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Wind Farm Layout Optimization Considering Commercial Turbine Selection and Hub Height Variation

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500 MW x $**2** million/MW (in average) = $**1** billion

~~**400** MW x $**2** million/MW (in average) = $**0.8** billion~~

400 MW for only $**0.65** billion or $**1.625** million/MW

100 MW for $**0.35** billion or $**3.5** million/MW

HOW ABOUT EXPLORING TRADE-OFF RANGE ?

Providing that

ALL CALCULATIONS ARE BASED ON DATA OFFERED

BY MANUFACTURERS & DEVELOPERS

Presentation Outline

1. WFLO - a background.
2. Research Objectives.
3. Wake Modelling
4. Commercial Turbines & Coefficients.
5. Power Calculations.
6. Simple Cost Analysis.
7. Optimization.
8. Results and Discussion.
9. Conclusions.
10. Further Work.

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1- WFLO, a background (1)

WFLO

It is the problem of how to design a wind farm so that desirable quantity (*P*, *CF*, etc.) is maximized and/or undesirable quantity (cost, noise, etc.) is minimized.

Design Variables

- N
- Turbines' siting
- Turbines' sizes
- Turbines' heights
- Owners' Decision

Constraints

- N
- Farm Area
- Total Cost
- Noise Level

Optimization Methodology

- GA
- Other Bio-Inspired
- MILP & MINLP
- MCO
- PSO
- other

Objective Function(s)

- P
- Cost Of Energy
- CF
- Noise Level
- Land Usage
- Multi-Objective

1- WFLO, a background (2)

- The first WFLO work has been published in 1994,
- 1994-2005: no significant contributions have been added,
- 2005-2009: few remarkable contributions,
- 2009-2014: wide awareness and variety in approaches,
- Very few studies considered turbine selection and/or hub height variation,
- Nobody implemented COMMERCIAL turbine selection,
- Nobody implemented general realistic C_T representation,
- Nobody considered more than TWO objective functions.

2- Research Objectives

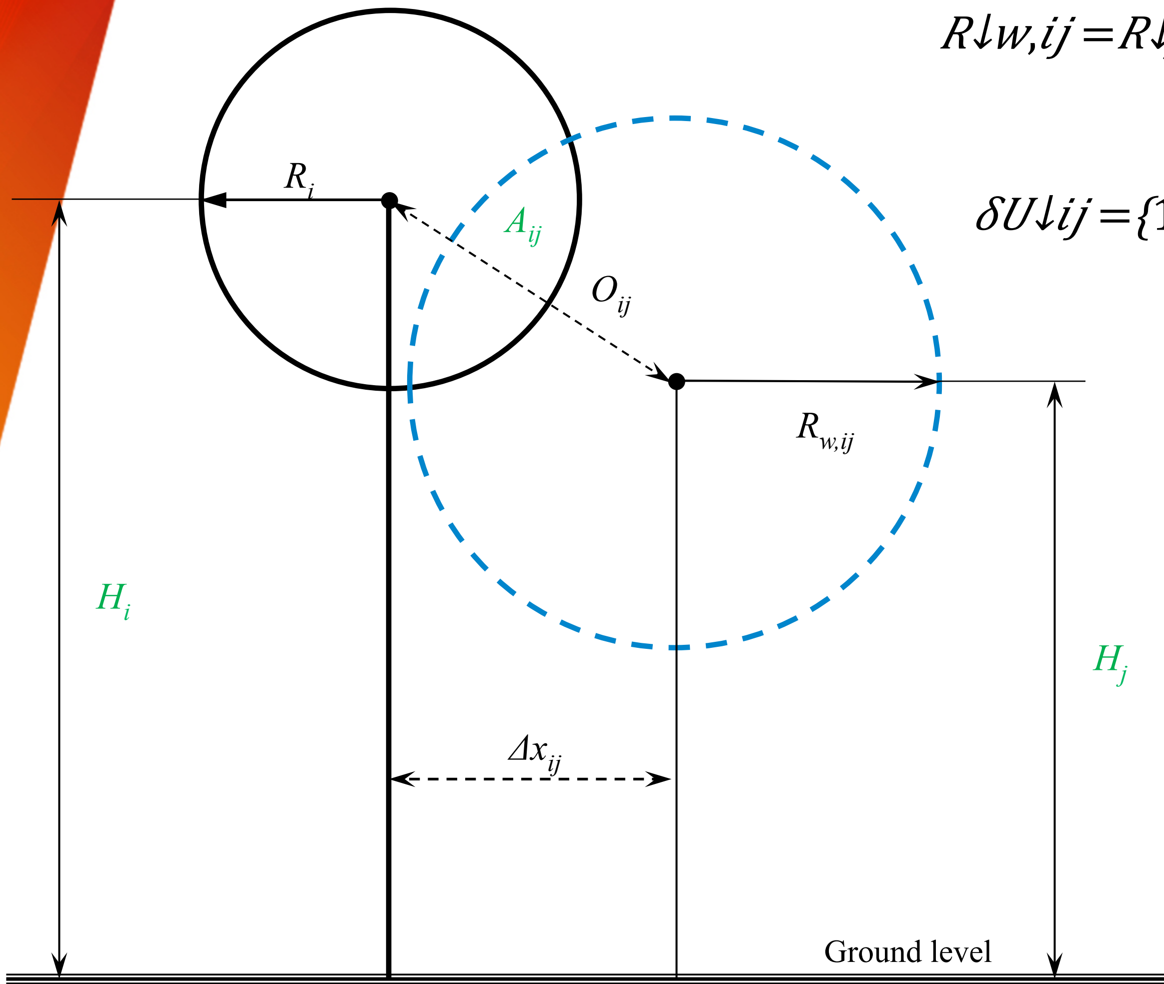
"The proposed work aims to add the commercial turbine selection and general realistic C_T representation to the WFLO, combined with hub height variation and considering three objective functions"

The investigated parameters:

- Selection among 61 HAWT (1.5 ~ 3 MW)
- Hub height ($80\ m \leq H \leq 140\ m$)
- Average spacing ($3.5\ D \leq S \leq 6\ D$)
- Reference wind speed (8 m/s $\leq U_{ref} \leq 12\ m/s$) @ 60 m

3- Wake Modelling

Jensen's Wake Model: Jensen (1983), Katic et al. (1986), and Frandsen (1992)



$$R_{w,ij} = R_j \left[\frac{1-a_j}{1-2a_j} \right]^{1/2} + (0.5/ln($$

$$\delta U_{ij} = \{ 1 - \sqrt{1 - C_{T,j}} / [1 + \alpha_j \Delta y_{ij} / R_j \ [1$$

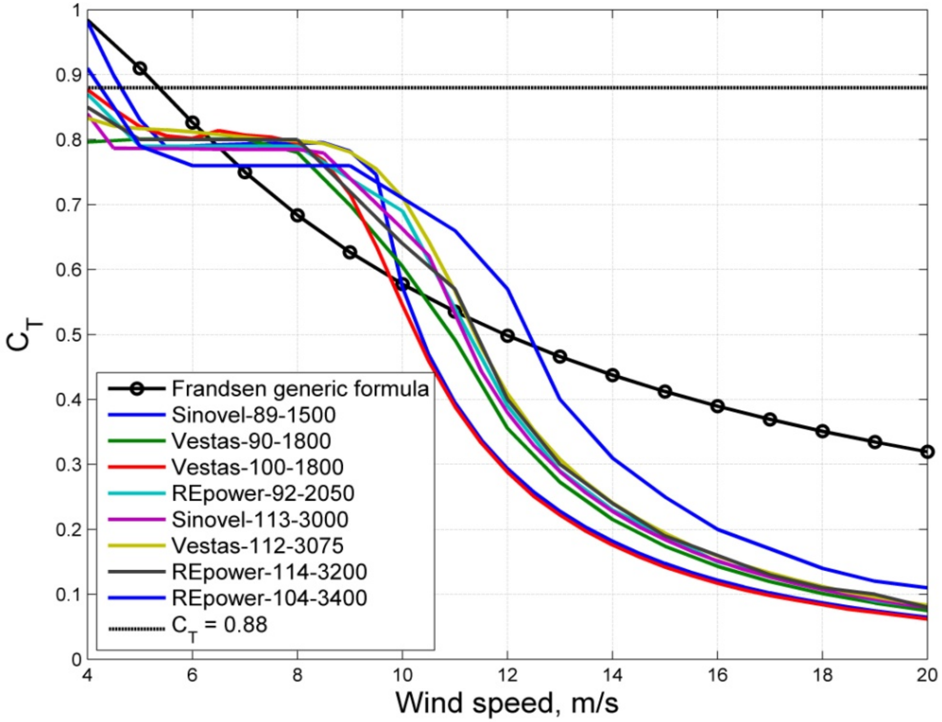
$$\delta U_i = \sqrt{\sum_{j=1}^{j=i-1} (\delta U}$$

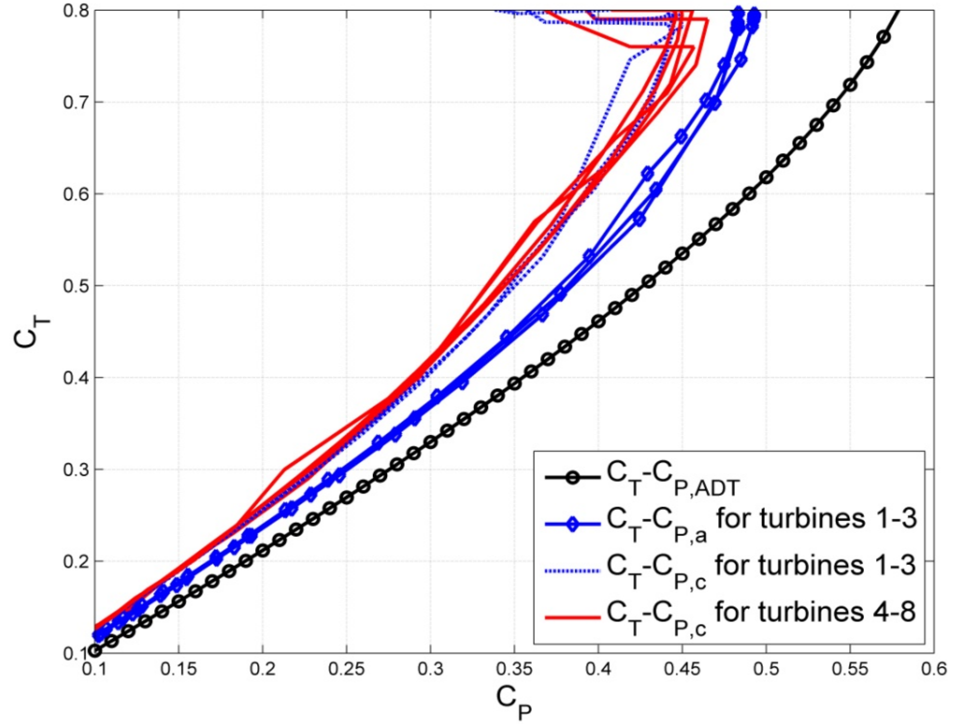
$$U_i = U_{o,i} (1 - \delta U_i)$$

$$U_{o,i} = U_{ref} [ln(H_i / z_o)/l$$

A Schematic front view, parallel to the wind direction, *Y*.

4- Commercial Turbines & Coefficients





- 61 numerical power curves are fitted with 9th degree polynomial,
- 8 c_T-$c_{P,c}$ and 3 c_T-$c_{P,a}$, could be found in the manuals,
- Neither Frandsen's formula nor $c_T = 0.88$ is accurate,
- Each of c_T-$c_{P,c}$, and c_T-$c_{P,a}$ has almost a general curve,
- c_T should be related to c_P instead of U.

5- Power Calculations

- Total output power

$$\boldsymbol{P}=\sum_{i=1}^{N} P_i=\sum_{i=1}^{N}\sum_{k=0}^{k=K} a_{ik}\left[U_{o,i}\left(1-\sqrt{\sum_{j=1}^{j=i-1}\left(\left\{1-\sqrt{1-\boldsymbol{C_{T,j}}}\Big/\left[1+\frac{\alpha_{\boldsymbol{j}}\Delta y_{ij}}{R_j\left[\frac{1-2\boldsymbol{a_j}}{1-\boldsymbol{a_j}}\right]^{1/2}}\right]^2\right\}\left(\frac{A_{ij}}{A_i}\right)\right)^2}\right)\right]^k$$

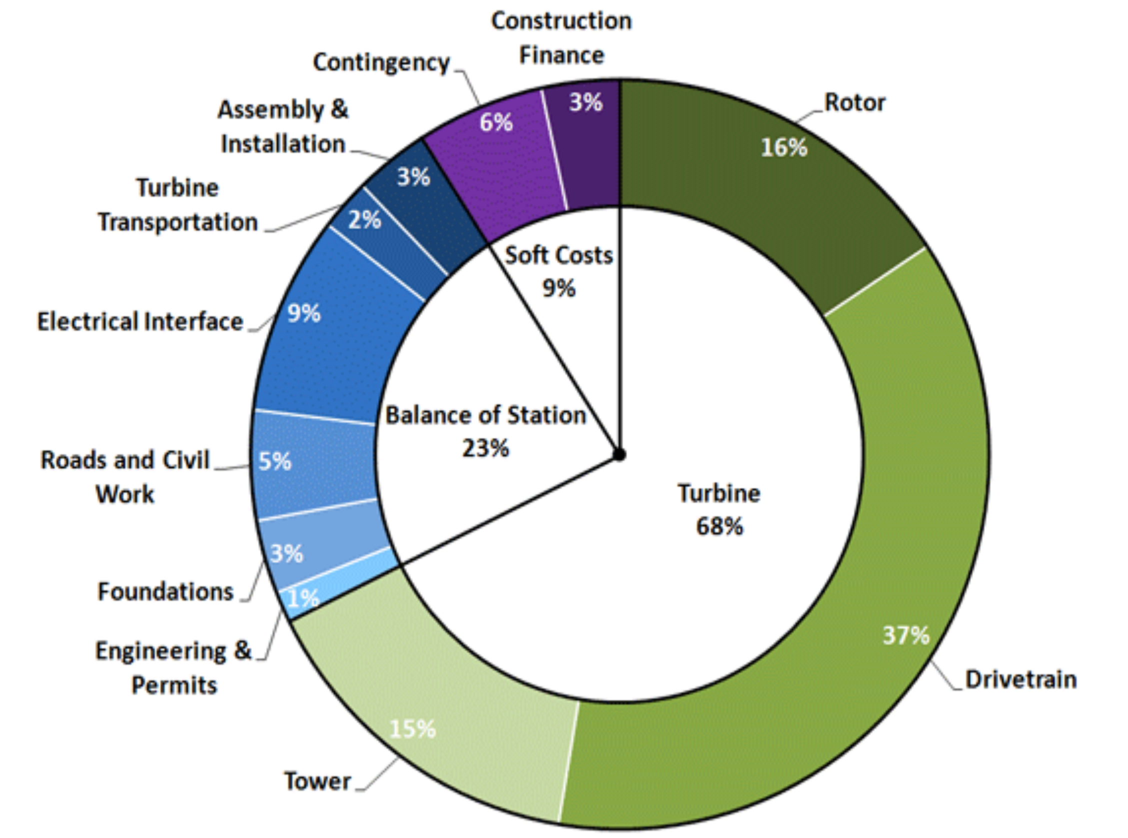
- Farm capacity factor

$$\boldsymbol{CF}=\frac{P}{IP}=\frac{\sum_{i=1}^{N}\sum_{k=0}^{k=K} a_{ik}\left[U_{o,i}\left(1-\sqrt{\sum_{j=1}^{j=i-1}\left(\left\{1-\sqrt{1-\boldsymbol{C_{T,j}}}\Big/\left[1+\frac{\alpha_{\boldsymbol{j}}\Delta y_{ij}}{R_j\left[\frac{1-2\boldsymbol{a_j}}{1-\boldsymbol{a_j}}\right]^{1/2}}\right]^2\right\}\left(\frac{A_{ij}}{A_i}\right)\right)^2}\right)\right]^k}{\sum_{i=1}^{N} P_{R,i}}$$

IP Installed Power P_R Rated Power

6- Simple Cost Analysis (1)

- Only the ICC is considered,
- Turbines' cost is the major cost component,
- The ICC of 1 MW at H = 80 m is considered unity and denoted Capital Cost Index (***CCI***),
- The tower cost = 0.15/0.68 = 0.2206 of the ***CCI***,



Typical Installed Capital Cost (ICC) breakdown of an onshore wind power project [*2011 Cost of Wind Energy Review, NREL Report, 2013*].

- An increase in H by 1 m costs 0.2206/80 = 0.0027575 of the ***CCI***,

6- Simple Cost Analysis (2)

- Capital Cost Index per Installed Power

$$CCIIP=\frac{CCI}{IP}=\frac{\sum_{i=1}^{N} P_{R,i}\left[1+0.0027575\left(H_i-H_{min}\right)\right]}{\sum_{i=1}^{N} P_{R,i}}$$

- Capital Cost Index per Output Power

$$\boldsymbol{CCIOP}=\frac{CCI}{P}=\frac{\sum_{i=1}^{N} P_{R,i}\left[1+0.2757\left(H_i-H_{min}\right)\right]}{\sum_{i=1}^{N}\sum_{k=0}^{k=K} a_{ik}\left[U_{o,} - \sqrt{\sum_{j=1}^{j=i-1}\left(\left\{\frac{1-\sqrt{1-\boldsymbol{C_{T,j}}}}{\left[1+\frac{\alpha_{\boldsymbol{j}}\Delta y_{ij}}{R_j}\left[\frac{1-2\boldsymbol{a_j}}{1-\boldsymbol{a_j}}\right]^{1/2}\right]^2}\right\}\left(\frac{A_{ij}}{A_i}\right)\right)^2}\right]^k}$$

7- Optimization

- The 3 objective functions are scaled, adapted, weighted, and combined into one Total Objective Function:

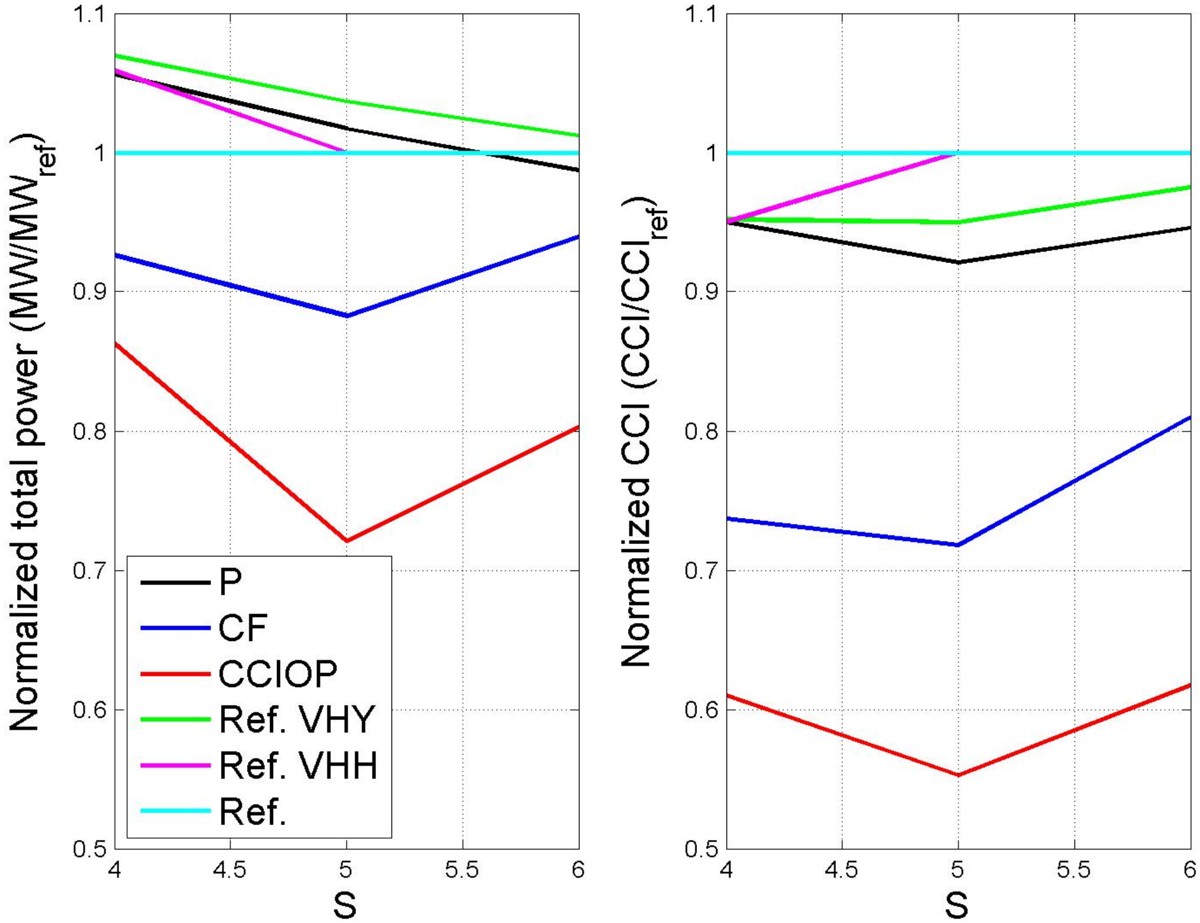
$$TOF = \omega_P f_P \frac{1}{P} + \omega_{CF} f_{CF} \frac{1}{CF} + \omega_C f_C \frac{CCI}{P}$$

$$\omega_P + \omega_{CF} + \omega_C = 1.0$$

- Scaling: turning all terms in to the same order of magnitude,
- Minimum turbines' proximity = 3 *D*
- `TolFun` = 10^{-15} (default = 10^{-6}),
- `ConFun` = 10^{-9} (default = 10^{-6}),
- `PopulationSize` = 10 ~ 50 *nvars* & `Generations` = 3,000.

8- Results and Discussion (1)

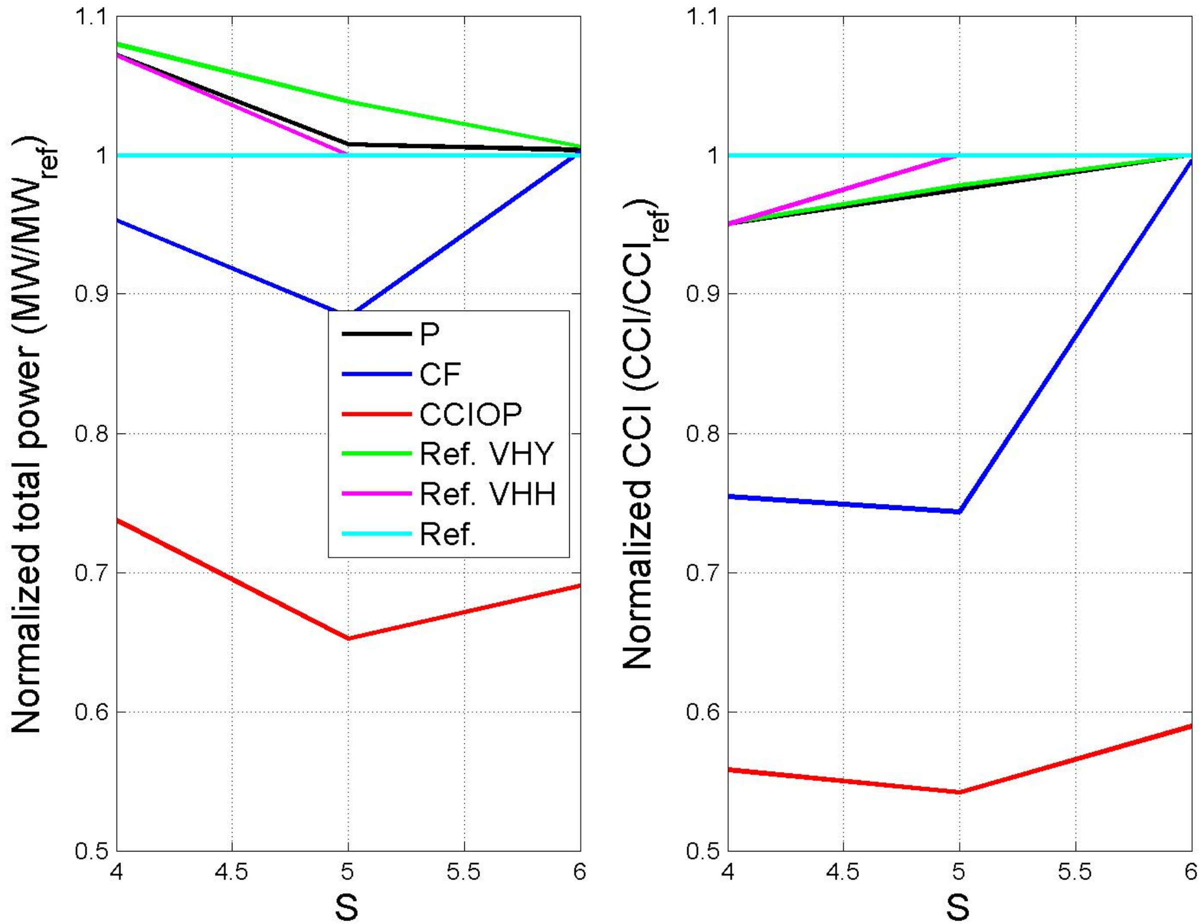
Case 1: Turbines In Line (parallel to wind direction), $N = 6$



Normalized P & CCI for case 1, $U_{ref.}$ = 8 m/s @ 60 m.

8- Results and Discussion (2)

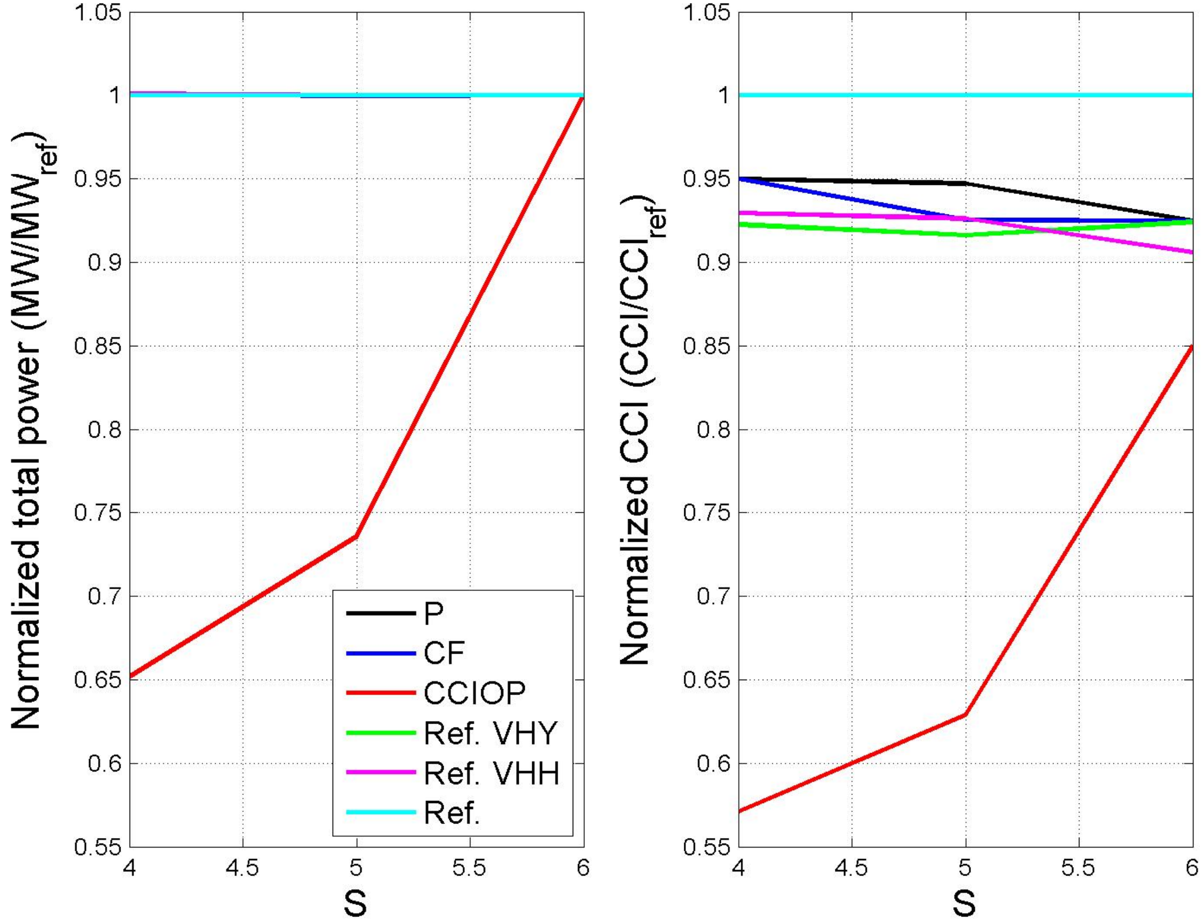
Case 1: Turbines In Line (parallel to wind direction), $N = 6$



Normalized P & CCI for case 1, $U_{ref.}$ = 10 m/s @ 60 m.

8- Results and Discussion (3)

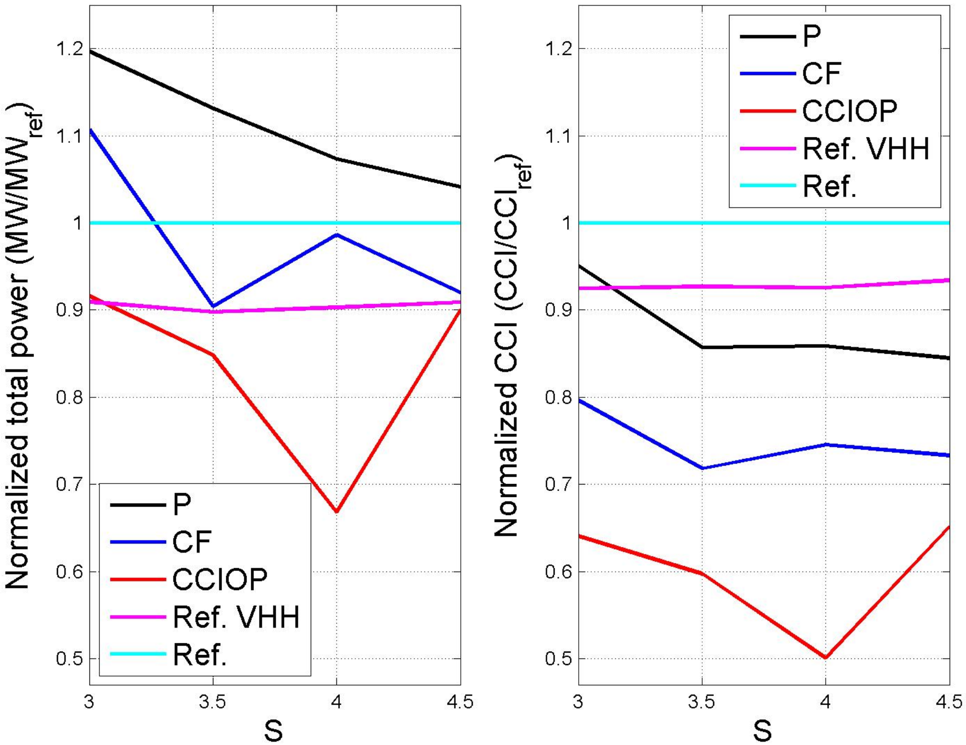
Case 1: Turbines In Line (parallel to wind direction), $N = 6$



Normalized P & CCI for case 1, $U_{ref.}$ = 12 m/s @ 60 m.

8- Results and Discussion (4)

Case 2: Small Rectangular Wind Farm, $N = 18$



Normalized P & CCI for 3x6 WF, $U_{ref.}$ = 8 m/s @ 60 m.

8- Results and Discussion (5)

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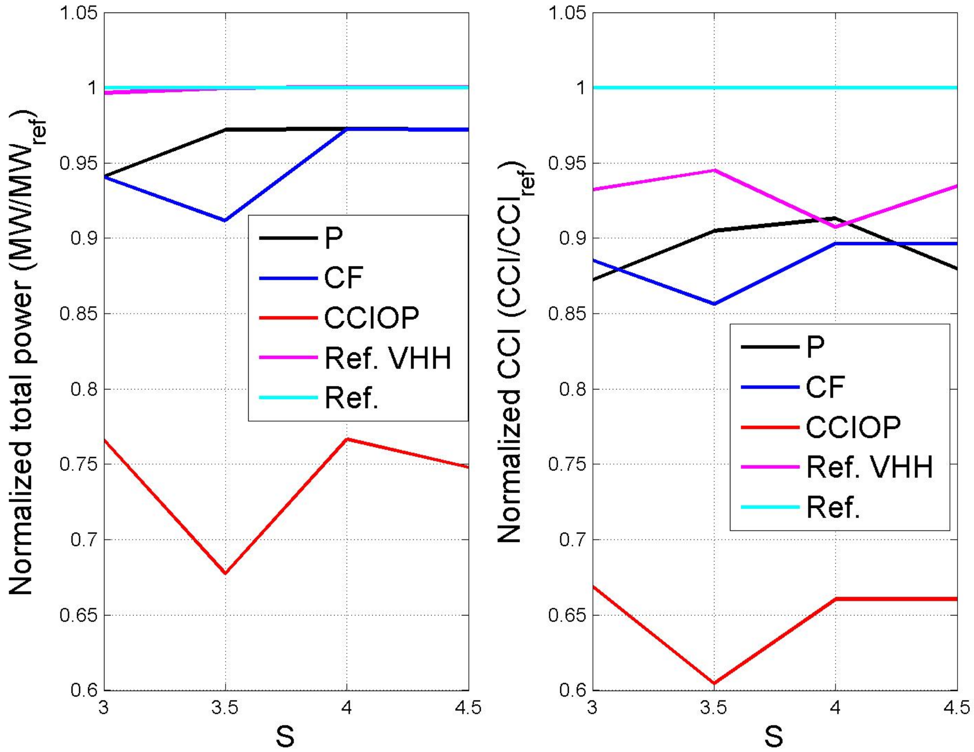
Case 2: Small Rectangular Wind Farm, $N = 18$



Normalized P & CCI for 3x6 WF, $U_{ref.}$ = 12 m/s @ 60 m.

8- Results and Discussion (6)

- The dependence of *P* and *CCI* on *U* and *S* is not smooth, which is expected, because the problem is not continuous, as the turbines' data are not. So, the results should be understood qualitatively not necessarily quantitatively.

- There is a wide margin of trade-off between power output and capital cost, so the weighting factors should be adjusted according to the design priorities in order to obtain the desirable optimum layout.

- At high wind speeds, all optimizations (except for minimum *CCIOP*) tend to develop almost the same output power as the reference case while costing less *ICC*.

8- Results and Discussion (7)

The range of trade-off between power and cost can be summarized as:

Case 1	P/P_{ref}		CCI/CCI_{ref}	
	from	to	from	to
CF	0.88	1.00	0.72	1.00
CCIOP	0.65	1.00	0.57	0.85

Case 2	P/P_{ref}		CCI/CCI_{ref}	
	from	to	from	to
CF	0.91	1.10	0.72	0.90
CCIOP	0.68	0.91	0.50	0.66

9- Conclusions

1. Wind farm design with identical turbines or even with different turbines from one manufacturer should be abandoned in favour of the turbine selection optimizations described in this proposal.

2. A wide band of optimum designs can be obtained according to the optimization preferences and priorities.

3. The representation of C_T in terms of the wind speed is not the right way.

4. The lack in C_T data could be overcome for multi-MW HAWT by generalization of the available data.

9- Conclusions

4. The proposed methodology is suitable for large scale WFs as well as for compact designs.

5. Taller towers are needed, not only to reach higher wind speeds, but also to reduce the wake effects in the compact WF designs.

6. The manufacturers should show more flexibility and accept the fair competition by providing more wind turbine designs and more accurate technical data.

10- Further Work

- Real case large wind farm.
- Modified wake model.
- More realistic wind profile.
- Noise Level minimization.
- TOF with different weighting factors.
- Optimization.

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QUESTIONS ?