	37.66	-118.99
W11	11819°	39.78	-120.69
W12	12514°	40.17	-120.39

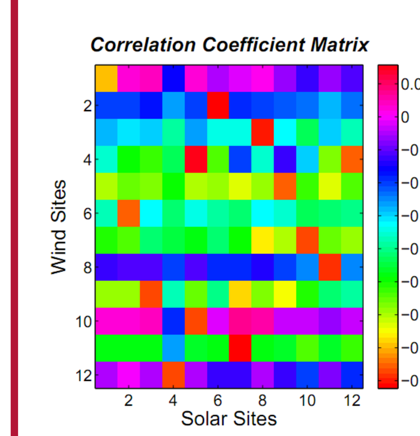
&

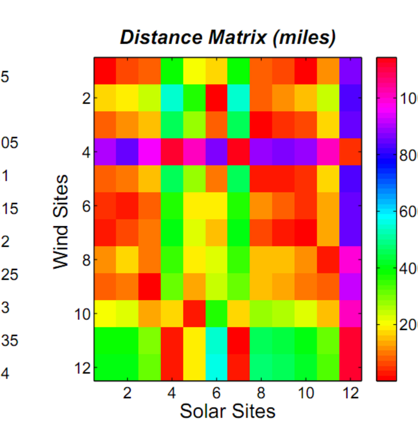
Solar DNI Data			
Serial #	ID	Latitude	Longitude
S1	117053505*	35.05	-117.05
S2	116053545*	35.45	-116.05
S3	117853605*	36.05	-117.85
S4	120153995*	39.95	-120.15
S5	118553775*	37.75	-118.55
S6	116253275*	32.75	-116.25
S7	120653985*	39.85	-120.65
S8	116753395*	33.95	-116.75
S9	116353445*	34.45	-116.35
S10	723815+	34.85	-116.80
S11	723840+	35.43	-119.05
S12	722670+	33.67	-101.82

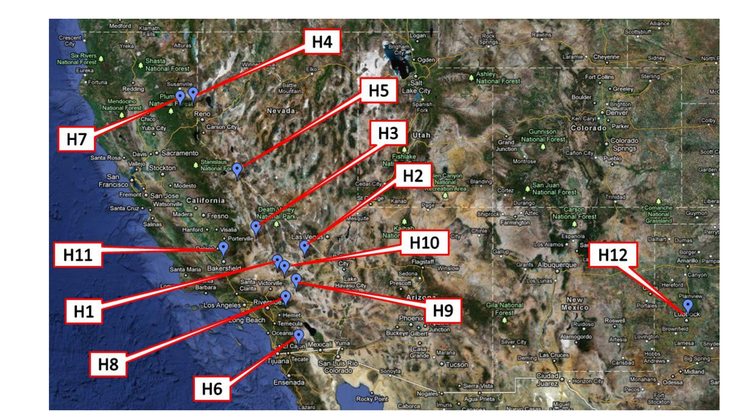
Hybrid Site	Pairing	Solar ID	Wind ID	Distance (miles)
H1	(S1,W1)	117053505	3579	6
H2	(S2,W6)	116053545	5606	33
H3	(S3,W9)	117853605	6172	12
H4	(S4,W12)	120153995	12514	20
H5	(S5,W10)	118553775	9039	25
H6	(S6,W2)	116253275	709	3
H7	(S7,W11)	120653985	11819	6
H8	(S8,W3)	116753395	1169	1
H9	(S9,W5)	116353445	1551	21
H10	(S10,W7)	723815	2832	4
H11	(S11,W8)	723840	2935	36
H12	(S12,W4)	722670	1481	49

Correlations between individual wind farms and solar radiation stations

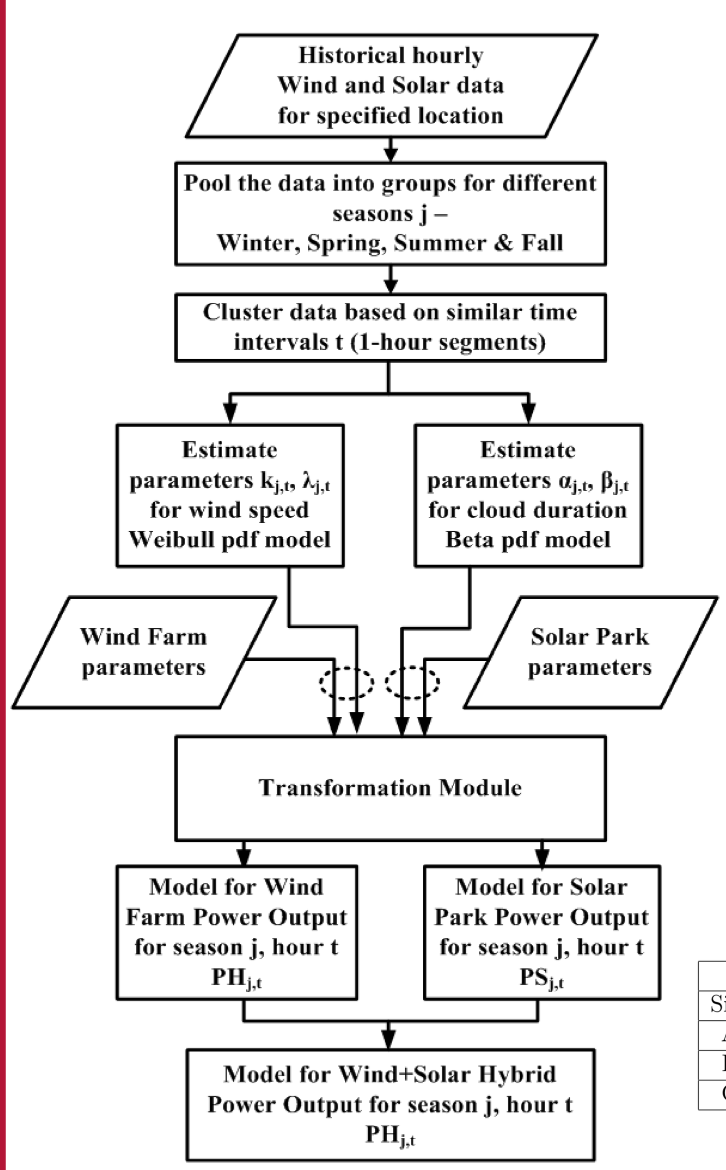








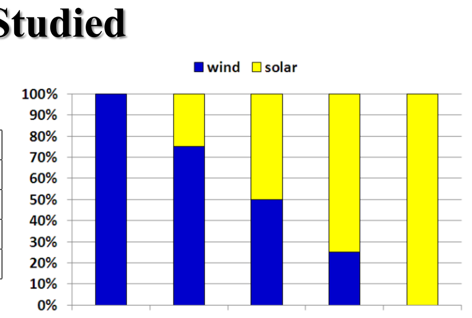
Wind-Solar MW Resource Assessment Model (MWRAM[3])



- Wind Power $P_w = f_1(\text{wind speed } v_t)$; $v_t \sim \text{Weibull}(\lambda_t, k_t)$
- Solar Power $P_s = f_2(\text{solar cloud cover } C_t)$; $C_t \sim \text{Beta}(\alpha_t, \beta_t)$
- Wind and solar power output can be modeled using transformation of variables.
- **Transformation Theorem:**
  - Let x be a random variable with pdf $= f_x(x)$ and cdf $F_x(x)$
  - y be another rv with $y = g(x)$
  - $f_y(y) = \sum_i \frac{f_x(x_i)}{|g'(x_i)|}$, where $g'(x) = \frac{dg(x)}{dx}$ and x_i are all the real roots of $y_i = g(x_i)$
- Hybrid ECS Output = $f_3(\text{wind power, solar power})$; $P_h(t) = P_w(t) + P_s(t)$

Locations and Cases Studied

CANDIDATE LOCATION SITES		
Site	HECS ID	Location
A	H10	Daggett Barstow, CA
B	H11	Bakersfield Meadows, CA
C	H12	Lubbock, TX



Mathematical Formulation

- Wind Model

$$f_{v_t}(v_t;\lambda_t,k_t) = \frac{k_t}{\lambda_t}\left(\frac{v_t}{\lambda_t}\right)^{k_t-1} e^{-(v_t/\lambda_t)^{k_t}}$$

$$f_{PW_t}(PW_t) = \begin{cases} 1 - e^{-(V_{ci}/\lambda_t)^{k_t}} - e^{-(V_{co}/\lambda_t)^{k_t}} & :PW_t = 0 \\ \frac{k_t({V_r}^3 - {V_{ci}}^3)}{3[PW_t({V_r}^3-{V_{ci}}^3)+PW_{max}{V_{ci}}^3]} \times \frac{\left[\frac{PW_t({V_r}^3-{V_{ci}}^3)+PW_{max}{V_{ci}}^3}{PW_{max}}\right]^{k_t/3}}{\lambda_t^{k_t}} \times e^{-\frac{\left[\frac{PW_t({V_r}^3-{V_{ci}}^3)+PW_{max}{V_{ci}}^3}{PW_{max}}\right]^{k_t/3}}{\lambda_t^{k_t}}} & :PW_t \in (0, PW_{max}) \\ e^{-(V_r/\lambda_t)^{k_t}} - e^{-(V_{co}/\lambda_t)^{k_t}} & :PW_t = PW_{max} \end{cases}$$

Here,
v = wind speed
λ = Weibull scale parameter
k = Weibull shape parameter
V_r = Turbine Rated speed
V_{ci} = Turbine cut-in speed
V_{co} = Turbine cut-out speed
P_r = Turbine Rated Power
T = Number of turbines
P_{max} = Rated Capacity of wind farm $= TP_r$

- Solar Model

$$f_{C_t}(C_t;\alpha_t,\beta_t) = \frac{\Gamma(\alpha_t+\beta_t)}{\Gamma(\alpha_t)\Gamma(\beta_t)} C_t^{\alpha_t-1}(1-C_t)^{\beta_t-1}$$

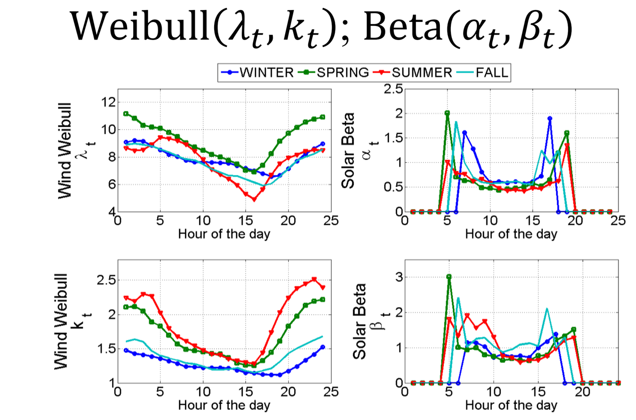
$$f_{PS_t}(PS_t) = \begin{cases} 0 & :PS_t = 0 \\ \frac{1}{PS_{t_{max}}}\frac{\Gamma(\alpha_t+\beta_t)}{\Gamma(\alpha_t)\Gamma(\beta_t)} \times \left(\frac{PS_t}{PS_{t_{max}}}\right)^{\beta_t-1} \times \left(1-\frac{PS_t}{PS_{t_{max}}}\right)^{\alpha_t-1} & :PS_t \in (0, PS_{t_{max}}) \\ 0 & :PS_t = PS_{t_{max}} \end{cases}$$

Here,
C = cloud cover fraction
α = Beta shape parameter
β = Beta shape parameter
A_c = Solar Collector area
H_{max} = Maximum DNI
η_{net} = Net efficiency of STECS
PS_{max} = Rated Capacity of solar park $= \eta_{net} H_{max} A_c$

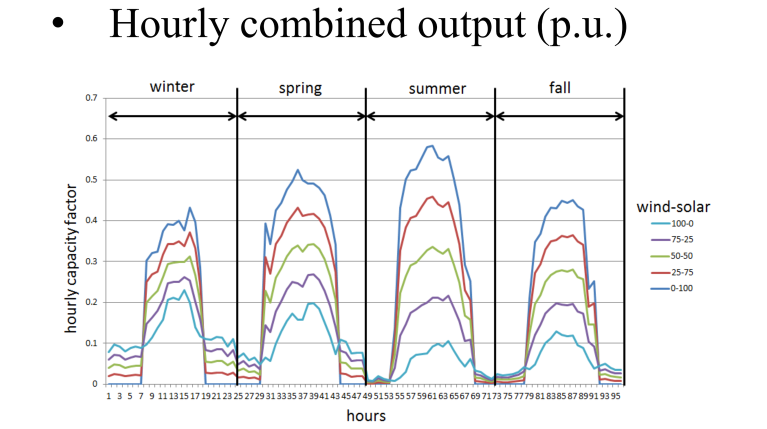
- Integrated Hybrid Model
  - $E(PH_t) = E(PW_t) + E(PS_t)$
  - If $0 \le E(PW_t) \le E(PW_{max})$ & $0 \le E(PS_t) \le E(PS_{max})$
    - $0 \le E(PH_t) \le E(PW_{max} + PS_{max})$

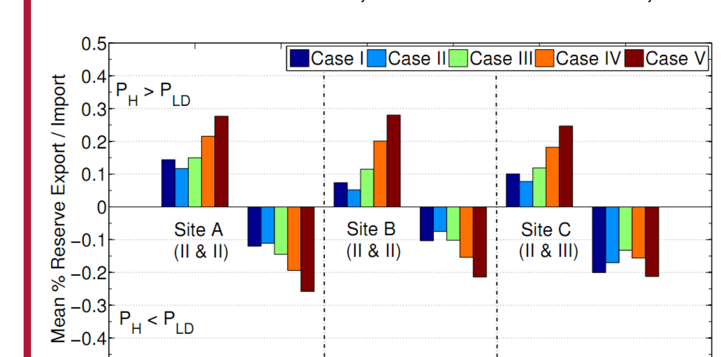
Sample Results & Applications of MWRAM

- Parameters Variation Weibull(λ_t, k_t); Beta(α_t, β_t)



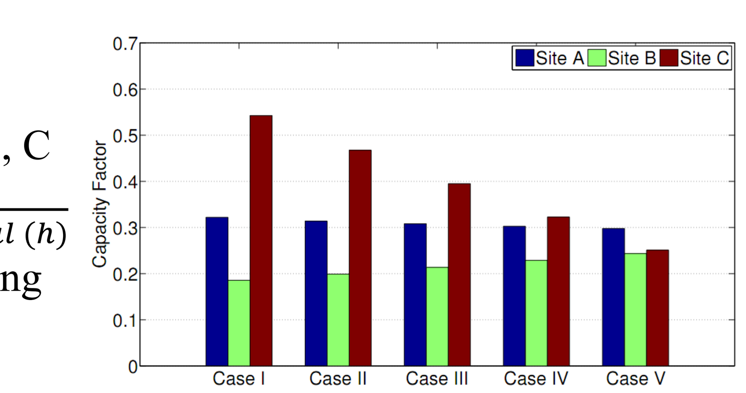
- Hourly combined output (p.u.)





- Variation of the Mean Reserve Requirements for Sites A, B and C for 20% penetration level.
- $P_H > P_{LD}$ ~ power export; $P_H < P_{LD}$ ~ power import
- Case II/ III give minimum reserve requirements for the different sites; leads to suitable sizing.

- Annual Average Capacity Factors for Sites A, B, C
- $CF = \frac{Energy\ Output\ (MWh)}{Rated\ Power\ of\ Plant\ (MW) \times Hours\ in\ interval\ (h)}$
- For preferred case selected, the CF allows ranking the shortlisted locations in terms of resource potential.



Annual Average Capacity Factors for Sites A, B, C

[1] "An Innovative Optimal Integration of Wind and Solar Resources for Reliable and Sustainable Power Generation", funded by National Science Foundation (NSF)
[2] GE Energy Consulting, Report CEC-500-2007-081-APB, "Intermittency Analysis Project: Appendix B - Impact of Intermittent Generation on Operation of California Power Grid", Jul. 2007
[3] Sarkar, S.; Ajjarapu, V.; , "MW Resource Assessment Model for a Hybrid Energy Conversion System With Wind and Solar Resources," *Sustainable Energy, IEEE Transactions on* , vol.2, no.4, pp.383-391, Oct. 2011