X-ROTOR
X-shaped Radical Offshore Wind Turbine for Overall Cost of Energy Reduction

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Modelled cost reductions for the X-Rotor Offshore Wind Turbine

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- Introduction
- Methodology
- Scenario
- X-Rotor – results & sensitivity analysis
- HAWT – results & comparison
- Conclusion

INTRODUCTION

"X-Rotor offshore wind turbine" concept (XRC)

Image courtesy of University of Strathclyde

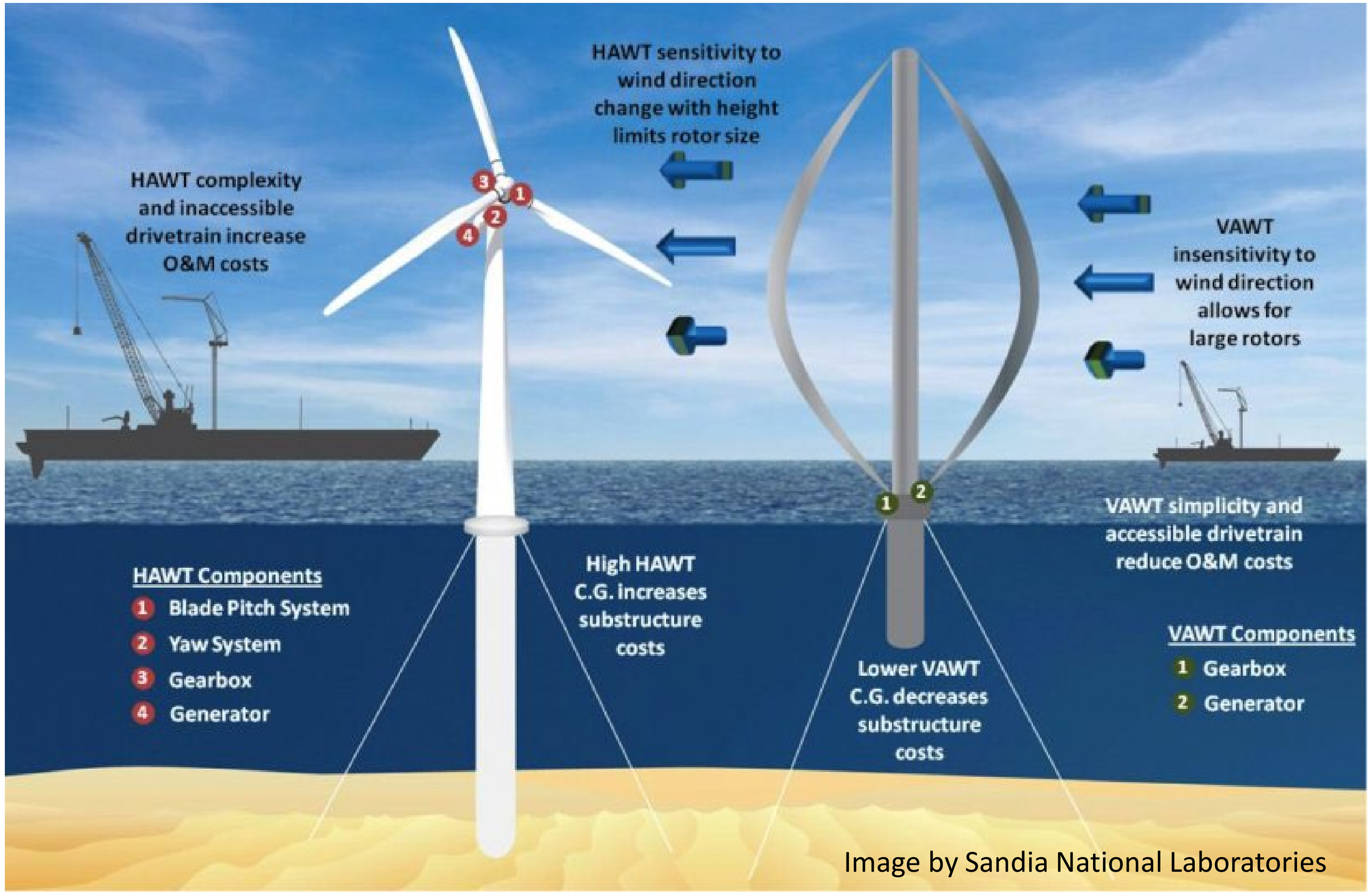


Image by Sandia National Laboratories

Innovative VAWT/HAWT hybrid addressing the disadvantages of VAWTs but retaining the advantages

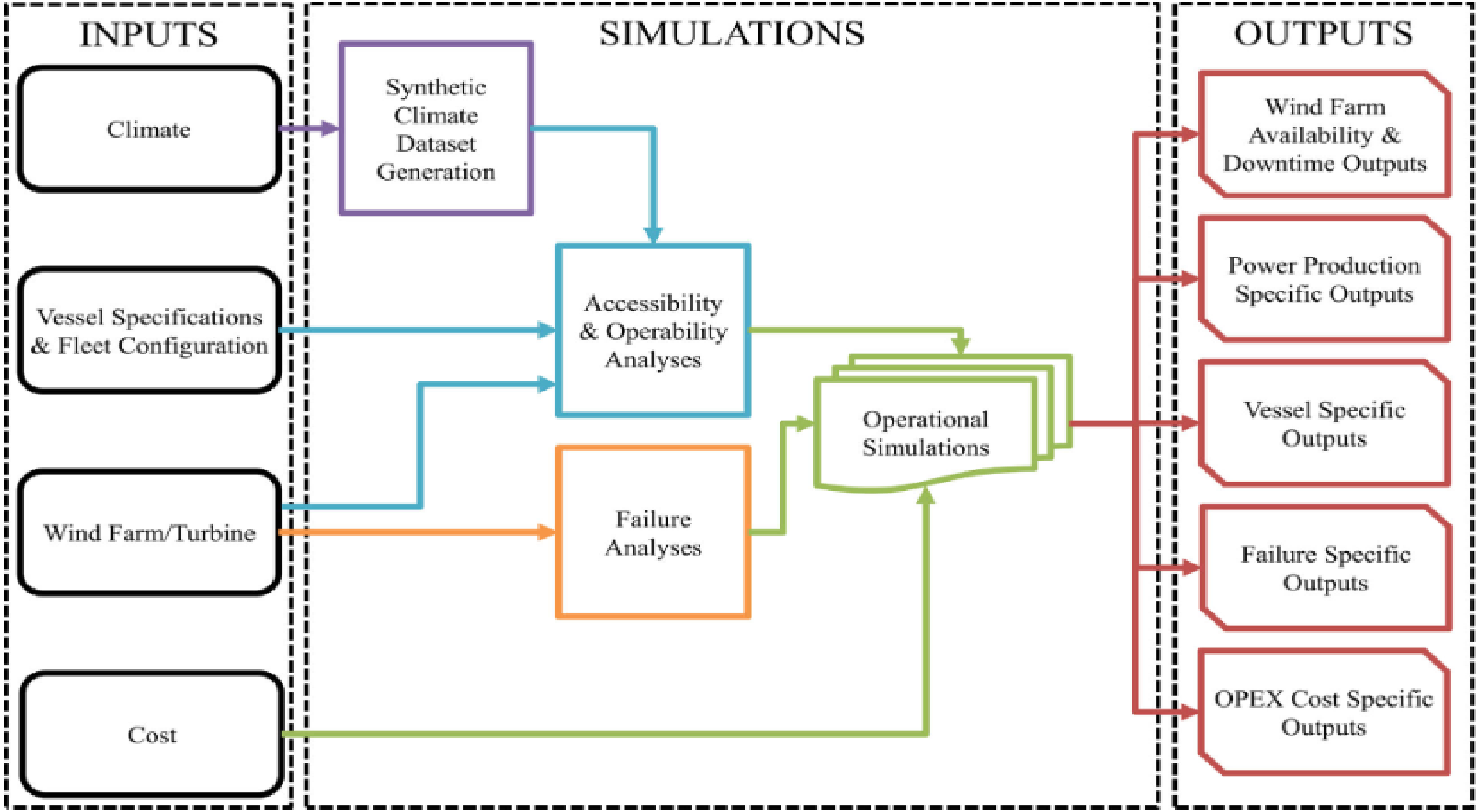
Initial analysis: XRC could reduce Levelised Cost of Energy (LCoE) by 20-30%

Objective

- Assess XRC LCoE including sensitivity analysis to consider key uncertainties
- Assess the LCoE of three traditional HAWT drivetrain configurations using the same methodology
- Evaluate the potential XRC cost savings and/or areas for further optimisation

METHODOLOGY

Strathclyde O&M model



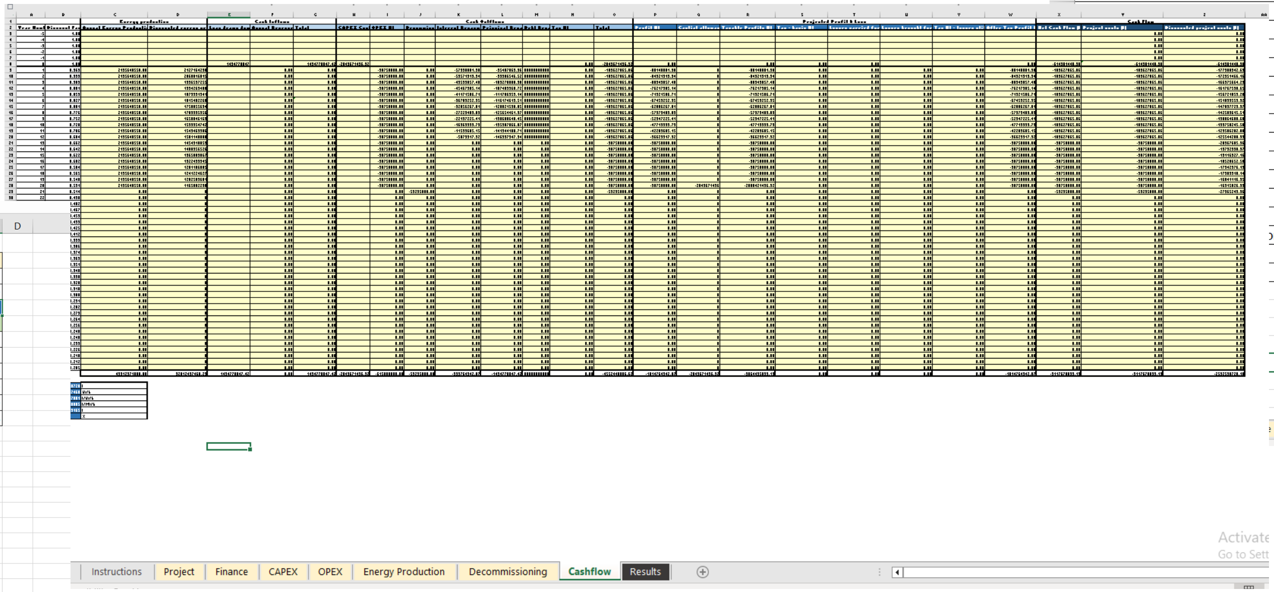
UCC LCoE tool - excel

Outputs

	A	B	C	D	E	F	G
1	**Project Input Summary**				**Project Results Summary**		
2	Project Name	*text*	X-ROTOR_Baseline		Project Costs	€	3117670839
3	Site Location	*text*	Hypothetical North Sea metocean data from FINO3		Discounted Project Costs	€	2592598720
4	Project Lifetime	*years*	20		Energy Production	MWh	4.3913E+10
		GW	0.5		Discounted Energy	MWh	3.2012E+10
		%	3.2%		Real LCOE	€/kWh	0.08
		€	1434770047		Real LCOE	€/MWh	80.99
		%	4%		NPV	€	-2.512E+09
		years	12		IRR	%	#NUM!
		year	1				
		%	0%				
		%	0%				
		%	0%				
		€	2049671496				
		€	30750000				
		€	53235000				
	on	*MWh/year*	2195648.55				
		%	50%				
		%	91%				

CAPEX | OPEX | Energy Production | Decommissioning | Cashflow | Results

Cash flow calculator



Inputs

	A	B	C	D
1	**Project inputs**	**Units**	**Value**	
2	Project Name	*text*	X-ROTOR_Baseline	
3	Site Location	*text*	Hypothetical North Sea metocean data from FINO3	
4	Project Lifetime	*years*	20	
5	Farm Capacity	*GW*	0.5	
6	Fixed/Floating	*select*	Fixed	
7	Water depth	*m*	not known	
8	Site area	*km 2*	not known	
9	Distance to grid connection	*km*	100	
10	Distance to port - installation	*km*	100	
11	Distance to port - O&M	*km*	100	
12	Commissioning year	xxxx	2018	
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				

Instructions | Project | Finance | CAPEX | OPEX | Energy Production | Decommissioning | Cashflow | Results

LCoE = Total lifecycle cost / Total Lifetime Energy Production

LCoE formula

$$\frac{I + \sum_{k=1}^{n} \frac{LP}{(1+r)^k} + \sum_{k=1}^{n} \frac{INT}{(1+r)^k} + \sum_{k=1}^{n} \frac{A^k}{(1+r)^k} + \sum_{d=n+1}^{f} \frac{D^d}{(1+r)^d}}{\sum_{k=1}^{n} \frac{E^k}{(1+r)^k}}$$

d	year in post-project decommissioning
f	post-project duration i.e. decommissioning
k	year in project lifetime
n	project lifetime
r	discount rate
A	Annual costs e.g. OPEX

D	Decommissioning costs
E	Energy produced
I	Investment costs i.e. CAPEX, installation etc.
INT	Interest payment
LP	Loan Payment

Discount rate

Financial Assumption	NREL	XROTOR
Debt %	67%	70%
Cost of equity	10%	10%
Cost of debt	4%	4%
Inflation rate	2.50%	2.50%
Tax rate	26.00%	N/A
Pre-tax WACC nominal	**5.98%**	**5.80%**
Pre-tax WACC real	**3.40%**	**3.22%**
After-tax WACC nominal	**5.28%**	**N/A**
After-tax WACC real	**2.72%**	**N/A**

NREL 2021 Cost of Wind Energy Review (T. Stehly and P. Duffy, 2022).

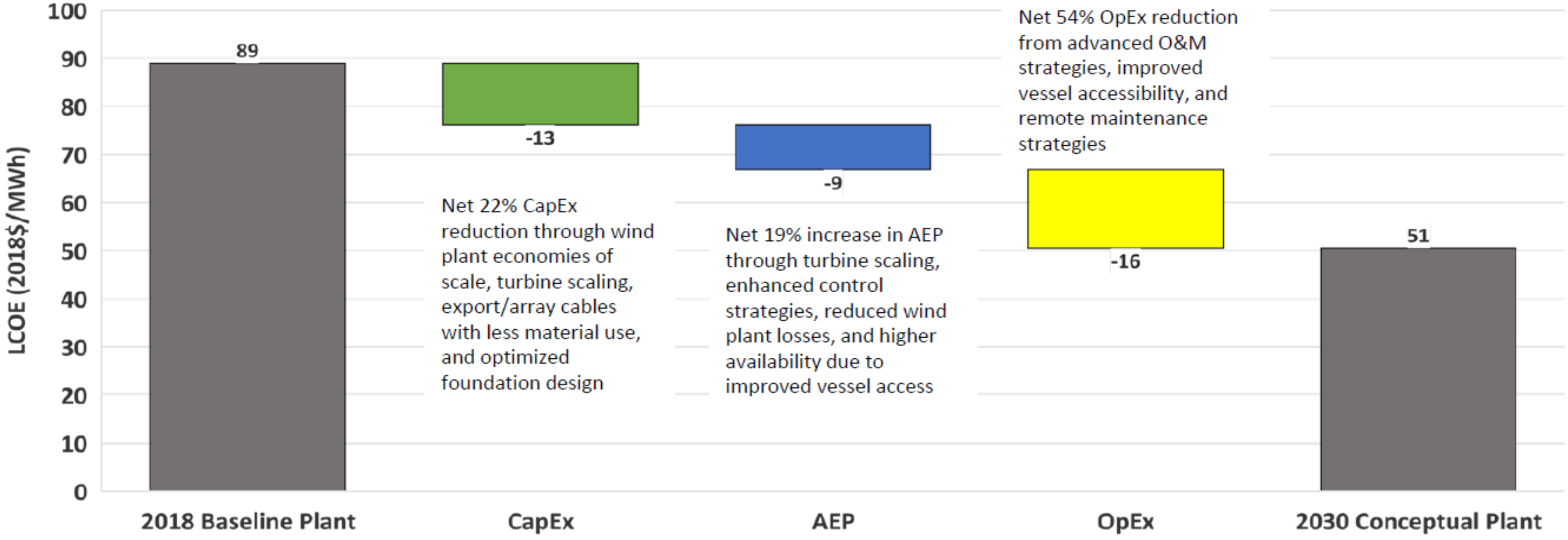
SCENARIOS

- Hypothetical North Sea site
- Project lifetime – 30 years
- 100 x 5MW, fixed-bottomed turbines
- 100km from shore
- Project commissioning: 2030
- Discount rate: 3.22%

Cost Reduction Pathway from 2021-2030

- CAPEX reduction of 16.5%
- OPEX reduction of 22.5%
- AEP increase of 14.25%

Government Performance and Results Act Cost Reduction Pathway From 2018 to 2030 for Fixed-Bottom Offshore Wind

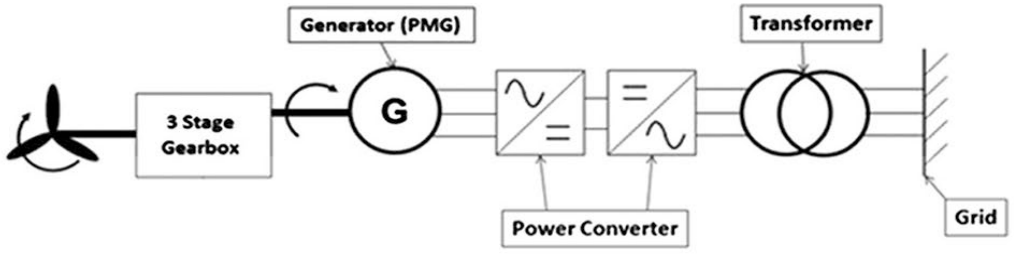


- The **GPRA baseline value starts at $89/MWh** (in 2018 USD) set in FY 2019 using 2018 reference project data reported in Stehly and Beiter (2019).
- The **GPRA target is $51/MWh by 2030** (in 2018 USD) and is derived for a fixed-bottom wind plant with 15 MW at the reference site based on cost reductions informed by technology innovations considered in the spatial economic analysis by Beiter et al. (2016).

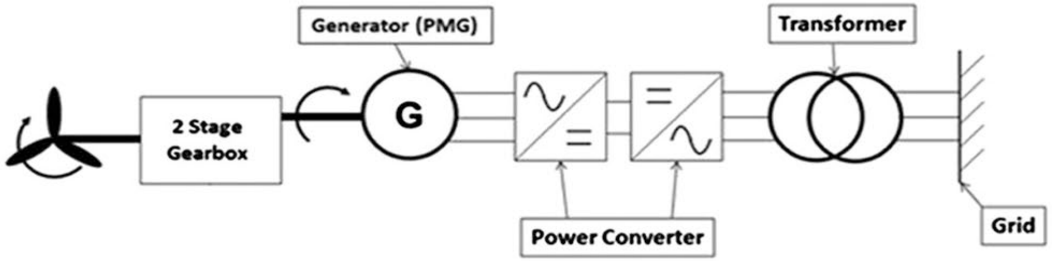
NREL | 19

NREL 2021 Cost of Wind Energy Review (T. Stehly and P. Duffy, 2022).

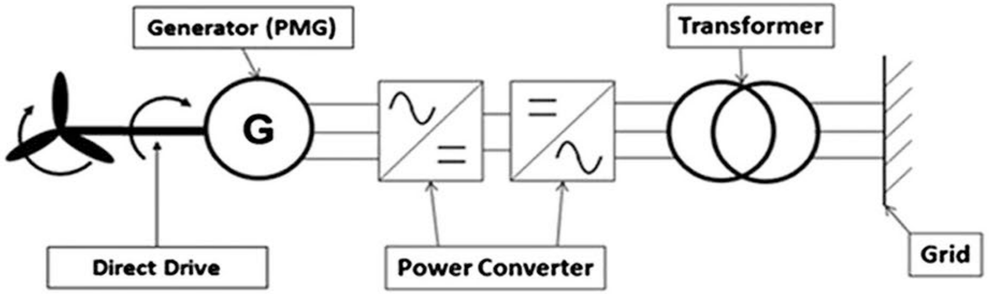
- Direct drive
- Geared Medium Speed (MS) – 2-stage
- Geared High Speed (HS) – 3-stage



Drivetrain 2: 3 Stage PMG FRC



Drivetrain 3: 2 Stage PMG FRC



Drivetrain 4: DD PMG FRC

IMAGE: J. Carroll et. al (2017). Availability, operation and maintenance costs of offshore wind turbines with different drive train configurations. Wind Energy, Volume: 20, Issue: 2, Pages: 361-378, First published: 26 July 2016, DOI: (10.1002/we.2011)

CAPEX breakdown

		X-Rotor	Direct Drivetrain	Geared MS - 2 stage	Geared HS - 3 stage
Development and project management	€/kW	69			
Turbine	€/kW	931	1014	950	908
Electrical infrastructure	€/kW	527			
Substructure and foundation	€/kW	377			
Contingency, construction finance, insurance during construction	€/kW	419			
Assembly and installation	€/kW	310			
Lease price	€/kW	135			
Plant commissioning	€/kW	26			
Decommissioning	€/kW	106			
Total CAPEX	€/kW	2,900	2,983	2,919	2,878

Direct Drivetrain

- No gearbox, but large generator with higher failure rate than geared generators.
- Expected to have higher rotor cost due to larger heavier blades.

Geared MS (2-stage) and HS (3-stage)

- MS cheaper gearbox with lower failure rate than HS, but more expensive generator with slightly higher number of failures.

XRC

- No gearbox, no specialist generator, no yaw system.
- Blades biggest cost-driver (34% of turbine CAPEX)

XRC O&M – Primitive

- 5 Crew Transfer Vessels (CTV) for minor repairs – undertaken offshore.
- Secondary HAWTs are modular and can replaced by the Service Operations Vessel (SOV).
- When one secondary HAWTs fails, the XRC is assumed to operate at 50%.
- Jack-Up Vessels (JUV) used for vertical axis component replacements, including the main bearings (high failure rate).
- Failure rates based on figures presented in C. Flannigan et. al (2022) with addition of a main bearing failure rate, see Fraser Anderson et. al (2023).

Vessel	Cost	Hiring strategy
CTV	4000	Pool of 5
SOV	30000	Fix-on-fail
JUV mob cost	800000	Fix-on-fail
JUV day rate	200000	

HAWT O&M

- 5 Crew Transfer Vessels (CTV) for minor repairs – undertaken offshore.
- Jack-Up Vessels (JUV) are used for major component replacements.
- The 3-stage geared HAWT failure rates are from Carroll et al. 2016
- The 2-stage geared HAWT & direct drive failure rates are taken from Carroll et al. 2017

Vessel	Cost	Hiring strategy
CTV	4000	Pool of 5
JUV mob cost	800000	Fix-on-fail
JUV day rate	200000	

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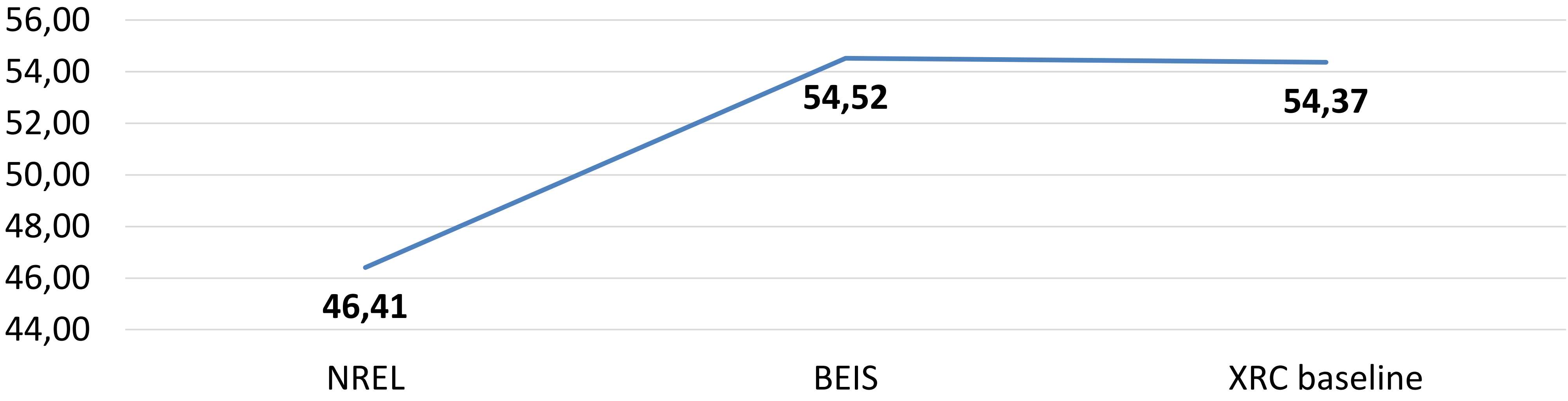
X-ROTOR - RESULTS & SENSITIVITY ANALYSIS

Baseline XRC LCoE & validation



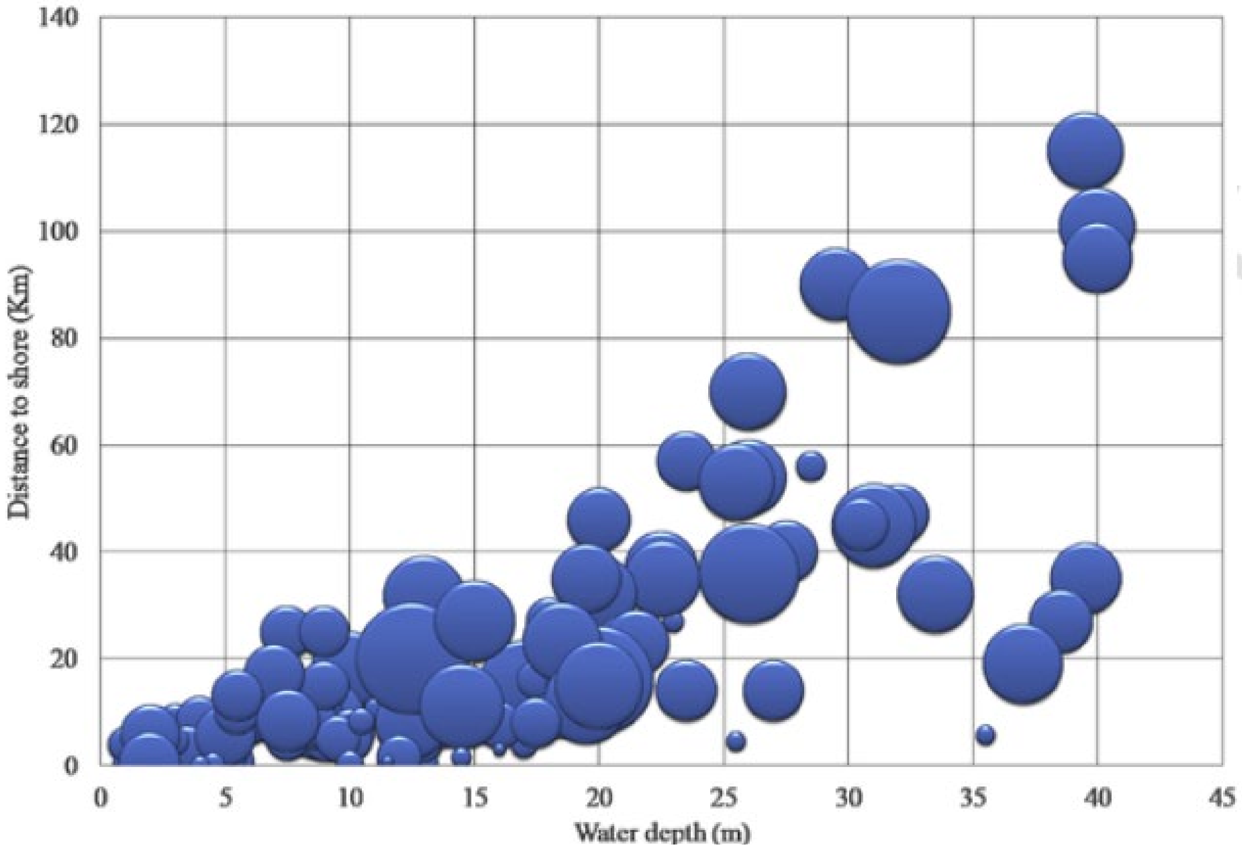
Maximising production

Partially Optimised O&M Strategy

- XRC 70% capacity when the secondary rotor fails;
- Using SOVs for main bearing replacements, assuming the XRC is equipped with an easy removal mechanism;
- Reduced failure rate of the generator…

c. 3 fewer SOV charters over the lifetime of the project.

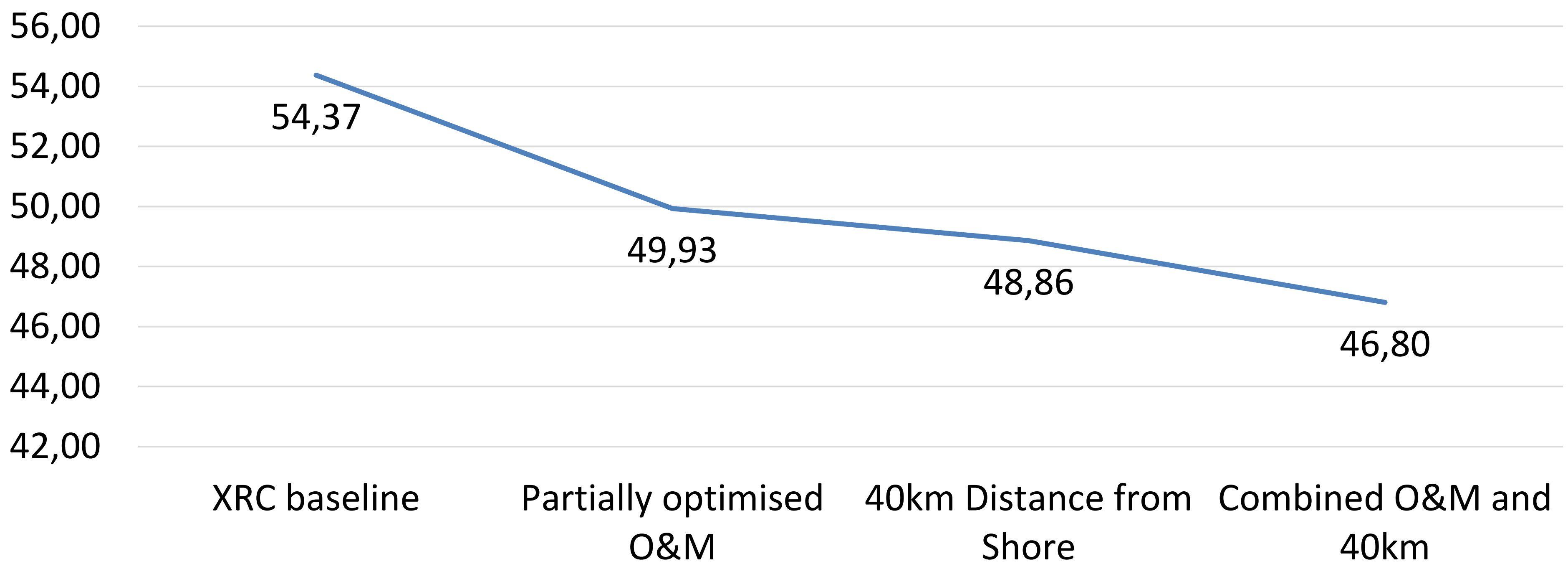
(Díaz & Soares, 2020)



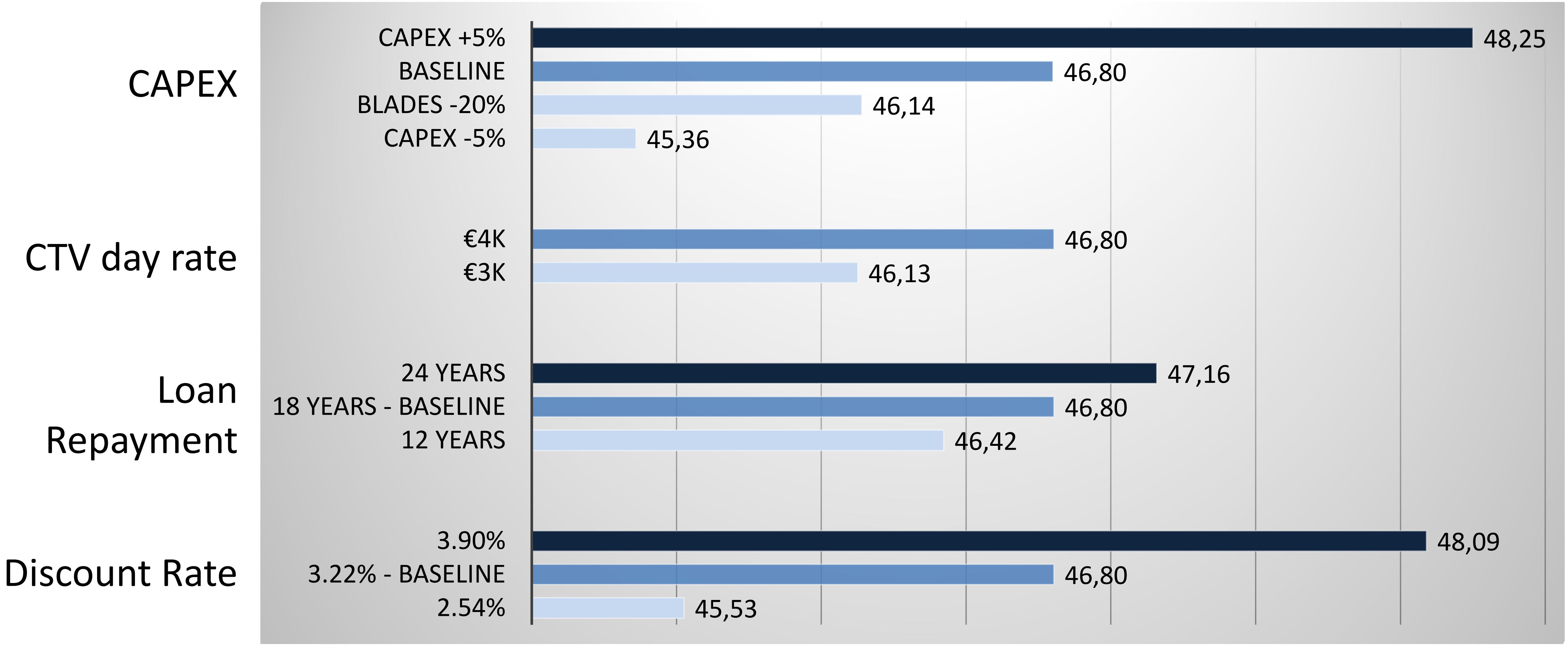
Reducing Distance from Shore – 40km

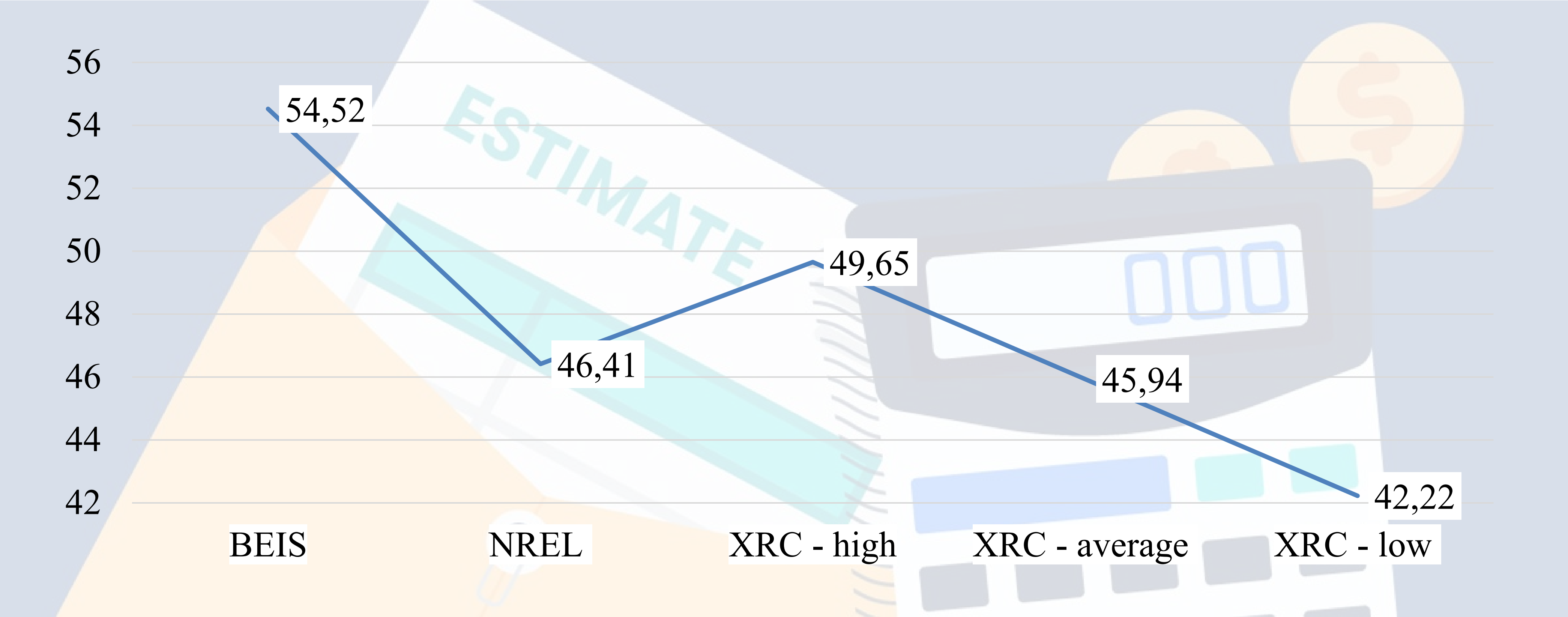
X-shaped Radical Offshore Wind Turbine for Overall Cost of Energy Reduction

Scenario	Project commissioning (year)	Project lifetime (years)	Annual OPEX (€m)	Annual Energy Production (MWh)	Availability (%)	LCoE (€/MWh)
XRC baseline	2030	30	34.18	2,486,939	89.29%	54.37
Opt OM & 40km	2030	30	27.69	2,655,951	94.91%	46.80



Financial assumptions



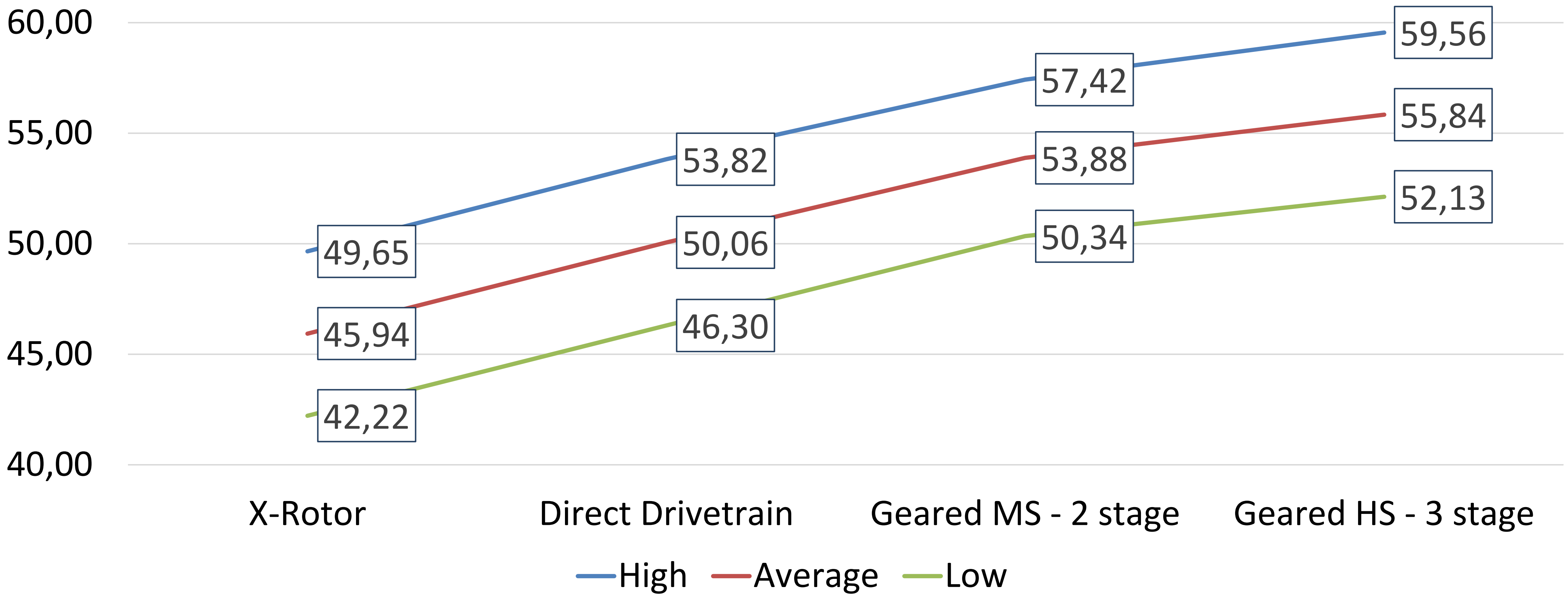


- Pre-tax WACC 2.54-3.9%
- Loan repayment period 12-24 years
- CTV day rate €3k-4k
- CAPEX +5%-(20% blade reduction and -5%)

HAWTS - RESULTS & COMPARISON

		X-Rotor	Direct Drivetrain	Geared MS - 2 stage	Geared HS - 3 stage
Farm capacity (MW)	MW	500			
Commissioning date	year	2030			
Project lifetime (years)	years	30			
Distance from shore	km	40			
Discount Rate	%	3.22%			
Turbine	€/kW	931	1014	950	908
Total CAPEX	€/kW	2,900	2,983	2,919	2,878
Annual O&M - fixed	€/kW/yr	16			
Annual O&M - variable	€/kW/yr	39	47	61	67
Total OPEX	€/kW/yr	55	64	78	83
Energy production	MWh/MW/yr	5,312	5,265	5,250	5,233
Capacity factor	%	60.6%	60.10%	59.90%	59.70%
LCoE	€/MWh	46.80	50.71	54.68	56.16

LCOE (€/MWh) comparison



	Savings Goal	Result
Turbine CAPEX	5-25%	5-14%
OPEX	25-50%	14-33%
LCOE	20-30%	8-19%

XRC LCoE

- 8-9% less than the Direct Drive HAWT
- 14-16% less than the Geared MS HAWT
- 17-19% less than the Geared HS HAWT

Conclusion

Advantages:

- Lower turbine CAPEX
- Lower OPEX and increased reliability
    - Reduced failures (no gearbox)
    - SOVs v. JUVs
    - Redundancy

Consideration	X-Rotor	Horizontal Axis Wind Turbine
Power take-off System (PTO)	2 or more	1
Height of Nacelle	25 m	90 m
Weight of Nacelle	10 t	>200 t
Jack-up Vessel Use (Major Replacements)	Vertical-axis Blades, Pitch	Gearbox, Generator, Blades, Pitch, Yaw
Onshore Maintenance	Secondary HAWT module (consists of rotor, generator and power converter)	Not Possible
Redundancy	Operates with single 2ndry Rotor	No Redundancy in PTO
Drivetrain type	No gearbox or multipole generator	Either gearbox or multipole generator
Yaw System	Not necessary due to rotaional symmetry	Yes
Scaling Solution	Add 2.5 MW 2ndry rotors	Increase size of all components

Potential savings

- Additional optimisation of the design
- Improved O&M strategy e.g. onshore maintenance for secondary HAWT module
- Consider impact of improved power density
- Considerable potential upscaling savings compared to traditional HAWT configurations
- Potential for floating wind

Any Questions?

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