# A two-stage multi-criteria decision for distributed wind and solar integration

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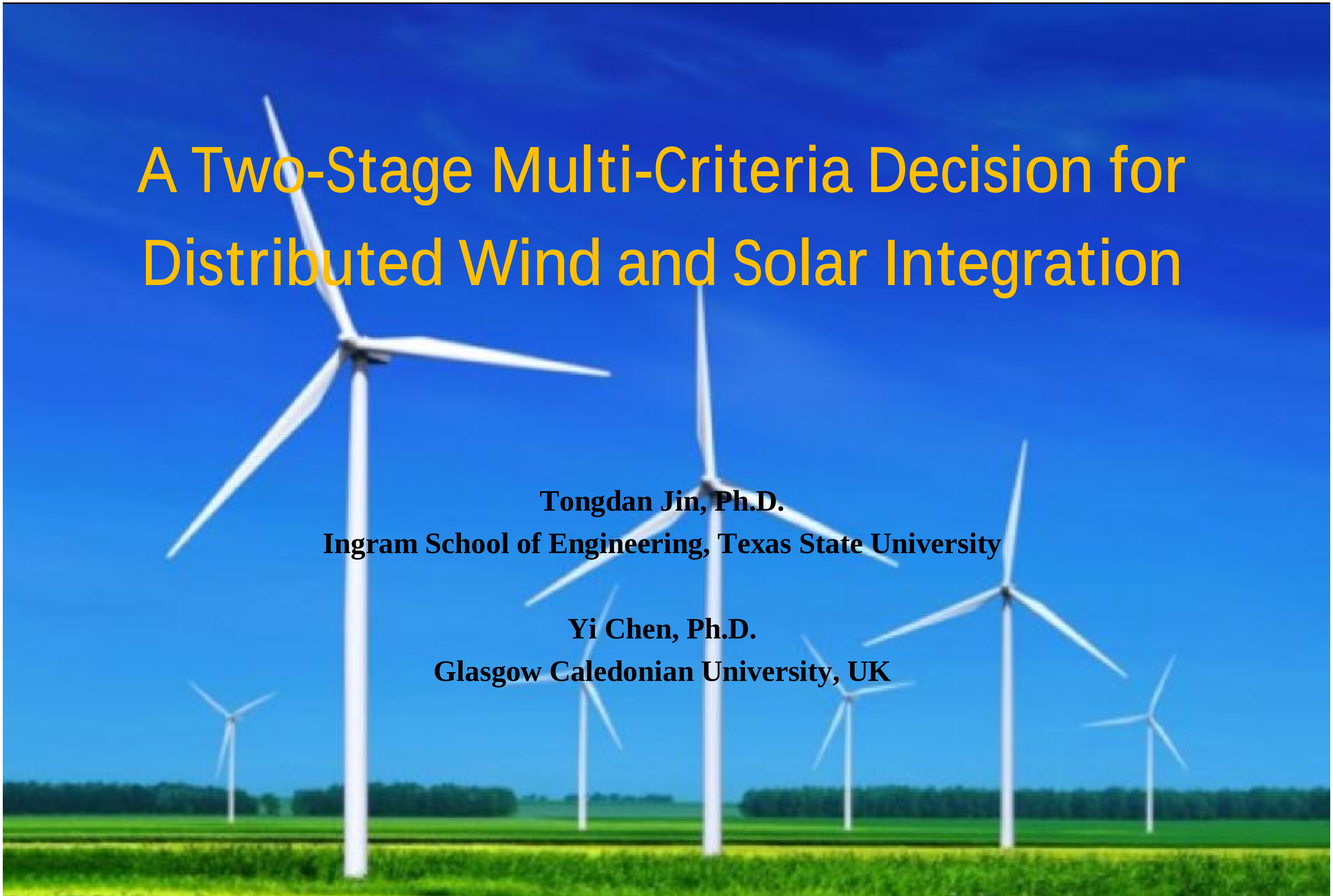

# A Two-Stage Multi-Criteria Decision for Distributed Wind and Solar Integration


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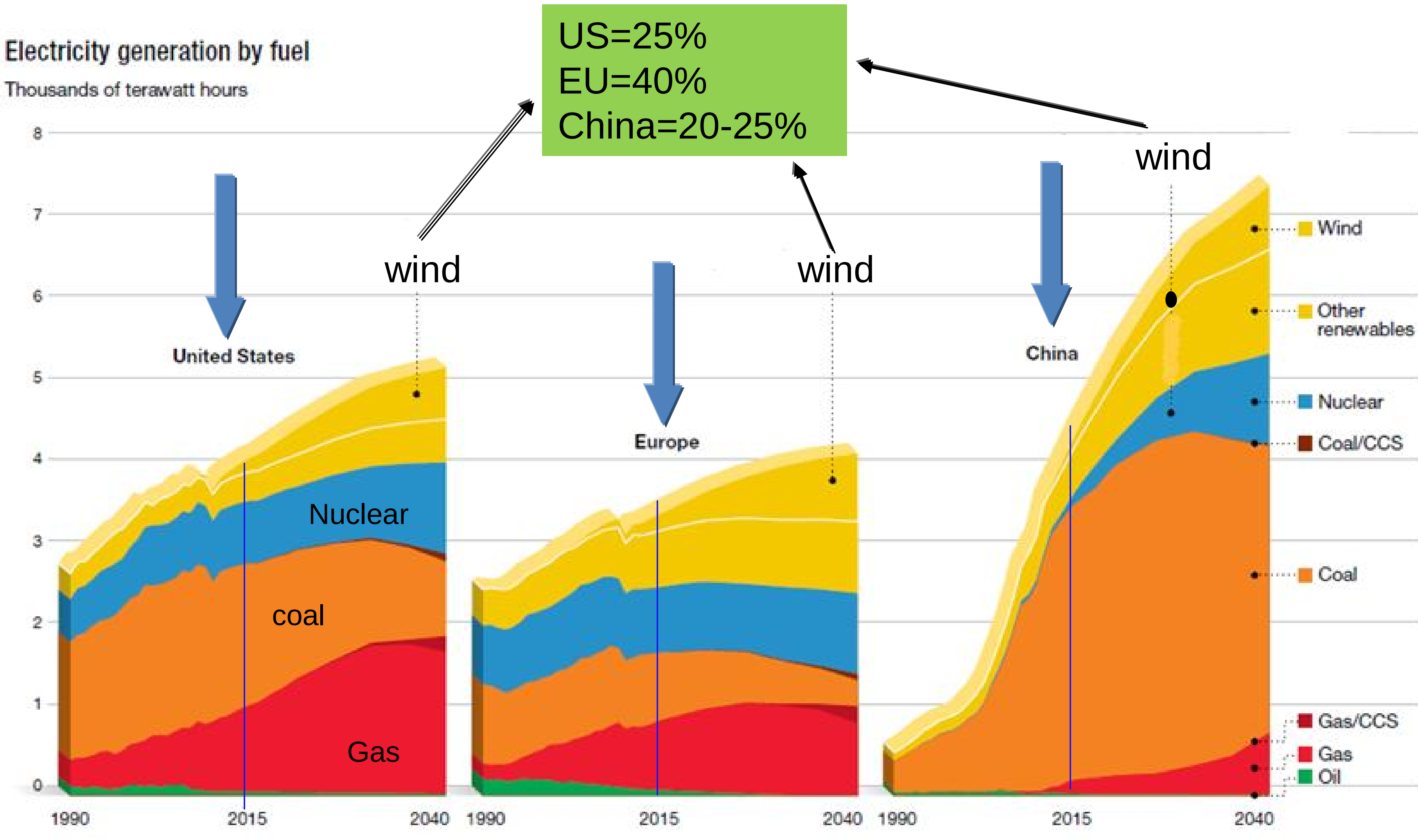
# Outline

- Toward Distributed Generation
- Characterizing Wind and Solar Generation
- Multi-Criteria Planning Model
- Numerical Experiment
- Conclusion

# Renewable Portfolio Standards in 2040

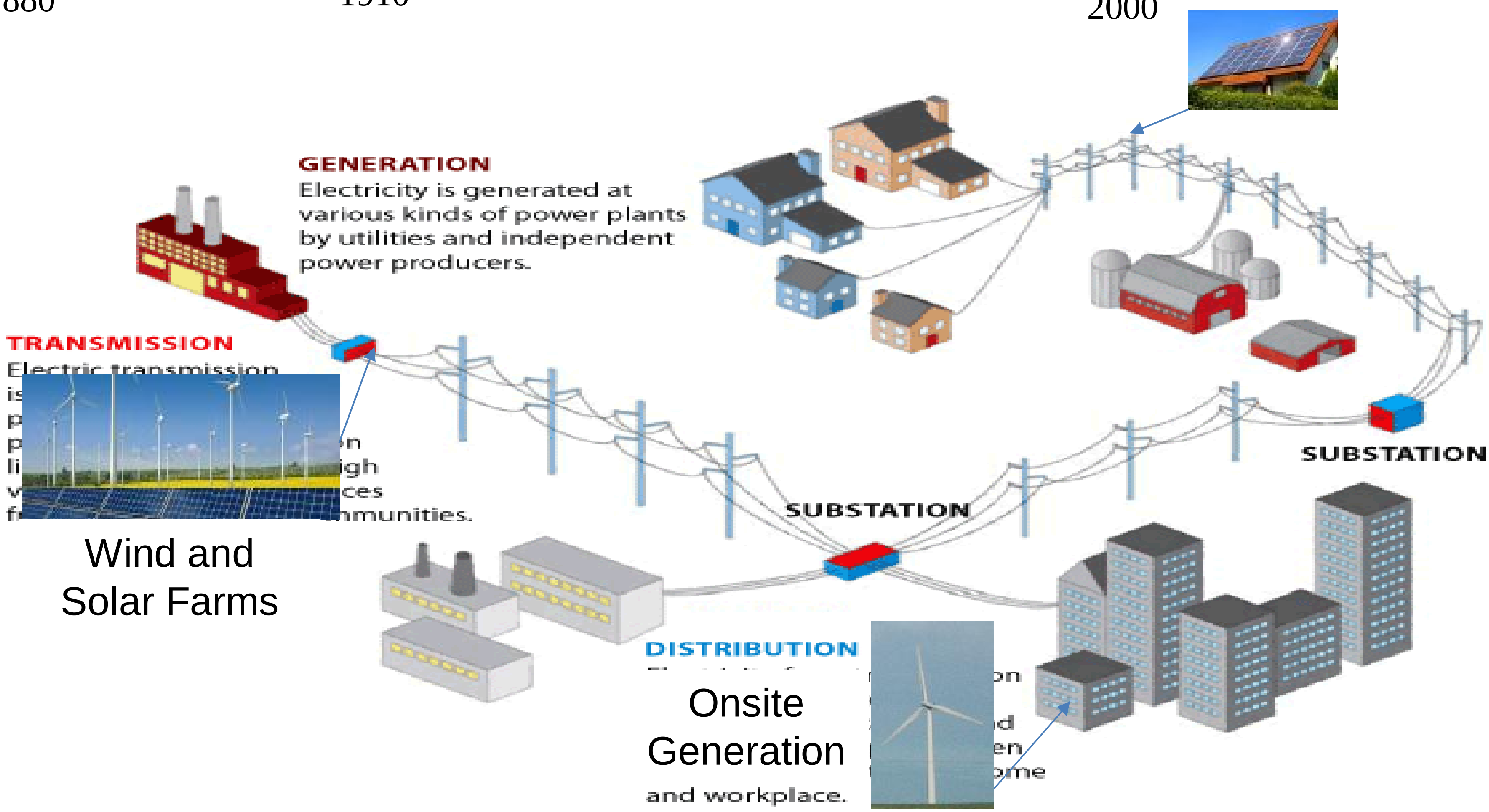



exxonmobil.com/energyoutlook

# The Rise of Distributed Power Service

| Distributed Power Age | Central Power Period | Rise of Distributed Power |
|---|---|---|

1880 — 1910 — 2000



# Wind power in Scotland

Wind power is Scotland's fastest growing renewable energy technology, with 2574 MW of installed capacity as of April 2011. For example:

**Whitelee Wind Farm** is the **largest** on-shore wind farm in the United Kingdom with 215 Siemens and Alstom wind turbines and a total capacity of **539** MW.

**The Clyde Wind Farm** is a **350** MW on-shore wind farm near Abington in South Lanarkshire, Scotland.

**The Robin Rigg Wind Farm** is a **180** MW development completed in April 2010, is an off-shore wind farm sited on a sandbank in the Solway Firth.

https://en.wikipedia.org/wiki/Wind_power_in_Scotland#Large_wind_farms

# Wind power in Scotland

Large wind farms in Scotland:

- Black Law Wind Farm
- Braes of Doune Wind Farm
- Clyde Wind Farm
- Crystal Rig Wind Farm
- Farr Wind Farm
- Hadyard Hill Wind Farm
- Robin Rigg Wind Farm
- Whitelee Wind Farm

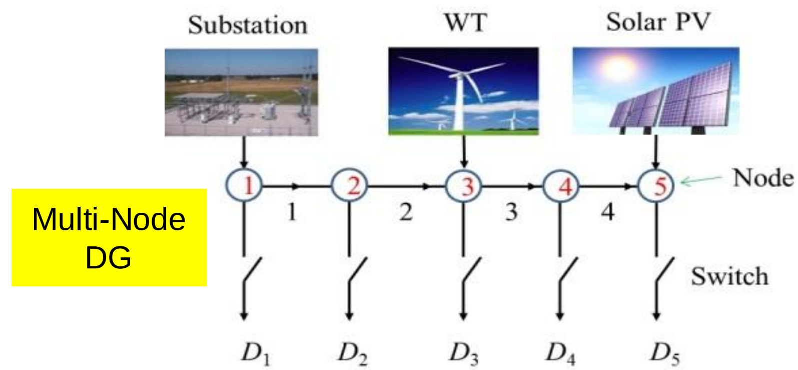
There is **further potential** for **expansion**, especially offshore given the high average wind speeds, and a number of large offshore wind farms are **planned**.

https://en.wikipedia.org/wiki/Wind_power_in_Scotland#Large_wind_farms

# Type of Distributed Generation (DG)

1) Generation backup
2) Onsite generation
3) Multi-node Generation
4) Microgrid System







A commercial micro-grid system in China
Location: Turpan, Xinjiang
Year: 2009
Capacity: 13.4 MW PV
Service: 7,000 homes
Funded: Energy Foundation China's Renewable Energy Program

# Key Notations

**x**=decision variables representing the **sizing** and **siting**

$\tau$=the **maintenance time** of DG system

$n$=number of nodes in the power system

$m$=number of available DG equipment type

$l$=number of link of the distribution network

$D_j$=power demand of node j, for $j$=1, 2, …, $n$

$P_j(\mathbf{x})$=power generation at node $j$, for $j$=1, 2, …, $n$

$V_j(\mathbf{x})$=voltage at node $j$, for $j$=1, 2, …, $n$

$I_k(\mathbf{x})$=current in link $k$, for $k$=1, 2, …, $l$

$P_r$=rated wind turbine power output

$f_w(y)$=wind speed distribution

$S$=hourly irradiance on PV, random variable

$P_s(S)$=power output of PV

$h$=PV efficiency

$A$=PV area

$T_o$=PV skin temperature

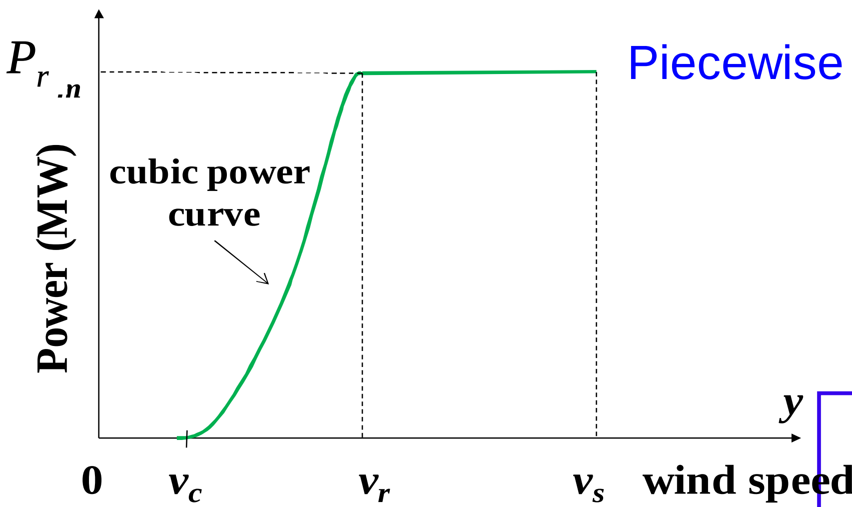
*mixed integration programming problem*

# Modeling Variable Power Output

- Time Series Model (.e.g. ARIMA Model)
- DG Simulations
- Astronomy/Physics Models (Observation)
- Moment Methods (Mean and Variance)

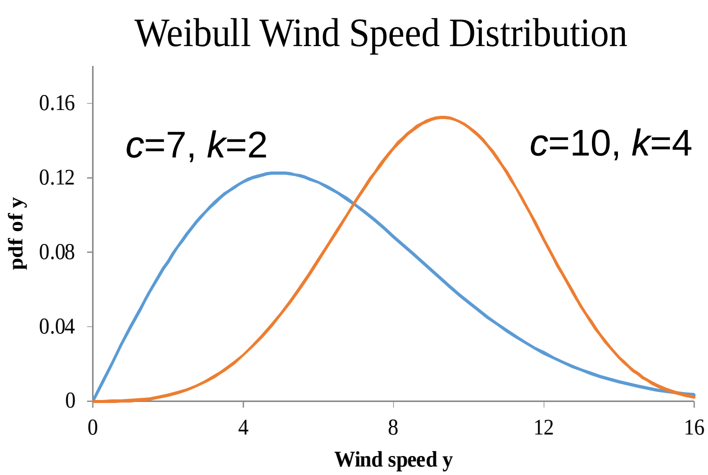
The models of ‘Wind’ and ‘Solar PV’ Power generation are given:

# Wind Power Generation




Piecewise Functions

$$P_w(y) = \begin{cases} 0 & 0 \le y < v_c,\ y > v_s \\ P_r\left(\dfrac{y}{v_r}\right)^3 & v_c \le y \le v_r \\ P_r & v_r \le y \le v_s \end{cases}$$




density function

$$f_w(y) = \left(\frac{k}{c}\right)\left(\frac{y}{c}\right)^{k-1} e^{-(y/c)^k}$$

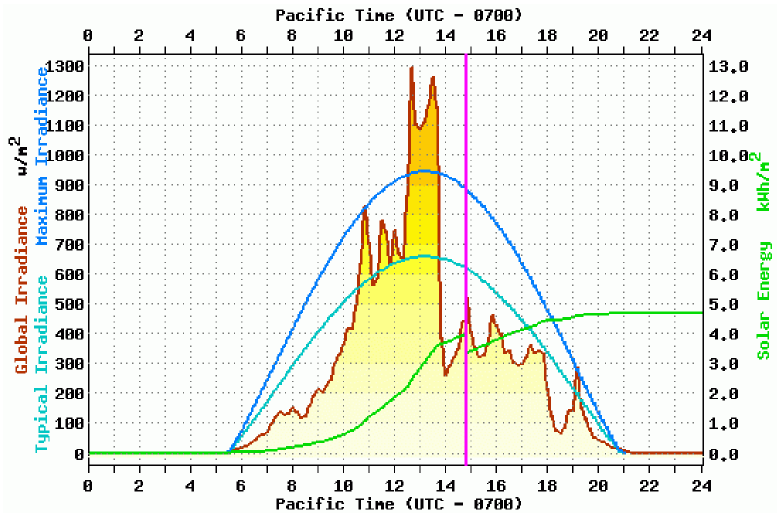
$$E[P(y)] = g\int_{v_c}^{v_r} x^3 f(y)dy + P_m\big(F(v_s) - F(v_r)\big)$$

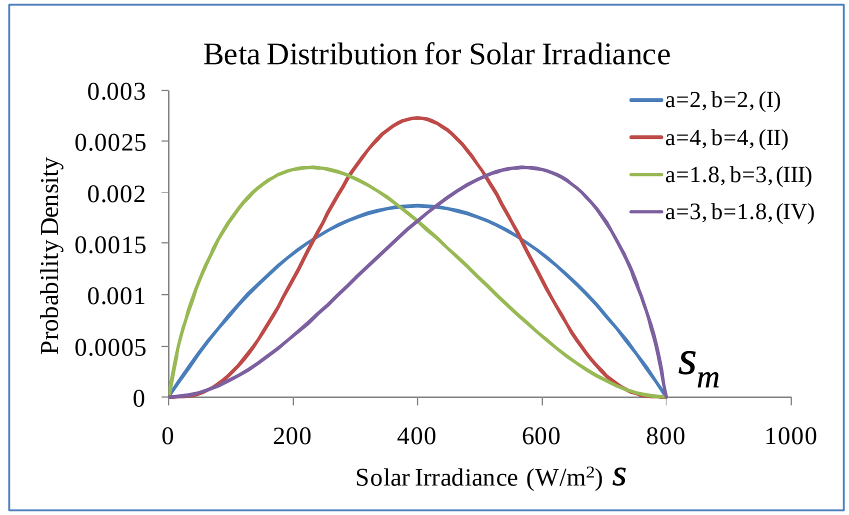
$$E[P^2(Y)] = g^2\int_{v_c}^{v_r} x^6 f(x)dx + P_m^2\big(F(v_s) - F(v_r)\big)$$

$$Var\big(P(Y)\big) = E[P^2(Y)] - \big(E[P(Y)]\big)^2$$

Where $g = P_r / v_r^3$

# Solar Photovoltaics (PV) Generation




$$P_s(S) = hAS\big(1 - 0.005(T_o - 25)\big)$$

density function

$$f_s(s) = \frac{\Gamma(a+b)}{s_m \Gamma(a)\Gamma(b)} \left(\frac{s}{s_m}\right)^{a-1} \left(1 - \frac{s}{s_m}\right)^{b-1}$$

Where

- $s_m$=maximum solar irradiance (W/m$^2$)
- $P_s(S)$=power output of PV
- $h$=PV efficiency
- $A$=PV area
- $T_o$=PV panel temperature

$$E[P_s(S)] = \frac{a_s s_m hA\big(1 - 0.005(T_o - 25)\big)}{a_s + b_s}$$

$$Var(P_s(S)) = \frac{a_s b_s s_m^2 h^2 A^2 \big(1 - 0.005(T_o - 25)\big)^2}{(a_s + b_s)^2 (a_s + b_s + 1)}$$

# Key Performance Measures of DG System

- **Technical**
  - Energy Supply Reliability
  - Power Quality (i.e. voltage stability)
  - Line Thermal Stress
- **Economical**
  - Return On Investment
- **Environmental-Social**
  - Carbon Savings/Climate Change
- **Political**
  - Renewable Portfolio Standards

# Technical Constraints

- **Reliability (loss-of-load probability):**

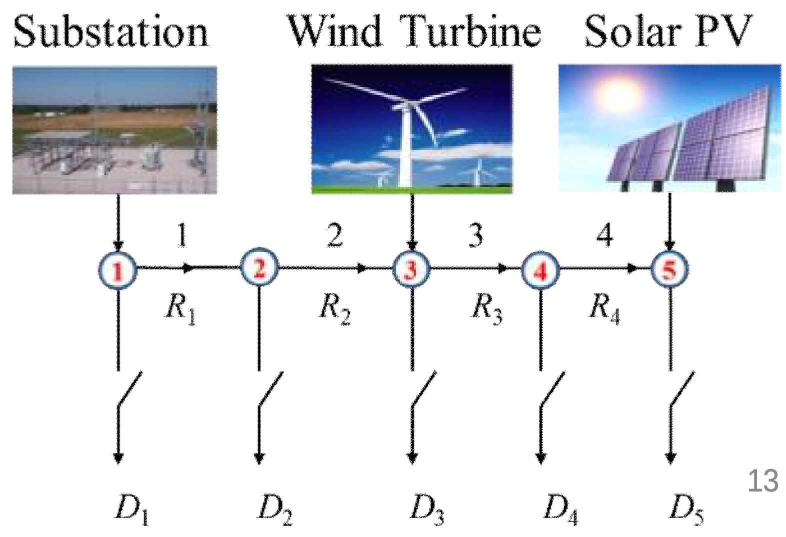
$$\Pr\{P(\mathrm{x}) \geq D\} \geq 1 - a_1$$

- **Power Quality:**

$$\Pr\{V_{\min} \leq V(\mathrm{x}) \leq V_{\max}\} \geq a_2$$

- **Thermal Limits**

$$\Pr\{I(\mathrm{x}) \leq I^{\max}\} \geq a_3$$



# Economic Goal

**Cost**=Install+Operation +Carbon Credits+Maintenance

$$f_1(\mathrm{x},\tau)=C_{DG}(\mathrm{x},\tau)$$

$$C_{DG}(\mathbf{x},\boldsymbol{\tau})=C_e(\mathbf{x})+C_o(\mathbf{x})+C_c(\mathbf{x})+C_m(\mathbf{x},\boldsymbol{\tau})$$

$$C_e(\mathrm{x})=\left(\frac{r(1+r)^h}{(1+r)^h-1}\right)\sum_{i=1}^{m}\sum_{j=1}^{n}x_{ij}a_{ij}P_{ij}^c$$

$$C_c(\mathbf{x})=\sum_{i=1}^{m}\sum_{j=1}^{n}t_i^a x_{ij}c_{ij}P_{ij}$$

$$C_o(\mathbf{x})=\sum_{i=1}^{m}\sum_{j=1}^{n}x_{ij}b_{ij}P_{ij}^c$$

$$C_m(\mathrm{x},\tau)=\sum_{i=1}^{m}\left(\frac{t_i^a\left(c_{fi}F_i(t_i)+c_{pi}R_i(t_i)\right)}{\int_0^{t_i}R_i(t)dt+t_{fi}F_i(t_i)+t_{pi}R_i(t_i)}\sum_{j=1}^{n}x_{ij}\right)$$

# Environmental and Political Goals

- **Environmental Goal: Maximize Carbon Savings**

$$\longrightarrow \quad f_2(\mathbf{x}, \boldsymbol{\tau}) = q \sum_{i=1}^{m} \sum_{j=1}^{n} t_i^a x_{ij} A_i(t_i) P_{ij}$$

- **Political Requirements**

$$\sum_{i=1}^{m} x_{ij} P_{ij}^c \le l E[D_j] \qquad \text{for } j = 1, 2, \ldots, n$$

**Renewable Portfolio Standards**

# A Multi-Criteria Approach to DG Planning

Decision variables:
$x_{ij}$ (binary)
$t_i$ (positive)

Min: $$f_1(\mathrm{x}, \tau) = C_{DG}(\mathrm{x}, \tau)$$

Max: $$f_2(\mathbf{x}, \boldsymbol{\tau}) = q \sum_{i=1}^{m} \sum_{j=1}^{n} t_i^a x_{ij} A_i(t_i) P_{ij}$$

Subject to: $$\Pr\{P(\mathbf{x}) < D\} \le a_1$$

$$\Pr\{V_{\min} \le V_j(\mathbf{x}) \le V_{\max}\} \ge a_2$$ for $j$=1, 2, …, $n$

$$\Pr\{I_k < I_k^{\max}\} \ge a_3$$ for $k$=1, 2, …, $l$

$$\sum_{i=1}^{m} x_{ij} P_{ij}^c \le l E[D_j]$$ for $j$=1, 2, …, $n$

# A Two-Stage Decision Making

**Stage 1: Determining x**

Min: $$f_1^{(1)}(\mathbf{x}) = E[C_e(\mathbf{x})] + E[C_o(\mathbf{x})] + E[C_c(\mathbf{x})] + Z_{1-q}\sqrt{Var(C_{DG}(\mathbf{x}))}$$

Max: $$f_2^{(1)}(\mathbf{x}) = q\sum_{i=1}^{m}\sum_{j=1}^{n} t_i^a x_{ij} E[P_{ij}]$$

Subject To:

$$m_{P(\mathbf{x})} \geq m_D + Z_{1-a_1}(s_{P(\mathbf{x})}^2 + s_D^2)^{1/2}$$

$$V_{\min} - Z_{(1-a_2)/2} s_{V_j(\mathbf{x})} \leq m_{V_j(\mathbf{x})} \leq V_{\max} + Z_{(1-a_2)/2} s_{V_j(\mathbf{x})}$$

$$m_{I_k(\mathbf{x})} \leq I_k^{\max} - Z_{a_3} s_{I_k(\mathbf{x})}$$

$$\sum_{i=1}^{m} x_{ij} P_{ij}^c \leq l E[D_j]$$

**Stage 2: Determining t**

Min: $$f_1^{(2)}(\boldsymbol{\tau};\mathbf{x}) = f_1^{(1)}(\mathbf{x}) + E[C_m(\boldsymbol{\tau};\mathbf{x})]$$

Max: $$f_2^{(2)}(\boldsymbol{\tau};\mathbf{x}) = q\sum_{i=1}^{m}\left(t_i^a A_i(t_i)\sum_{j=1}^{n} x_{ij} E[P_{ij}]\right)$$

Subject To: $$t_i > 0$$

# Numerical Experiment: A**13**-Node Network

**Input Data**

1)The mean and the standard deviation of $D_j$

2)Wind speed and solar irradiance distributions

3)Wind turbine (WT) power curve

4)Costs associated with WT and PV maintenance

5)Lifetime distribution of WT and PV units

6) $a_1$, $\alpha_2$, $a_3$, and $l$

**WT and PV Options (*m*=5)**

| *i* | DER | Capacity (MW) |
|---|---|---|
| 1 | WT1 | 1.0 |
| 2 | WT2 | 1.5 |
| 3 | WT3 | 2.0 |
| 4 | PV1 | 0.5 |
| 5 | PV2 | 1.0 |

**Output Data**

1)Where to place the WT/PV?

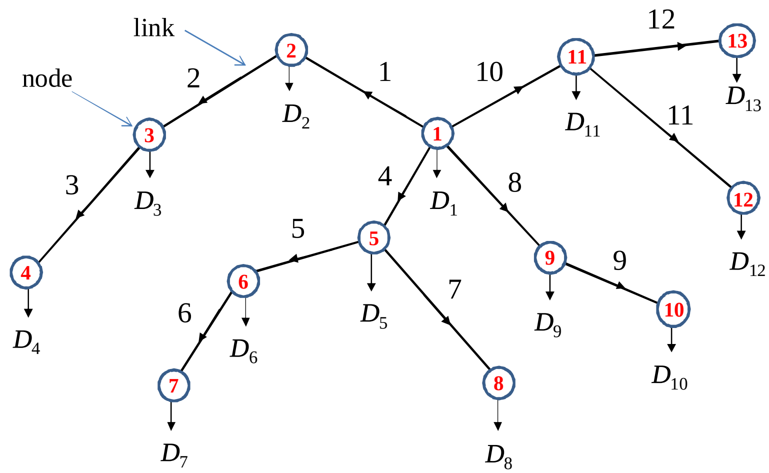
$x$ 2)The size of WT/PV units

$t$ 3)The maintenance time of WT/PV

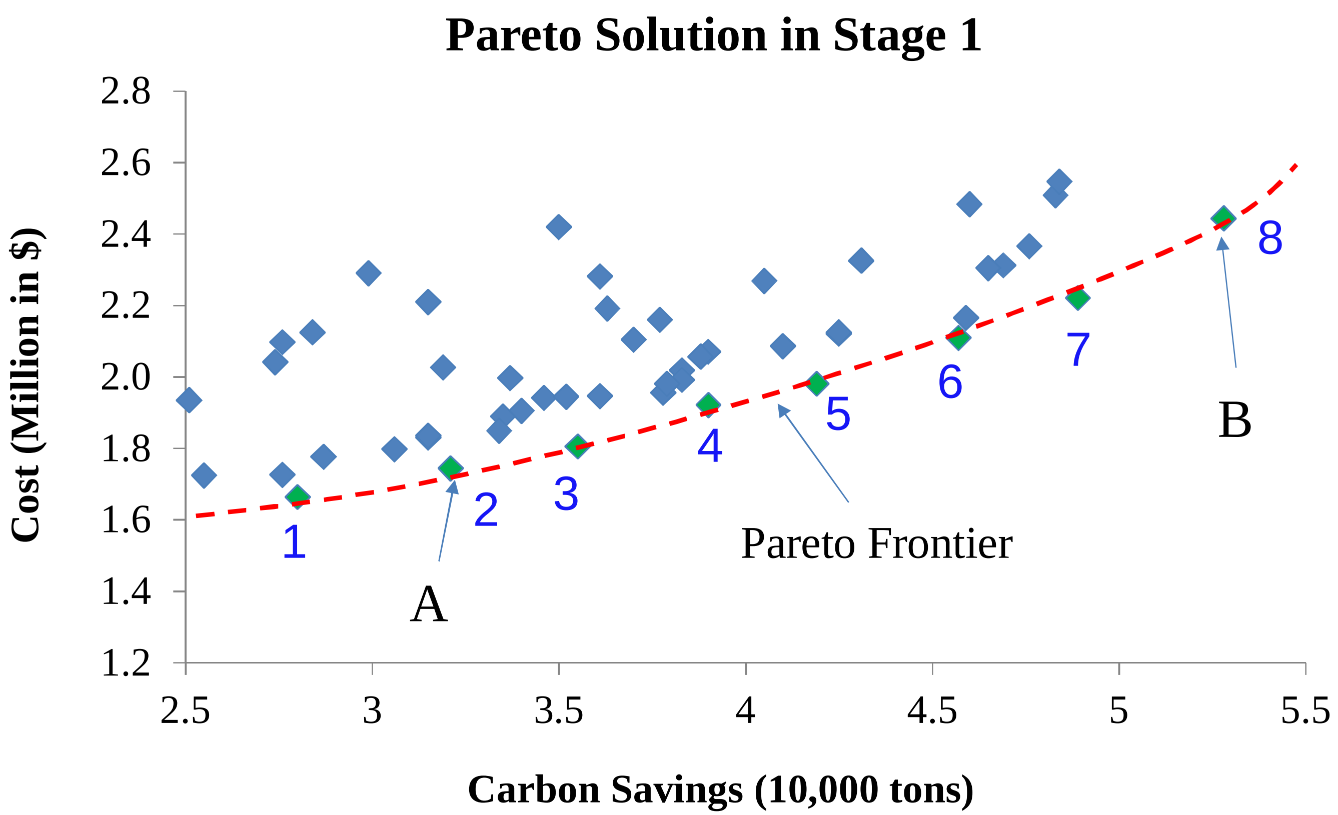
$f_1$ 4)Annualized system cost

$f_{12}$ 5) Carbon savings estimation

**Testing on 13-Node Network (*n*=13)**



# Pareto Solution in **Stage 1**



# Selected Pareto Solutions in **Stage 2**

| Solution No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Carbon (´$10^4$ tons) | 2.737 | 3.134 | 3.465 | 3.803 | 4.082 | 4.450 | 4.774 | 5.140 |
| Cost (´$\$10^6$) | 1.913 | 2.035 | 2.103 | 2.347 | 2.368 | 2.597 | 2.716 | 2.942 |
| j=1 | SS | SS | SS | SS | SS | SS | SS | SS |
| 2 | 5 | 4 | 4 | 4 | 5 | 3 | 1 | 3 |
| 3 | 4 | 5 | 5 | 5 | 4 | 5 | 5 | 5 |
| 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 5 | 0 | 2 | 2 | 2 | 2 | 1 | 2 | 2 |
| 6 | 0 | 2 | 2 | 3 | 1 | 3 | 3 | 3 |
| 7 | 5 | 1 | 1 | 2 | 2 | 3 | 3 | 3 |
| 8 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 |
| 9 | 1 | 0 | 0 | 2 | 0 | 1 | 1 | 2 |
| 10 | 2 | 1 | 3 | 1 | 3 | 2 | 3 | 2 |
| 11 | 1 | 2 | 0 | 1 | 2 | 1 | 3 | 3 |
| 12 | 4 | 5 | 5 | 1 | 2 | 1 | 1 | 3 |
| 13 | 1 | 0 | 2 | 1 | 2 | 2 | 2 | 2 |
| $t_1$ (hour) | 2,860 | 2,793 | 2,876 | 2,943 | 2,936 | 3,019 | 3,105 | n/a |
| $t_2$ (hour) | 2,820 | 2,734 | 2,808 | 2,892 | 2,889 | 3,024 | 3,118 | 2,734 |
| $t_3$ (hour) | n/a | n/a | 2,869 | 2,925 | 2,957 | 3,041 | 3,195 | 2,773 |
| $t_4$ (hour) | 10,732 | 10,615 | 10,743 | 10,887 | 10,860 | n/a | n/a | n/a |
| $t_5$ (hour) | 7,644 | 7,419 | 7,635 | 7,861 | 7,886 | 8,150 | 8,490 | 7,419 |

(SS=Substation)

# Conclusion

- The power industry is **transitioning to distributed** and **renewable** generation to mitigate the climate change.

- A DG planning is a **multi-criteria** decision making, taking into **4 impacts:** account economic, technical, environmental and regularly factors.

- Propose a **two-stage optimization algorithm**: 1) **allocating** DG **siting** and **sizing**; and 2) **determining** the maintenance **times**.

- Demonstrated on a **13-node** network, showing the benefits to reliability, voltage stability and thermal stress release.

- Future research incorporates emerging technologies: **vehicle-to-grid** and **demand response**.

# Thank You !
# Q and A