ATLANTIS

Industry Day

A NEW METRIC SPACE

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U.S. Department of Energy

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ATLANTIS = acronym for "***A**erodynamic **T**urbines, **L**ighter and **A**float, with **N**autical **T**echnologies and **I**ntegrated **S**ervo-control*".

The Greek philosopher Plato (428-348 BC) cited Atlantis in his dialogues as the lost continent of the ancient times that disappeared in the depths of the sea.

Outline

1.- LCOE

- Definition review
- Dependence on external/internal factors

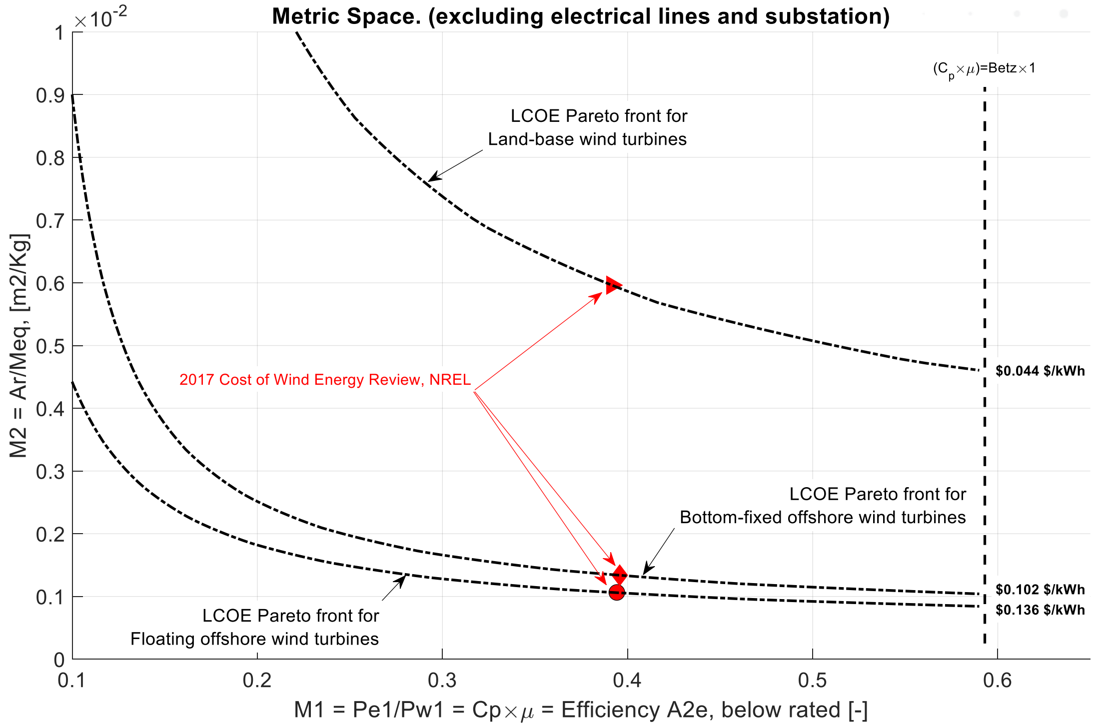
2.- New Metric Space

- Dependent on technology only
- M1 metric
- M2 metric
- LCOE Pareto-optimal fronts

3.- Case studies

4.- Program performance target

5.- Examples: new designs



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CHANGING WHAT'S POSSIBLE

1.- LCOE

Definition review

Wind projects are calculated in terms of their life-cycle cost, known as the ***Levelized Cost Of Energy*** (*LCOE*). *LCOE* is calculated as dollars per MWh, or cents of dollar per kWh, and is a function of:

(1) the *capital expenditures* or **CapEx** of the turbine (in $), which includes the cost of the blades, nacelle, tower, electrical generator, gearbox, pitch and yaw systems, power electronics, floating platform, mooring system, anchor system, etc.;

(2) the *fixed charge rate* or **FCR** (in 1/year), which includes the cost of money, taxes and amortization;

(3) the *operation and maintenance expenditures* or **OpEx** (in $/year);

(4) the *annual energy production* or **AEP** (in kWh), which depends on the site wind characteristics.

$$LCOE = \frac{(FCR\ CapEx) + OpEx}{AEP} = \left[\frac{\$ / \ year}{kWh / \ year} \right]$$

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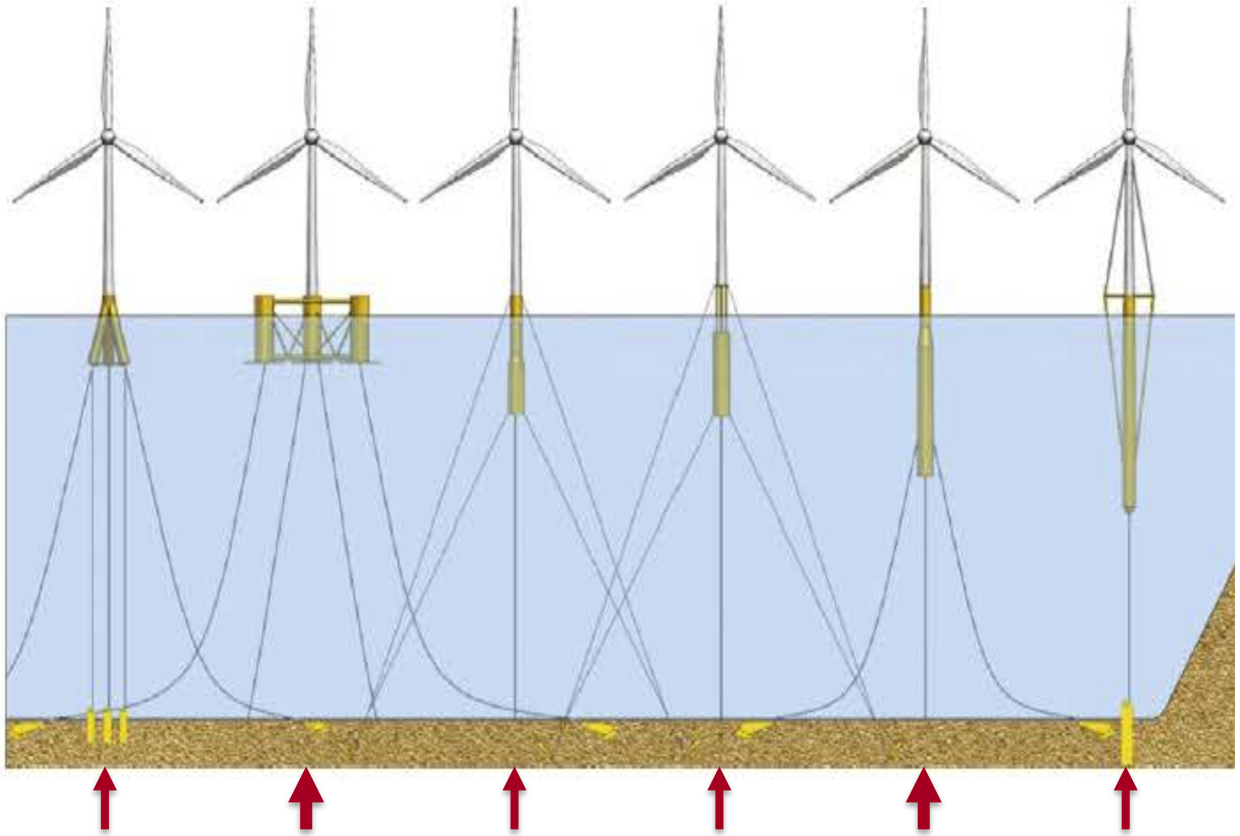
LCOE dependence on external/internal factors

CASE STUDY



(a) Turbine:

Turbine rated power 5 MW
Turbine rotor diameter 126 m
Turbine hub height 90 m
Water depth 200 m

(b) Farm:

500-MW project size (100 WTs)
Distance from shore 200 km

(c) AEP:

3,125 h/year at rated power, considering:
45.7% Capacity factor
Losses: Wake 7%, Grid 1.8%,
Availability 93.8%, Other 9%

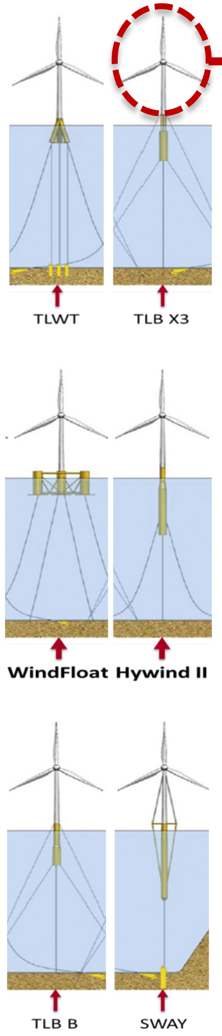
(d) Economics:

FCR of 10%

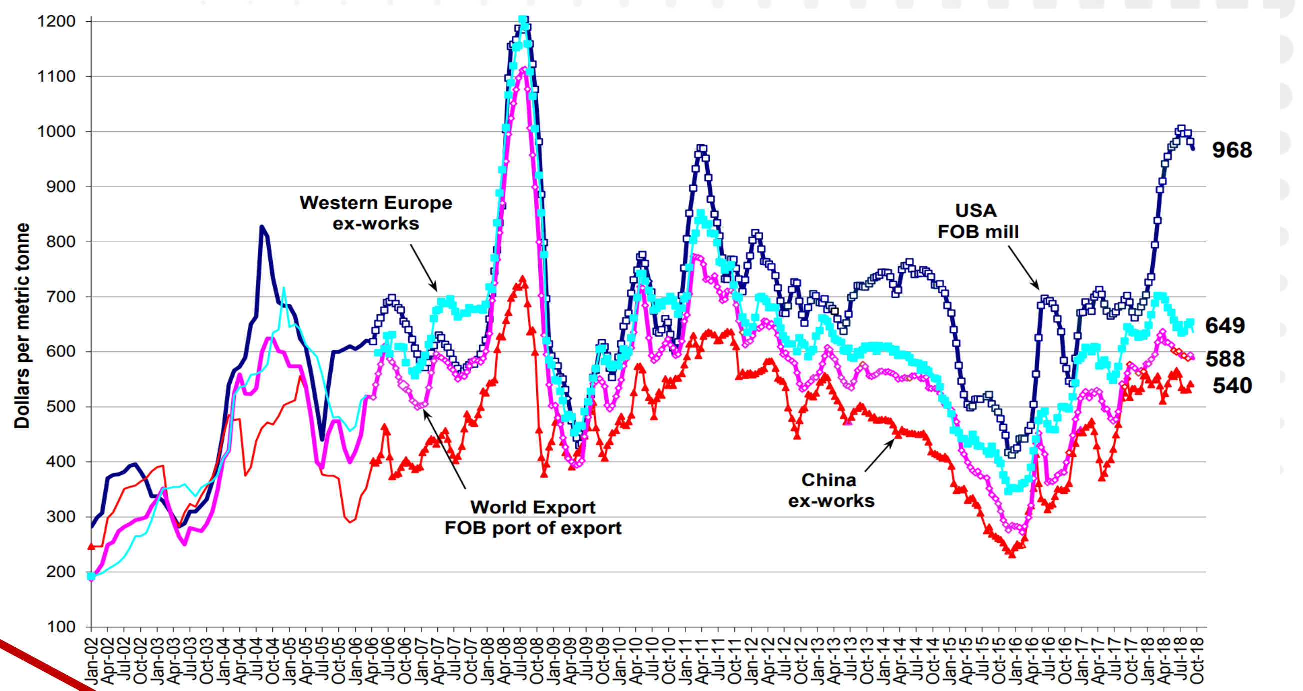
[1]. A. Myhr, C. Bjerkseter, A. Ågotnes, T. Nygaard, *Levelised cost of energy for offshore floating wind turbines in a life cycle perspective*, Renewable Energy, Vol. 66, pp. 714-728, June 2014.

[2]. J. Jonkman, S. Butterfield, W. Musial, and G. Scott, *Definition of a 5-MW Reference Wind Turbine for Offshore System Development.* Technical Report NREL/TP-500-38060, February 2009.

(a) Cost of steel dependence



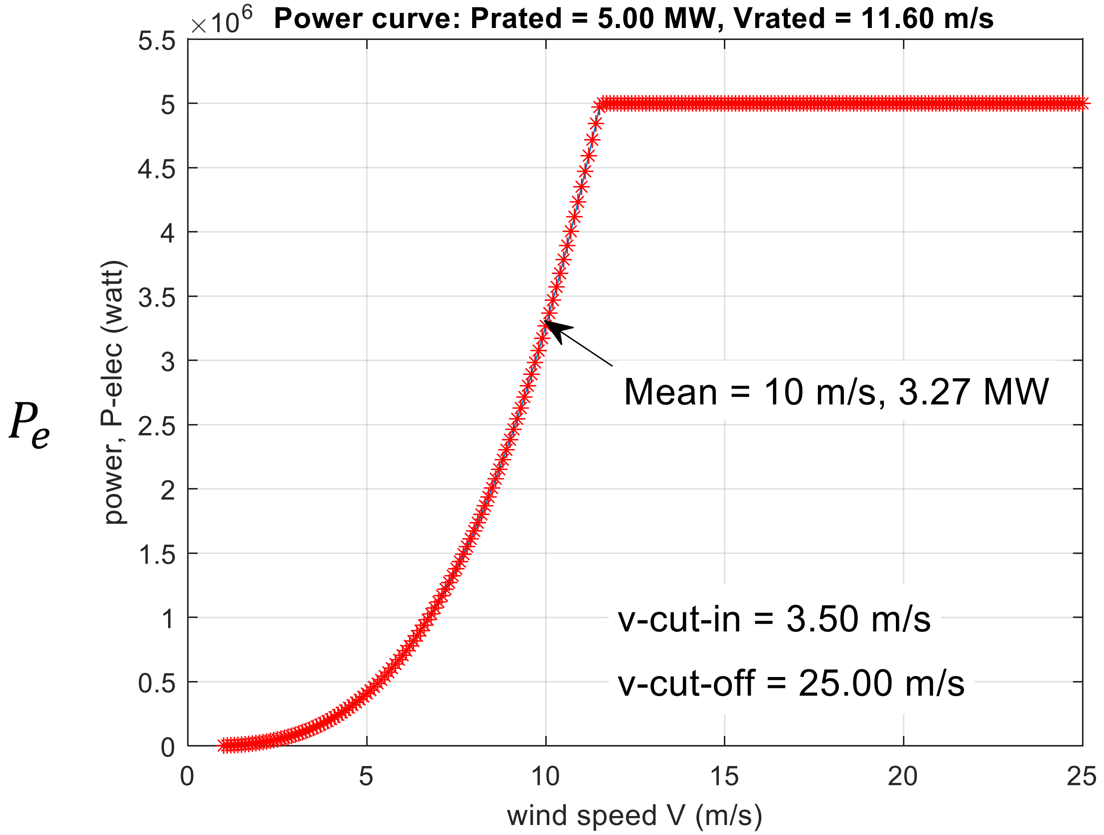
5 MW ref wind turbine (only the turbine)	Total mass (Mg)	Steel (%)	Steel mass (Mg)
3 blades	53	0	0
Hub	57	98	56
Nacelle	240	82	197
Tower	347	93	323
Total turbine	**697**	**83**	**576**



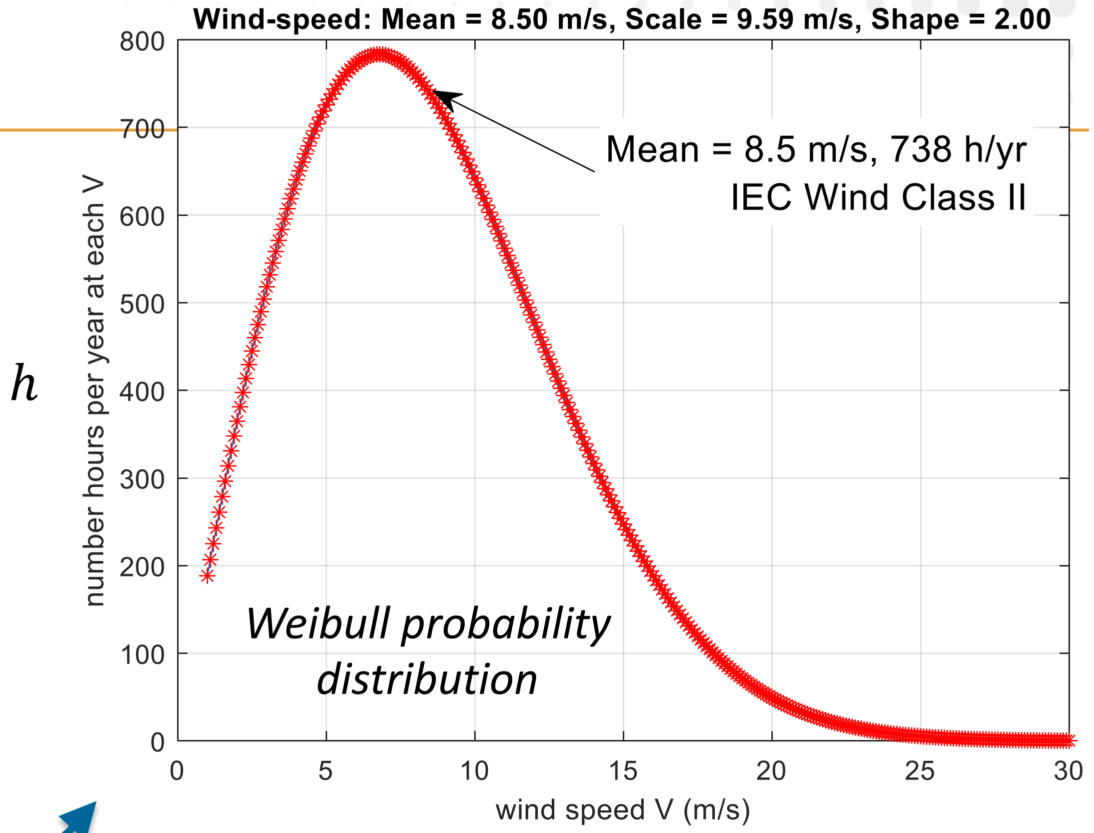
			Steel mass					
	Principles	*Name*	*Platform steel mass (Mg)*	*Turbine mass steel (Mg)*	*Anchor system mass steel (Mg)*	*Mooring lines mass steel (Mg)*	*Total steel mass (Mg)*	*% of CAPEX is steel cost*
1	Tension-Leg-Wind-Turbine	**TLWT**	550	576	153	350	1629	**56**
2	**WindFloat**	**WindFloat**	**2500**	576	68	68	3211	**68**
3	Tension-Leg-Buoy	**TLB B**	445	576	120	350	1491	**59**
4	Tension-Leg-Buoy	**TLB X3**	521	576	108	350	1555	**60**
5	**Spar-catenary**	**Hywind II**	**1700**	576	51	47	2374	**61**
6	Tension-Leg-Spar	**SWAY**	1100	576	140	77	1892	**65**

$$\text{CapEx (\$)} = f(\mathit{Cost\ of\ steel})$$

(b) Site dependence



Turbine power curve



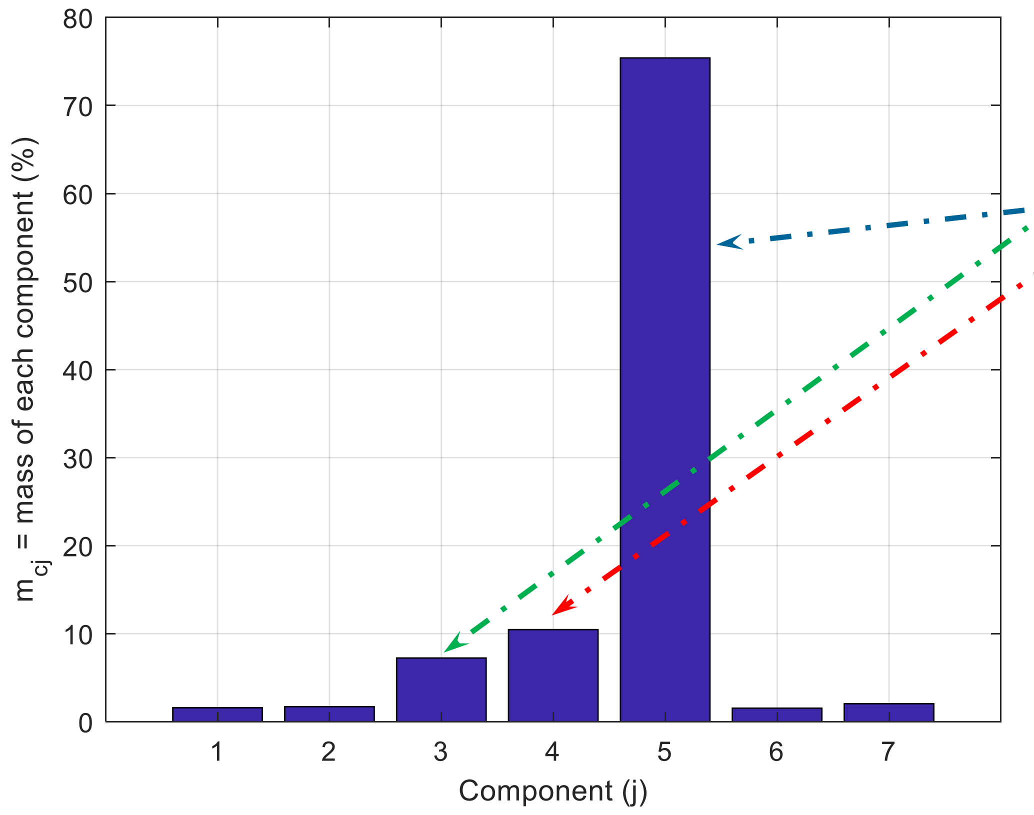
Site properties

" * "

Convolution

AEP (kWh) $= P_e * h = \left(0.5\, \rho\, A\, C_p\, \mu\, V^3\right) * h$

(c) Mass dependence



j	Component	m_{cj}
1	Rotor (blades)	6.32061e4
2	Hub (with bearings and pitch systems)	6.31076e4
3	Nacelle (generator, drive-train, yaw…)	2.65710e5
4	Tower	3.62860e5
5	Floating platform	2.65366e6
6	Mooring system	6.70963e4
7	Anchor system	7.88500e4
8	Electrical system (substation, lines)	5.16302e5

Principal components in mass are:

Floating platform (m_{c5} ≈ 75%)
Tower (m_{c4} ≈ 10%),
Nacelle (m_{c3} ≈ 7%)
Rotor (m_{c1} ≈ 2%).

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2.- New metric space

Based on internal properties

Equations

$$\boldsymbol{M_1} = f_1(\overline{\text{efficiency}})$$

$$\boldsymbol{M_1} = \left.\frac{\sum_{k=1}^{n} P_{e1}(k)}{\sum_{k=1}^{n} P_{w1}(k)}\right|_{at\ V_1} = \frac{1}{n}\sum_{k=1}^{n} C_p(k)\,\mu(k) = \overline{C_p\,\mu}$$

$$P_{e1}(k) = \frac{1}{2}\,\rho\,A_r\,C_p(k)\,\mu(k)\,V_1^3$$

$$P_{w1}(k) = \frac{1}{2}\,\rho\,A_r\,V_1^3$$

$$C_p(k) = C_{pmax}(k)$$

$$\mu(k) = \left(1 - L_g(k)\right)\left(1 - L_{dt}(k)\right)\left(1 - L_w(k)\right)\left(1 - L_e(k)\right)\left(1 - L_o(k)\right)A_v(k)$$

where:

- → n = number of WTs in the farm,
- → ρ = 1.225 kg/m^3 is the density of the air,
- → $A_r = \pi R^2$ is the swept area of the WT rotor in m^2, which is the same for each turbine of the farm.
- → V_1 is the selected undisturbed upstream below-rated wind velocity (for example = 8 m/s),
- → μ = efficiency of the WT, including (all in per unit):
  - L_g: generator losses,
  - L_{dt}: drive-train (gearbox and power electronics) losses,
  - L_w: wake effect losses due to the aerodynamic interaction of turbines in the farm,
  - L_e: electrical losses (substation and electrical lines, intra-wind-farm and farm-to-shore),
  - L_o: other losses,
  - A_v: wind turbine availability.

New metric space

<u>*Based on internal properties*</u>

Equations

$$\boldsymbol{M_2} = f_2\left(\frac{\text{area}}{\text{mass}}\right)$$

$$\boldsymbol{M_2} = \frac{n\,A_r}{\sum_{k=1}^{n} M_{eq}(k)}$$

$$M_{eq}(k) = \sum_{j=1}^{z} m_j(k)$$

$$m_j(k) = f_{tj}\left(1 + f_{mj} + f_{ij}\right) m_{cj}\Big|_k$$

where:

→ n = number of WTs in the farm

→ $A_r = \pi R^2$ is the swept area of the WT rotor in m^2, which is the same for each turbine of the farm

→ f_t = material factor = cost original material ($/kg) / cost steel of reference ($/kg)

→ f_m = manufacturing factor = cost manufacturing of component ($/kg) / cost original material of the component ($/kg)

→ f_i = installation factor = cost installation of component ($/kg) / cost original material of the component ($/kg)

→ m_c = mass of each major component of the FOWT (kg)

→ z = number of main components of the WT

Metric space. Tables

$$M_{eq} = \sum_{j=1}^{z} m_j$$

$$m_j = f_{tj}\,(1 + f_{mj} + f_{ij})\,m_{cj}$$

Table 2. Manufacturing and installation factors

f_m = cost manufacturing of component ($/kg) / cost original material of the component ($/kg)

f_i = cost installation of component ($/kg) / cost original material of the component ($/kg)

j	Component (*j* = 1 to 8)	Manufacturing factor f_{mj}	Installation factor f_{ij}
1	Rotor (blades)	3.87	0.10
2	Hub (with bearings and pitch system)	11.00	0.10
3	Nacelle (with drive-train, electrical generator, power converters, yaw, etc.)	9.49	0.10
4	Tower	1.69	0.10
5	Floating platform	2.00	0.13
6	Mooring system	0.14	0.52
7	Anchor system	6.70	3.48
8	Electrical system (substation, intra-farm lines, farm-to-shore lines)	0.14	0.52

Table 1. Material factors (raw materials)

f_t = cost original material ($/kg) / cost steel of reference ($/kg)

Material	Material factor f_t
Aluminum alloys	4.0
Brass (70Cu30Zn, annealed)	1.1
CFRP Laminate (carbon fiber reinforce polymer)	80.0
Copper alloys	1.5
GFRP Laminate (glass-fiber reinforced plastic or fiberglass)	4.0
Lead alloys	0.6
Nickel alloys	3.0
Pre-stressed concrete	0.3
Titanium alloys	22.5
Steel of reference, to calculate f_t factors	**1.0**

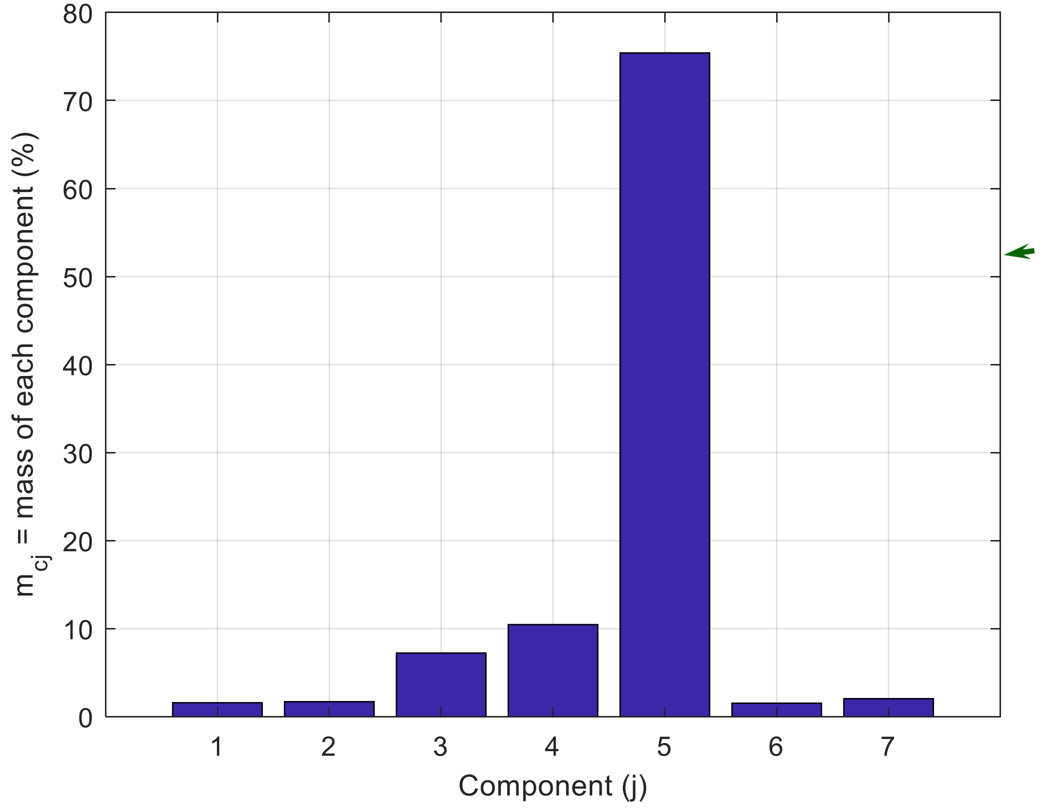
$$CapEx = \left(\sum_{j=1}^{z=8} f_{tj}\,(1 + f_{mj} + f_{ij})\,m_{cj}\right) C_{S\_ref}$$

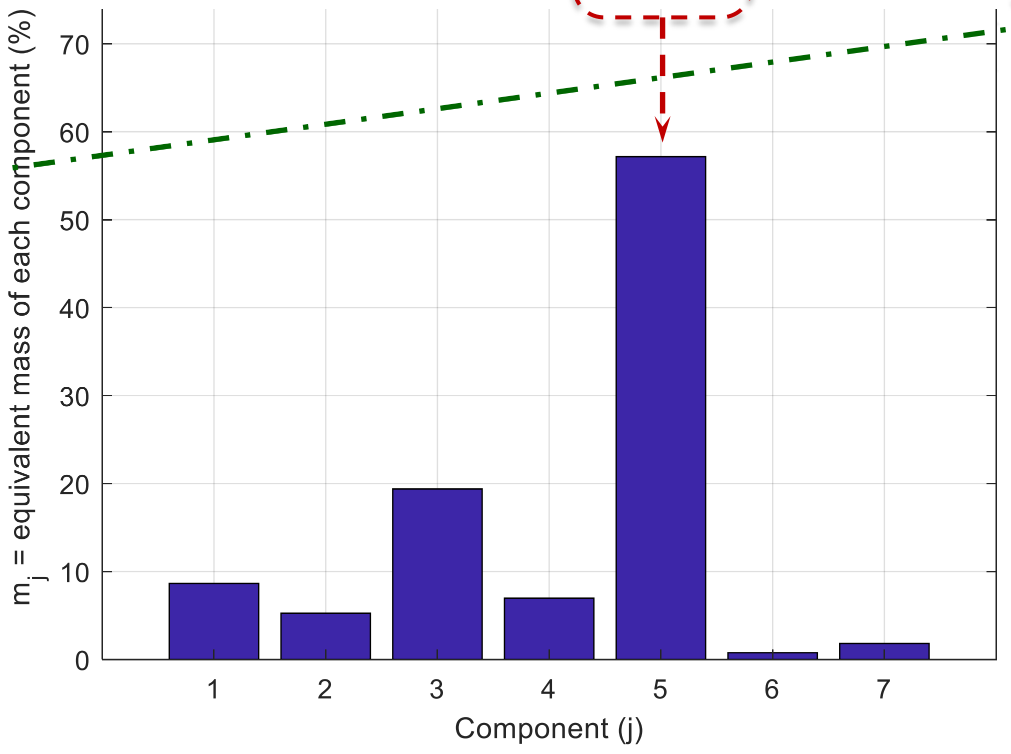
$C_{S\_ref} = \$2/kg$ (high corrosion resistant austenitic stainless steel)

Myhr, A., Bjerkseter, C., Ågotnes, A., Nygaard, T. (2014). Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. Renewable Energy, Vol. 66, pp. 714-728.

FOWT masses

j	Component	m_j	f_{tj}	f_{mj}	f_{ij}	m_{cj}
1	Rotor (blades)	1.25591e6	4	3.87	0.10	6.32061e4
2	Hub (with bearings and pitch systems)	7.63601e5	1	11.00	0.10	6.31076e4
3	Nacelle (generator, drive-train, yaw…)	2.81488e6	1	9.49	0.10	2.65710e5
4	Tower	1.01191e6	1	1.69	0.10	3.62860e5
5	Floating platform	8.30277e6	1	2.00	0.13	2.65366e6
6	Mooring system	1.11380e5	1	0.14	0.52	6.70963e4
7	Anchor system	2.64380e5	0.3	6.70	3.48	7.88500e4
8	Electrical system (substation, lines)	0 (excluded)	1.5	0.14	0.52	5.16302e5





Principal components in the total mass and total equivalent mass M_{eq} are:
Floating platform ($m_{c5} \approx 75\%$, $m_5 \approx 58\%$), **Nacelle** ($m_{c3} \approx 7\%$, $m_3 \approx 19\%$), **Rotor** ($m_{c1} \approx 2\%$, $m_1 \approx 9\%$), **Tower** ($m_{c4} \approx 10\%$, $m_4 \approx 7\%$).

CHANGING WHAT'S POSSIBLE

FOWT in the Metric space

j	Component	m_j	f_{tj}	f_{mj}	f_{ij}	m_{cj}
1	Rotor (blades)	1.25591e6	4	3.87	0.10	6.32061e4
2	Hub (with bearings and pitch systems)	7.63601e5	1	11.00	0.10	6.31076e4
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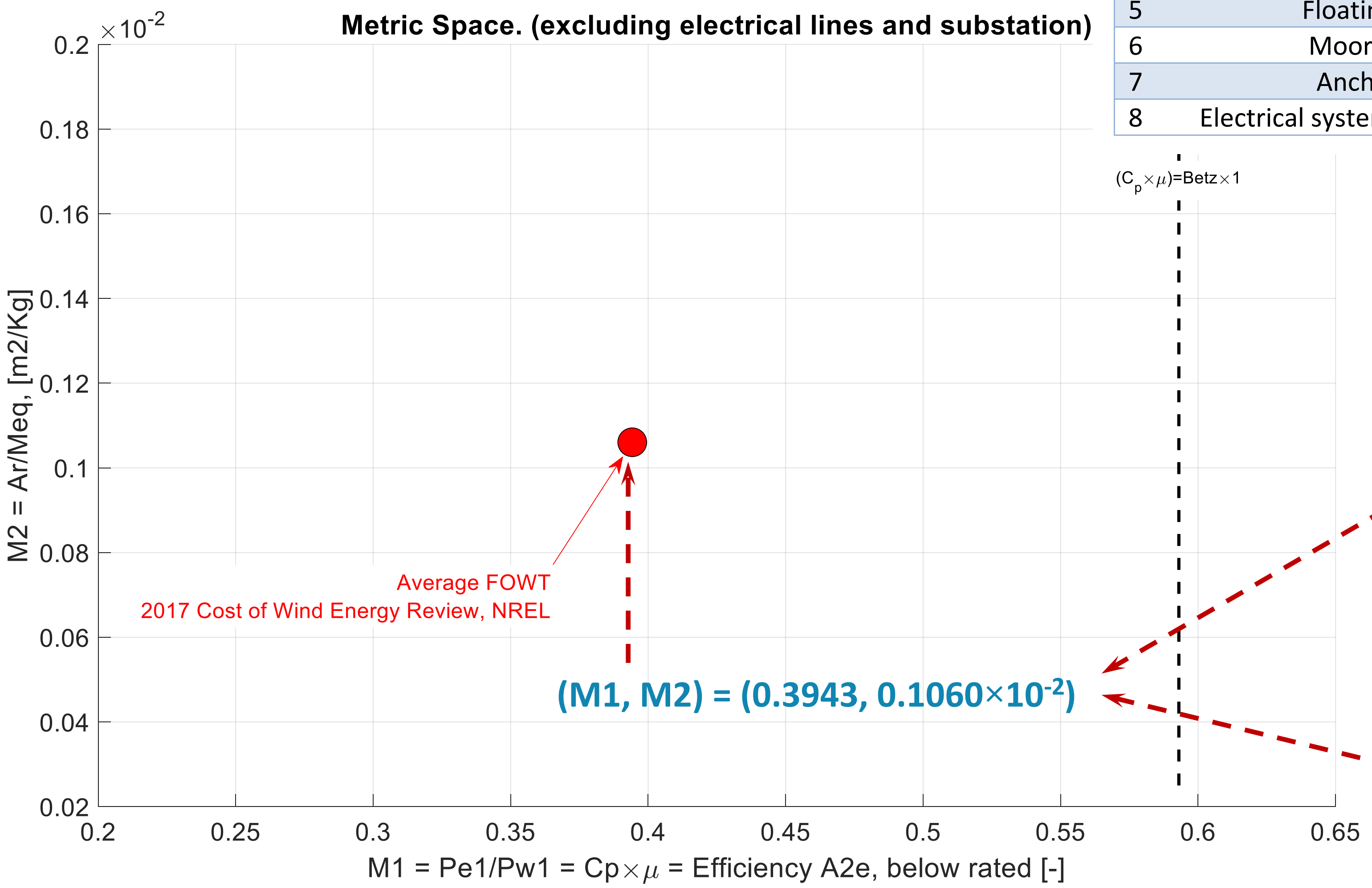
Table 3



- **Metric M1**:

  $C_{pmax} = 0.47$

  $L_g = 0.04; L_{dt} = 0.02; L_w = 0.05$

  $L_e = 0; L_o = 0; A_v = 0.9387$

  M1 = 0.3943

- **Metric M2**:

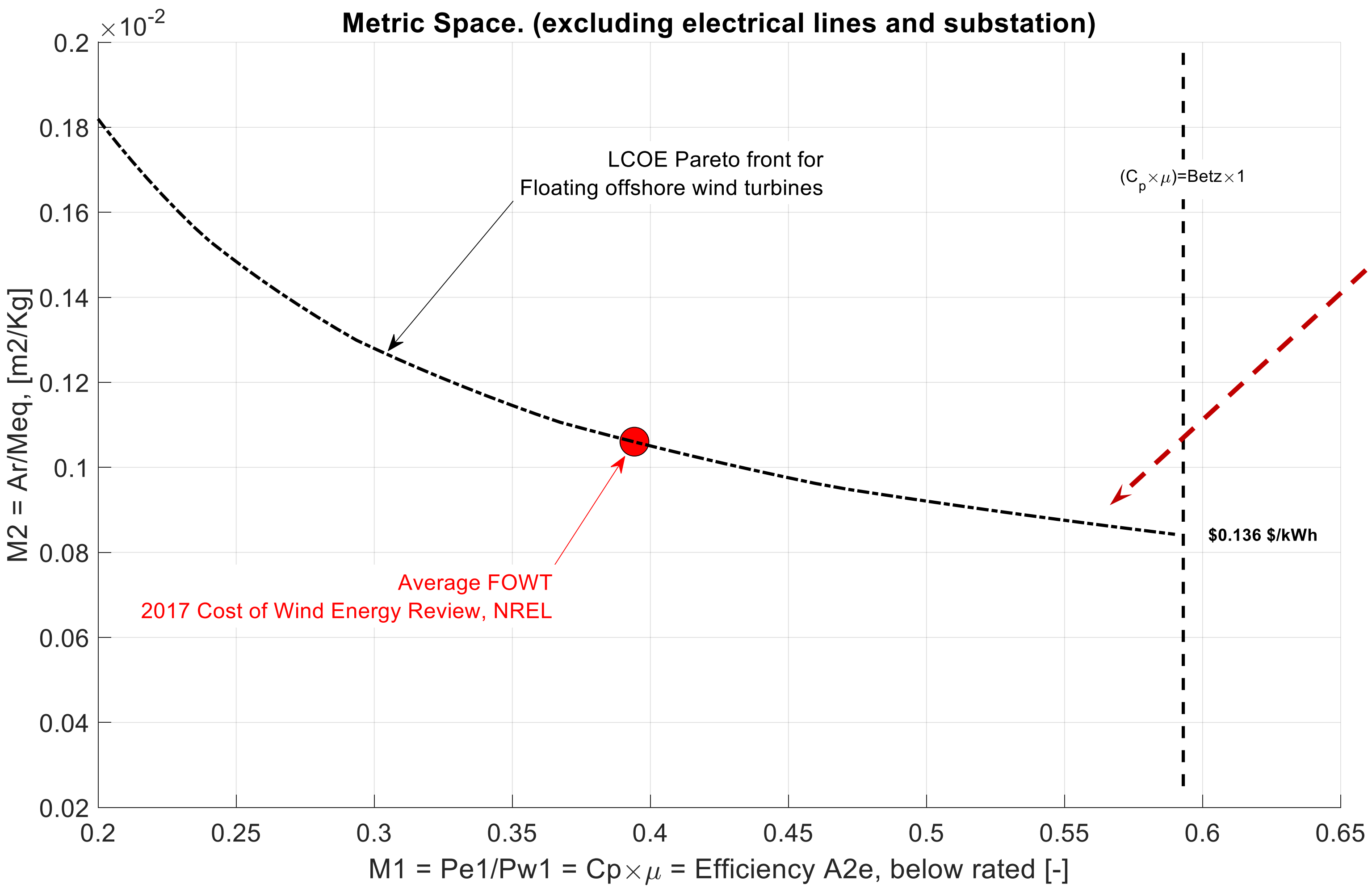
  $A_r = 15{,}394\ m^2$

  $M_{eq} = 14.5248\times10^{-2}$ (*Table 3*)

  M2 = $0.1060\times10^{-2}\ m^2/kg$

Stehly, T., Beiter, P., Heimiller, D., Scott, G. (2018). 2017 Cost of Wind Energy Review. National Renewable Energy Laboratory. Technical Report NREL/TP-6A20-72167

LCOE in the Metric space



Putting the two metrics M1 and M2 together in a two-dimension orthogonal space, we can identify **LCOE Pareto-optimal fronts** for each case of study.

M1 affects AEP.

As M1 increases, AEP also increases, and LCOE decreases

($M_1 \uparrow \rightarrow\ AEP \uparrow\ \rightarrow\ LCOE \downarrow$).

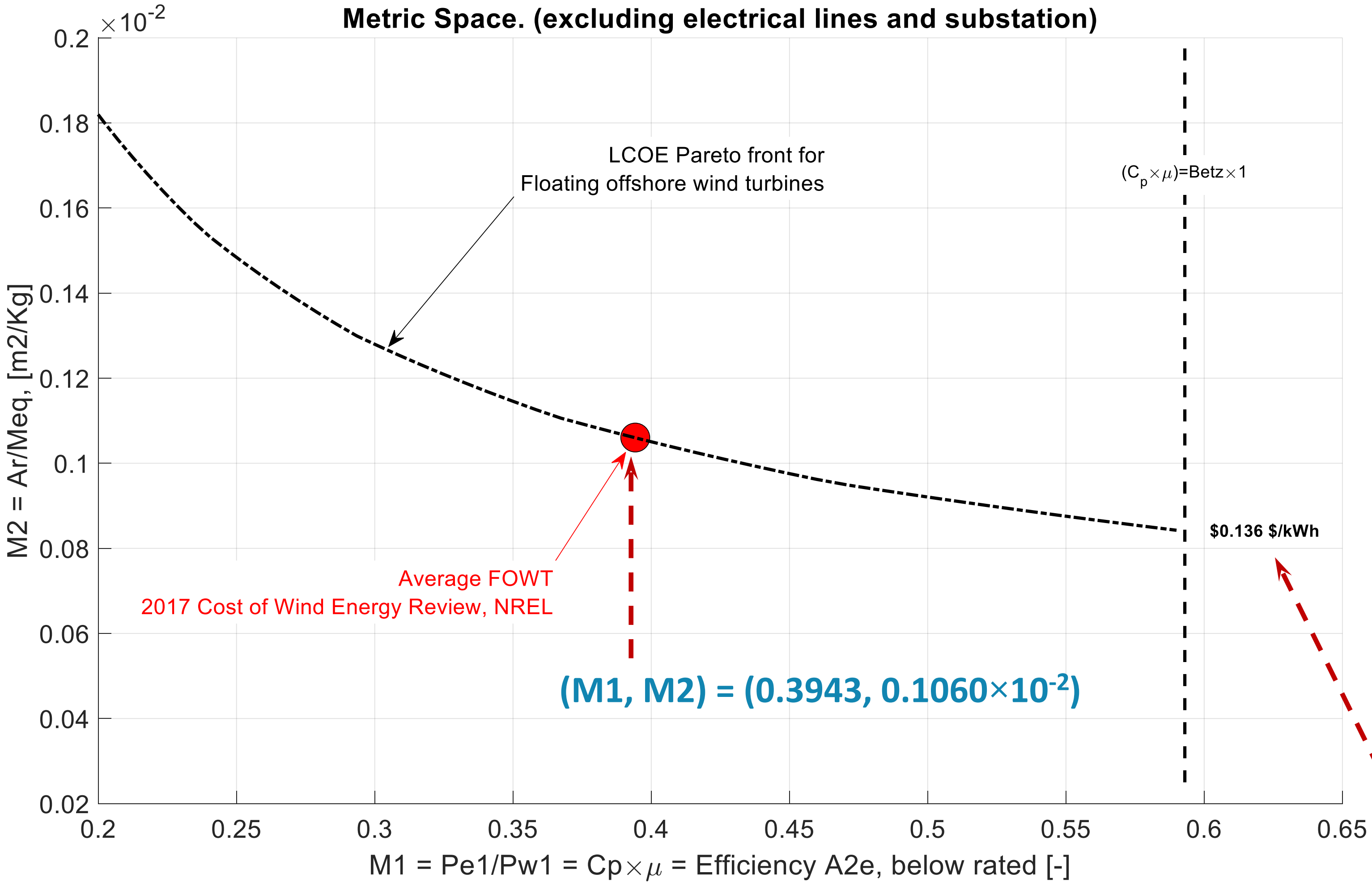
M2 affects CapEx.

As M2 increases, CapEx decreases, and LCOE decreases

($M_2 \uparrow \rightarrow CapEx \downarrow\ \rightarrow\ LCOE \downarrow$).

Stehly, T., Beiter, P., Heimiller, D., Scott, G. (2018). 2017 Cost of Wind Energy Review. National Renewable Energy Laboratory. Technical Report NREL/TP-6A20-72167

LCOE in the Metric space



- ***Associated LCOE calculation***

(not needed for M1, M2):

A pair (M1,M2) can give different LCOE results. The LCOE depends on additional parameters related to the site and economic factors.

Parameters

→ Per = 5.64 MW
→ Wind: Average speed V_{ave} = 8.97 m/s, k = 2.1 (Weibull), $V_{cut\text{-}in}$ = 3 m/s, $V_{cut\text{-}out}$ = 25 m/s
→ Sea: North Atlantic
→ Annual energy production, AEP = 3732 MWh/MW/yr (wind shear effect = 0.90593)
→ Fixed charge rate, FCR = 8.2%
→ OpEx = 86 $/kWe/yr
→ Water depth = 100 m
→ Distance from shore = 30 km
→ Number of turbines in wind farm = 107
→ Project number of years = 20 years
→ Cost of Steel of reference = $2/Kg (high corrosion resistant austenitic stainless steel)

Gives: **LCOE = $0.1362/kWh**

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Stehly, T., Beiter, P., Heimiller, D., Scott, G. (2018). 2017 Cost of Wind Energy Review. National Renewable Energy Laboratory. Technical Report NREL/TP-6A20-72167

Wind class

IEC 61400-1 edition 2

IEC-61400 standards Wind Class

$$I_{long} = \frac{\sigma_{v,long}}{\mu_{v,long}}$$

$$\sigma_{v,long} = \frac{I_{15}\ (15 + \lambda\ \mu_{v,long})}{(\lambda + 1)}$$

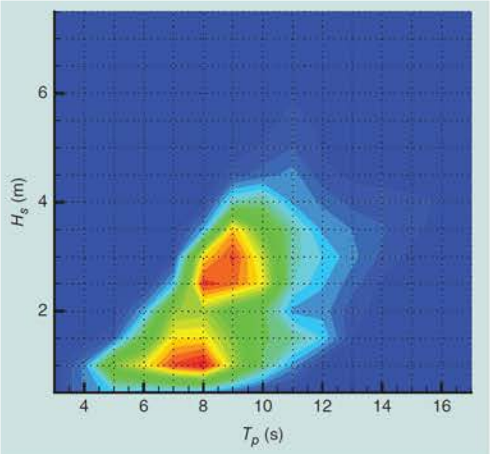
	Wind Class				
	I	**II**	**III**	**IV**	**S**
v_{ref} (m/s)	70	**59.5**	52.5	42.0	Values to be specified by the manufac -turer
v_{ave} (m/s)	10	**8.5**	7.5	6	
a (I_{15})	0.18	0.18	0.18	0.18	
λ	2	2	2	2	
b (I_{15})	0.16	**0.16**	0.16	0.16	
λ	3	3	3	3	

v_{ref} = reference wind speed (10-min mean of the extreme wind speed with a recurrence period of 50 years at the hub height)
v_{ave} = annual average wind speed at hub height, ***a*** = category higher turbulence sites, ***b*** = category lower turbulence sites

I_{15} = turbulence intensity at 15 m/s
$\sigma_{v,long}$ = annual standard deviation of the longitudinal wind speed at hub height, λ = slope parameter
$\mu_{v,long}$ = annual average of the 10-minutes mean of the longitudinal wind speed at hub height

Sea state

Wave height and period increase with an increase in the driving wind speed



Sea state category		Sea state group	ID	SSER	v
Swell dominated sea state	a	I	0.220	0.800	0.24
		II	0.364	0.555	0.32
		III	0.550	0.800	0.65
Wind–sea dominated sea state	b	I	0.220	1.800	0.15
		II	0.364	1.800	0.22
		III	0.550	1.800	0.23
Mixed wind–sea and swell systems with comparable energy	c	I	0.220	1.100	0.28
		II	0.364	1.220	0.38
		III	0.550	1.100	0.52

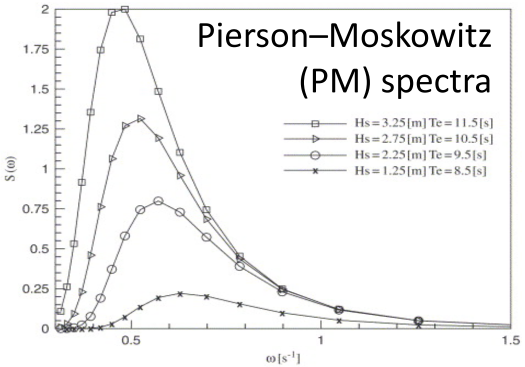
World Meteorological Organization Sea State Code (Douglas Sea Code)

Sea State	Wave height (m)	Characteristics
0	0	Calm (glassy)
1	0–0.10	Calm (rippled)
2	0.10–0.50	Smooth (wavelets)
3	0.50–1.25	Slight
4	1.25–2.50	Moderate
5	2.50–4.00	Rough
6	4.00–6.00	Very rough
7	6.00–9.00	High
8	9.00–14.00	Very high
9	14.00+	Phenomenal

$$S_T(T) = AT^3e^{-BT^4}$$

$$A = 8.10\times10^{-3}\,\frac{g^2}{(2\pi)^4}$$

$$B = 0.74\left(\frac{g}{2\pi V}\right)^4$$



Pierson–Moskowitz (PM) spectra

3.- Case studies

- ***Floating Offshore WT***:

  M1 = 0.3943

  M2 = 0.1060×10^{-2} m^2/kg

  LCOE = $0.136/kWh

- ***Bottom-fixed Offshore WT***:

  M1 = 0.3957

  M2 = 0.1338×10^{-2} m^2/kg

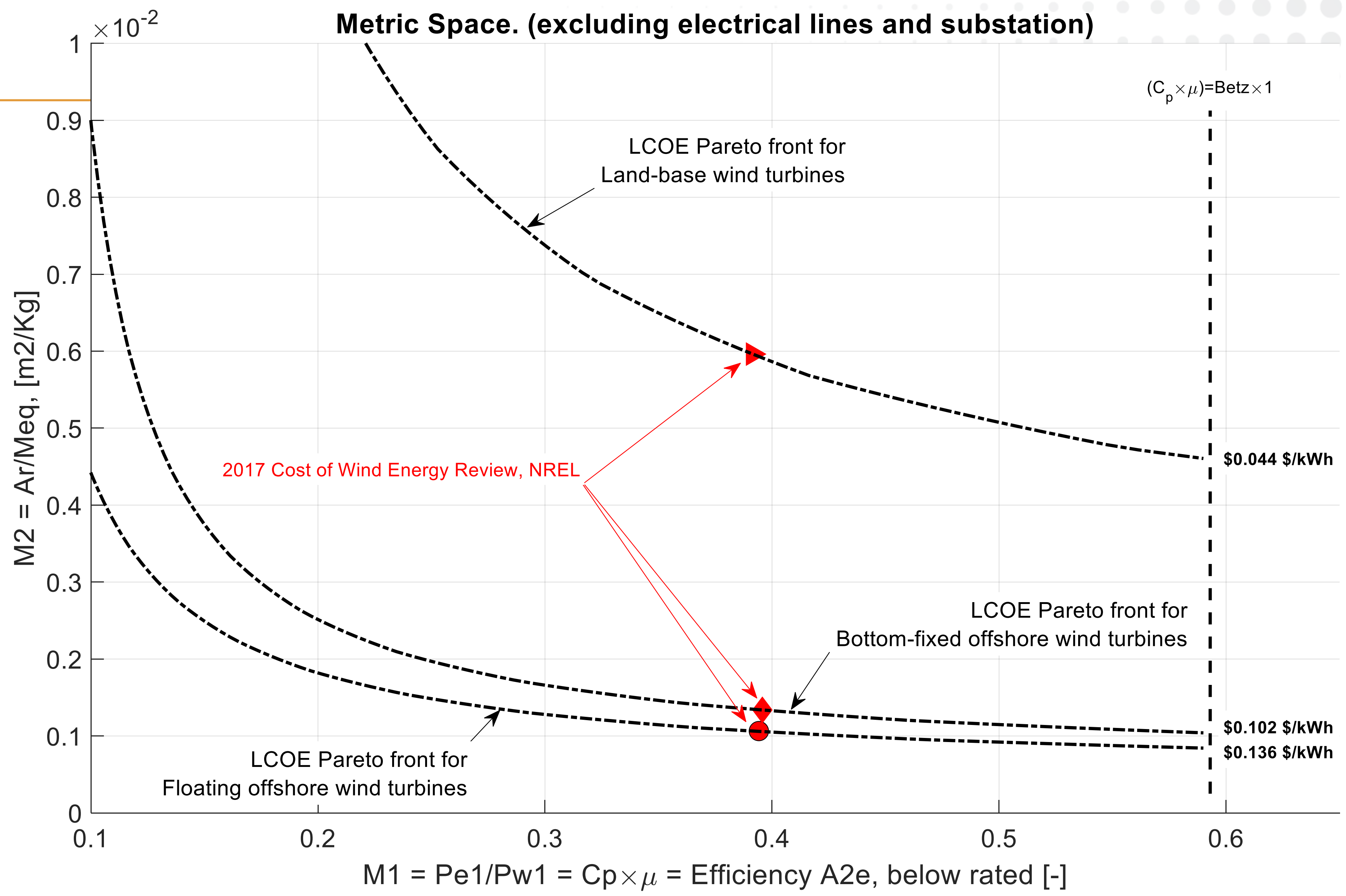
  LCOE = $0.102/kWh

- ***Land-based WT***:

  M1 = 0.3915

  M2 = 0.5962×10^{-2} m^2/kg

  LCOE = $0.044/kWh



Stehly, T., Beiter, P., Heimiller, D., Scott, G. (2018). 2017 Cost of Wind Energy Review. National Renewable Energy Laboratory. Technical Report NREL/TP-6A20-72167

4. Program target

Control Co-Design

- ***Properties A***:

(1) Equivalent mass of the components (ft, fm, fi, mc);

(2) Area of the rotor (A);

(3) Aerodynamic, electrical and mechanical efficiencies (Cp ,μ)

- ***Properties B***:

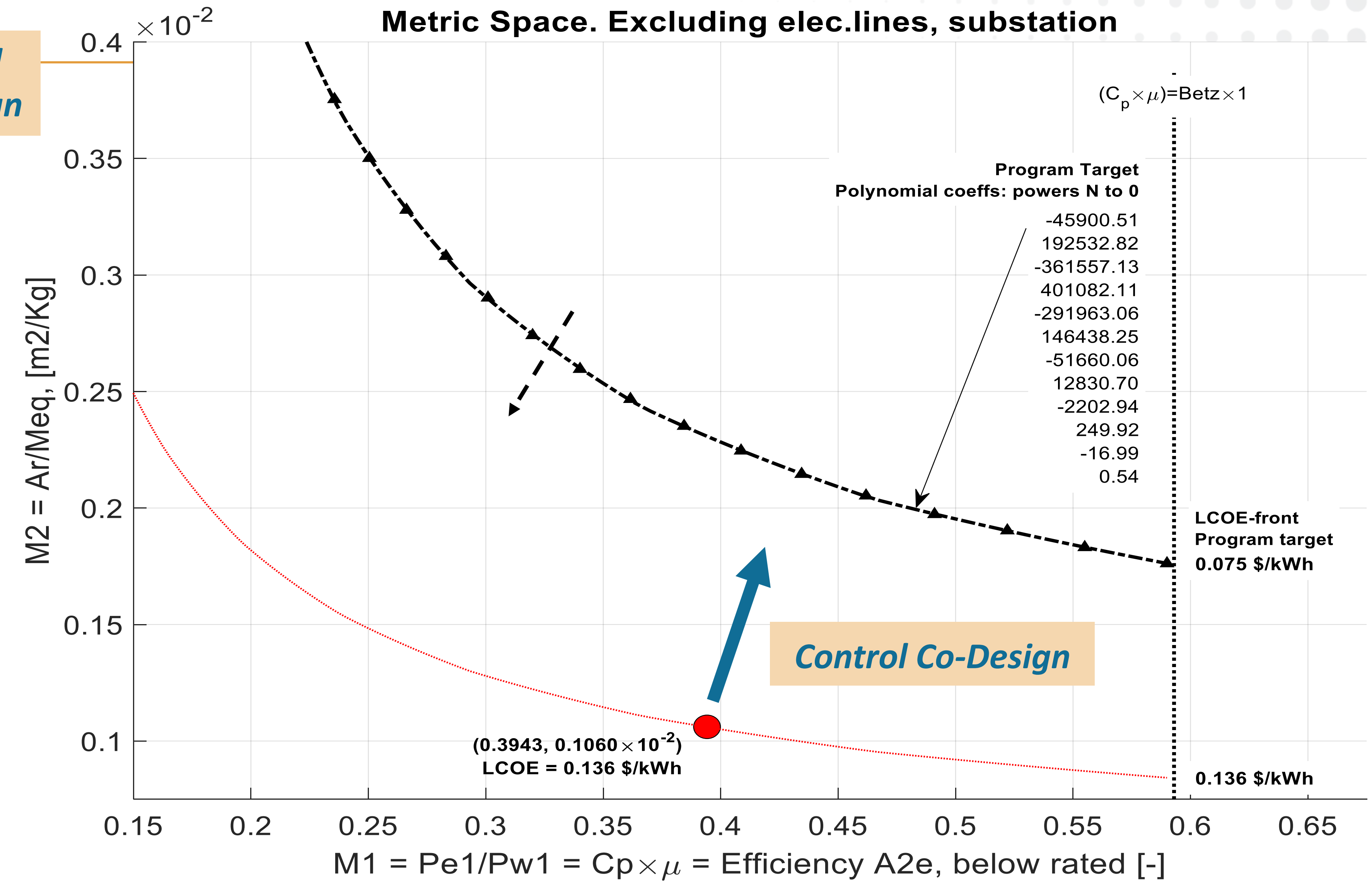
(1) Site factors defined by atmospheric conditions, wind velocity, turbulence intensity, density of the air, Sea state, waves, etc;

(2) Economic factors described by the fixed charge rate, which depends on the cost of money, taxes and amortization; eco. of scale;

(3) Operation and maintenance costs;

(4) Cost of steel of reference;

(5) Rated power.



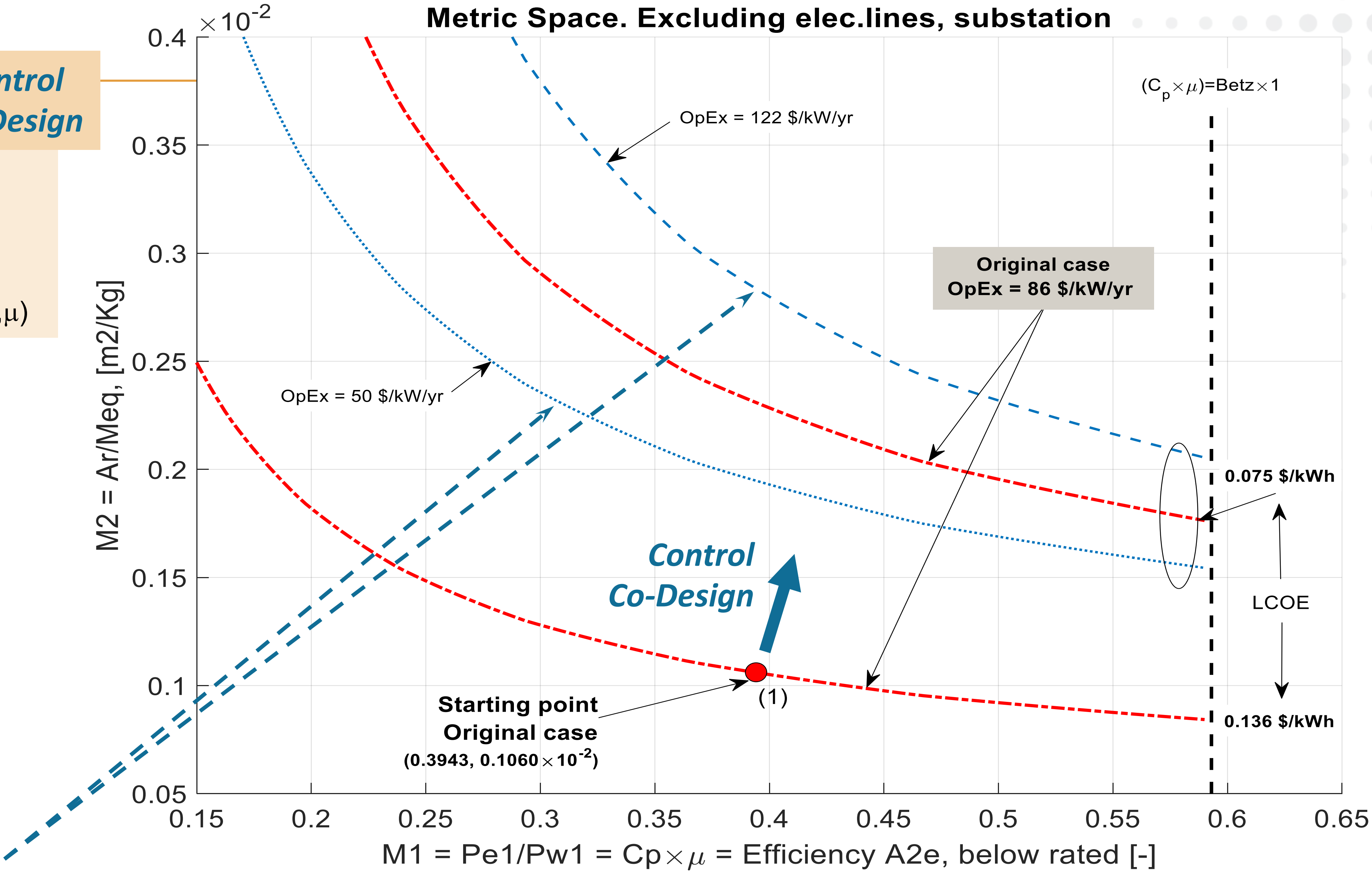
Program target

- ***Properties A***:

(1) Equivalent mass of the components (ft, fm, fi, mc);
(2) Area of the rotor (A);
(3) Aerodynamic, electrical and mechanical efficiencies (Cp ,μ)

- ***Properties B***:

(1) Site factors defined by atmospheric conditions, wind velocity, turbulence intensity, density of the air, Sea state, waves, etc;
(2) Economic factors described by the fixed charge rate, which depends on the cost of money, taxes and amortization; eco. of scale;
(3) Cost of steel of reference;
(4) Rated power
(5) Varying Operation and maintenance costs (OpEx)



Program target

Control Co-Design

- ***Properties A***:

(1) Equivalent mass of the components (ft, fm, fi, mc);
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- ***Properties B***:

(1) Site factors defined by atmospheric conditions, wind velocity, turbulence intensity, density of the air, Sea state, waves, etc;
(2) Economic factors described by the fixed charge rate, which depends on the cost of money, taxes and amortization; eco. of scale;
(3) Cost of steel of reference;
(4) Rated power
(5) Operation and maintenance costs (OpEx)

- ***Assumptions***:

(1) Site factors defined by:
  - Wind: site with average speed of V = 8.97 m/s at hub height, Weibull probability distribution with shape factor = 2.1 and scale factor = 10.13, turbulence intensity = 16%, Vcut-in = 3 m/s, Vcut-out = 25 m/s, and a wind shear effect = 0.90593.
  - Sea state: North Atlantic
  - Density of the air: 1.225 kg/m^3

(2) Economic factors:
  - Fixed charge rate, FCR = 8.2%
  - Economy of scale: wind farm power density. WFPD target ≥ 2.5 MW/km^2
  - Water depth = 100 m
  - Distance from shore = 30 km
  - Project lifetime = 20 years
  - Cost of substation + intra-wind-farm + farm-to-shore lines (included with WFPD target)

(3) Cost of steel of reference, C_{Sref} = 2 $/kg (high corrosion resistant austenitic stainless steel)
(4) Rated power, Per ≥ 5.64 MW
(5) Operation and maintenance costs. OpEx ≤ 86 $/kW/year
(6) LCOE_target ≤ $0.075/kWh

5. Examples: new designs

- ***FOWT. Example 1***:

M1 = 0.3943

M2 = 0.1060×10^{-2} m^2/kg

LCOE = $0.136/kWh

R = 70 m,
Masses:
FP x 1.00,
T x 1.00,
R x 1.00,
N x 1.00,
Cp = 0.47

- ***FOWT. Example 2***:

M1 = 0.3775

M2 = 0.2458×10^{-2} m^2/kg

LCOE = $0.073/kWh

R = 70 m,
Masses:
FP x 0.25,
T x 1.00,
R x 0.50,
N x 0.50,
Cp = 0.45

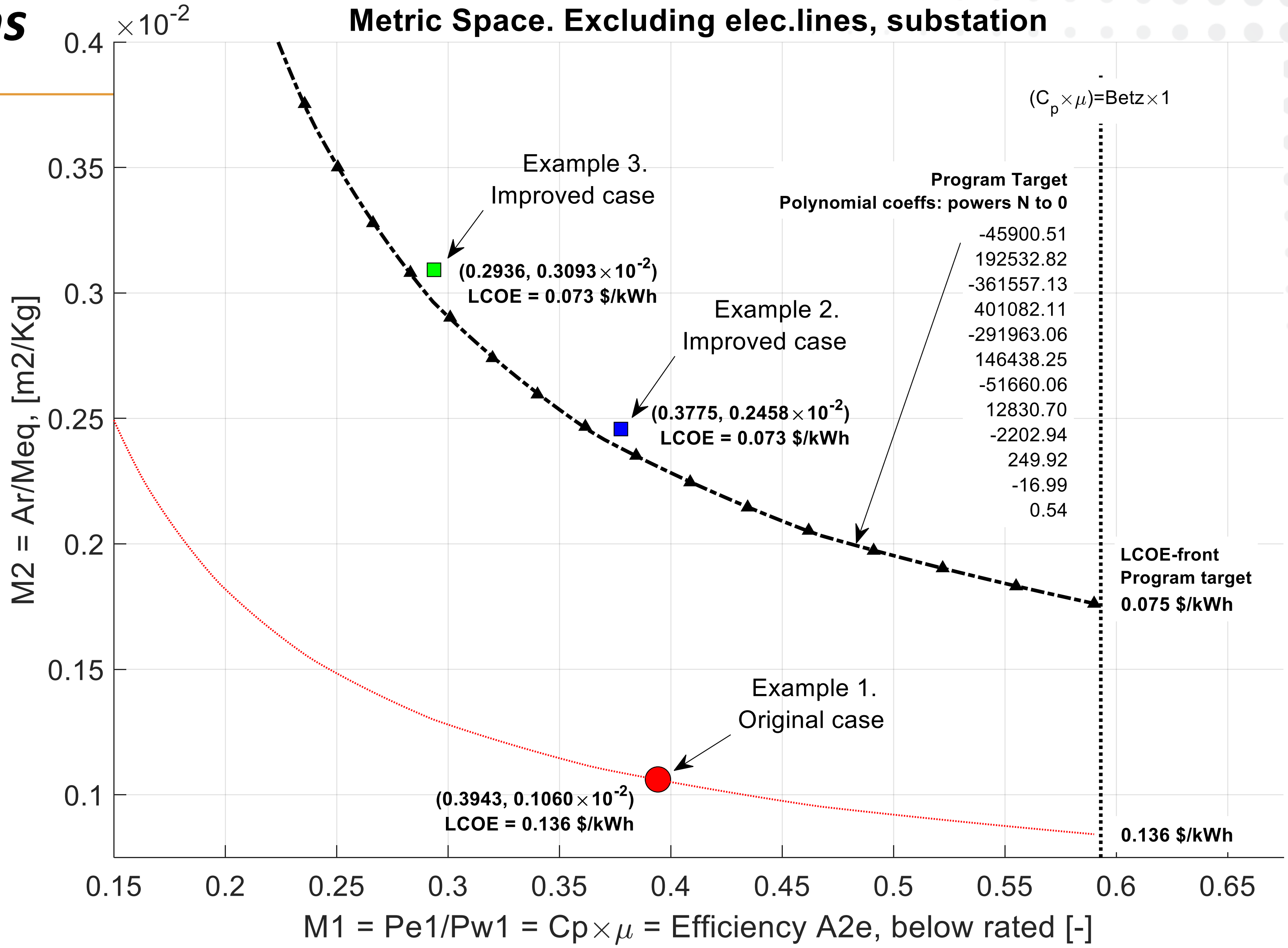
- ***FOWT. Example 3***:

M1 = 0.2936

M2 = 0.3093×10^{-2} m^2/kg

LCOE = $0.073/kWh

R = 70 m,
Masses:
FP x 0.20,
T x 0.14,
R x 0.50,
N x 0.50,
Cp = 0.35



ARPA-E CHANGING WHAT'S POSSIBLE

THANKS!!

The ATLANTIS team