A Comparison of Generator Technologies for Offshore Wind Turbines

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The Fine Print

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Design Matrix

- Generator technologies
  - Interior permanent-magnet direct drive (IPM)
  - Low temperature superconducting (LTS)
  - Medium-speed geared configuration (gear ratio 120) with surface-mounted permanent-magnet generator (MS-PMSG)

- Ratings of 15/17/20/22/25 megawatts (MW)

- Floating and fixed bottom

- Design and optimization supported by the Wind-Plant Integrated System Design and Engineering Model (WISDEM®) and Wind Energy with Integrated Servo control (WEIS).

Wind Turbine Configurations

- Specific power International Energy Agency (IEA) 15 MW 325 W/m[2]
- Max blade tip speed of 95 m/s

Parameter	Units	Nameplate Power (MW) 15	17	20	22	25
Rotor Diameter	m	242.2	257.9	279.7	293.36	312.7
Blade Length	m	117.2	124.7	135.3	141.78	151.2
Hub Diameter	m	7.9	8.4	9.2	9.8	10.4
Rotor Overhang	m	12.0	13.0	14.0	15.0	16.0
Rated Rotor Speed	rpm	7.5	7.0	6.5	6.2	5.8
Rated Shaft Torque	MNm	20.1	24.3	31.0	35.8	43.3

rpm: revolutions per minute

Parameter	Units	Generator architecture DD-LTSG	DD-IPMSG	MS-PMSG
Rotor-stator config		Inner rotor	Outer rotor	Inner rotor
Gear ratio		1:1	1:1	1:120
Target efficiency	%	97	95	96
Rated terminal voltage	kV	3.3	3.3	3.3

Cost Model

- Bill of materials scaled by unit cost of materials and electricity consumption
  - Includes "buy-to-fly" multipliers
  - U.S. average cost of electricity for industry in 2022 = $0.078 per kilowatt-hour (kWh)
- Cost and mass of cooling system scales by generator rating and diameter
  - Cooling cost multiplier = $124 per kilogram (kg)
- Bureau of Labor Statistics manufacturing estimates final cost is 18.9% capital, 61.9% materials, 19.3% labor, so our materials estimate is scaled by 1/0.619 to obtain final cost.

Material	$/kg	Buy to fly	kWh/kg
Copper	7.30	1.26	96.2
Steel	1.56	1.21	15.9
Elec Steel	4.44	1.21	26.9
NdFeB	66.72	1.0	79.0
NbTi	45.43	1.0	79.0

Cooling Mass

Rating (MW)	LTS (t)	IPM (t)	MS-PMSG (t)
15	10.6		1.3
17	12.0		1.5
20	14.9		1.8
22	16.4		2.0
25	18.7		2.3

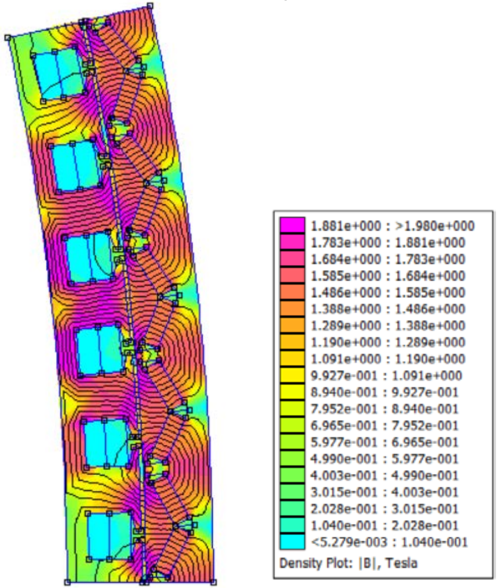
Comparison of Generator Technologies

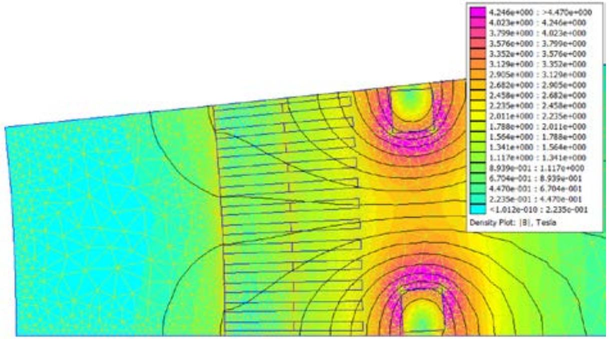
Source: NREL/PR-5000-85341

- Design optimization used finite element method magnetics (FEMM) models of generator sections; particularly important for permanent-magnet designs

- Code is publicly available at https://github.com/WISDEM/GeneratorSE/

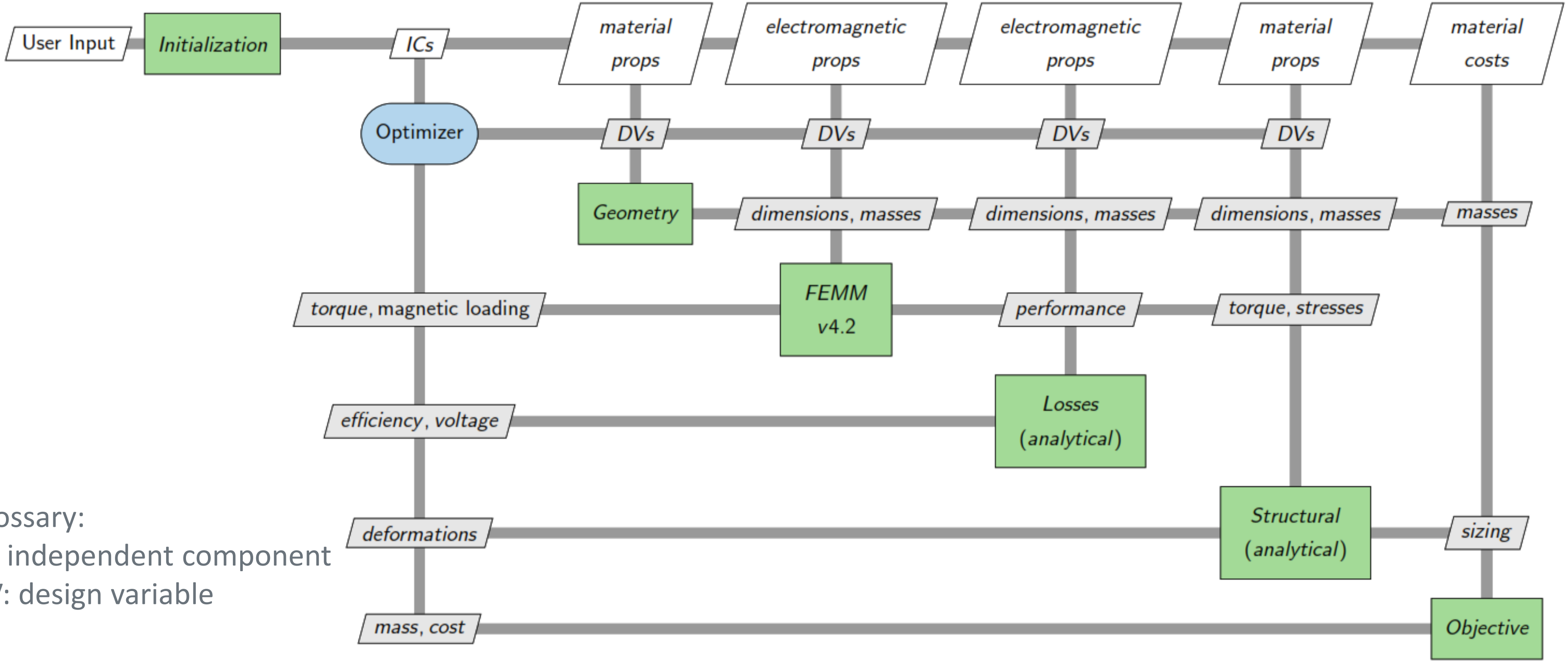
- Cost vs. mass minimizations
  - We moved ahead with the minimum-cost designs.
  - Results are very sensitive to the unit costs of the materials.





Source: NREL/PR-5000-85341

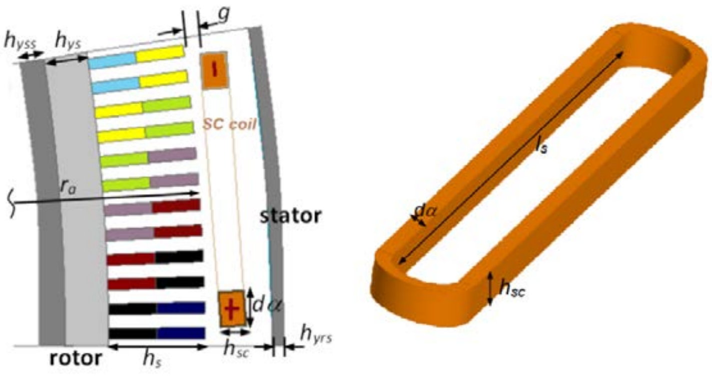
Generator Design Optimization



Glossary:
IC: independent component
DV: design variable

LTS Design

- Optimal design parameters generally avoid extremes
- Good cost and consistent efficiency across power

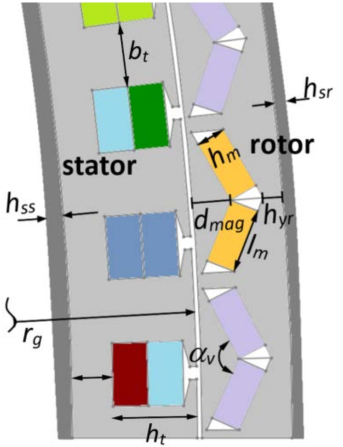


Symbol	Description	Units	Bounds Lower	Bounds Upper
r_a	Stator radius	m	3	4.75
h_s	Winding height	mm	50	400
l_s	Axial length	m	0.75	1.75
h_{sc}	Field coil height	mm	30	250
N_{sc}	Field coil turns	-	1500	3500
h_{yr}	Rotor yoke thickness	mm	150	300
pp	Pole pairs	-	15	40
N_c	Stator turns per coil	-	1	7
$d\alpha$	Wire width	deg	0.2	0.6
h_{ss}	Stator support rim thickness	mm	25	600
h_{sr}	Rotor support rim thickness	mm	25	500
t_r	Rotor disc thickness	mm	25	500
t_s	Stator disc thickness	mm	25	500

Symbol	Description	Units	Nameplate Power (MW) 15	17	20	22	25
r_a	Stator radius	m	4.5	4.5	4.75	4.75	4.75
h_s	Winding height	mm	148	166	180	220	263
l_s	Axial length	m	1.0	1.0	1.0	1.0	1.0
h_{sc}	Field coil height	mm	40	30	35	45	73
N_{sc}	Field coil turns	-	1504	1506	1606	1806	2102
I_{sc-op}	Field current	A	451.67	527.86	516.47	500.21	514.73
h_{yr}	Rotor yoke thickness	mm	150	150	150	150	150
pp	Pole pairs	-	38	37	39	39	39
N_c	Stator turns per coil	-	1	1	1	1	1
$d\alpha$	Field coil width	deg	0.749	1.316	1.258	1.258	1.310
T_{ratio}	Torque ratio	-	1.02	1.08	0.98	1.02	1.02
Ep_{ratio}	Terminal voltage ratio	-	0.98	0.80	0.84	0.86	0.82
η	Efficiency	-	98.4	98.4	98.5	98.4	98.4
M_{gen}	Total mass	t	192.1	192.9	207.8	217.3	228.6
C_{gen}	Total cost	k$	4944.4	5270.5	6078.9	6631.5	7369.8

IPM Design

Source: NREL/PR-5000-85341



- Difficulty maintaining efficiency target at high power
- Mass and cost increase with increasing power than LTS design

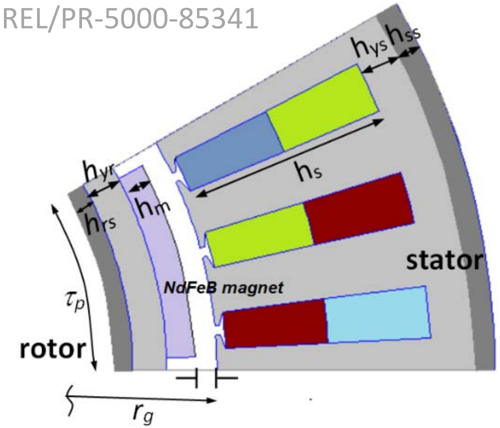
Symbol	Description	Units	Bounds Lower	Bounds Upper
r_a	Stator radius	m	3	4.75
h_t	Tooth height	mm	40	350
l_s	Axial length	m	0.75	2.5
d_{mag}	Vertex to rotor inner radius	mm	50	250
h_m	Magnet thickness	mm	5	60
h_{yr}	Rotor yoke thickness	mm	20	300
h_{ys}	Stator yoke thickness	mm	20	300
pp	Pole pairs	-	50	200
N_c	Turns per coil	-	2	10
b_t	Tooth width	mm	20	100
J_s	Winding current density	A/mm^2	3	6
h_{ss}	Stator support rim thickness	mm	40	200
h_{sr}	Rotor support rim thickness	mm	40	200
t_r	Rotor disc thickness	mm	50	300
t_s	Stator disc thickness	mm	50	300

Symbol	Description	Units	Nameplate Power (MW) 15	17	20	22	25
r_a	Stator radius	m	4.5	4.5	4.75	4.75	4.75
l_s	Axial length	m	2.5	2.5	2.5	2.5	2.5
h_t	Tooth height	mm	107	120	137	149	214
b_t	Tooth width	mm	34.5	32.6	32.5	28.7	33.5
d_{mag}	Vertex to rotor inner radius	mm	50	50	50	50	50
h_m	Magnet thickness	mm	16.3	22.0	30.8	48.3	47.3
h_{yr}	Rotor yoke thickness	mm	30	97	94	74	81
h_{ys}	Stator yoke thickness	mm	61.2	48.0	53.8	62.5	115.2
pp	Pole pairs	-	60	65	60	55	55
N_c	Turns per coil	-	4	4	4	4	4
J_s	Winding current density	A/mm^2	6	6	6	6	6
T_{ratio}	Torque ratio	-	1.05	1.01	1.05	1.06	1.05
Ep_{ratio}	Terminal voltage ratio	-	0.81	0.91	0.89	0.82	0.80
η	Efficiency	-	94.7	94.6	94.7	94.9	93.8
M_{gen}	Total mass	t	314.0	382.9	445.9	460.6	507.5
C_{gen}	Total cost	k$	6298.5	7516.0	9334.5	10708.2	11819.7

MS-PMSG Design

Source: NREL/PR-5000-85341

- Consistent efficiency across power
- Greater mass and cost increase with increasing power than LTS design



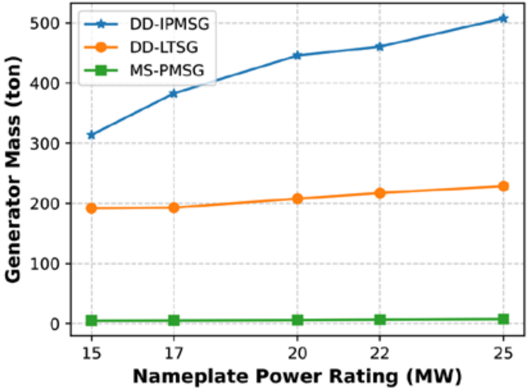
Symbol	Description	Units	Bounds Lower	Bounds Upper
	Electric machine design variables			
r_g	Air-gap radius	m	0.5	2.0
l_s	Axial length	m	0.5	2.5
h_s	Slot height	mm	25	100
g	Air-gap length	mm	6	9
h_m	Magnet height	mm	5	75
pp	Pole pairs	-	4	10
$ratio$	Ratio of pole width to pole pitch	-	0.7	0.85
N_c	Stator turns per coil	-	2	12
I_s	Stator current	A	500	6000
h_{yr}/h_{ys}	Rotor/Stator yoke thickness	mm	10	100
	Structural design variables			
h_{sr}/h_{ss}	Rotor/Stator support rim thickness	mm	45	250
n_r/n_s	Number of rotor/stator spokes	-	5	15
b_r/b_s	Rotor/Stator circumferential arm dimension	m	0.1	1.5
d_r/d_s	Rotor/Stator arm depth	m	0.1	1.5
t_{wr}/t_{ws}	Rotor/Stator arm thickness	mm	1	200

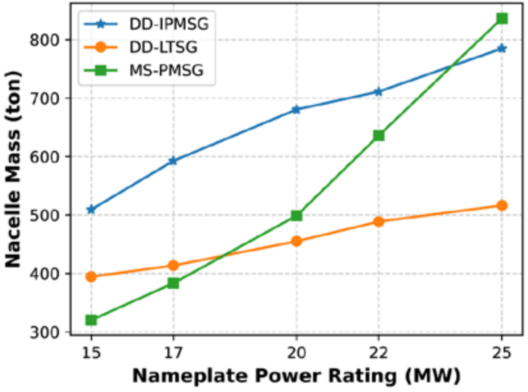
Symbol	Description	Units	Nameplate Power (MW) 15	17	20	22	25
r_g	Air-gap radius	m	0.5	0.5	0.5	0.5	0.5
l_s	Axial length	m	0.59	0.60	0.66	0.69	0.80
h_s	Slot height	mm	25	25	26	26	25
g	Air-gap length	mm	9	9	9	9	9
h_m	Magnet height	mm	12	14	18	28	34
pp	Pole pairs	-	10	10	10	10	10
$ratio$	Ratio of pole width to pole pitch	-	0.83	0.83	0.85	0.85	0.85
N_c	Stator turns per coil	-	2	2	2	2	2
I_s	Stator current	A	6000	6000	6000	6000	6000
h_{yr}	Rotor yoke thickness	mm	96	81	44	38	45
h_{ys}	Stator yoke thickness	mm	26	28	35	41	40
T_{ratio}	Torque ratio	-	1.02	0.99	1.00	0.99	0.95
Ep_{ratio}	Terminal voltage ratio	-	1.09	1.07	1.10	1.10	1.20
η	Efficiency	-	0.968	0.972	0.975	0.977	0.977
M_{gen}	Total mass	t	5.116	5.382	6.094	6.810	7.715
C_{gen}	Total cost	k$	325.2	366.1	436.8	499.1	575.7

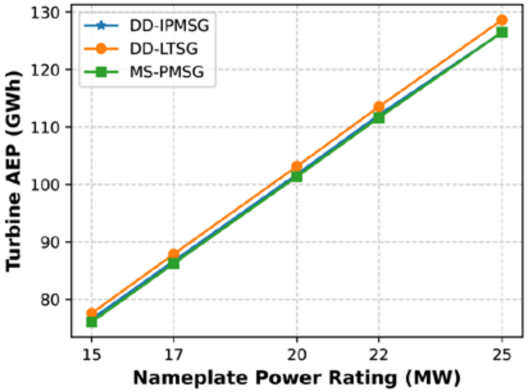
Source: NREL/PR-5000-85341

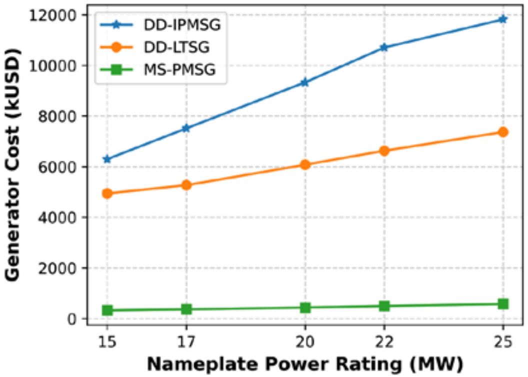
Mass and Cost Trends

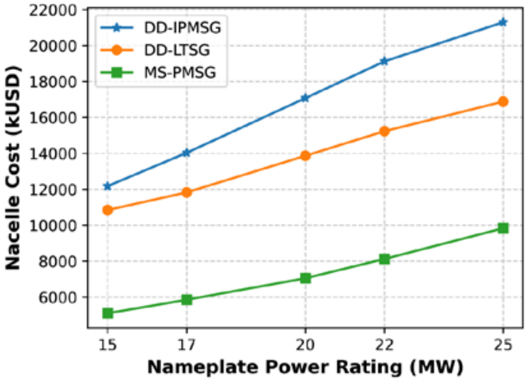
Bounds on armature diameter limit growth of mass, not of cost, and IPMSG design at 25 MW does not meet efficiency requirement.





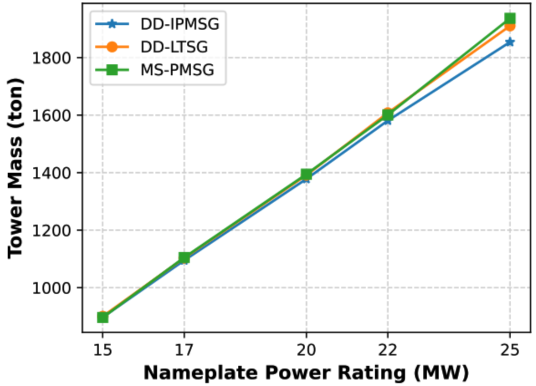


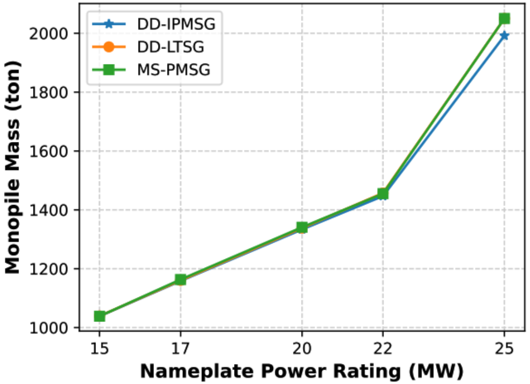


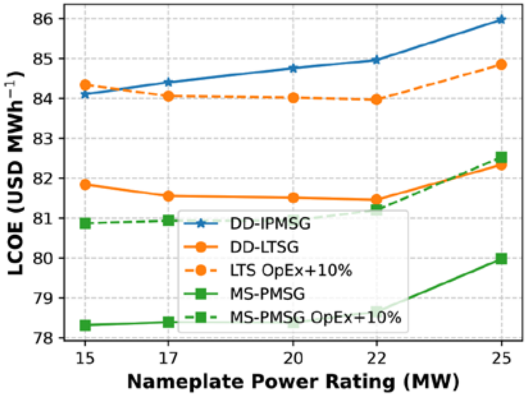


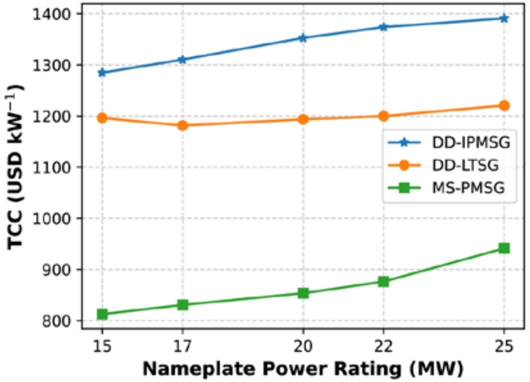
Fixed Bottom Designs

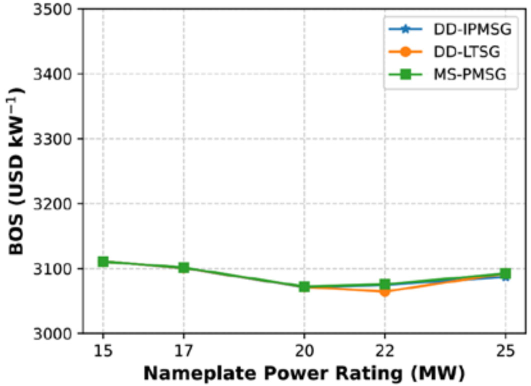
- Operational expenditure (OpEx) costs of 110 $/kW/yr.
- LCOE results are very sensitive to this number, see LTS and MS-PMSG results for OpEx costs increased by 10%.







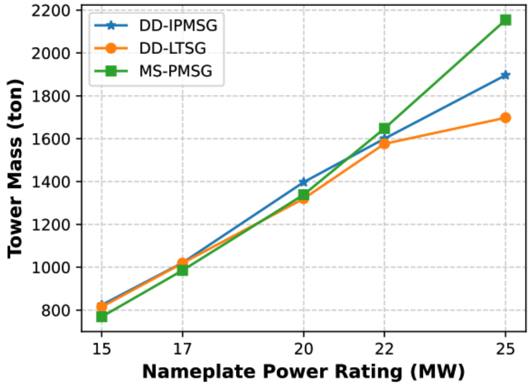


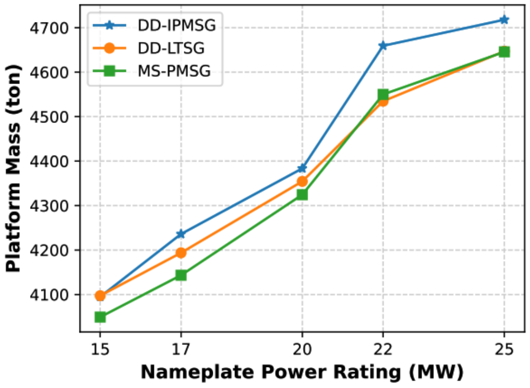


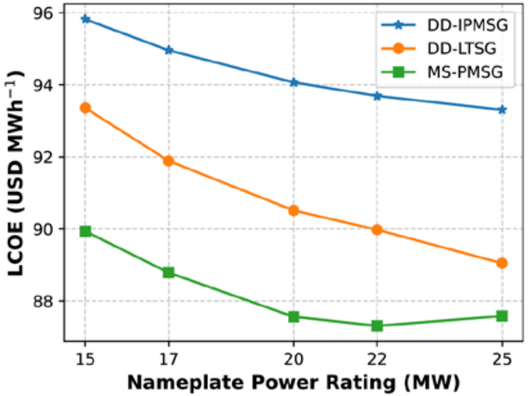
Source: NREL/PR-5000-85341

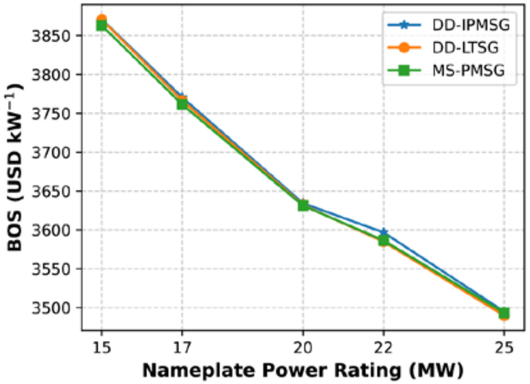
Floating Designs

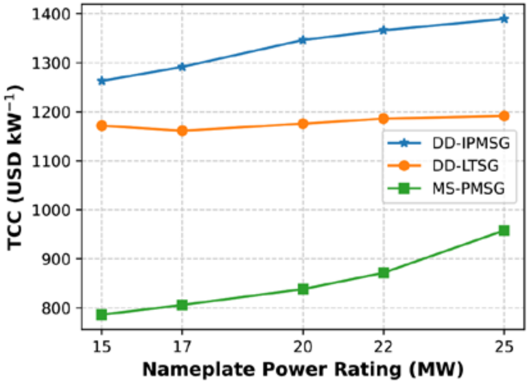
- Similar platform masses and BOS costs across generator technologies.
- At 25 MW, MS-PMSG and LTS are closer.











Summary

- Three drivetrain technologies (IPM, MS-PMSG, and LTS) at five ratings (15, 17, 20, 22, and 25 MW), fixed-bottom and floating evaluated in WISDEM and WEIS
- IPM efficiency struggles at higher power; could indicate topology limitations.
- LTS efficiency suggests no limitation over power; less sensitive to cost and efficiency change with power.
- MS-PMSG shows improving efficiency with power level, but higher rate of cost increase than LTS.
- Results are sensitive to models (material properties, costs, operations and maintenance), so focus on trends rather than specific numbers.

Summary

- LTS reduces LCOE by 2%–3% compared to IPM, which struggles especially at higher ratings.
- Despite the lower drivetrain efficiency, MS-PMSG shows the lowest cost of energy. However, we did not model operations and maintenance costs, which might increase with a gearbox or new technology, and results are very sensitive to OpEx.
- LCOE decreases with increasing rating for floating. For fixed bottom, it stays flat from 15–20 MW, and increases at 25 MW.

Q&A

NREL/PR-5000-85341