IOWA STATE UNIVERSITY
Electrical Power and Energy Systems (EPES)
Department of Electrical & Computer Engineering (ECpE)

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# MW Resource Assessment Model for a Hybrid Energy Conversion System With Wind and Solar Resources

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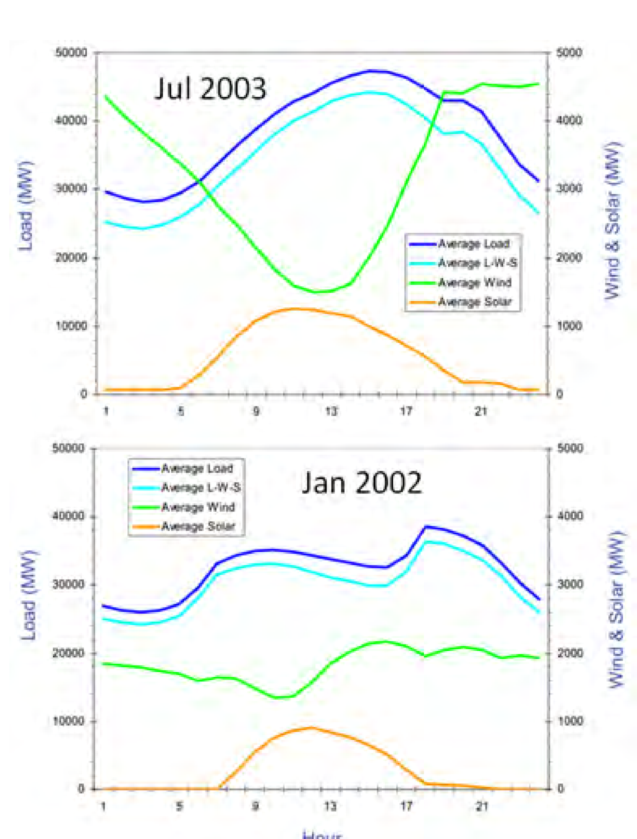
## Challenges in Grid Integration of Renewable Energy

- 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.

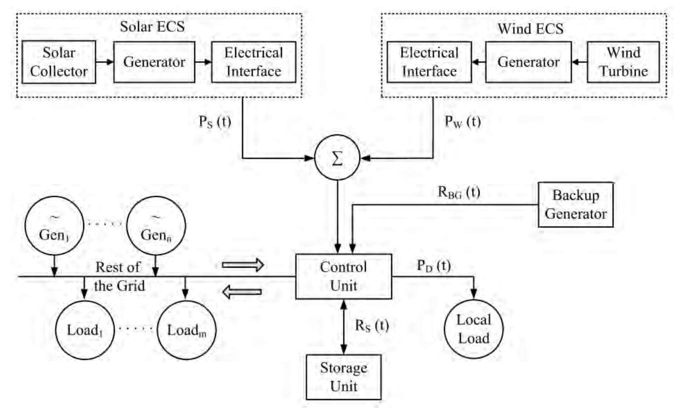



- California Average wind and solar output, along with net demand – July 2003 & Jan 2002 (scaled to 2010 levels)[2]

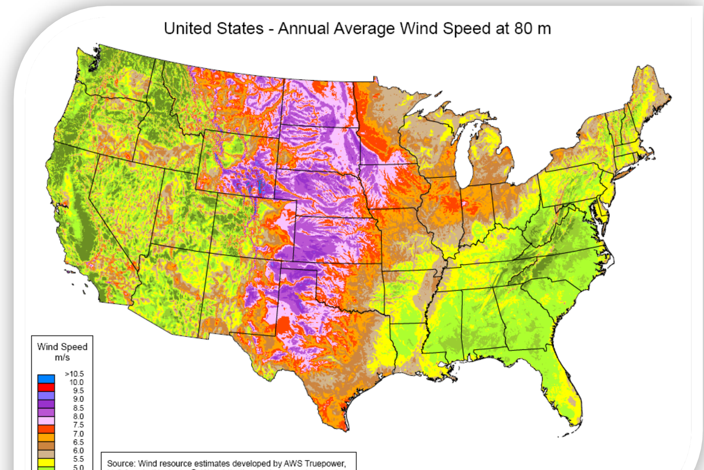
### Taking Advantage of Hybrid Wind-Solar Generation:

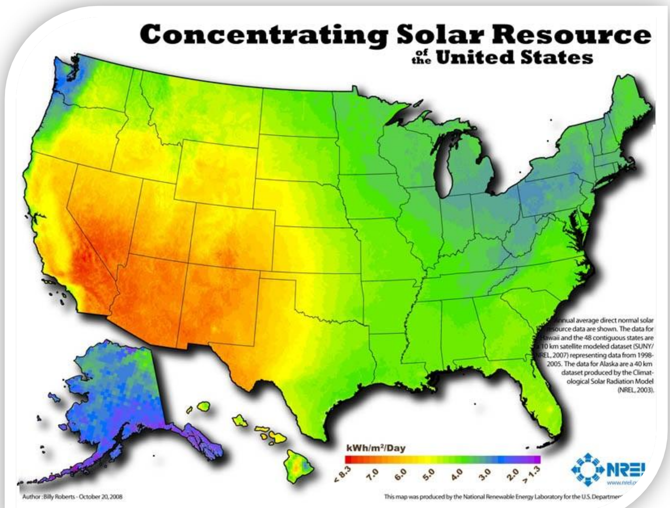
- Complementary solar and wind plant profiles when considered in aggregate can be a good match to the load profile.
- As compared to stand-alone plants, the hybrid plant would require less storage or reserve capacity.
- Reduction in emissions, generation of additional jobs, security of supply etc.

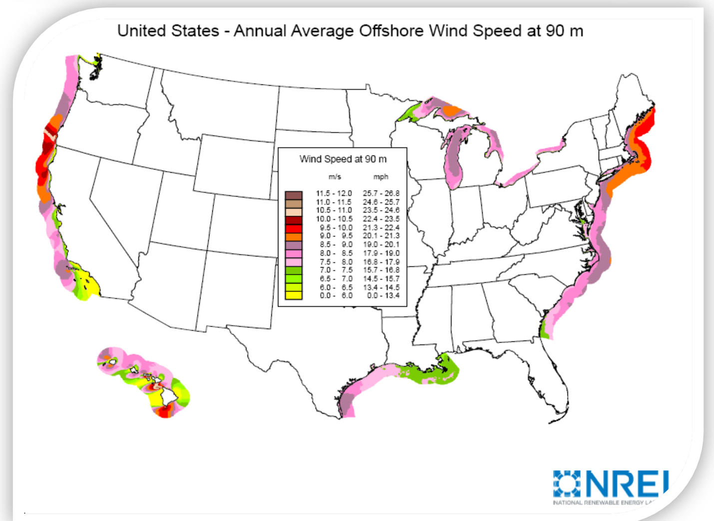
**Schematic of Wind & Solar Hybrid Energy Conversion System (HECS)**

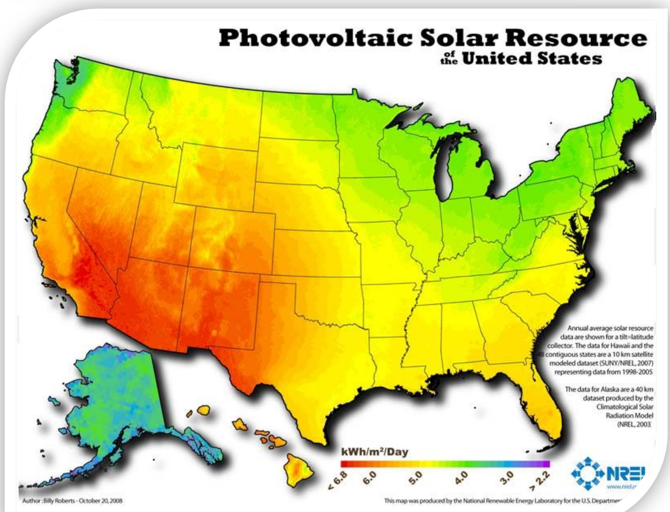



## Wind (*Onshore & Offshore*) & Solar (*Concentrating & Photovoltaic*) Resource of USA




## 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.

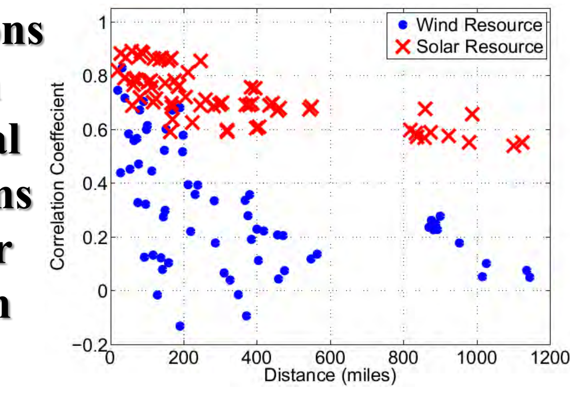
| Wind Speed Data | | | |
|---|---|---|---|
| Serial # | ID | Latitude | Longitude |
| W1 | 3579° | 35.08 | -116.96 |
| W2 | 709° | 32.71 | -116.27 |
| W3 | 1169° | 33.94 | -116.76 |
| W4 | 1481° | 34.11 | -101.17 |
| W5 | 1551° | 34.16 | -116.37 |
| W6 | 5606° | 35.56 | -116.61 |
| W7 | 2832° | 34.86 | -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 |

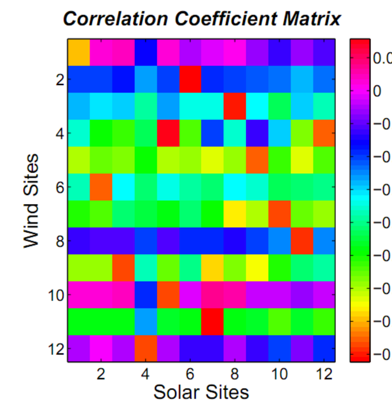
&

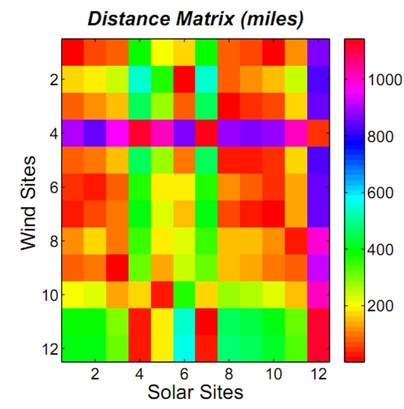
| Solar DNI Data | | | |
|---|---|---|---|
| Serial # | ID | Latitude | Longitude |
| S1 | 117053505* | 35.05 | -117.05 |
| S2 | 116053545* | 35.45 | -116.05 |
| S3 | 117853605* | 36.05 | -117.85 |
| S4 | 120153995* | 39.95 | -120.15 |
| S5 | 118553775* | 37.75 | -118.55 |
| S6 | 116253275* | 32.75 | -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 |

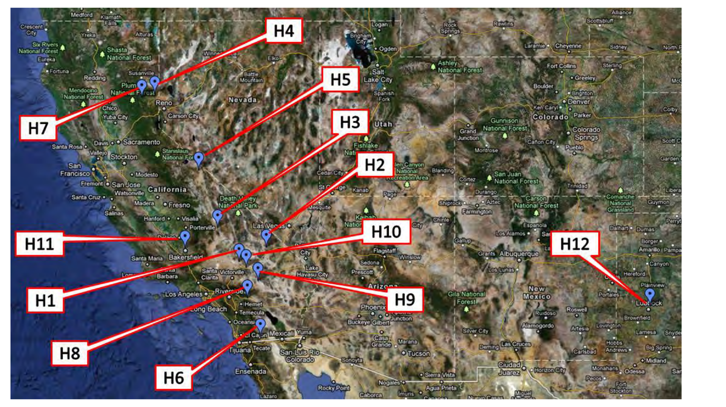
| Hybrid Site | Pairing | Solar ID | Wind ID | Distance (miles) |
|---|---|---|---|---|
| H1 | (S1,W1) | 117053505 | 3579 | 6 |
| H2 | (S2,W6) | 116053545 | 5606 | 33 |
| H3 | (S3,W9) | 117853605 | 6172 | 12 |
| H4 | (S4,W12) | 120153995 | 12514 | 20 |
| H5 | (S5,W10) | 118553775 | 9039 | 25 |
| H6 | (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**

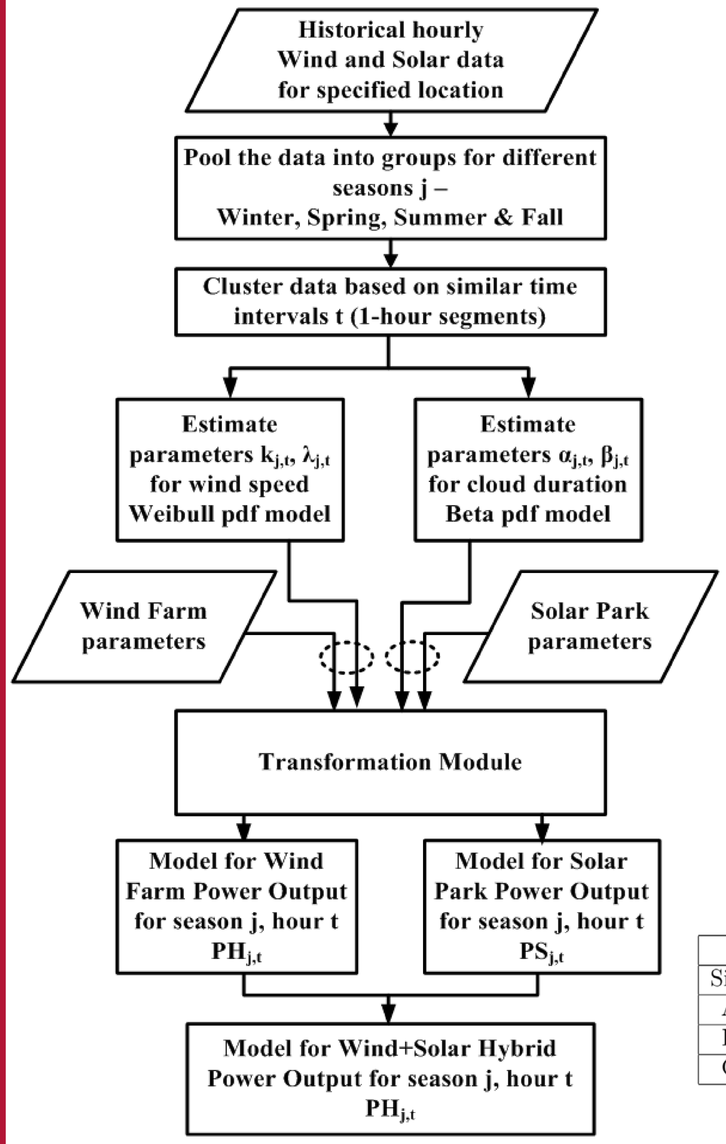


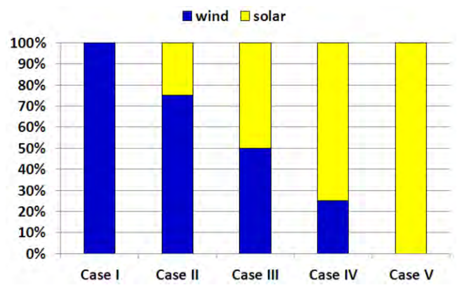

## Wind-Solar MW Resource Assessment Model (MWRAM[3])




- Wind Power $P_w = f_1$(wind speed $v_t$); $v_t \sim \text{Weibull}(\lambda_t, k_t)$
- Solar Power $P_s = f_2$(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 = $f_3$(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
$\lambda$ = 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

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

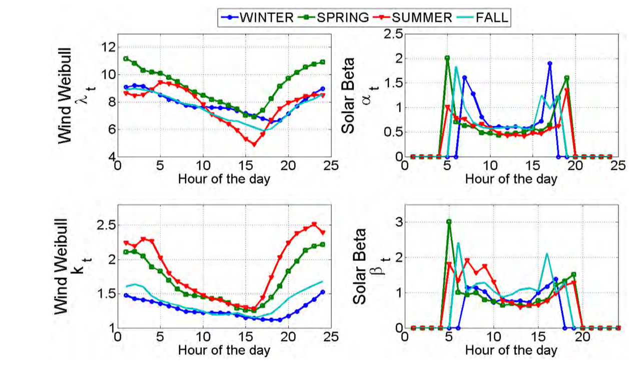
$$f_{PS_t}(PS_t) = \begin{cases} 0 & : PS_t = 0 \\ \frac{1}{PS_{t_{max}}}\frac{\Gamma(\alpha_t+\beta_t)}{\Gamma(\alpha_t)\Gamma(\beta_t)} \times \left(\frac{PS_t}{PS_{t_{max}}}\right)^{\beta_t-1} \times \left(1-\frac{PS_t}{PS_{t_{max}}}\right)^{\alpha_t-1} & : PS_t \in (0, PS_{t_{max}}) \\ 0 & : PS_t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

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

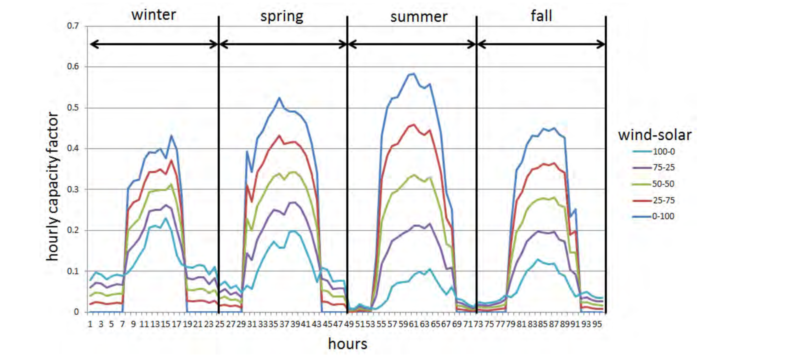
- Integrated Hybrid Model
  - $E(PH_t) = E(PW_t) + E(PS_t)$
  - If $0 \le E(PW_t) \le E(PW_{max})$ & $0 \le E(PS_t) \le E(PS_{max})$
    - $0 \le E(PH_t) \le E(PW_{max} + PS_{max})$

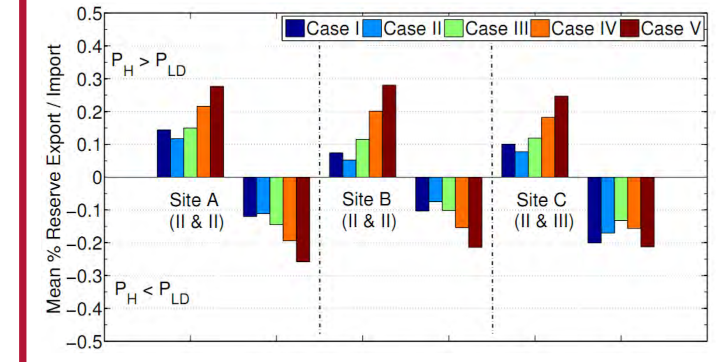
## Sample Results & Applications of MWRAM

- Parameters Variation Weibull$(\lambda_t, k_t)$; Beta$(\alpha_t, \beta_t)$



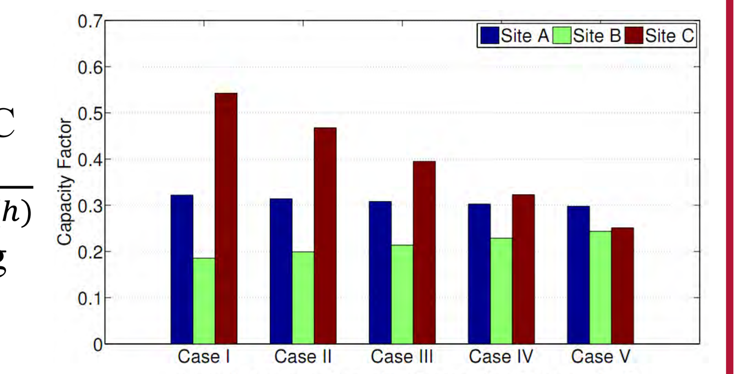

- Hourly combined output (p.u.)




- 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