ARUP

Offshore Wind Farm Design 2023

Shaping the green energy transition from offshore wind production

Peter A Thompson
Director of Geotechnics and East Asia Energy Business Leader

15 December 2023

Arup Across The Globe

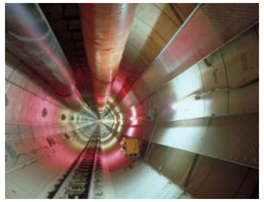
Local knowledge, global reach

- Arup is a global, independent firm of designers, planners, engineers, consultants and technical specialists.
- In the energy space, our markets include Hydrogen, Renewable Energies, Conventional Energies, Grid Interconnections and Energy Storage.
- We are one of the largest and most successful international engineering consultancies.
- In 2023, Over 19,000 staff working with 6,800 clients in 150 countries and an annual turnover of over £3.2bn.
- Arup is a wholly independent organisation owned in trust. With no shareholders or external investors, our firm is able to independently determine its own priorities and direction as a business.

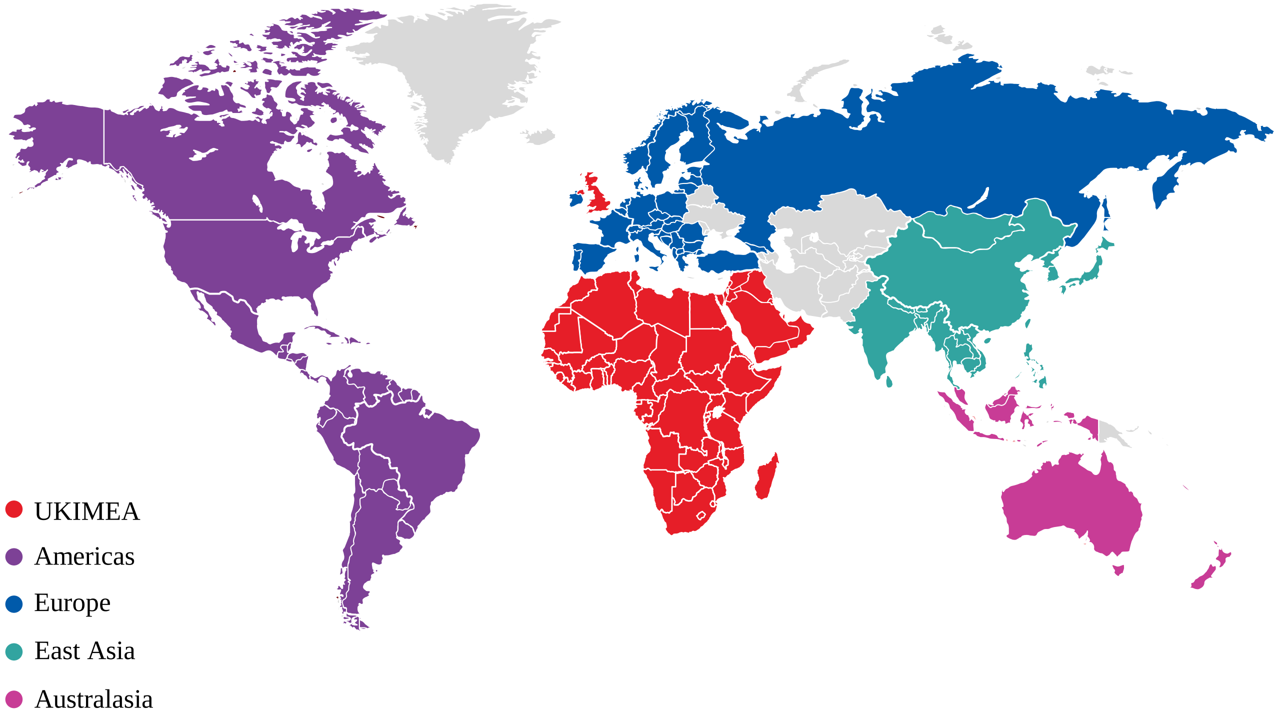

Building Design


Economics & Planning


Infrastructure Design


Management Consulting


Specialist Services



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Arup’s Reach

Global office location & staff numbers

$3.2bn
turnover

75 years
of profitable
trading debt free

19,000+ staff
working on local, national and
international projects

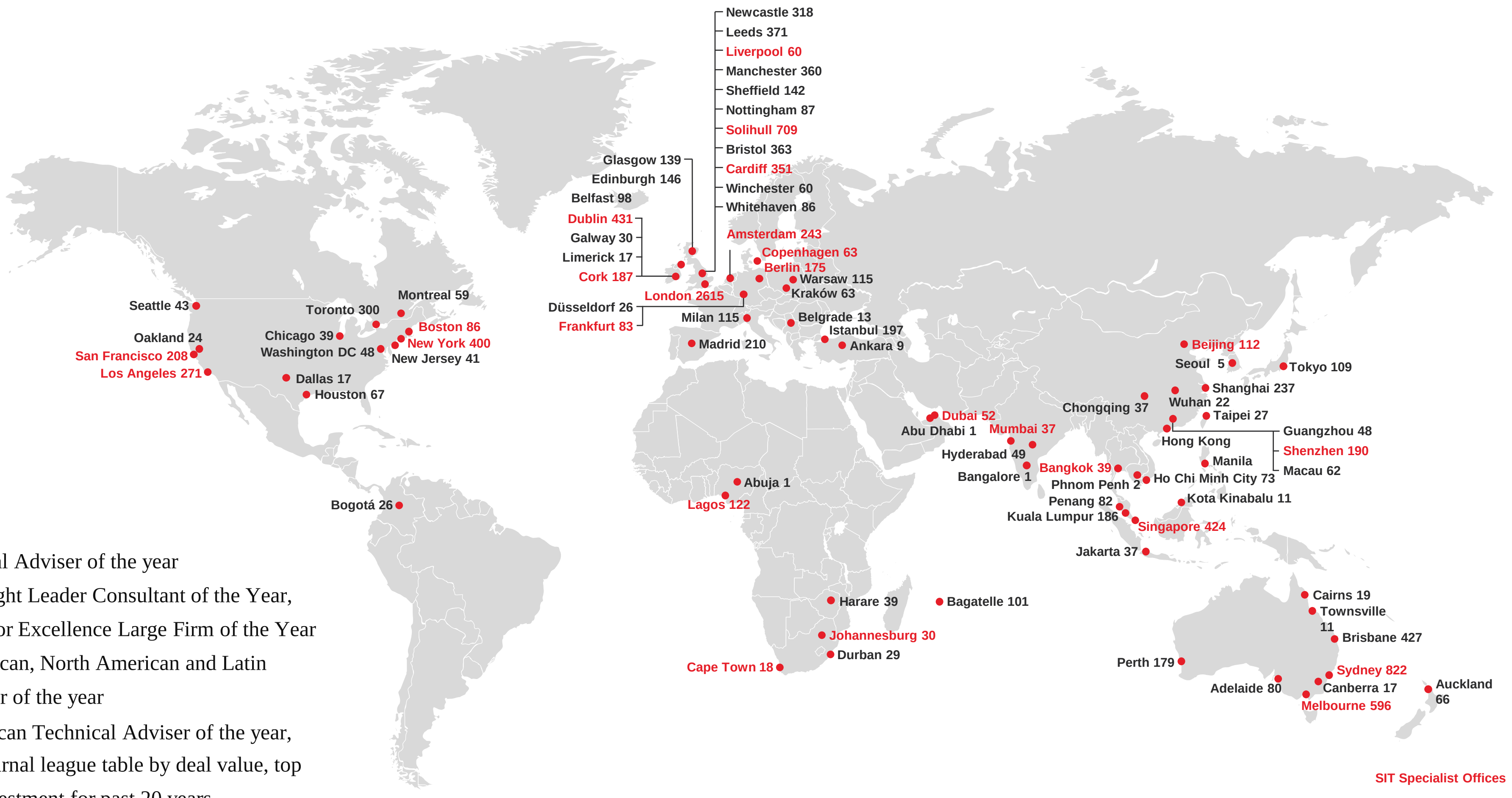
5,500+ staff
Working in the Asia
Pacific region

2021 - European Technical Adviser of the year

2020 - International Thought Leader Consultant of the Year, Consult Australia Awards for Excellence Large Firm of the Year

2019 - European and African, North American and Latin American Technical Adviser of the year

2018 - European and African Technical Adviser of the year, Arup tops Infrastructure Journal league table by deal value, top advisor in infrastructure investment for past 20 years



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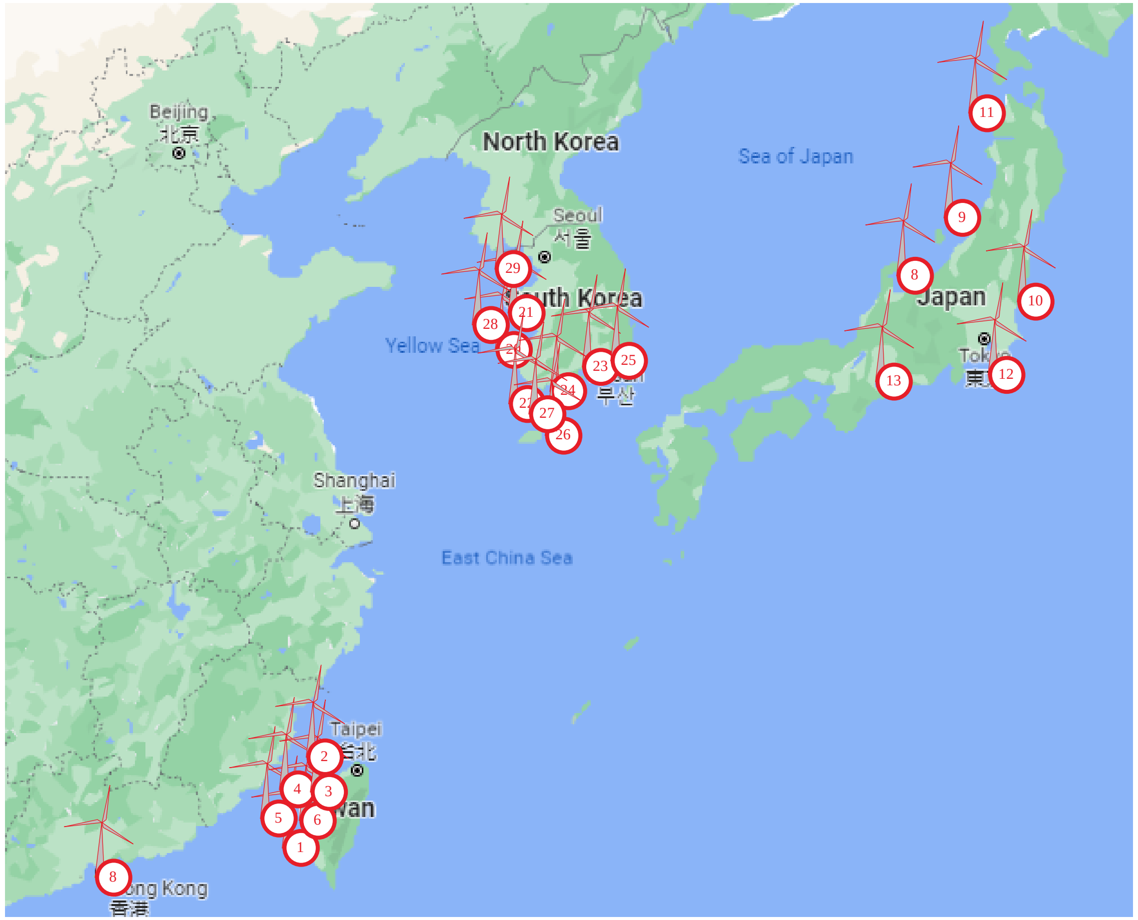
Arup Offshore Wind Track Record – Asia

Extensive Integrated Advisory Experience

#	Wind Farm	MW	Developer/ Operator	Country
1	Changfang Xidao	600	CIP	Taiwan
2	Yunlin	640	WPD	Taiwan
3	Hai Long	1000	NPI / Yushan	Taiwan
4	Greater Chunghua	900	Orsted	Taiwan
5	Taiwan OWF Site Prospecting	-	RWE	Taiwan
6	Market Entry Assessment	-	John Laing	Taiwan
7	Taiwan Site Screening	-	CLP	Taiwan
8	HK Offshore	150	CLP	Hong Kong
9	Akita Port	55	Kajima	Japan
10	Noshiro Port	88	Kajima	Japan
11	Kashima Port	187	Obayashi	Japan
12	Mutsu Bay	800	Confidential	Japan
13	Kujukuri	600	Eurus	Japan
14	Japan Market Entry	-	Japan Wind Development	Japan
15	Japan Market Entry	-	Confidential	Japan
16	Pacifico Energy Portfolio	-	Pacifico Energy	Japan
17	India Market Entry	-	Confidential	India
18	Indonesia Site Prospecting	-	Confidential	Indonesia
19	Philippines Roadmap	-	World Bank Group / DOE	Philippines
20	Anmado Concept & FEED	532	AWC	Korea
21	Monopile Foundation Study	-	GS E&C	Korea
22	Market Entry Study	-	Northland Power	Korea
23	Market Entry Study	-	Vena Energy	Korea
24	Energy Yield Assessment	520	Vena Energy	Korea
25	TDD for multiple Sites	-	RWE	Korea
26	Typhoon Risk Assessment	-	RWE	Korea
27	Wando-Geumil OSS Topside	600	Blue Wind	Korea
28	Jacket Structure Concept	400	Foresys	Korea
29	O&M Market Study	1,200	Confidential	Korea
30	Portfolio Acquisition	3900	Confidential	APAC



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Arup Offshore Wind Service

Global expertise from design to technical due diligence

Foundations

- Monitoring and life extension
- Monopiles
- Jackets
- Suction buckets
- Gravity bases
- Reinforced concrete
- Steel.

Geotechnical

- Ground modelling
- Cables and mooring
- Ground investigations
- Site selections.

Electrical

- Foundations
- DC and AC
- Electrical
- Mechanical
- Structural design
- Offshore cabling
- Consenting and approvals.

Environmental

- GIS
- Constraint mapping.

Corporate Finance

- Process advice
- Fundraising and financial structuring
- Financial modelling
- Commercial structuring
- Investment case.

Transaction Advice

- Technical
- Business planning
- Environmental review
- H&S review.

Strategy and Economics

- Strategy and business case
- Policy and regulatory analysis
- Economic impact analysis
- Commercial due diligence
- Energy modelling
- Market and supply chain review.

Transforming the Global Energy System

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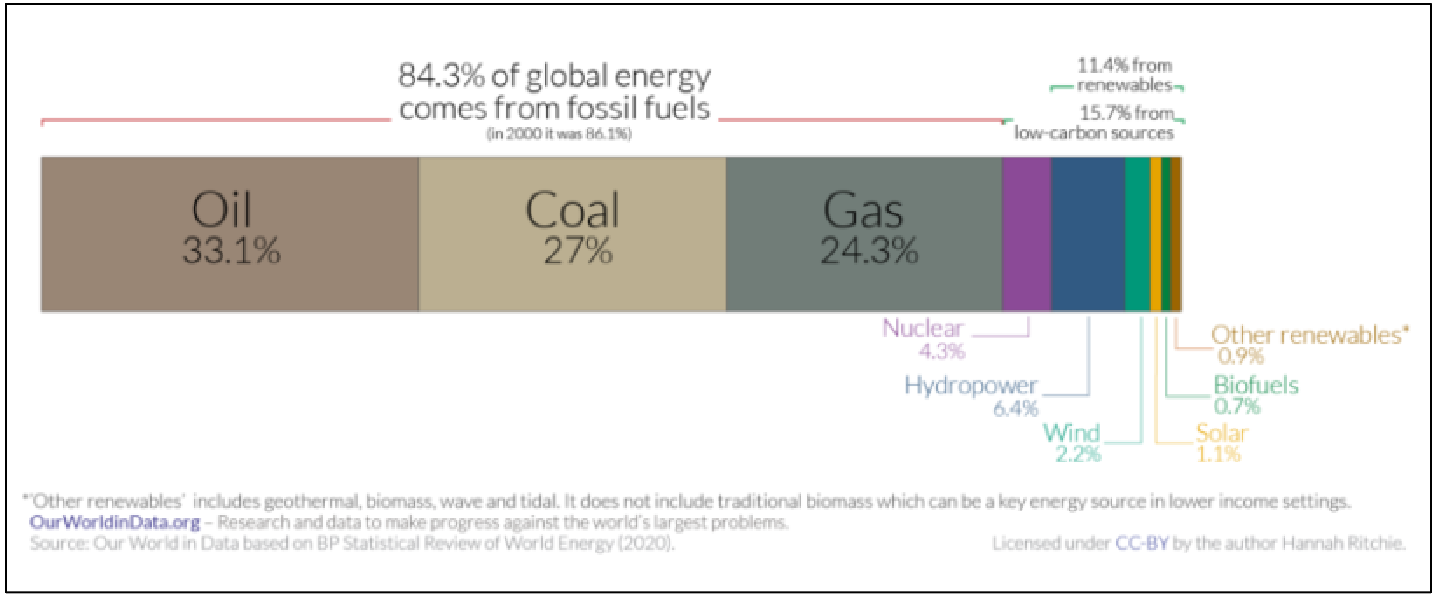
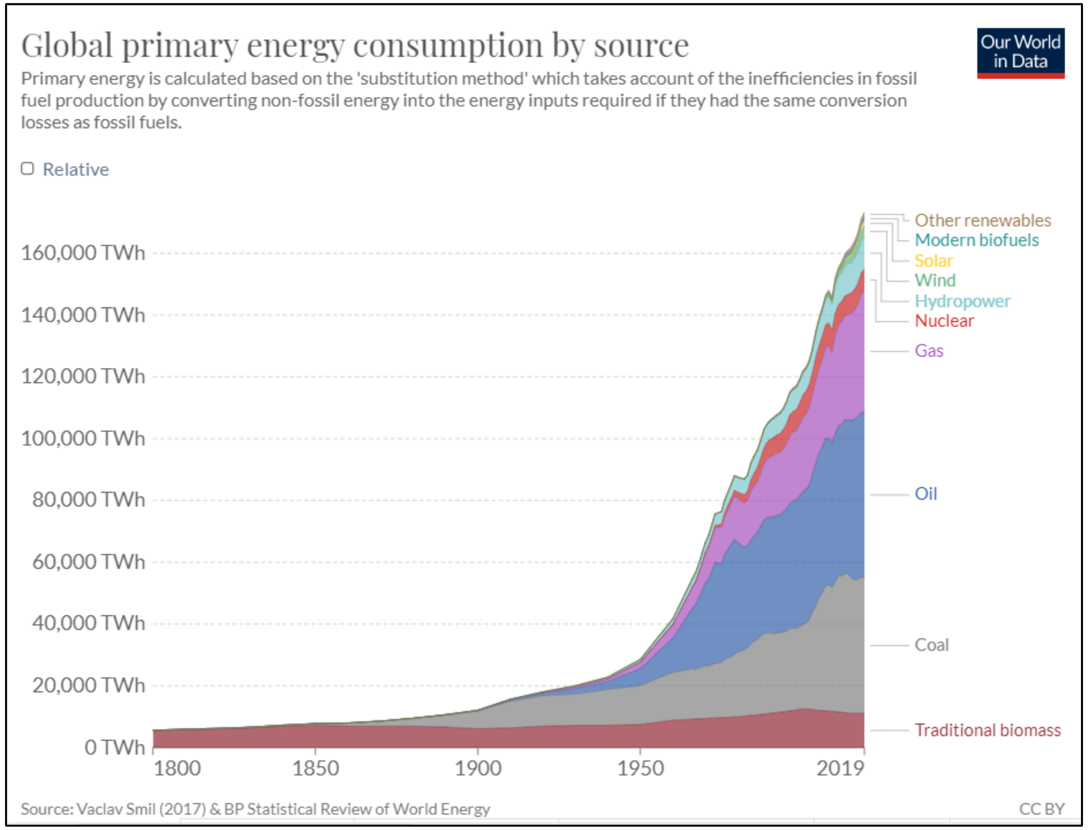
How to speed up the race to net zero



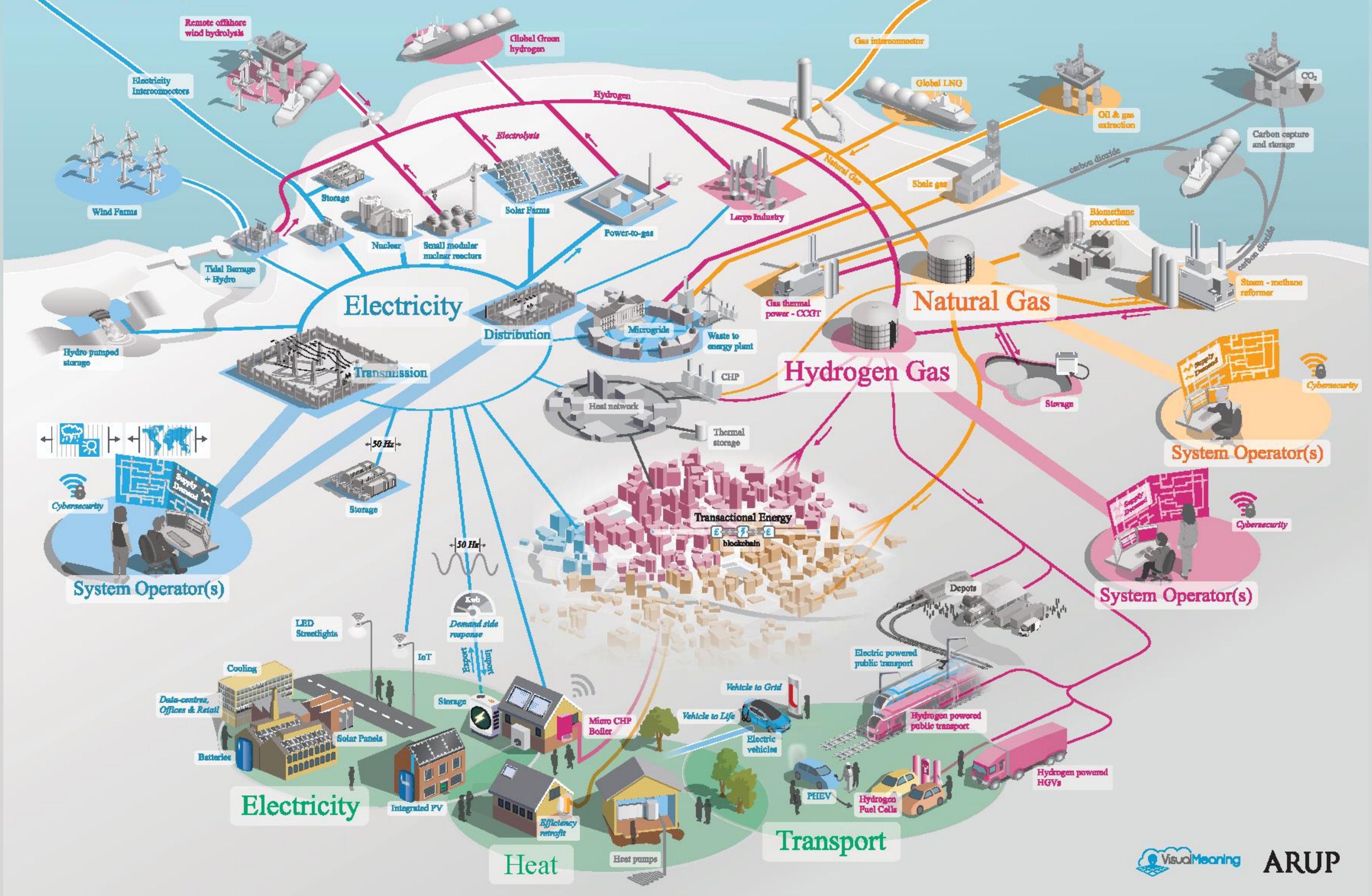
In 2019 84% of primary energy came from fossil fuels. It was 86% in 2000…….



…….because demand is growing almost as quickly as our ability to build low carbon alternatives.

We need to reduce their CO_2 emissions to net zero by 2050.

Energy System 2030/40



Electrification at Pace

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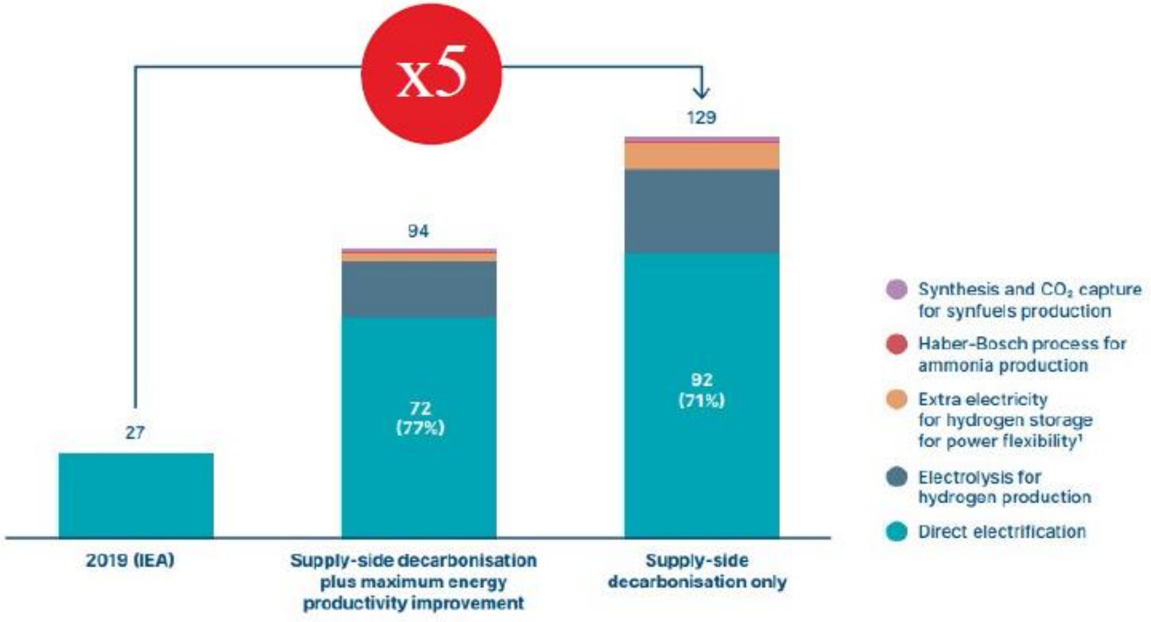
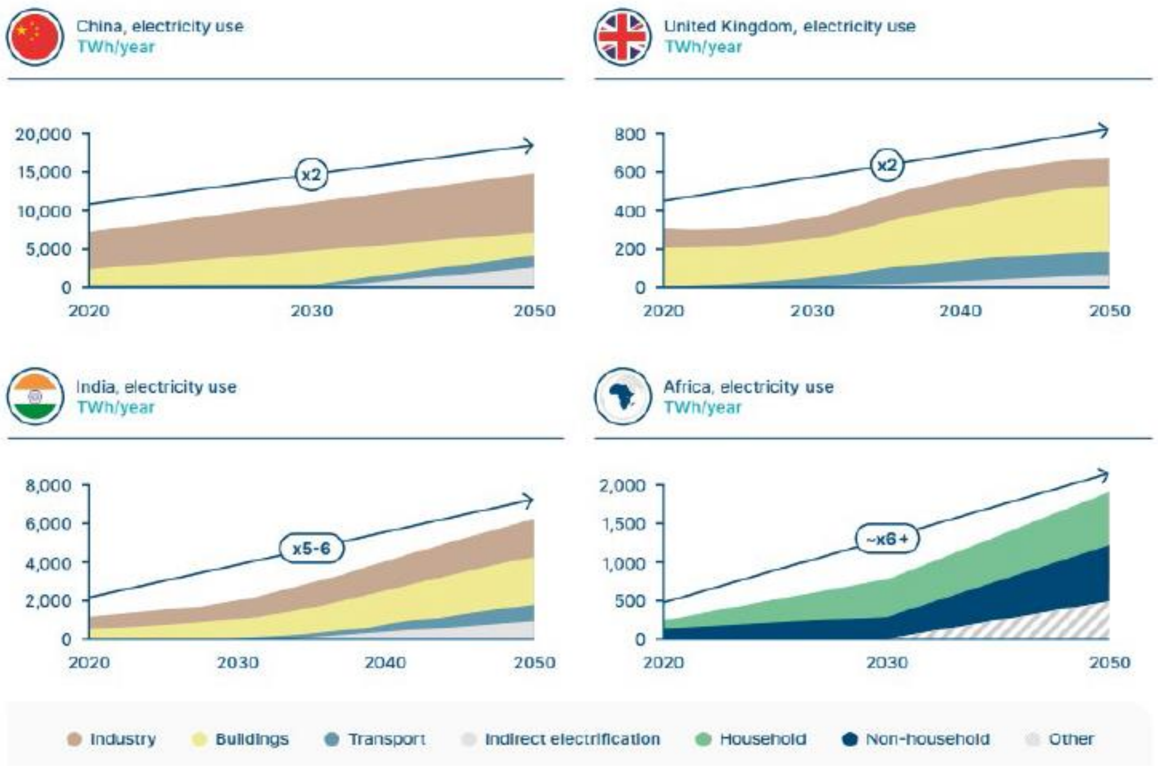
Up to 5x more electrification growth required by 2050



NOTE: Assumes 85% green hydrogen production in 2050.
[1] Extra electricity for hydrogen storage for power flexibility only covers the electricity loss due to the transformation into hydrogen and back to electricity.
SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission (2021), IEA (2020), *World Energy Outlook*



Gross 2050 electricity generation will reach ~90,000 to 129, 000 TWh/year

27,000 to 129,000 TWhr/year

Source: Energy Transitions Commission "30 years to electrify the global economy", April 2021. LINK

A Rapid Ramp Up is Required 2020-2030

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Electrification, Transmission, Hydrogen, CCS and Renewables need to quadruple in investment

US$260bn/pa

US$ 820bn/pa

Electrical Transmission
& Distribution

1mn EVCP

40mn EVCP
US$ 90bn/pa

EV Charging points

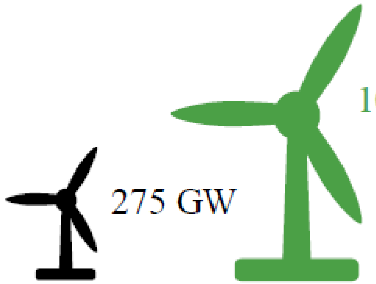
US$1bn/pa

US$ 40bn/pa

CO2 and Hydrogen
Infrastructure

275 GW

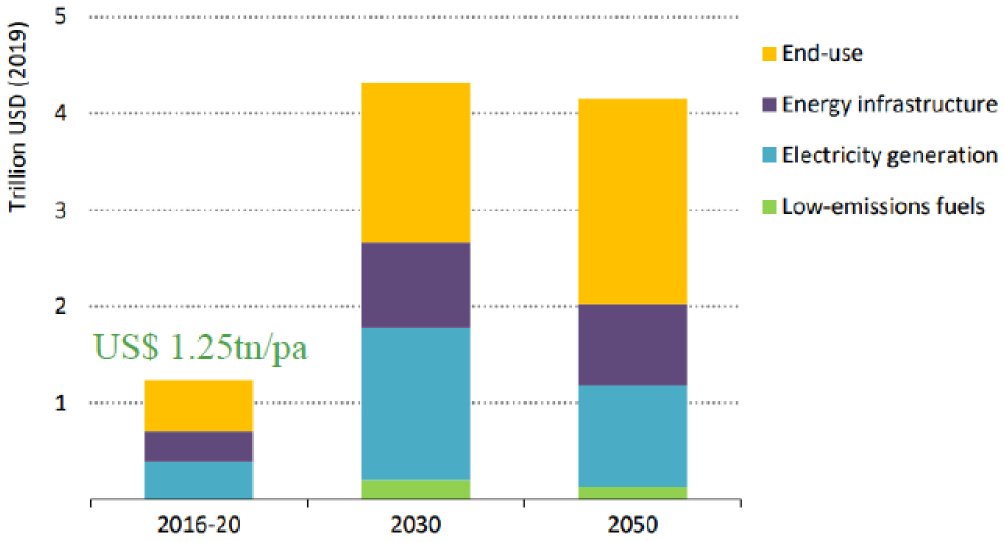
1000 GW



Installed Wind
and Solar

Clean energy investment ramp-up (annual)

US$ 4.3tn/pa by 2030



Source: IEA 'Net zero by 2050', May 2021. LINK

Global Offshore Wind Speeds

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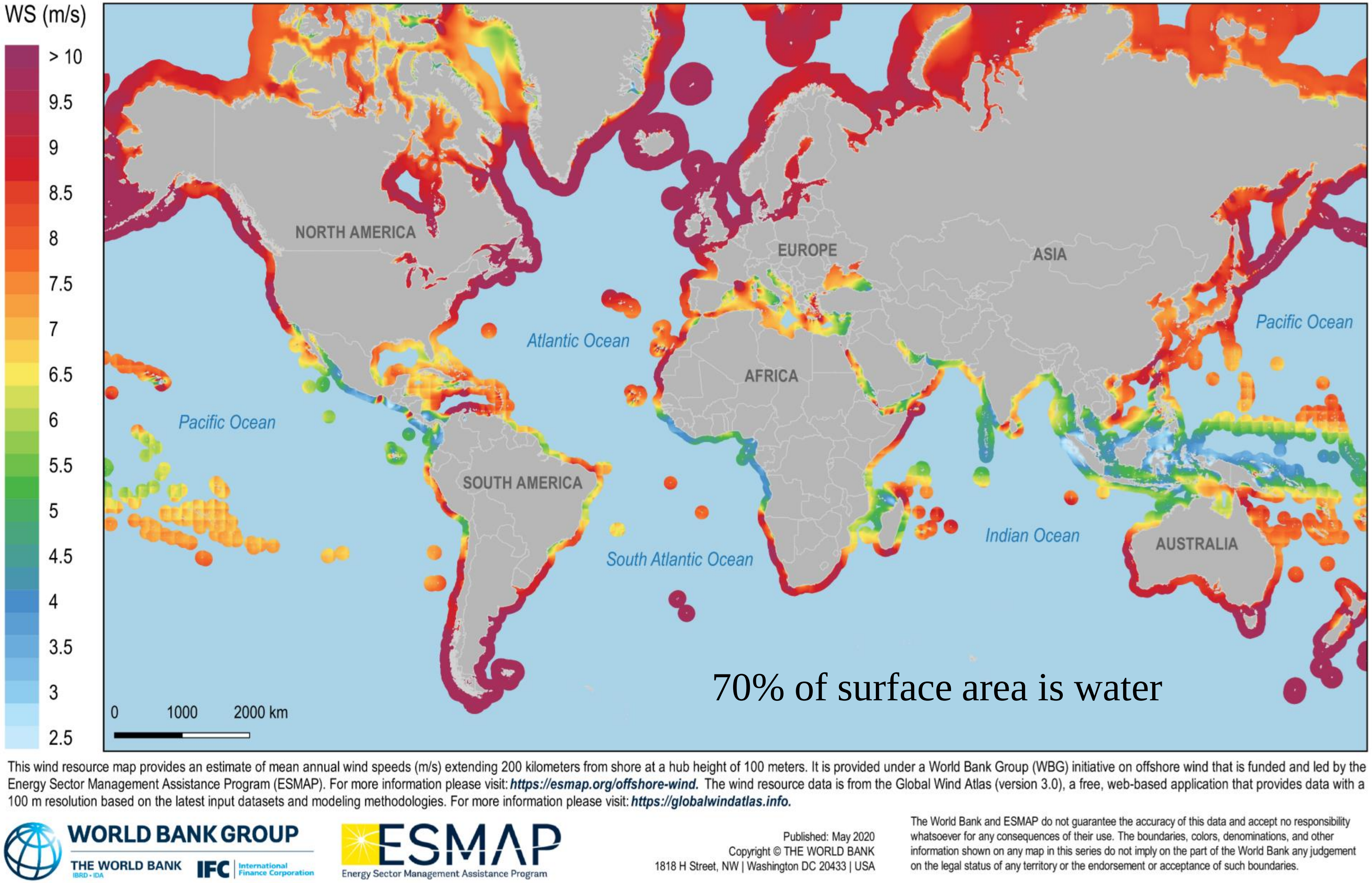
The best wind is found close to the poles and along ocean coastlines



70% of surface area is water

Global Offshore Wind Energy

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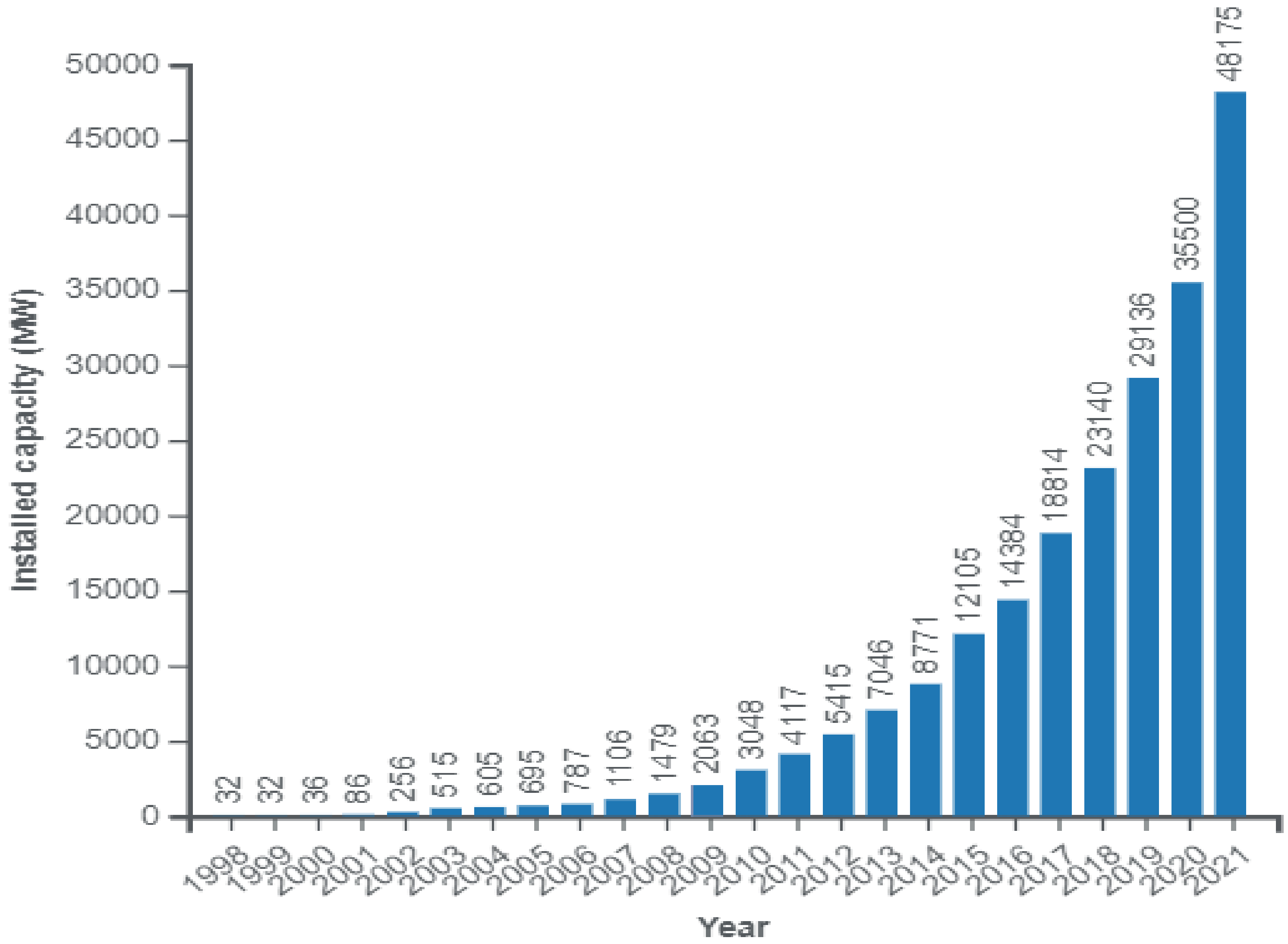
ESMAP
Energy Sector Management Assistance Program

Assessment of 115 countries around the world for practical/ commercial reach

- Regions with wind speeds > 7m/s above 100m
- Fixed offshore wind less than 50m depth
- Floating suitable for 50m to 1000m water depth
- Only regions 200km from shore
- Turbine planting density of 3MW per km^2 (wind speed 7-8m/s) and 4MW (wind speed 8m/s)
- Ignore isolated regions
- **Total Energy Potential = 71,000 GW (> global electricity demand) (20,000GW fixed and 51,000GW floating)**

Current Total Installed Wind Capacity

A total of 48.2GW Installed by 2021



Offshore wind has accelerated rapidly since 2010 due to technological advances and falling costs

Expectations For Next 15 Years

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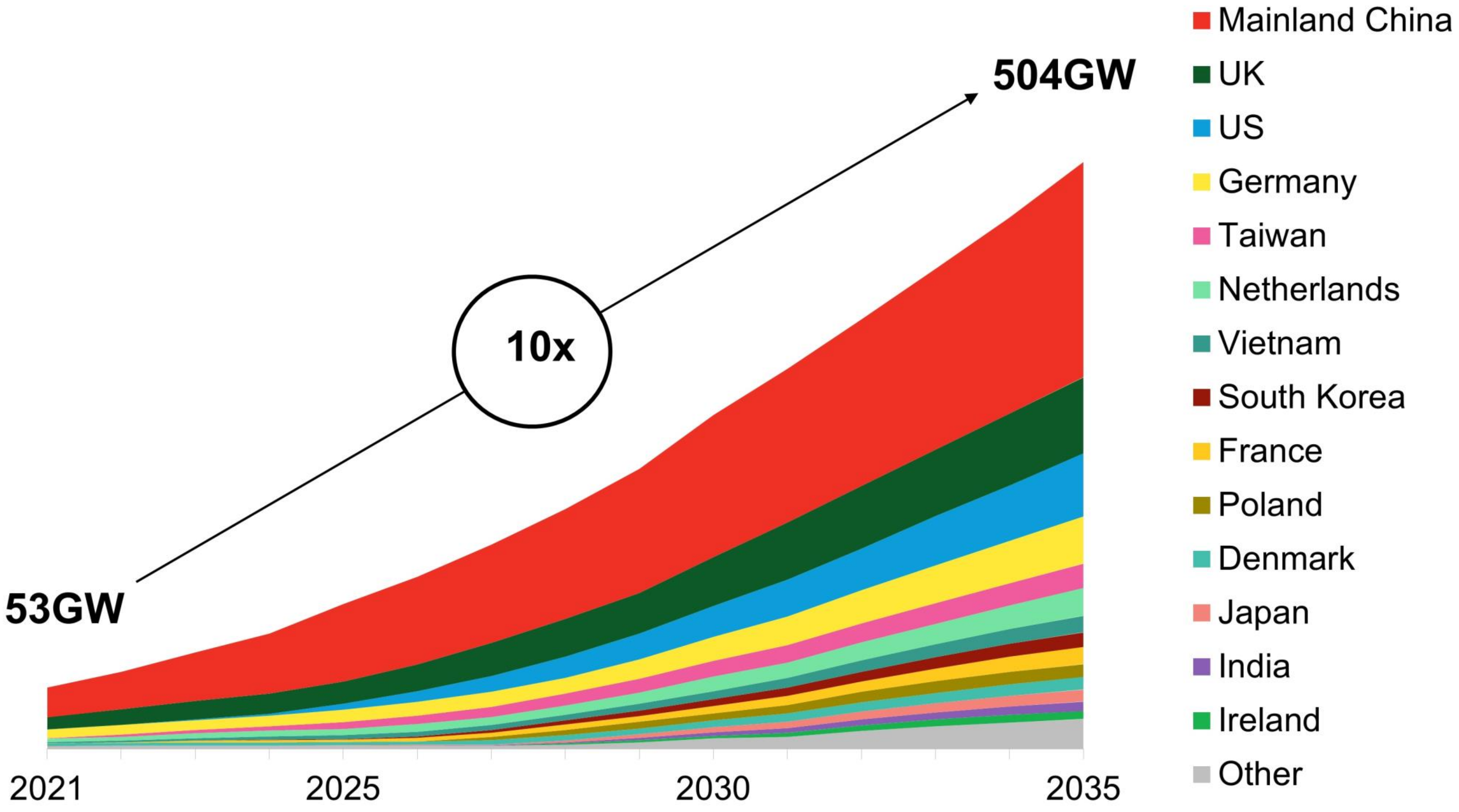
Growth of over 10 times expected over the current 15 years



Offshore Wind Capacity Awarded in 2021-22

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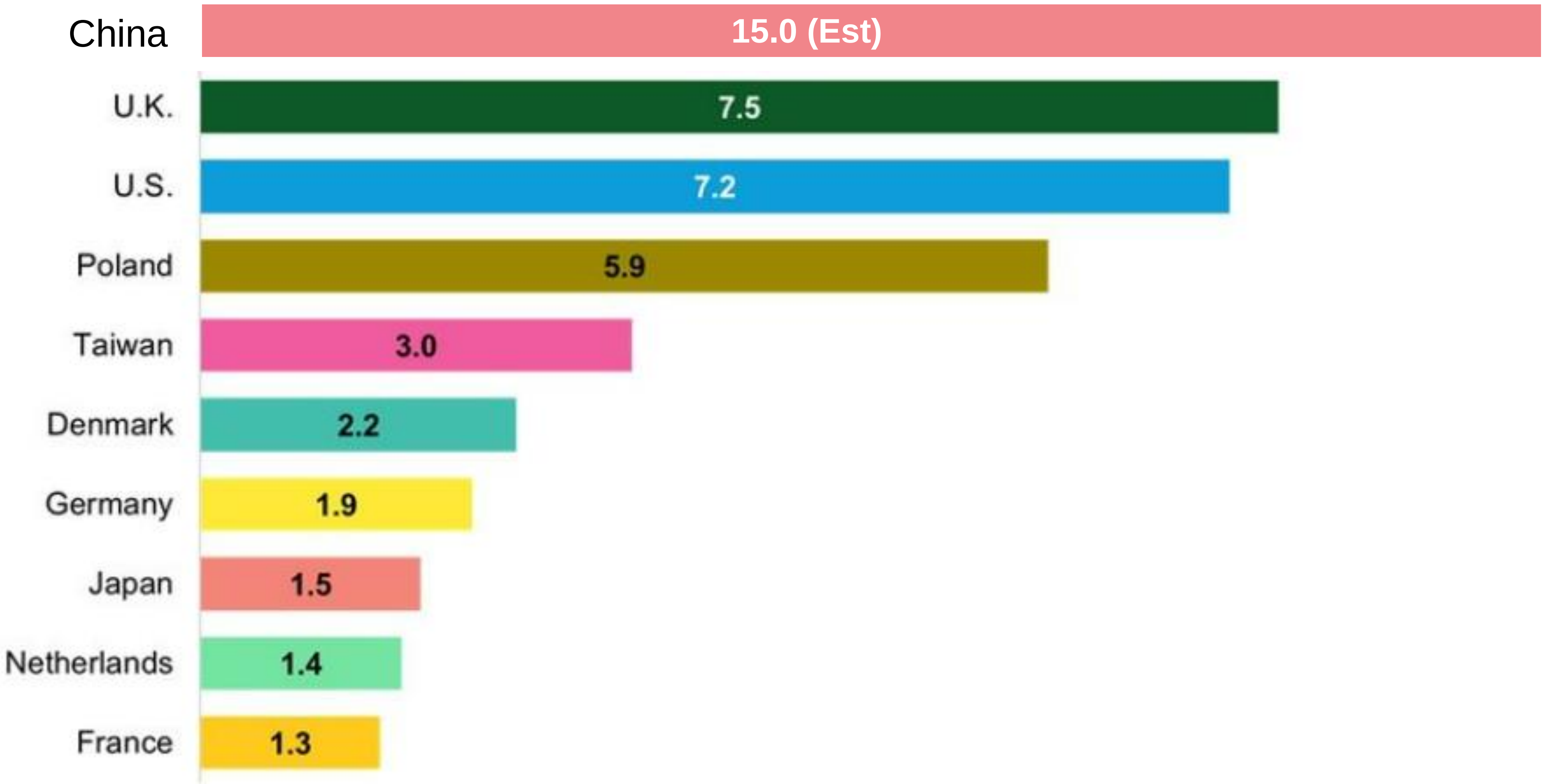
Key Markets in UK, China, USA and Europe Accelerating Due to Energy Security



Source: BloombergNEF

World Leading Opportunity Over 30 Years

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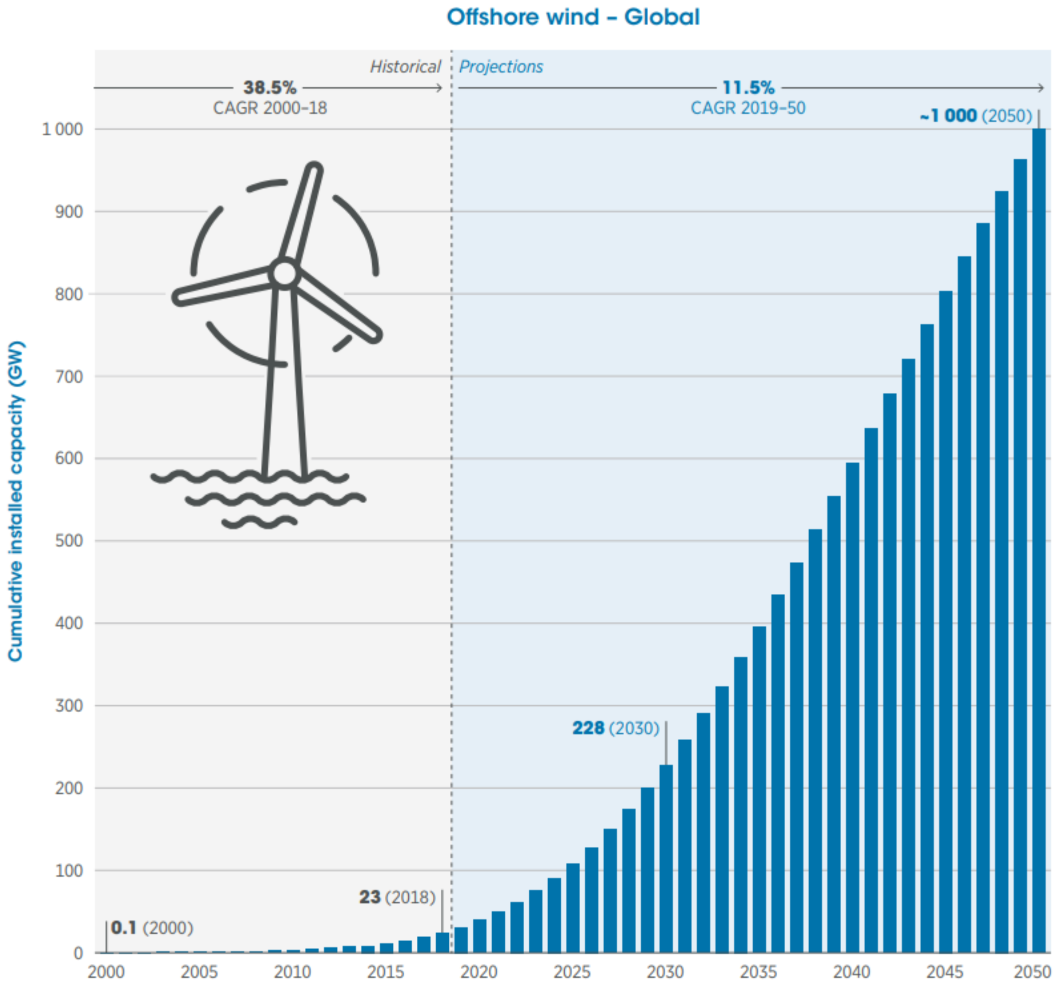
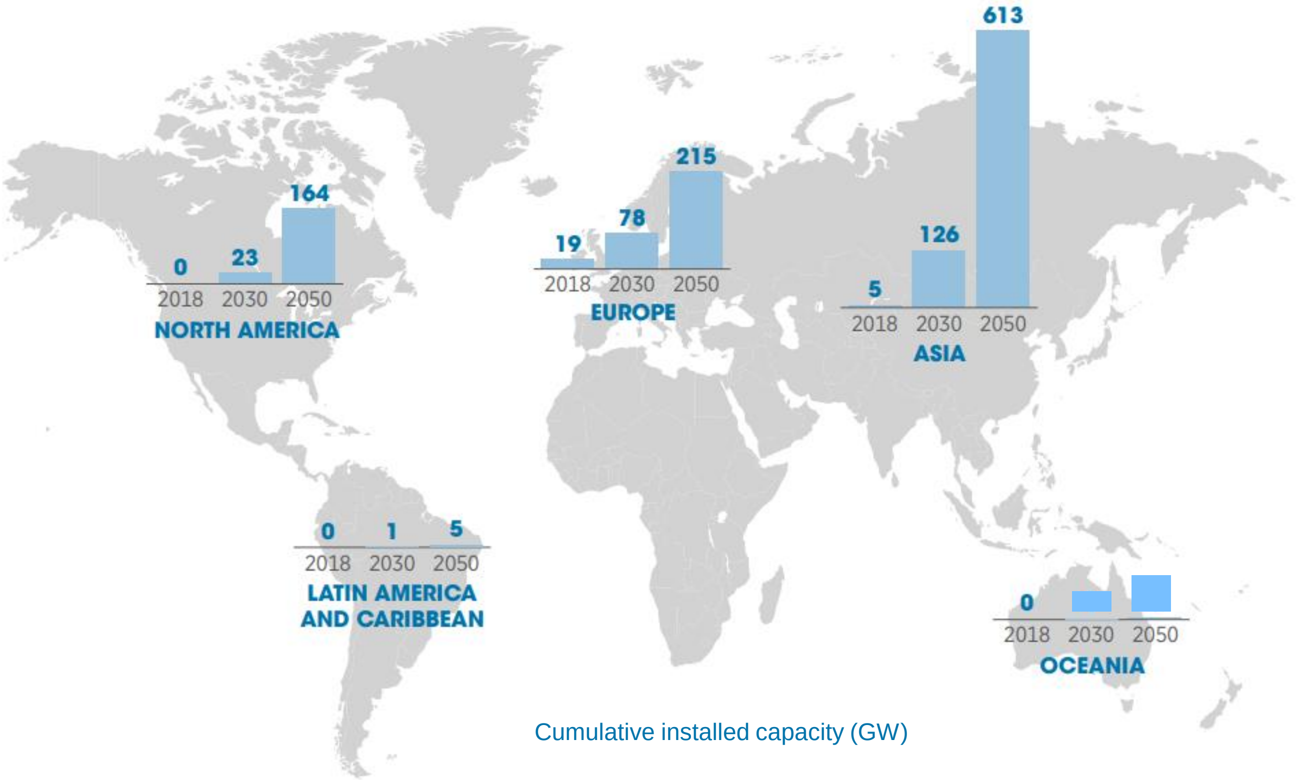
Key ascendant offshore wind markets

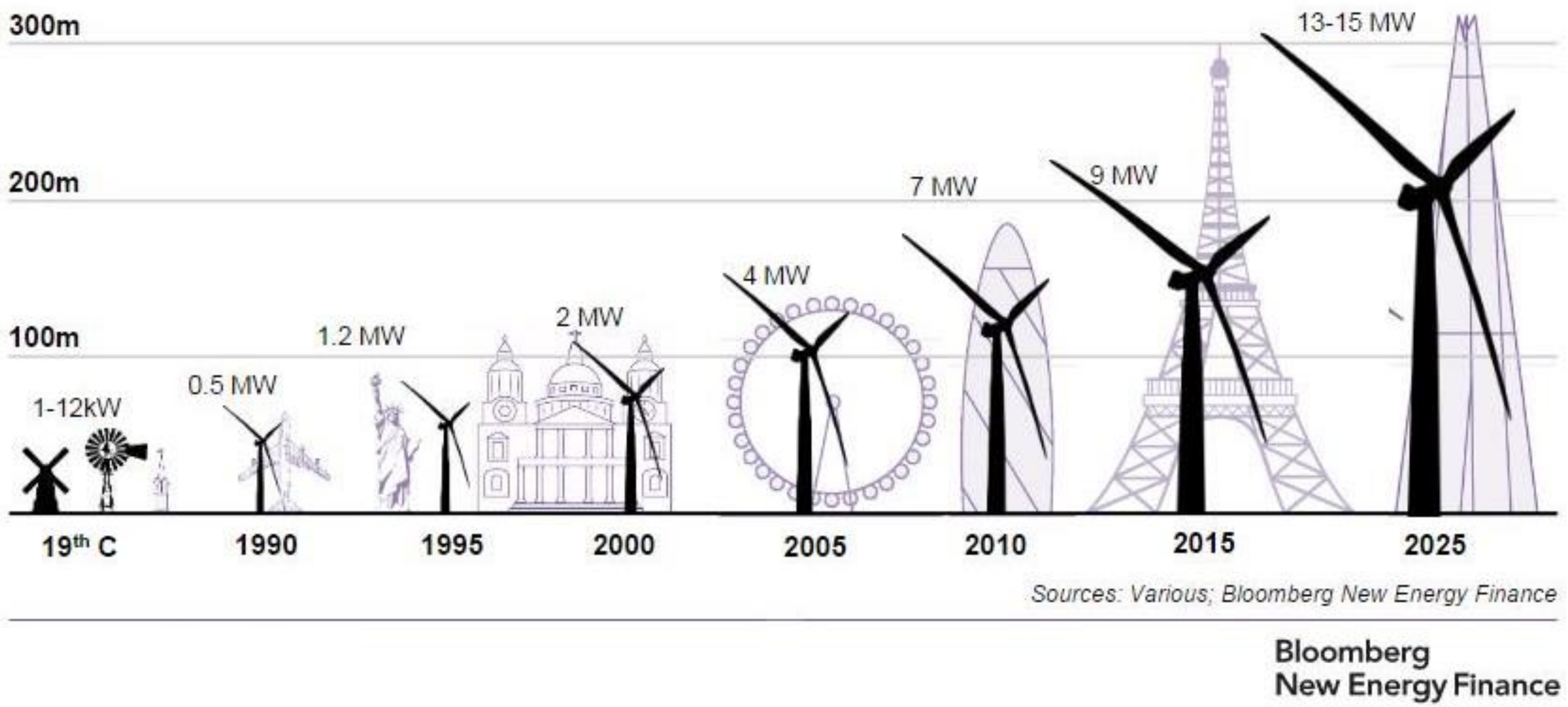




Source: IRENA, Oct 2019 'Future of Wind' report LINK

Evolution of Offshore Wind Turbine Capacity

Turbines Technology has increased significantly of the past 20 years



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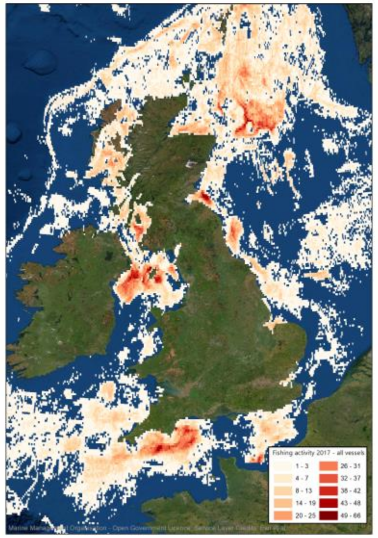
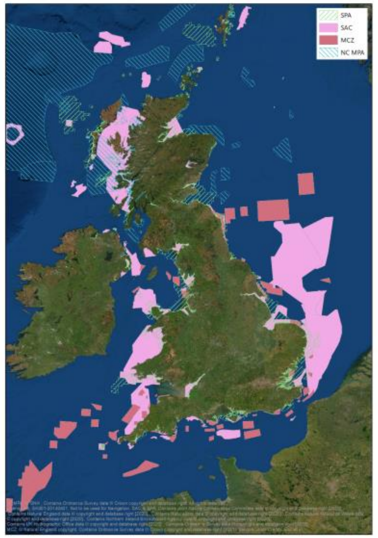
Setting Up and Offshore Wind Project

Pre-Project Development and Project Management

- Development and Consenting Services
- Target Site Identification and Assessments
  - Prospecting for suitable sites and comparison of different attributes.
- Environmental Impact Assessments
  - Environmental Surveys
  - Benthic Environmental Surveys
  - Fish and Shellfish Surveys
  - Ornithological Surveys
  - Marine Mammal Surveys
  - Human Impact Surveys





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Enabling Offshore Wind Deployment

Rapid and accurate LCOE assessments

SCALE balances site conditions, geospatial considerations, and constraints, to provide the Levelized Cost of Energy (LCOE) and recommended foundations and turbines for any given site. Primarily driven by

- Wind Resources
- Water Depth
- Distance from Shore

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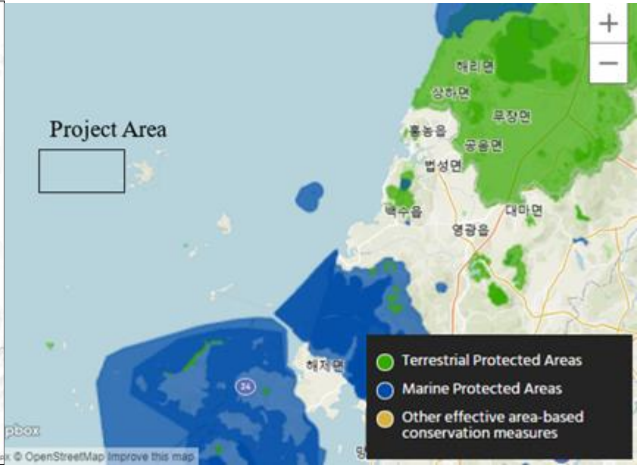
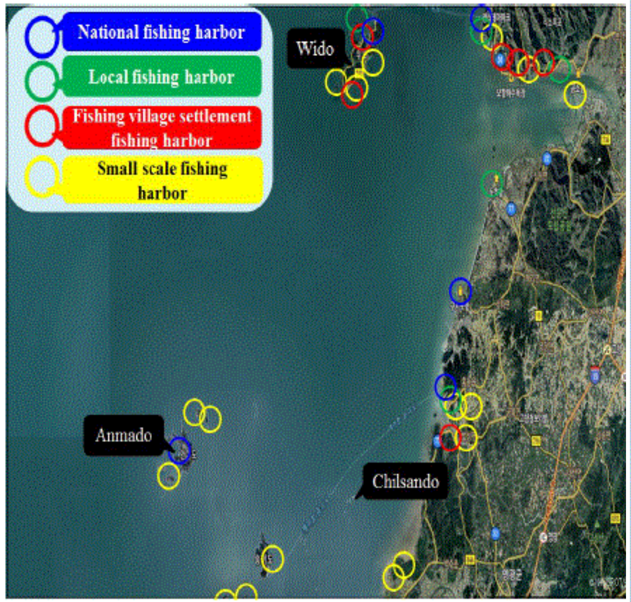
Site Constraint Mapping

Evaluation of Site Conditions

- Assess the Study Area with respect to different constraints
  - Environmental Sensitive Area
  - Coral Reefs
  - Fishery Activities
  - Military Affairs
  - Cultural Activities
  - Nearby Large Infrastructure and Construction Projects





Setting Up and Offshore Wind Project

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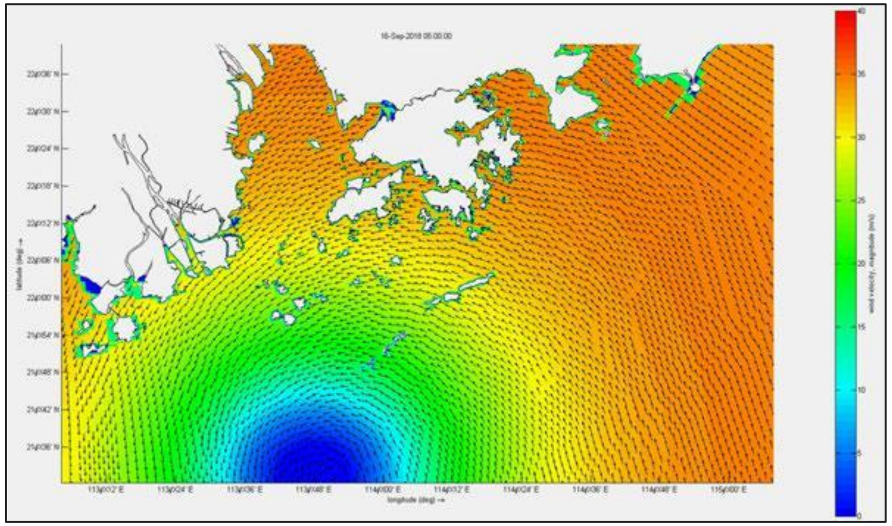
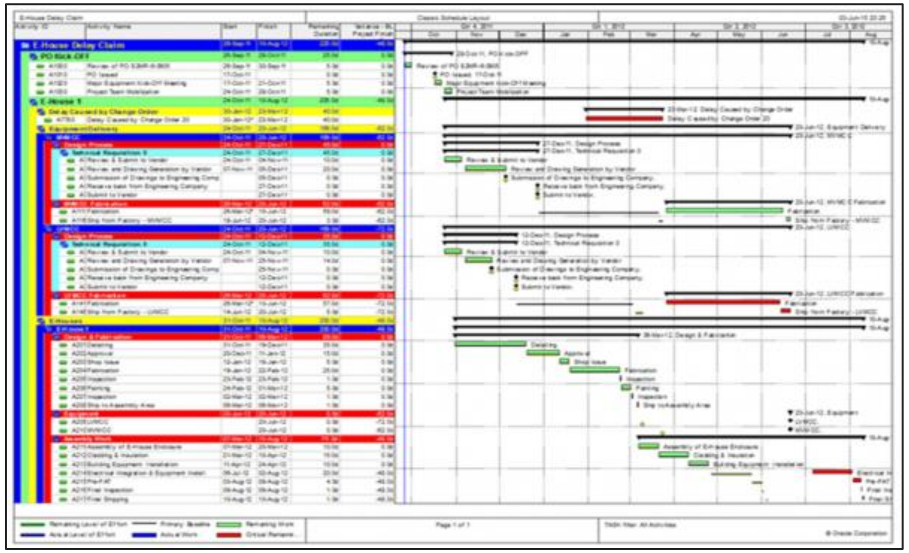
Site characteristics, programming and permitting

- Metocean Studies
  - Comprehensive study of ocean environmental conditions including bathymetry, wind , waves, currents, temperatures etc.
- Project Programming
  - Master programme and identification of the project critical path
  - Identification of key project programme risks
  - Monitoring to identify and mitigate delays and equipment purchase planning
- Project Permitting and Licencing Support
  - Early studies for the procurement of development licences.





Setting Up and Offshore Wind Project

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Site characteristics and turbine selection

- Wind Resource Monitoring and Assessment
  - Planning and implementation of suitable wind measuring equipment
  - Data collection and compilation
  - Interpretation of the results & business case
- Geotechnical and Geophysical Assessments
  - Planning and procurement of geotechnical and geophysical surveys
  - Derivation of geological models for the site.
- Turbine Selection
  - Assessment of suitable turbine types, class and sizes for given conditions
  - Optimal and extreme wind speeds. turbulence effects
  - Cost and efficiency
  - Operations and Maintenance

Setting Up and Offshore Wind Project

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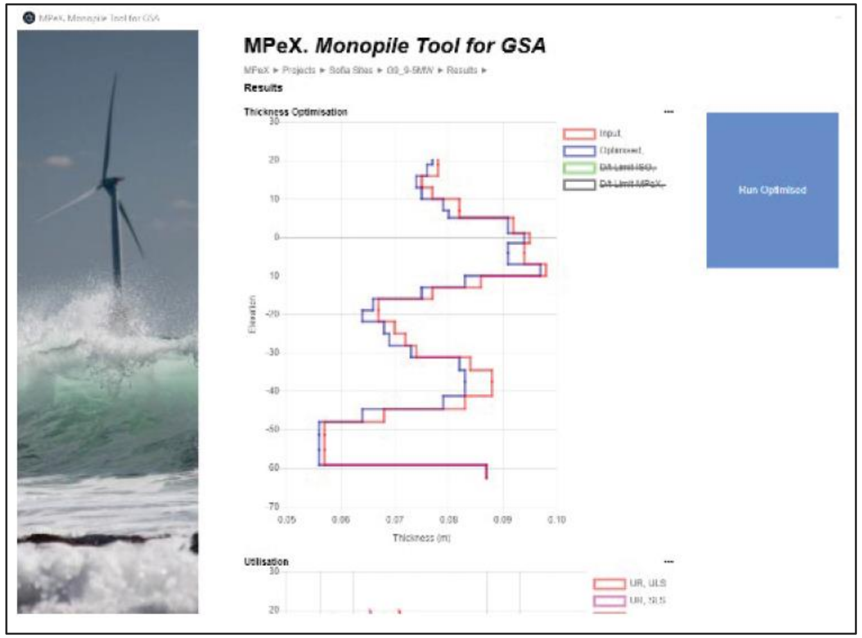
Concept and FEED services

- Energy Yield Assessments & Micro-Siting Analysis
  - Interpretation of the wind monitoring results using specialized software
  - Assessment of the micro-climate at the selected wind farm site
  - Determination of initial site layout plans to maximise annual yield

- Initial Concept and Pre-Feed Designs
  - Development of initial concept and Pre-Feed designs
  - Basis for EPC tendering.
  - Development of initial cost estimates
  - Facilitate the planning and purchase of balance of plant equipment.



Source: Arup; Offshorewindbiz

Turbine Layouts

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Turbine Layouts are Determined to Maximise Wind Energy Capture while Minimising Wake Losses

https://projekter.aau.dk/projekter/files/198432593/thesis_Fischetti.pdf

Micro Siting and Energy Yield Assessment

Layout Optimisation

Stage 1. Impact of phase 2 project

Stage 2. Layout optimisation compared to the original layout.

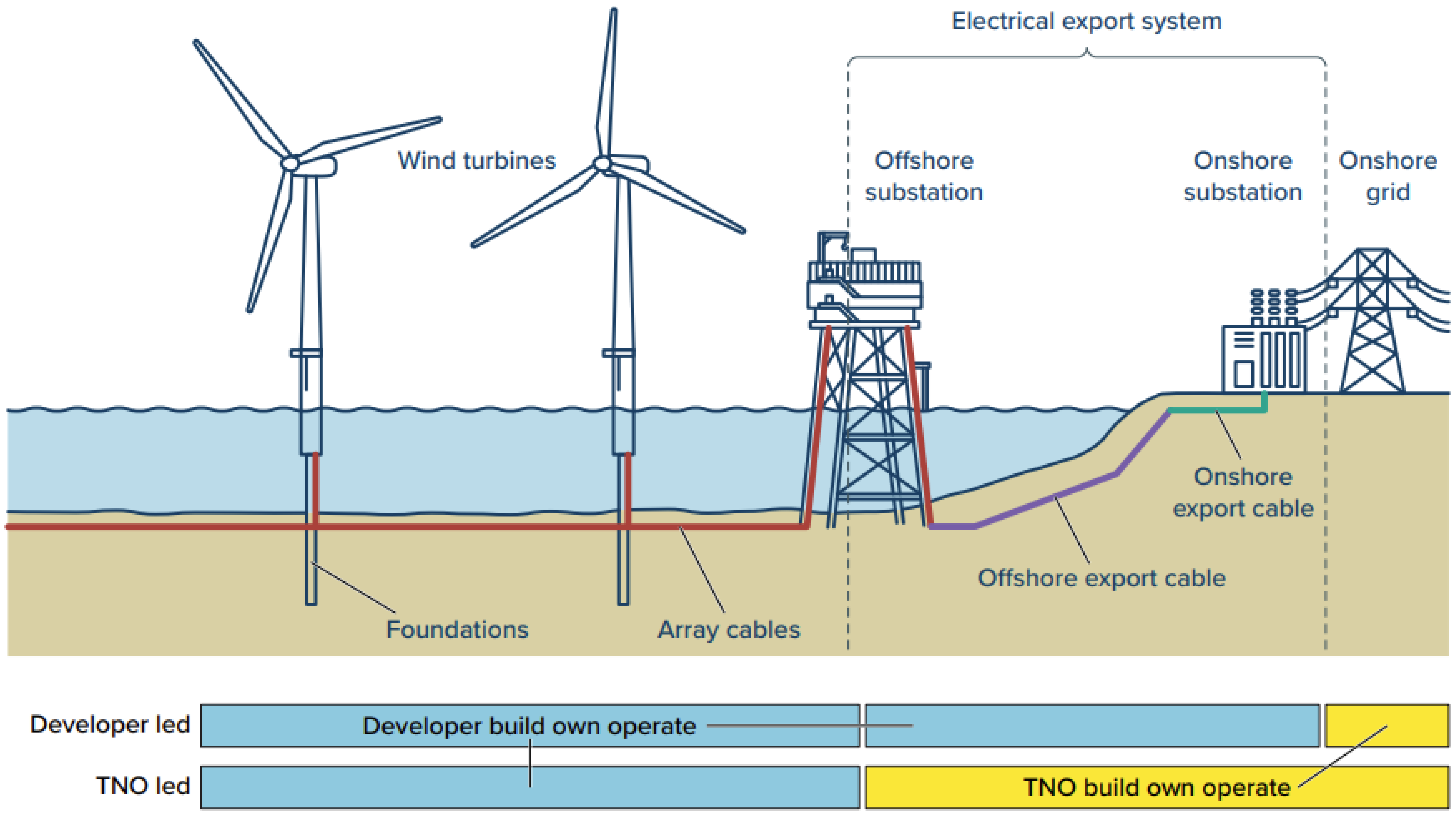
Stage 3. Selection of the best AEP among three turbines.

Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11
Doosan DS205 8MW without neighboring OWF.	Doosan DS205 8MW with neighboring OWF.	Doosan DS205 8MW with neighboring OWF and the Phase 2 project.	Doosan DS205 8MW with the neighboring OWF	Unison U210 10MW with the neighboring OWF.	Vestas V162 6MW with the neighboring OWF	SGRE200 10MW with the neighboring OWF	GE Haliade X 12MW with the neighboring OWF	Doosan DS205 8MW with the neighboring OWF and the Phase 2 project.	SGRE200 10MW with the neighboring OWF and the Phase 2 project.	GE Haliade X 12MW with the neighboring OWF and the Phase 2 project.

Red: Phase 1
Blue: Phase 2
Green: Neighboring OWF

Schematic Layout of an Offshore Wind Farm

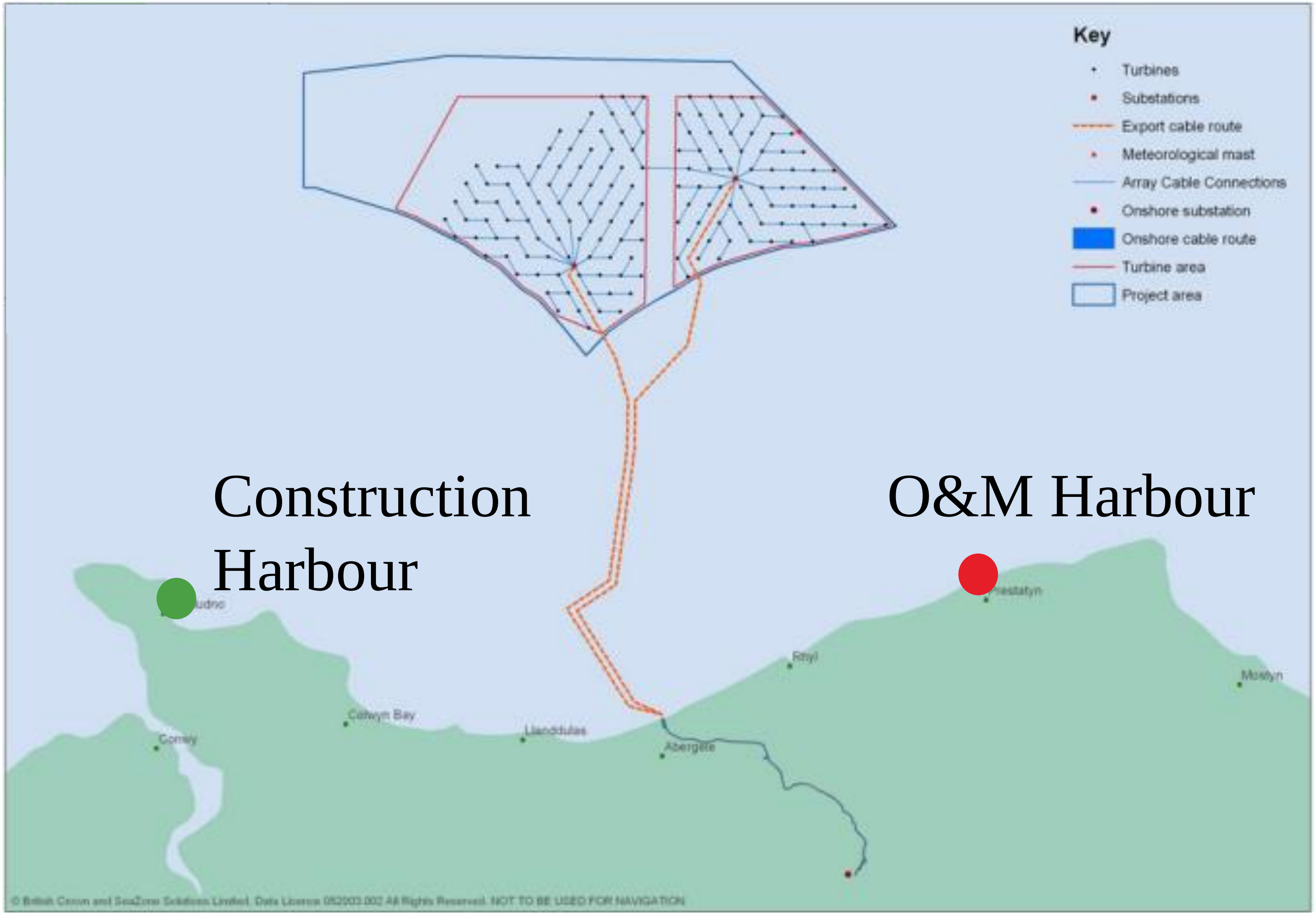
Grid Connections are optimised for cost considering distances and losses



Courtesy of World Bank – Key Factors For Successful Development of Offshore Wind Farms in Emerging Markets

Idealised Offshore Wind Farm

Typical Characteristics for a Real-Life Offshore Wind Farm



https://projekter.aau.dk/projekter/files/198432593/thesis_Fischetti.pdf

Setting Up and Offshore Wind Project

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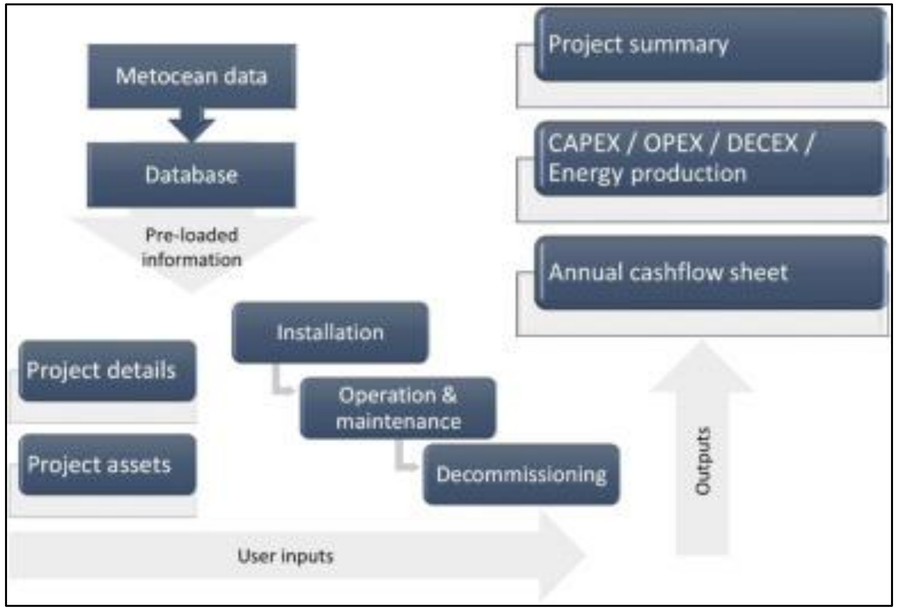
Assessment of project risks and financial modelling

- Grid Connection Studies
  - Location and available capacity of suitable existing substations
  - Optimal cabling arrangements including offshore substations
  - Grid impact studies - determine the impact of wind power to network
- Risk Assessments
  - Risk management processes to identify key project risks
  - Risk management plan and identification of suitable mitigation measures
- Capex and Opex Assessments
  - Financial models to assess the likely Capex and Opex based on experience
  - Development of suitable contingencies to account for potential risks.



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Installation and Commissioning

Project construction, connection and testing

- Construction ports preparation
- Offshore logistics planning
- Installation of key civil works
  - Foundation Installation
  - Offshore Substations
  - Onshore Substations
  - Turbine Installation

Courtesy of NJ EDA

Courtesy of Sinovel Wind Co. Ltd

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Installation and Commissioning

Project construction, connection and testing

- Offshore Cable Installation
  - Export cables routing and burial
  - Inter- array cables routing and burial
- Onshore Cable Installation
  - Onshore cable landing
  - On-land permitting and laying
  - Connection to onshore sub-station
- Commissioning and Testing

Courtesy of Van Ord

Courtesy of London Array

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Operations and Maintenance

Asset management throughout the lifetime of the wind farm

- Operation & Maintenance Port Establishment
  - Offices/ warehouse
  - Operations centre

- Maintenance and Service
  - Blade Inspection and Repair
  - Balance of Plant Maintenance and Repair

- Foundation Inspection and Repair

Courtesy of Orsted

Foundation Design of Wind Turbines - Offshore

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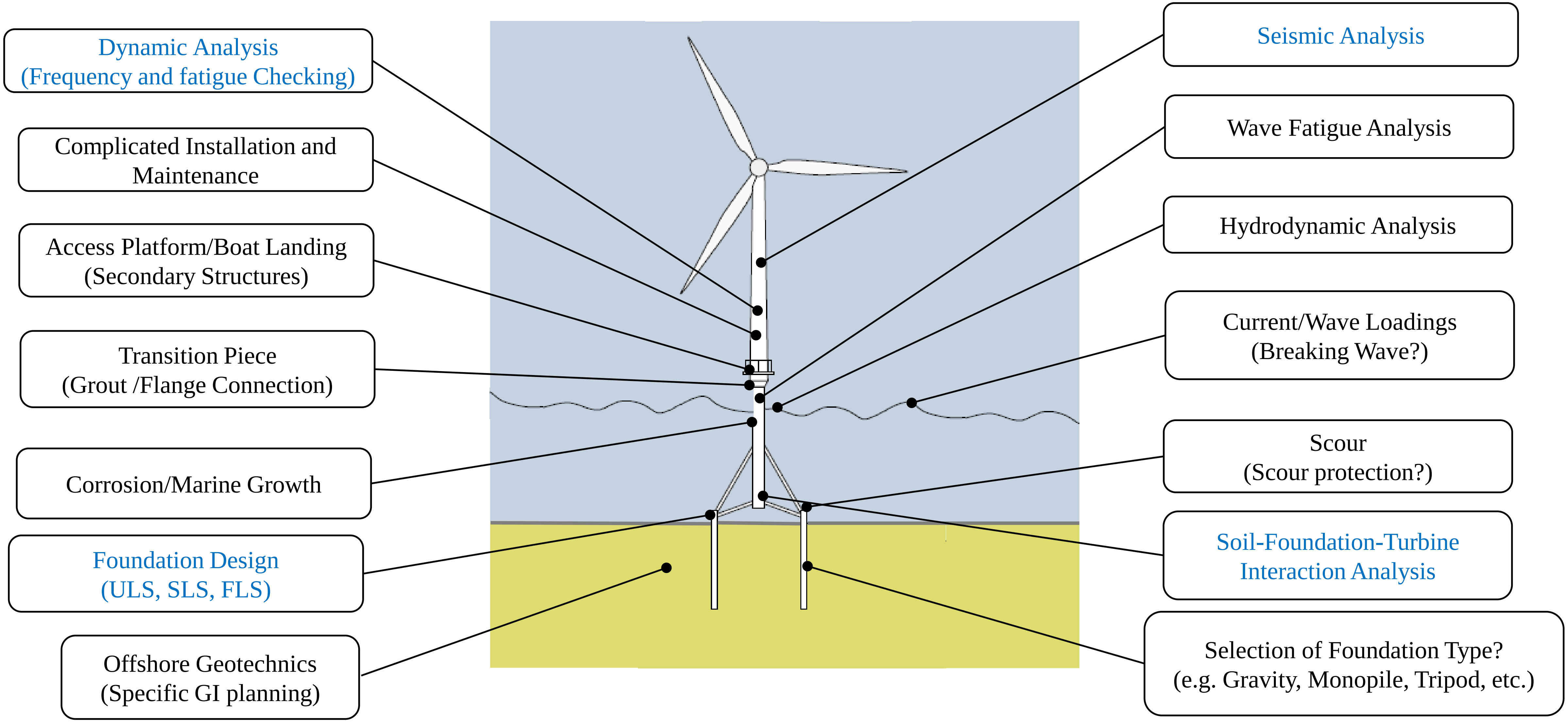
Asset management throughout the lifetime of the wind farm



Offshore Foundation Types

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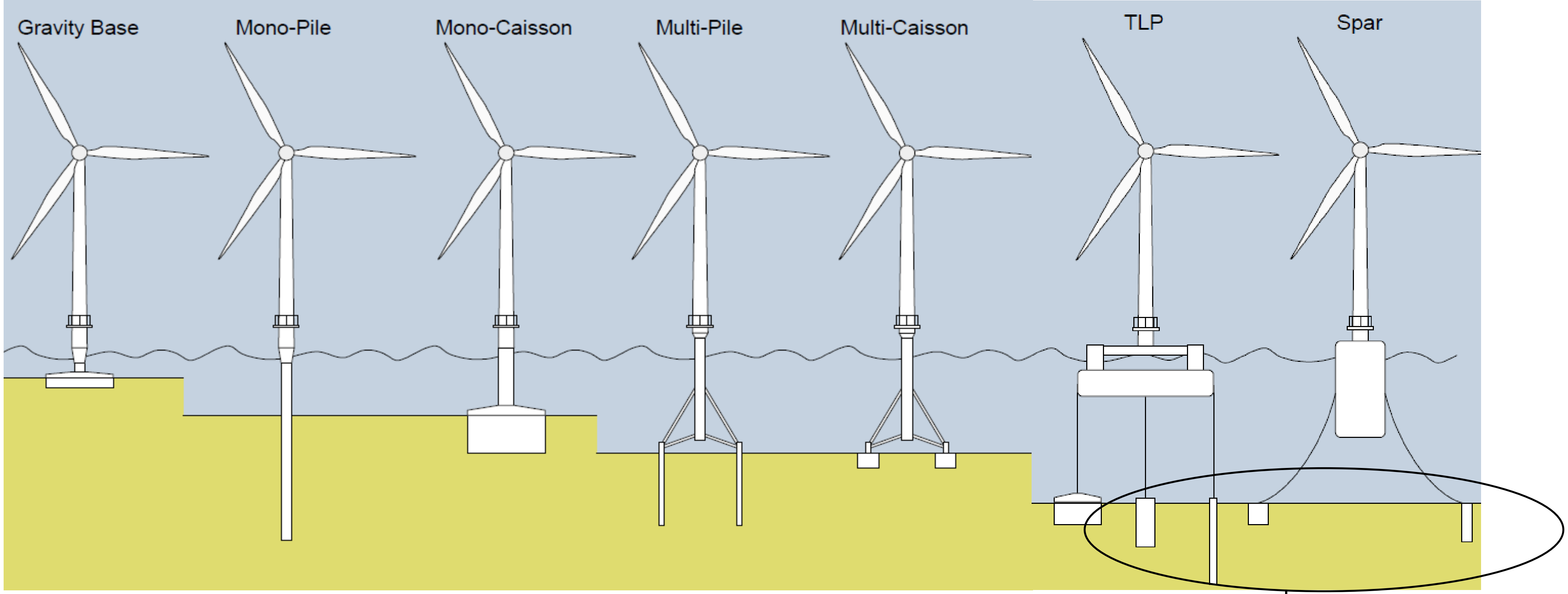
Foundation selection generally based on water depths and ground conditions



Drag anchors

Suction anchors

Torpedo anchors

Source: B. Byrne Geotechnique Lecture

Concept Development – Finding the Best Solution

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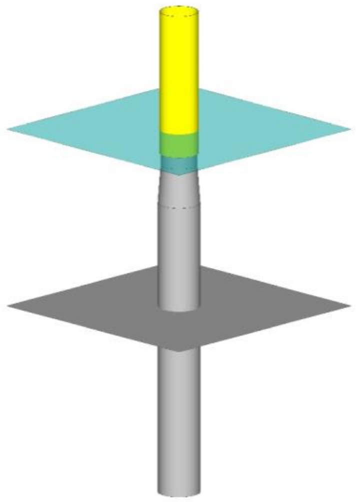
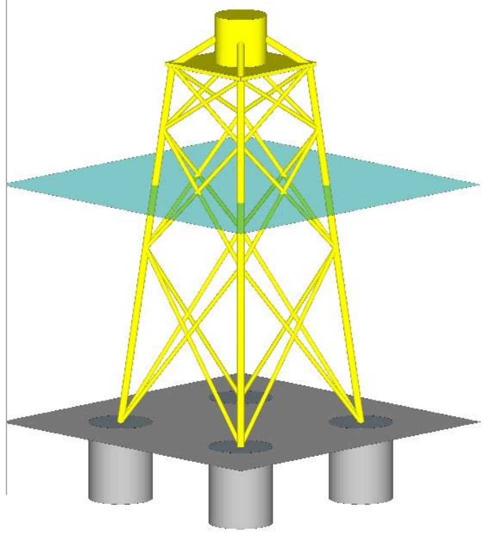
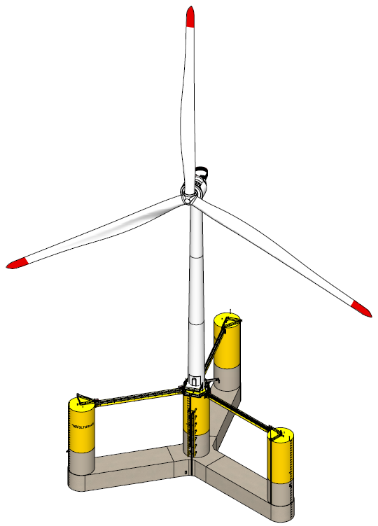
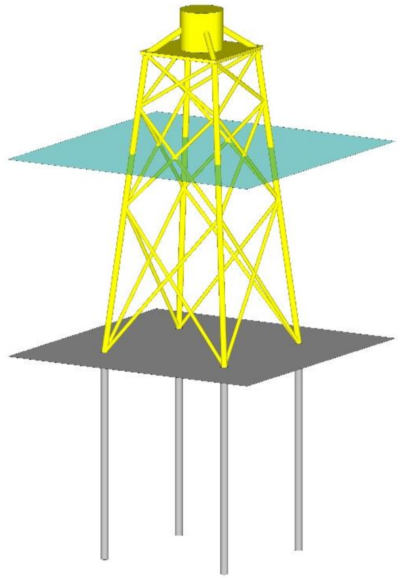
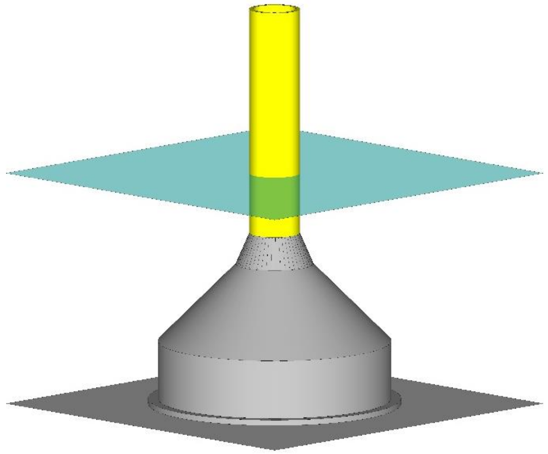
Foundation selection generally based on water depths and ground conditions

- Consideration of technical, financial, business planning and project management to realize viable offshore wind development solutions.
- Use of efficient Offshore Wind Foundation screening tools to identify the most promising foundation solutions


Monopiles

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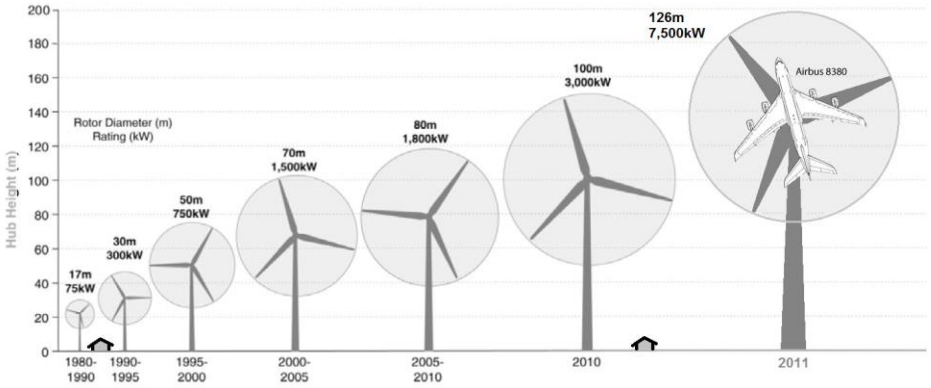
Simplest and most economic foundation system in shallow water

- Current industry preference is for monopiles in up to 30m water depth
- Typically up to 6m diameter but up to 11m diameter monopiles commercially available
- Relatively simple design
- Overall vibration and deflection are subject to large cyclic lateral loading and moments due to current and wave loads.
- Need for transition piece to level the mast above



Monopiles – XL – Going Bigger and Deeper

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As depths increase and turbine sizes grow the monopile needs to get larger

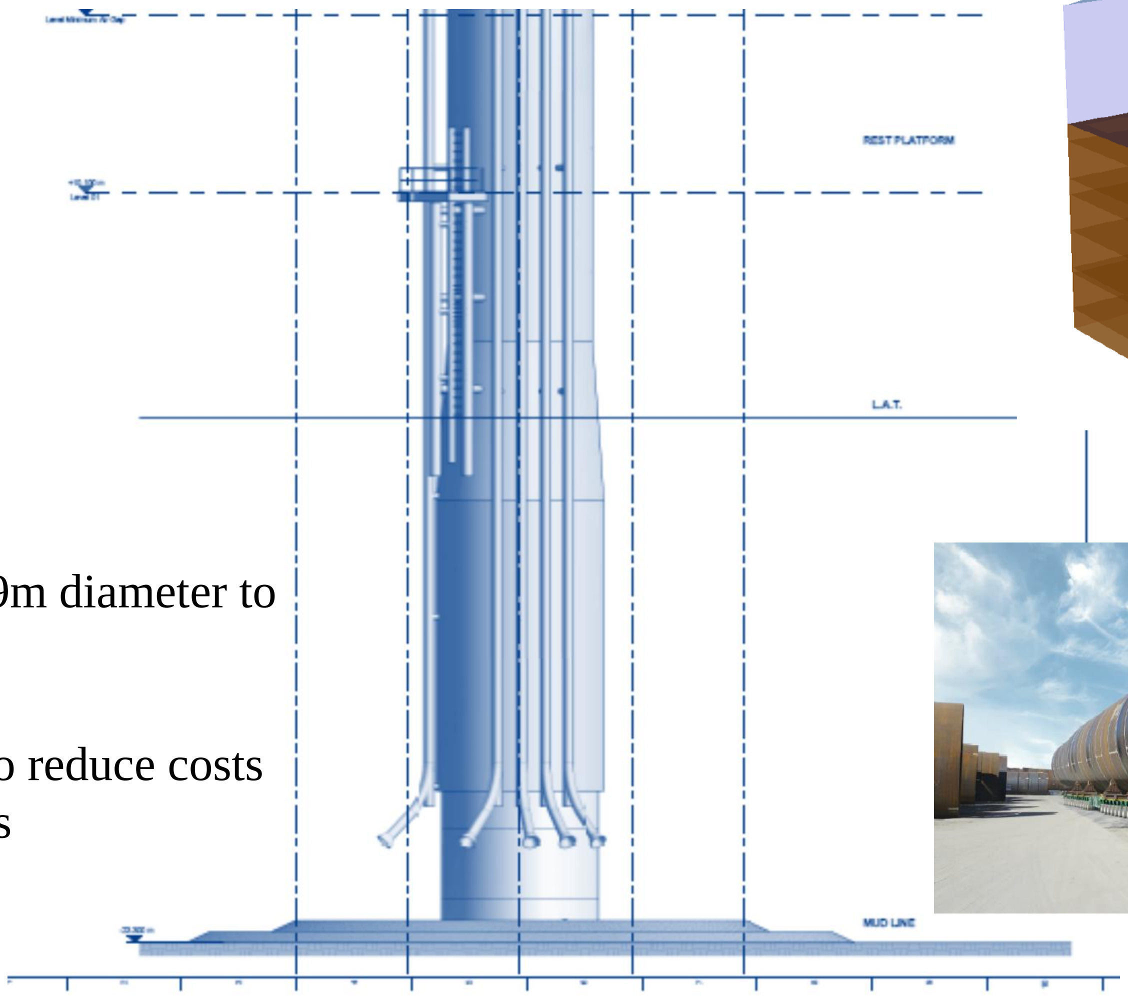
- Wind farm installations are moving further offshore and bigger turbines are being developed

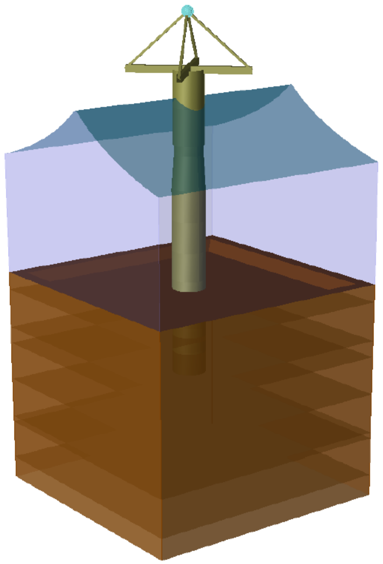
  - ➢ Deeper water
  - ➢ Deeper penetration
  - ➢ Larger diameter
  - ➢ Heavier
  - ➢ Increased waves

- Advanced geotechnical engineering

- 12MW turbine in 30m water depth: > 8m to 9m diameter to achieve minimum frequency

- Future wind farms will demand innovation to reduce costs while managing the overall risk new concepts





Pre or Post Pile Jackets

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Jacket foundations are becoming a popular solution as shallow areas are already taken

- Suitable for deeper water in excess of 20m to 50m and rough sea conditions but can also work in shallow water
- Designs for depths > 40m prepared
- Lower wave loads compared to monopiles
- Fabrication expertise widely available
- Higher construction costs and potentially higher maintenance costs

courtesy of Alamy

Suction Buckets

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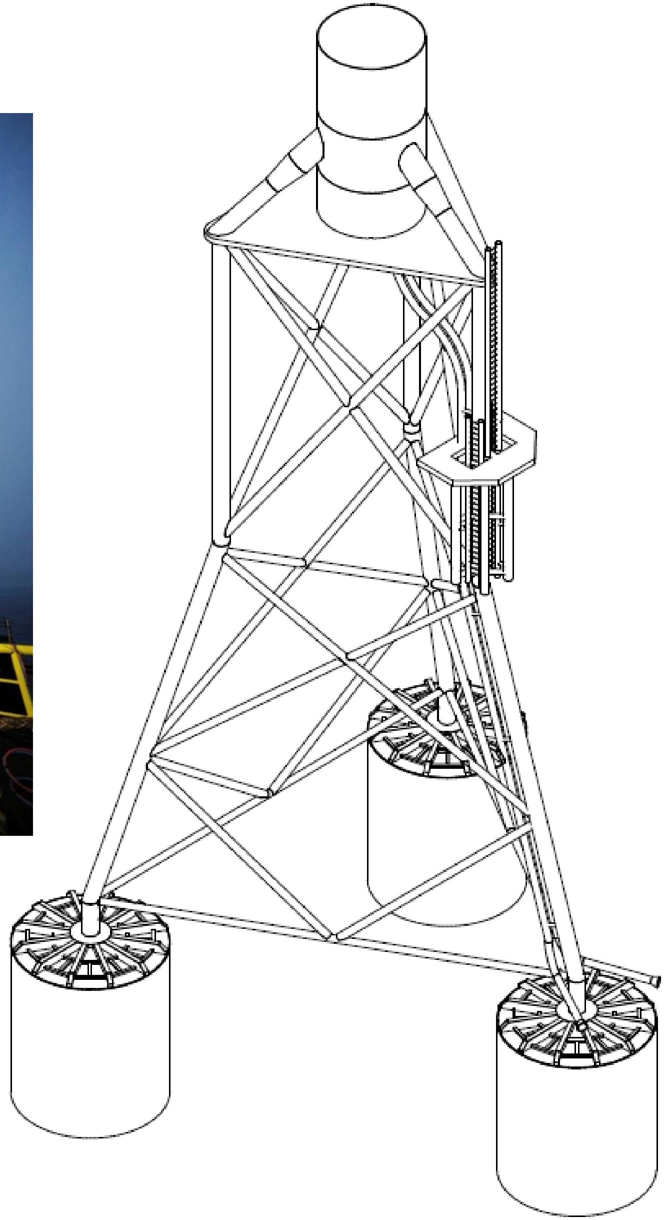
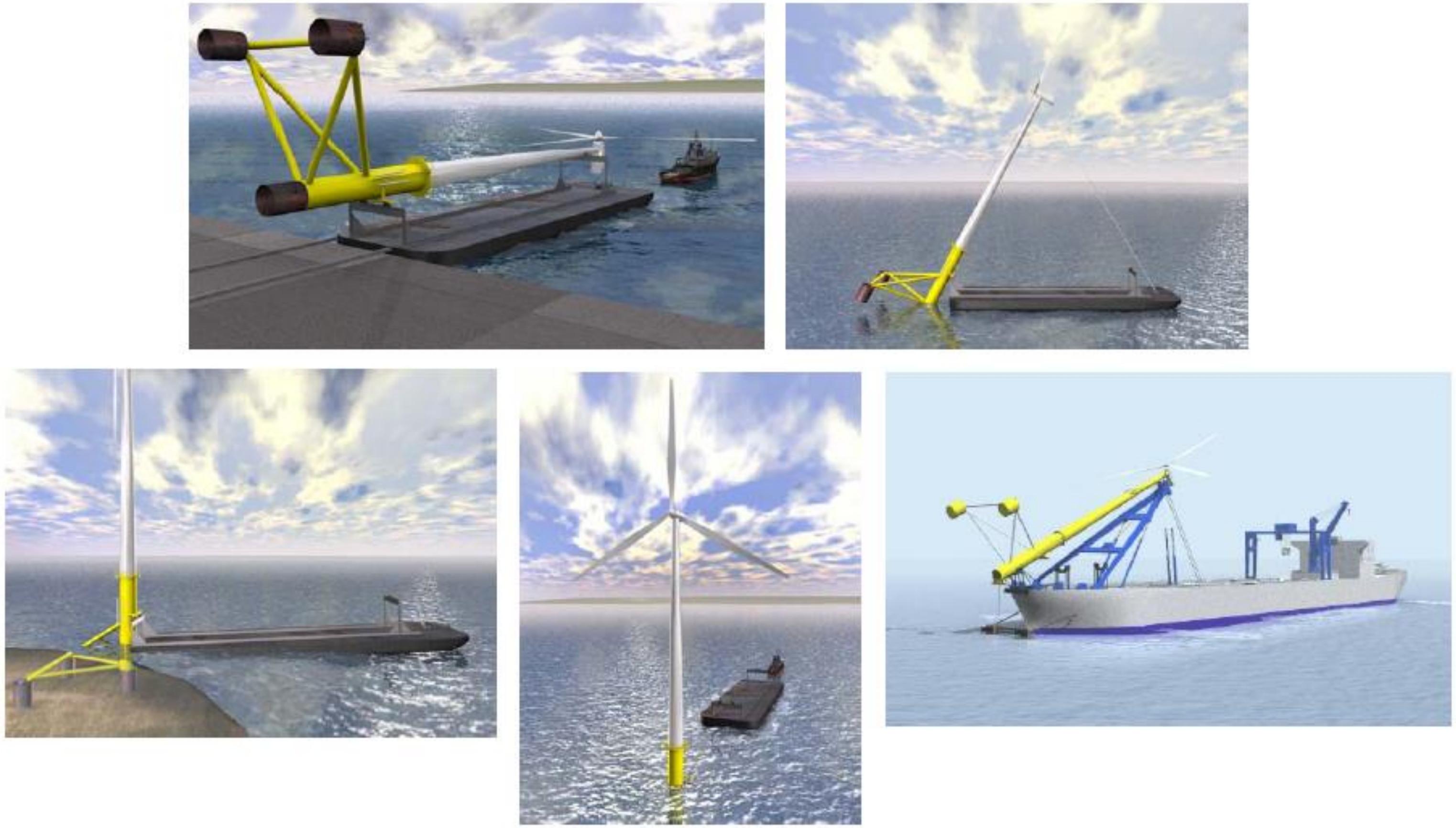
Suction buckets are a solution for sites underlain by softer ground

- Used in O&G for many years with high capacities
- Key advantages for offshore wind turbines
  - ➢ faster installation,
  - ➢ shallower penetration,
  - ➢ large capacities,
  - ➢ suitable for weaker soils,
  - ➢ reduced installation operation.
  - ➢ no pre-drilled piles, and
  - ➢ can be installed and removed quickly.
- Can lead to significant LCOE savings
- Efficient use requires key expertise in geotechnical engineering and soil structure interaction.



WindACE – Self Installing Mast

Innovative solutions are being developed for greater cost effectiveness



Suction bucket foundations installed by upending complete turbine and foundation assembly

Concrete Gravity Foundation

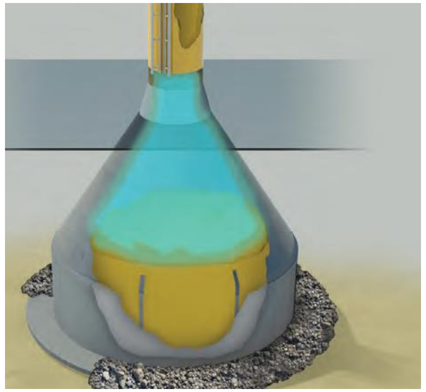
ARUP

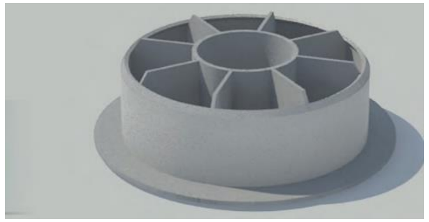
Concrete gravity bases are a solution for sites underlain by harder ground

A simple solution for offshore wind turbine foundation funded by UK Department of Energy & Climate Change:

- No heavy lifting
- No special vessels
- Minimized seabed preparation

Typical Principal Data:	
Turbine	6 MW
Water depth	35 m
Hub height	90 m
Outer diameter, caisson	31 m
Concrete volume	2,800m3
Steel reinforcement	890 tonne





An innovative foundation design

Floating Concepts

ARUP

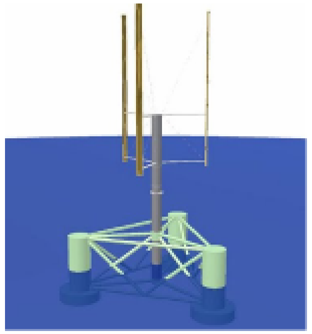
Floating offshore wind is becoming more popular as sites become deeper

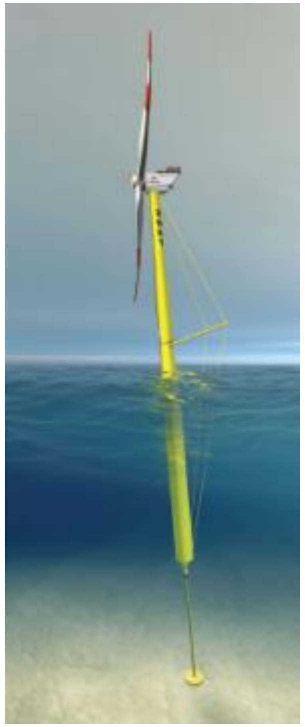
- Many different solutions being developed

- Largely supported by national or international research and development through demonstration funding programmes

- Poised to move to true commercialization very soon

- Generally more expensive than other systems due to the deep water conditions and high technology but costs are coming down as technology improves





…and many more…

Cost Challenge in Deep Water

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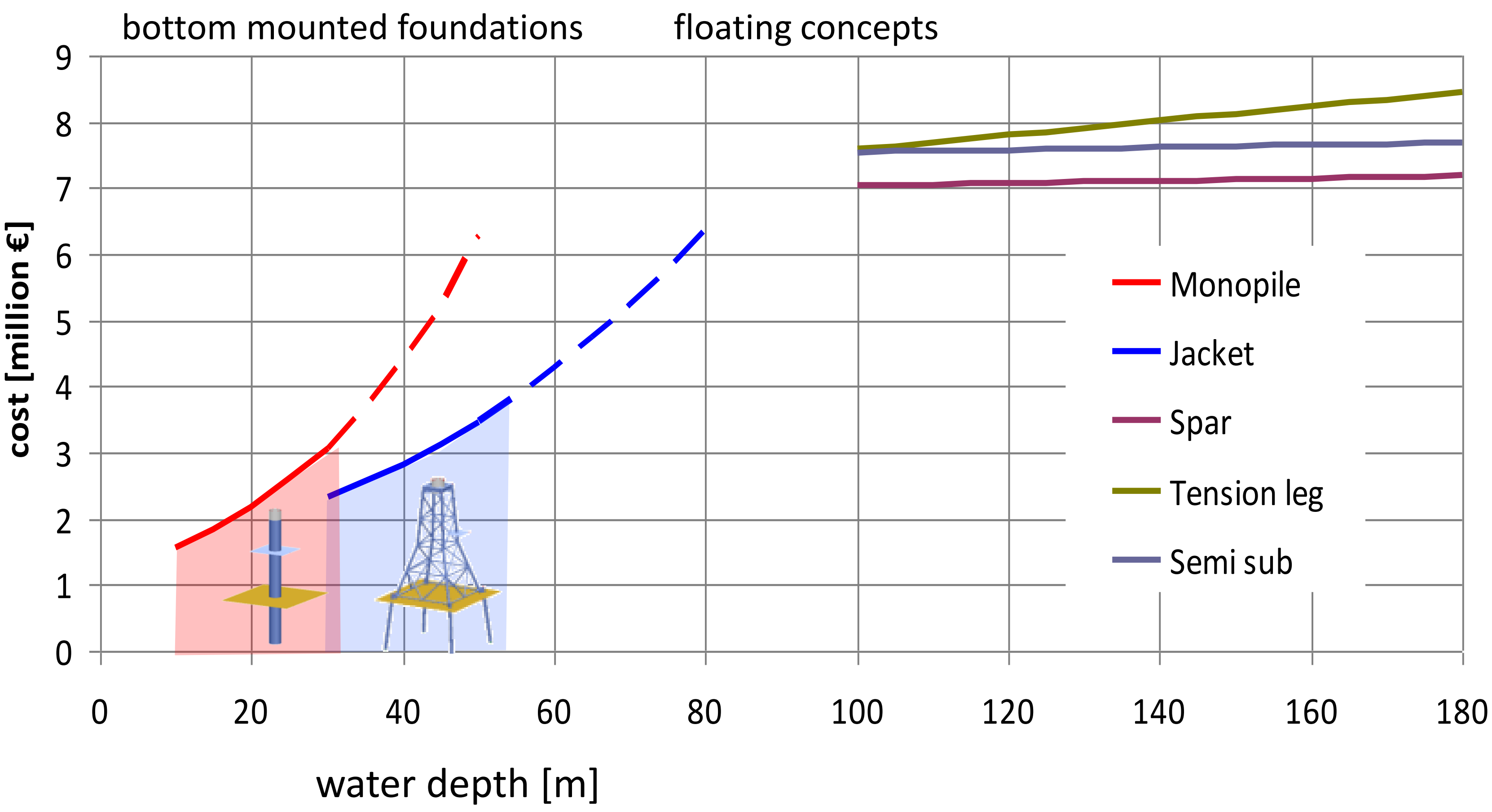
Foundations generally become more expensive with depth but costs will come down with scale



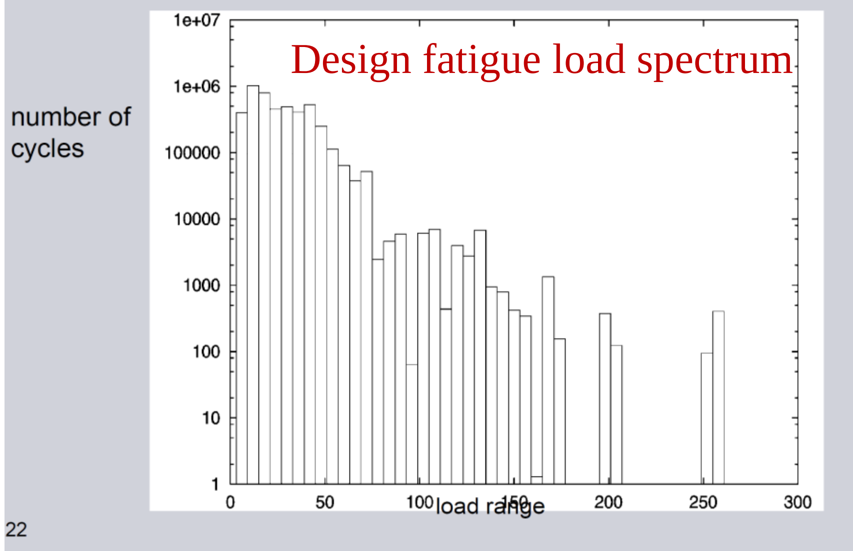
Manufacturing cost models for 8 MW turbine foundations (various sources)

Turbine Foundation Design Approach

ARUP

Fatigue is a key concern for foundation designers

- 25-year design life
- Detailed load combinations to consist of both ultimate and fatigue load conditions
- Control natural frequency of entire turbine and substructure to be within specified ranged provided by turbine supplier
- Control deflection and rotation at interface level to be within acceptable limit specified by turbine supplier (0.5 degrees)



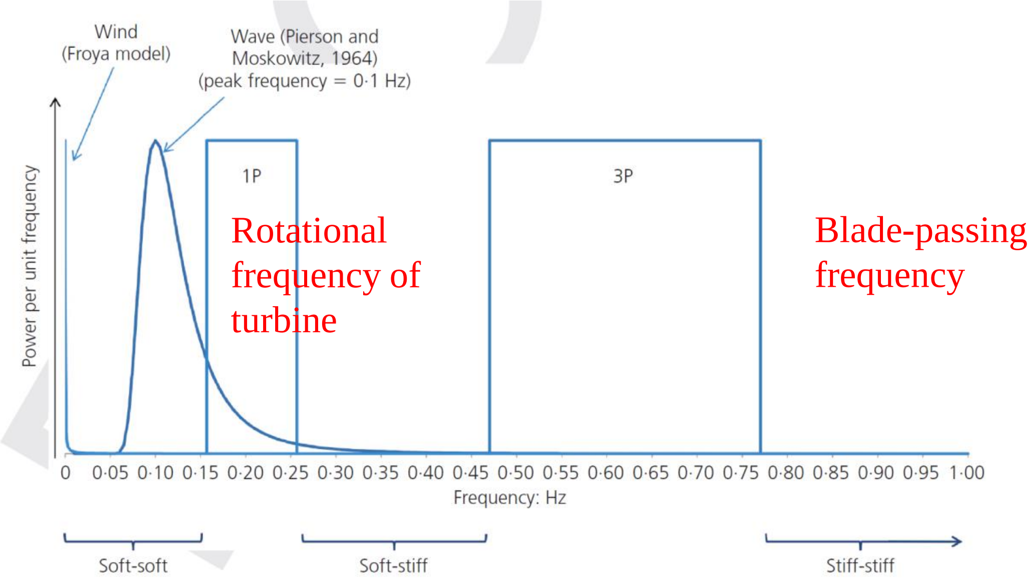


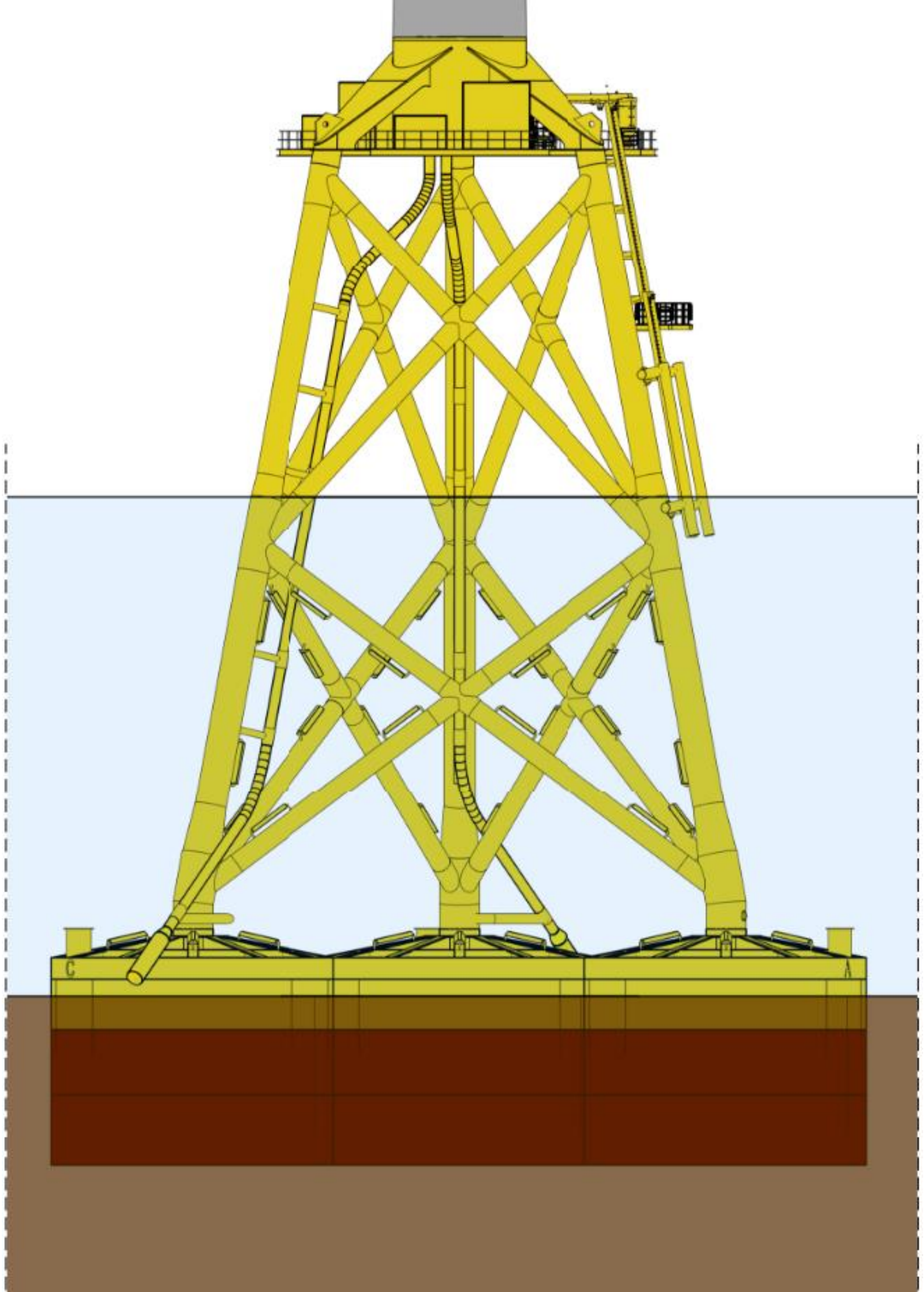
Figure 1. Forcing frequencies plotted against power spectral density for Vestas V120 4·5 MW wind turbine

Frequencies 频率	**1 p (Hz)**	**3 p (Hz)**
	0.17 – 0.27	0.51 – 0.81

Jacket Foundation Overview

What makes up a jacket structure?

- Tower
- Transition piece
- Jacket
- Fixity to seabed
  - Suction buckets
  - Piles
- Secondary steel
  - Boat landing
  - J-tubes/Cables



Foundation Design Approach

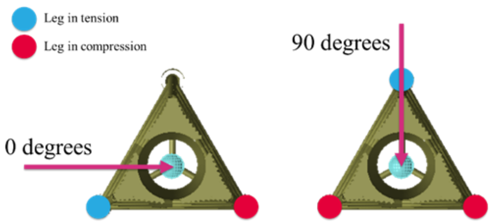
Jackets

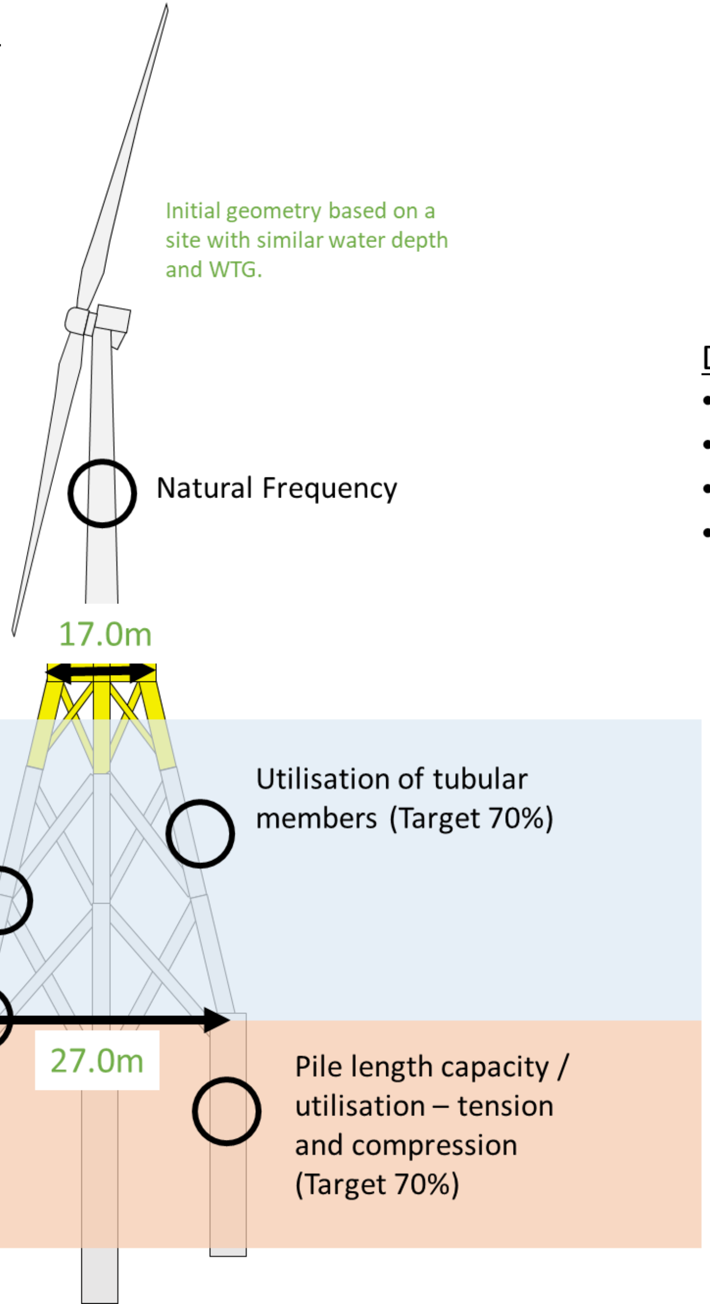
<u>Environmental Loading:</u>
- WTG Supplier Wind Loading
- Representative Design Wave Loading

<u>Seismic Loading:</u>
- El Centro 1940 NS
- Response Spectrum Analysis

Assume 3-leg spacing:
Structurally most-efficient, though 4-leg can have other non-structural savings.

Two directions

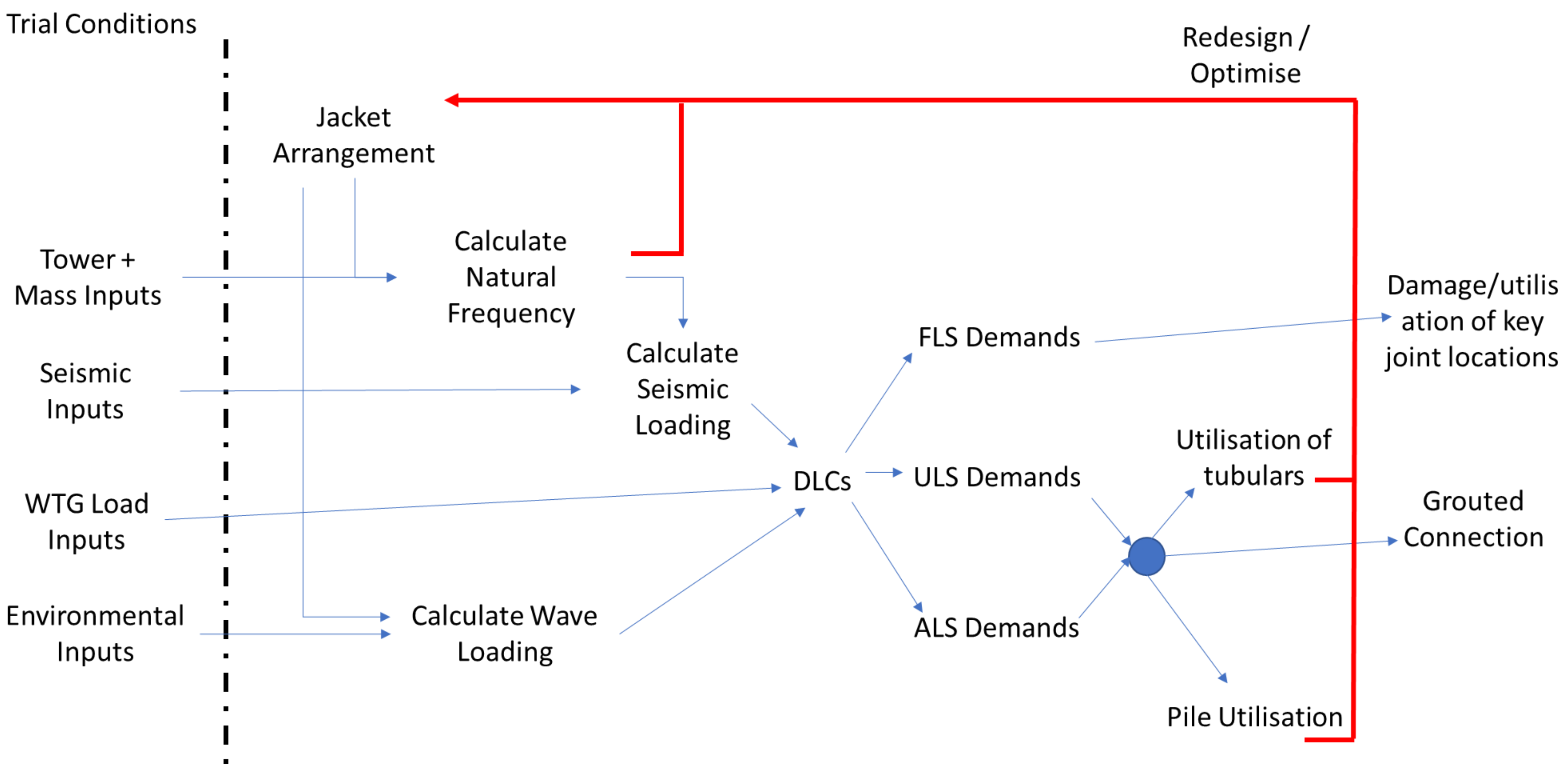




<u>Deliverables:</u>
- Design Basis
- Design Report
- Design Sketch
- Material Take-off Sheet

Foundation Design Approach

Jacket



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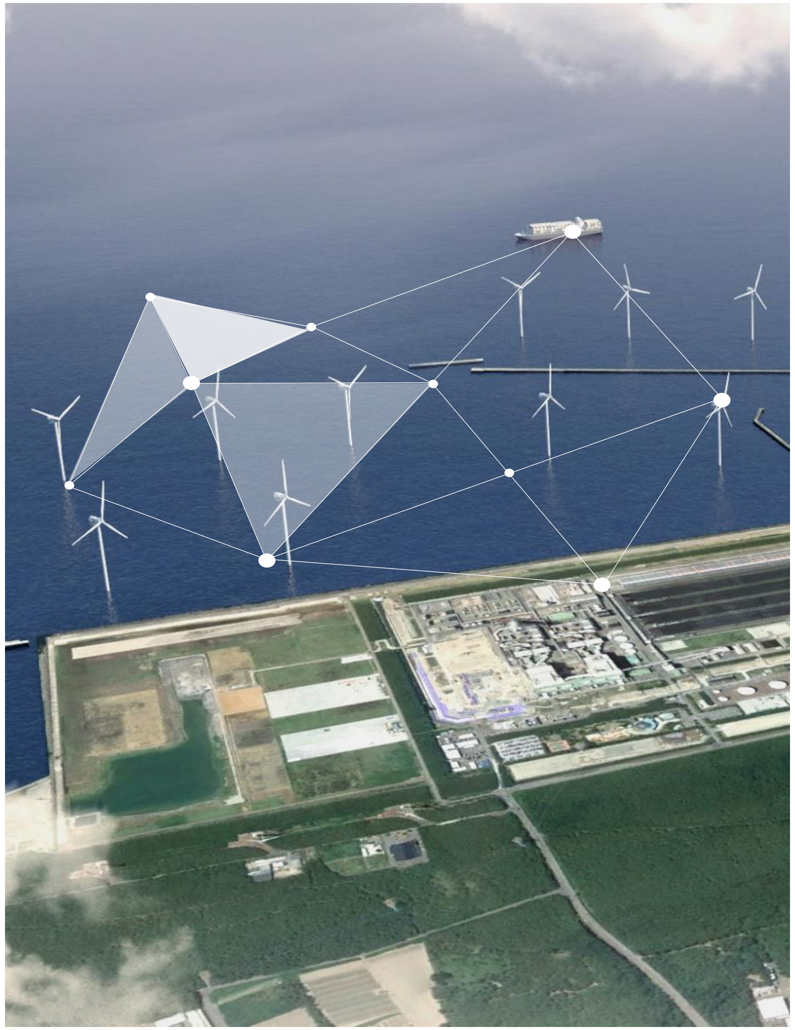
Automating Foundation Design

Rapid and accurate LCOE assessments

Optif couples Arup's expert knowledge and digital to provide a significant reduction in the time taken to evaluate designs, allowing repeatable, scalable results to improve end quality and safety.



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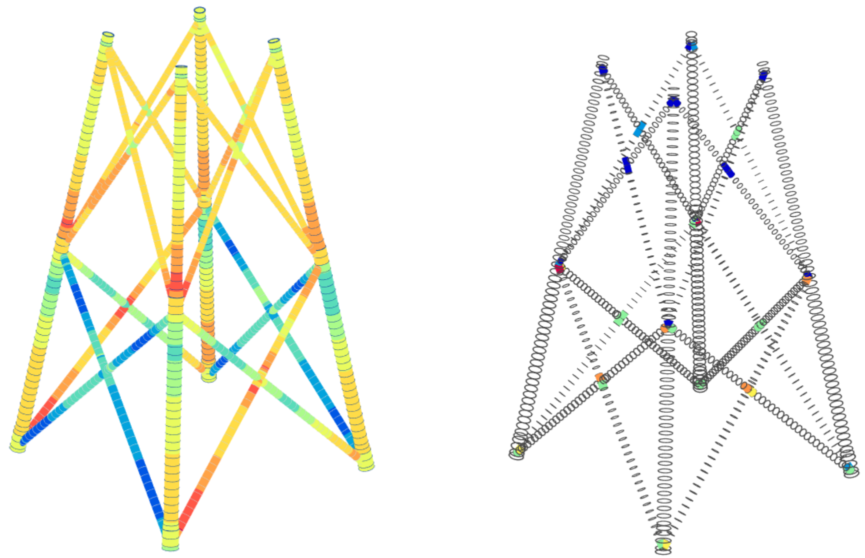
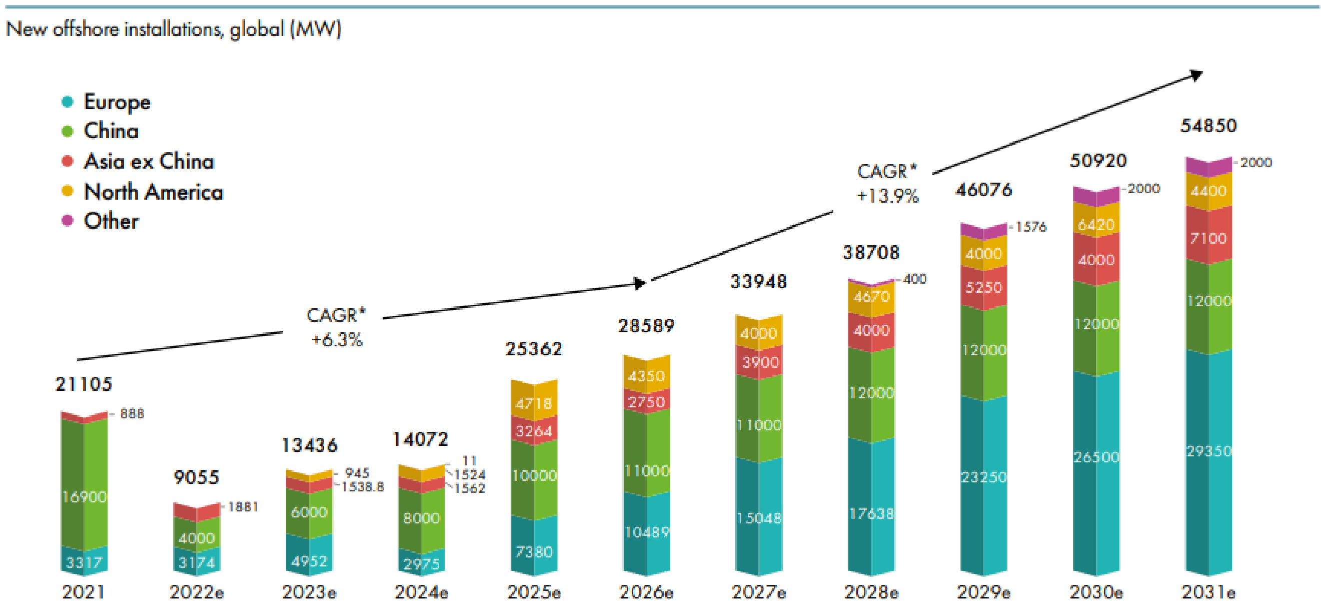
Design Tool Development

Why do we need a tool for foundation design?

- Growing global demand
- Complex analysis
- Well suited to automation
- ‘Off the shelf’ software not available to do what we want (and is expensive)
- Automation can embed best practices and analysis consistency across projects





Optif Solution

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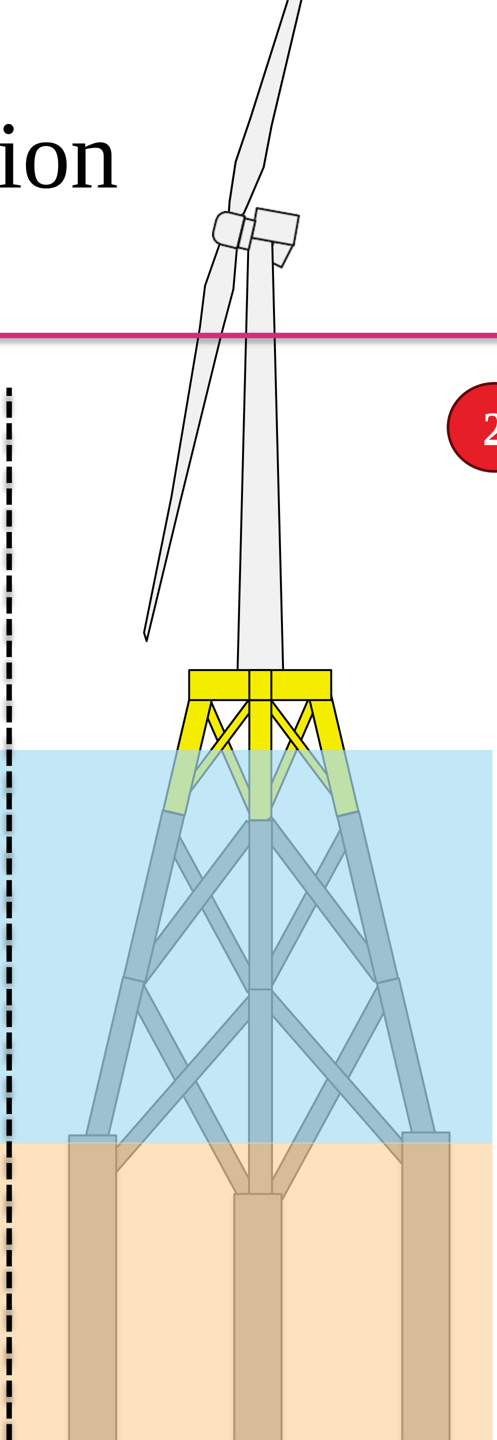
1 Design Scenario



1 Wind Turbine Loading

2 Wave Conditions

3 Water Depth

4 Soil Conditions

Iterate over required design scenarios

2 Design Solution

A. Top Leg Spacing

B. Number of legs
C. Number of bays
D. Leg Geometry
E. Brace Geometry

F. Bottom Leg Spacing

G. Pile Geometry

3 Iterate to find optimal solutions

Automated Workflow

Generate finite element model

Soil Structure Interaction

Check steel to design codes

Assess natural frequency

Calculate steel tonnage/CAPEX

Pass or fail

Optif Solution

Capabilities

Model – FEM + Hydro

- Parametric definitions of monopile and jacket structure

Loading

- Gravity, wind, wave and seismic loads considered

Analyses

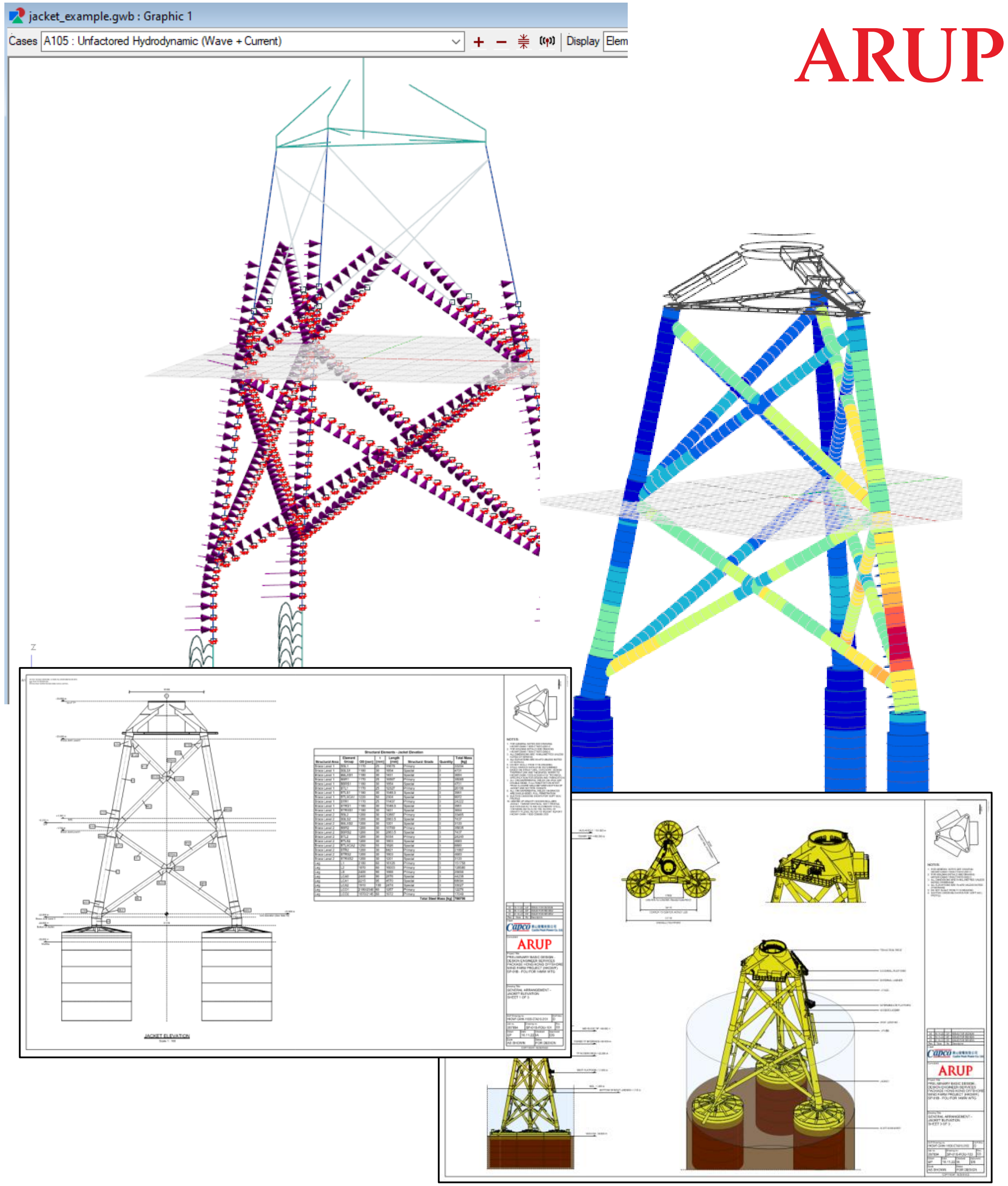
- Static, modal, soil-structure interaction (SSI), seismic and wave

Code Checking

- ULS – ISO19902 – tubular, conical and joint checks
- FLS - DNV-RP-C203 – weld and joint checks

Drawings

- Automated drawings from monopile/jacket parameterisations



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Soil Model Development

Soil models becoming more complex

Material models used in-house:

Simple model

[Linear elastic]

Mohr Coulomb

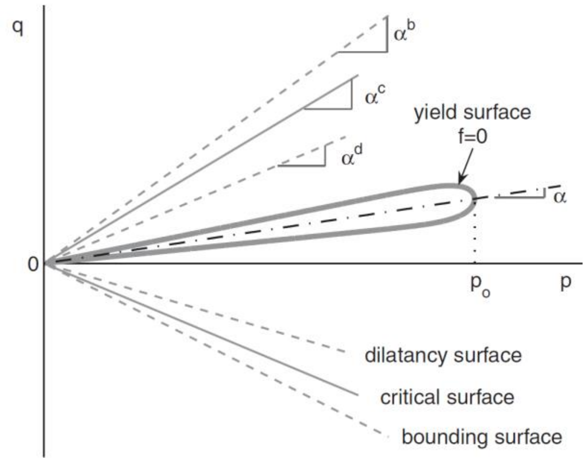
Brick Model

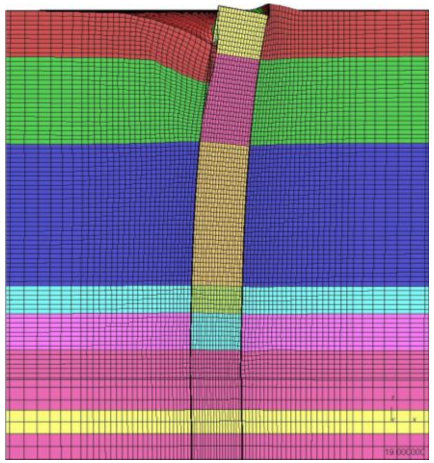
MAT-hysteretic

Nor-Sand

Sanisand LSDyna 3D

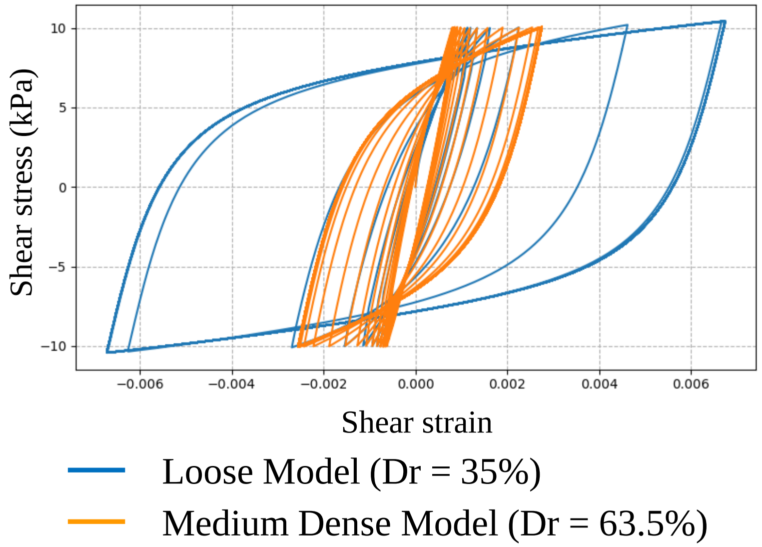
Advanced model

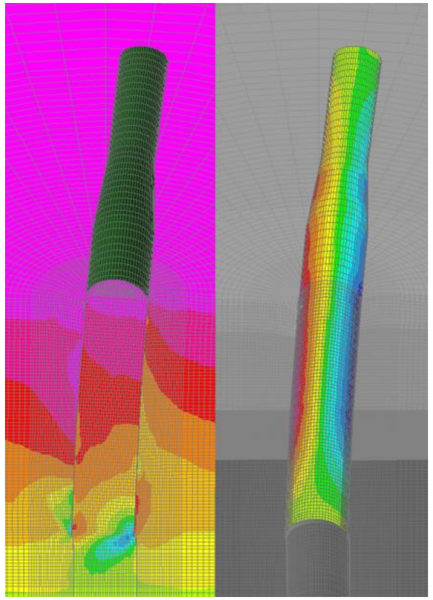




Model calibration:

- Drained/undrained monotonictriax tests
- Undrained cyc triaxial test





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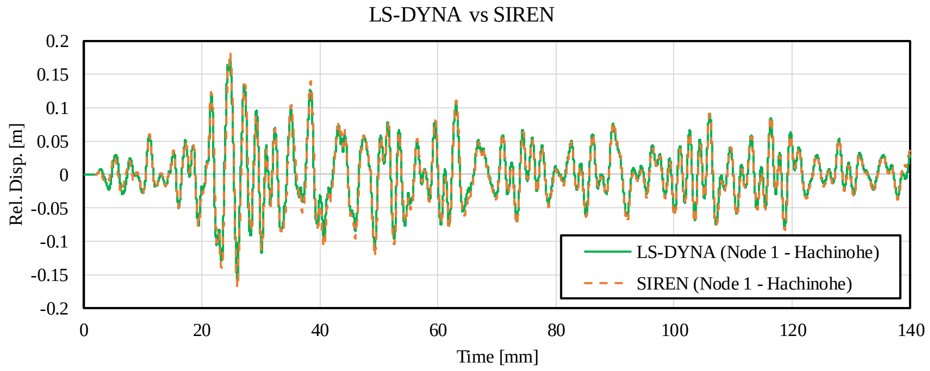
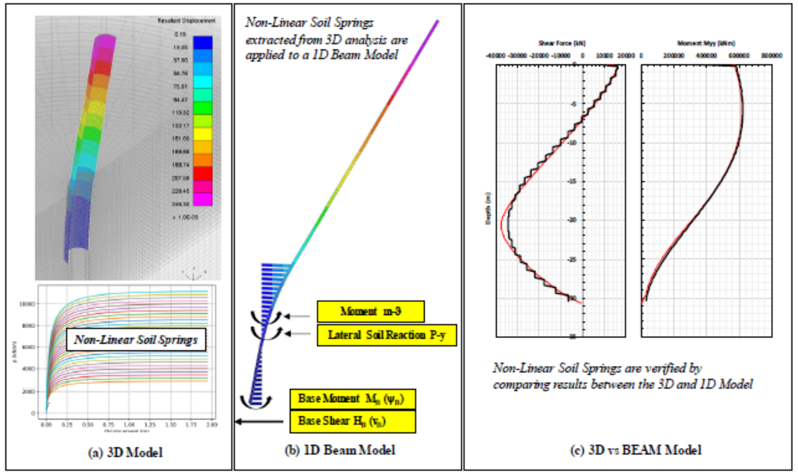
Site Response Analysis and Liquefaction Assessment

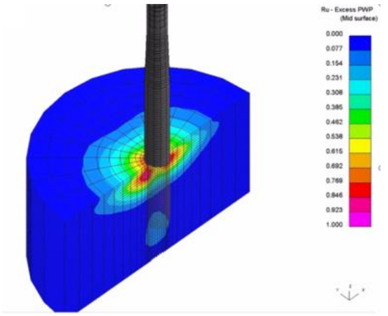
On-going Involvement

- Use in-house Oasys SIREN or LS-Dyna for site response analysis for
  - Develop site-specific response spectrum
  - Derive cyclic shear stress for site-specific liquefaction assessment
- Carry liquefaction assessment based on CPT and SPT GI data according to local code, Recommendations for Design of Building Foundations





(a) 3D Model (b) 1D Beam Model (c) 3D vs BEAM Model



Advanced Analysis and Parametric Studies

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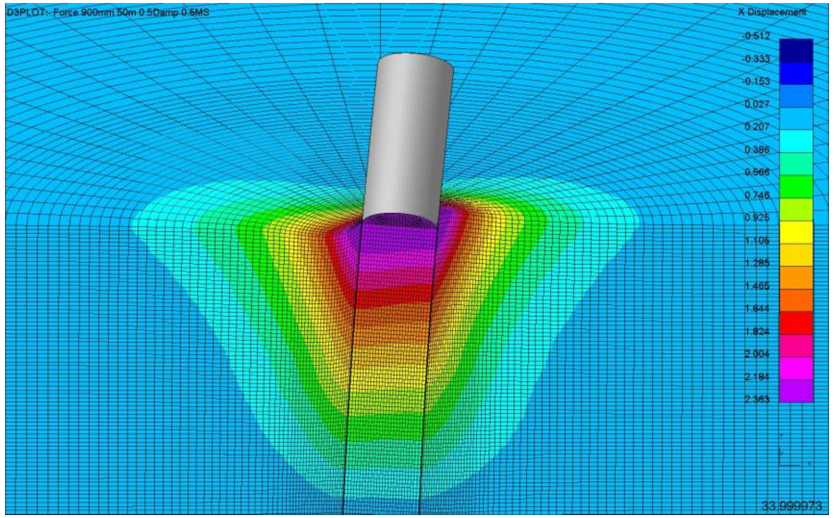
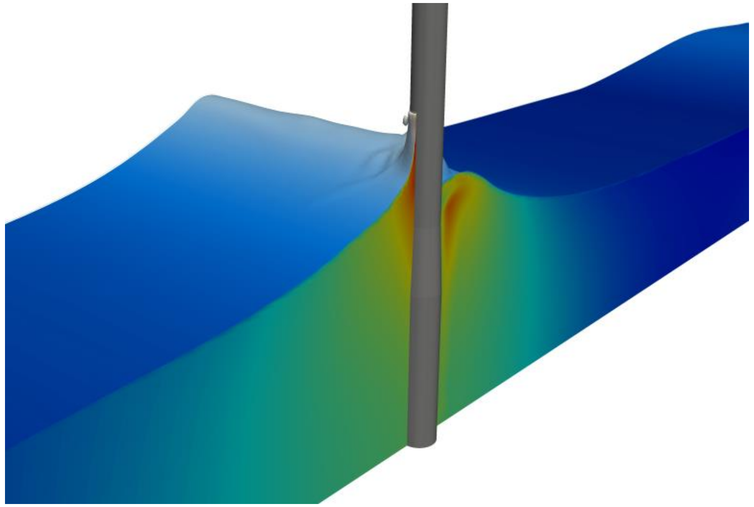
Computational methods employed for more detailed analysis

- Monopile remedial works – grouted and flanged connections
- Fatigue assessment and dynamic analysis
- BIM and integrated data models
- Automative design
- Scour Assessment & CFD modelling including ringing
- Decommissioning





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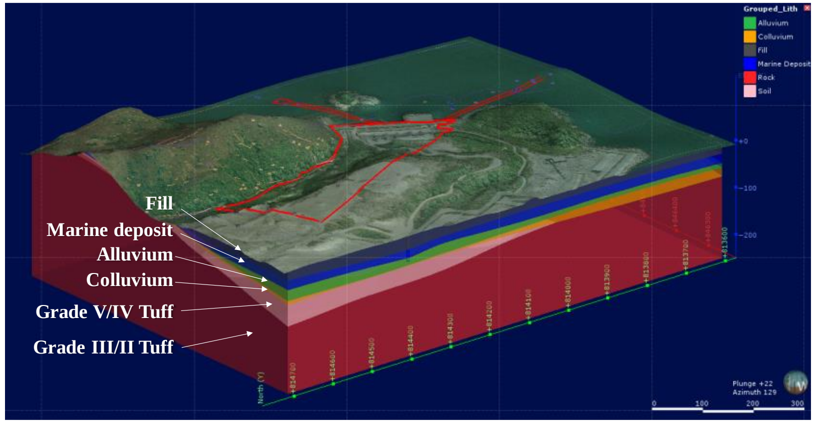
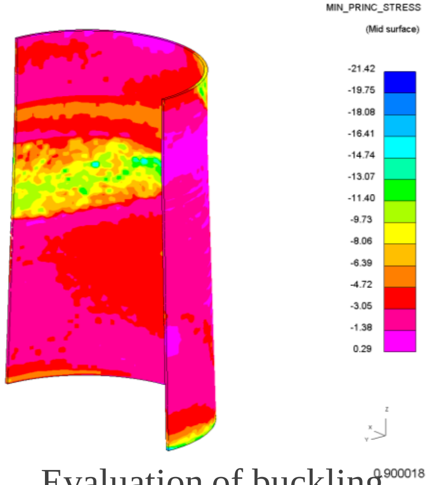
Advanced Numerical Analysis

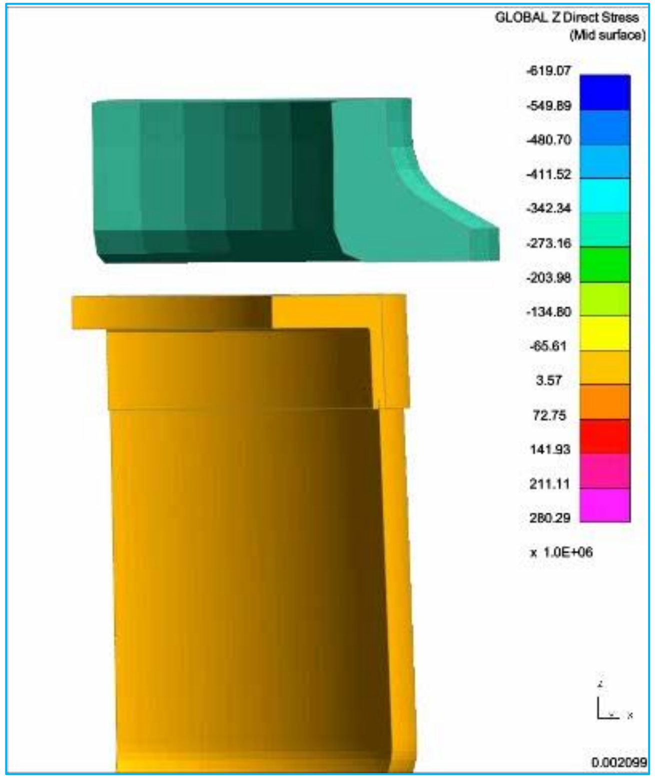
Examples of Advanced Engineering Analysis



3D Ground Model



Evaluation of buckling



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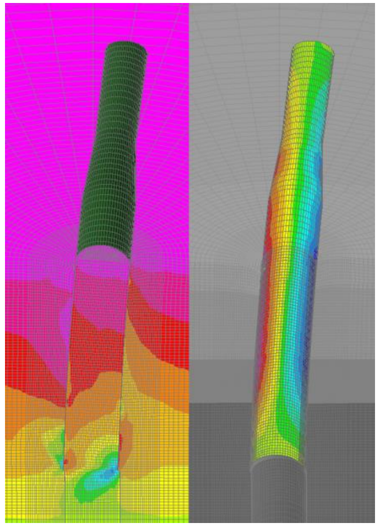
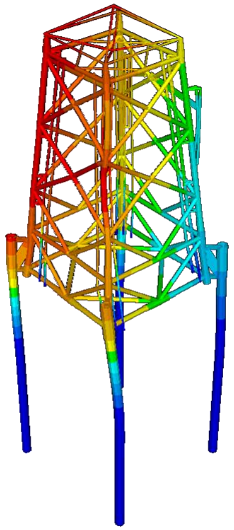


Soil Structure Interaction Analysis



Jacket

Hammering of monopile with flange connection in LS-DYNA

Effects of Wave Ringing

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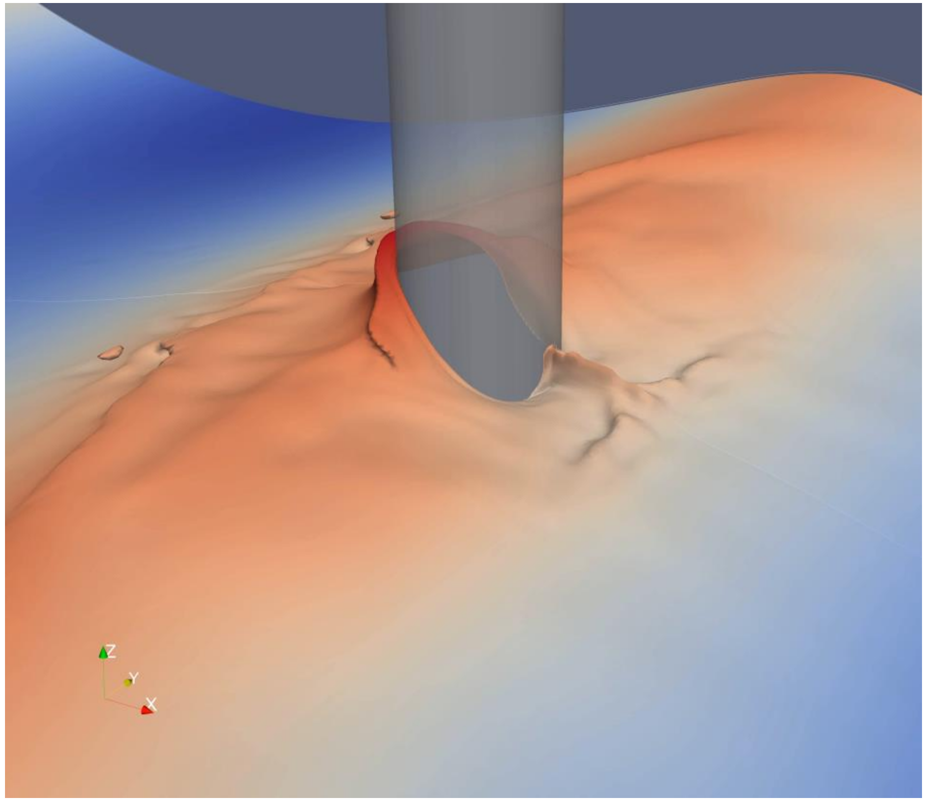
Wind Turbine Monopiles Becoming Vulnerable?

- “Pure” ringing is a result of wave scattering from the surface of the structure, resulting in a resonant excitation of the first bending mode.

- In practice, impulsive loads from wave slamming may act in combination to amplify the effect.

- A failure to consider dynamic structural response can result in significant under-prediction of extreme wave loads.

- Scale tests or computational fluid dynamics offers a solution



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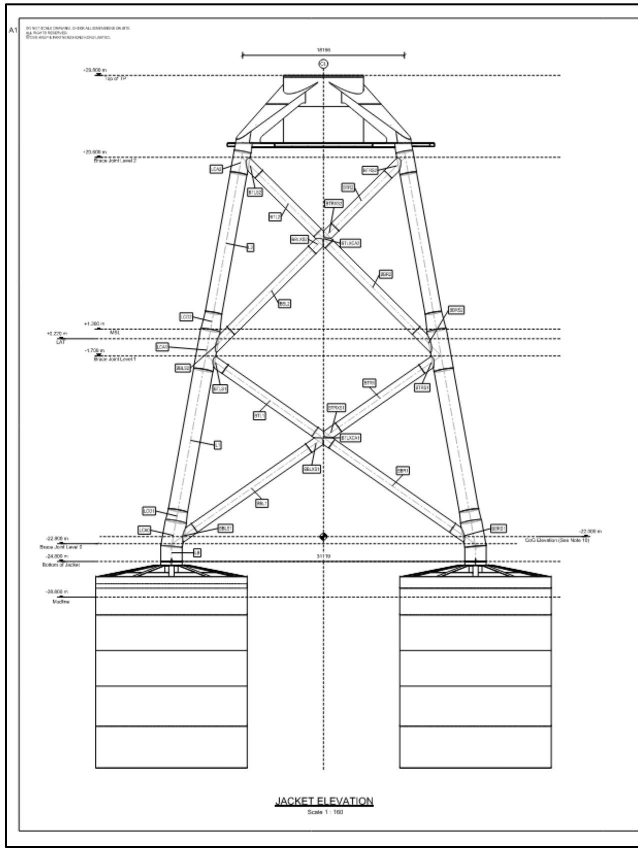
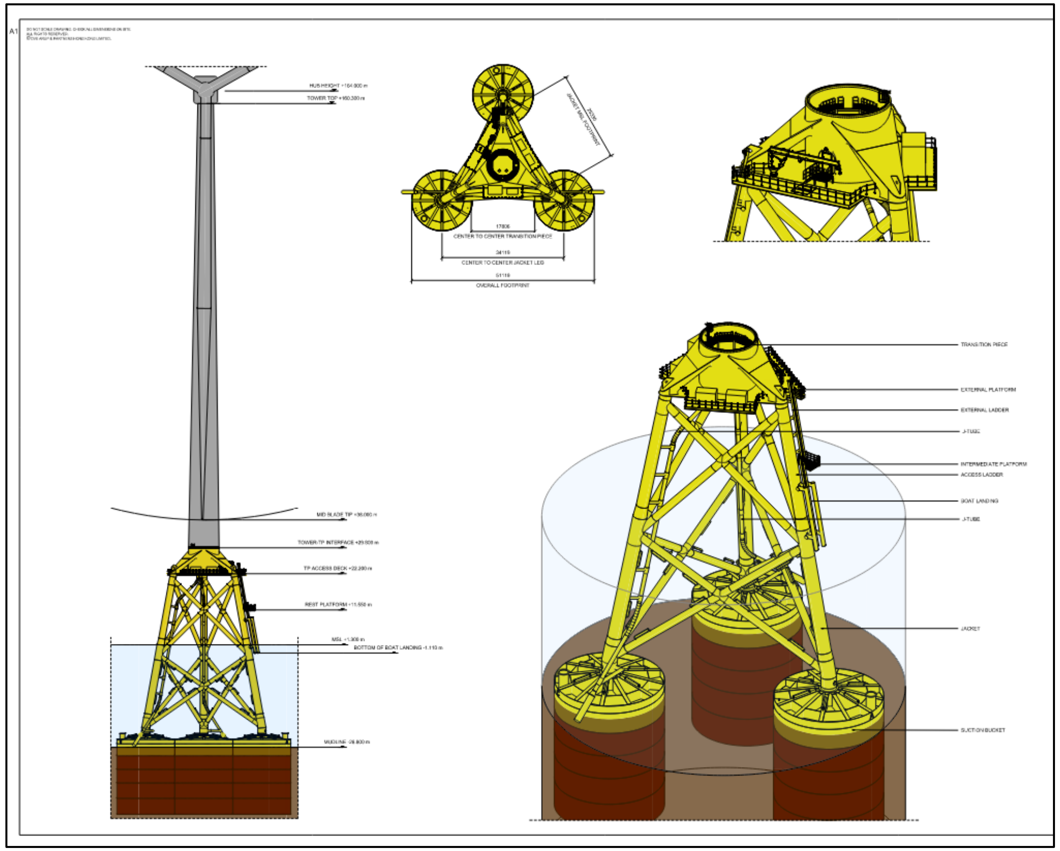
Sample Drawing Output

Suction Bucket Jacket



Structural Elements - Jacket Elevation							
Structural Area	Element Group	OD [mm]	t [mm]	Length [mm]	Structural Grade	Quantity	Total Mass [kg]
Brace Level 1	BBL1	1170	25	15678	Primary	3	33204
Brace Level 1	BBLS1	1180	30	1854	Special	3	4731
Brace Level 1	BBLXS1	1180	30	1431	Special	3	3654
Brace Level 1	BBR1	1170	25	16567	Primary	3	35085
Brace Level 1	BBRS1	1180	30	1854	Special	3	4731
Brace Level 1	BTL1	1170	25	12327	Primary	3	26106
Brace Level 1	BTLS1	1180	30	1548.5	Special	3	3961
Brace Level 1	BTLXCA1	1220	50	2304	Special	3	9972
Brace Level 1	BTR1	1170	25	11437	Primary	3	24222
Brace Level 1	BTRS1	1180	30	1548.5	Special	3	3961
Brace Level 1	BTRXS1	1180	30	1431	Special	3	3654
Brace Level 2	BBL2	1200	30	12887	Primary	3	33465
Brace Level 2	BBLS2	1200	30	2863.5	Special	3	7437
Brace Level 2	BBLXS2	1200	30	1201	Special	3	3120
Brace Level 2	BBR2	1200	30	13799	Primary	3	35835
Brace Level 2	BBRS2	1200	30	2863.5	Special	3	7437
Brace Level 2	BTL2	1200	30	9334	Primary	3	24240
Brace Level 2	BTLS2	1200	30	1803	Special	3	4683
Brace Level 2	BTLXCA2	1250	55	1826	Special	3	8880
Brace Level 2	BTR2	1200	30	8421	Primary	3	21867
Brace Level 2	BTRS2	1200	30	1803	Special	3	4683
Brace Level 2	BTRXS2	1200	30	1201	Special	3	3120
Leg	L1	2180	60	16126	Primary	3	151758
Leg	L2	1870	60	16003	Primary	3	128580
Leg	LB	2400	90	1668	Primary	3	25656
Leg	LCA0	2400	90	2876	Special	3	44238
Leg	LCA1	2215	95	4570	Special	3	68094
Leg	LCA2	1910	100	2474	Special	3	33027
Leg	LCO1	2180/2340	60	1257	Primary	3	12276
Leg	LCO2	1870/2145	60	1972	Primary	3	17049
						Total Steel Mass [kg]	788706



Life Extension & Asset Management

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5 to 10 yrs more asset life is pure revenue compared to original business models

- LEAP provides ongoing insight into the condition of foundations over their entire lifetime.
- It enables life extensions to be justified, providing significant value to asset owners and the offshore wind industry.

ARUP

A Full-Lifecycle Digital Twin Approach

Arup suite of digital tools developed to enhance design solutions

We've developed a data led approach to automating processes across the entire development lifecycle

Planning | Design | Construction | Operation & maintenance

SCALE
Deployment model

Virtual Engage
Stakeholder management

OPTIF
Optimised foundations

CONNECT
Construction data management

LEAP
Life extension & asset management

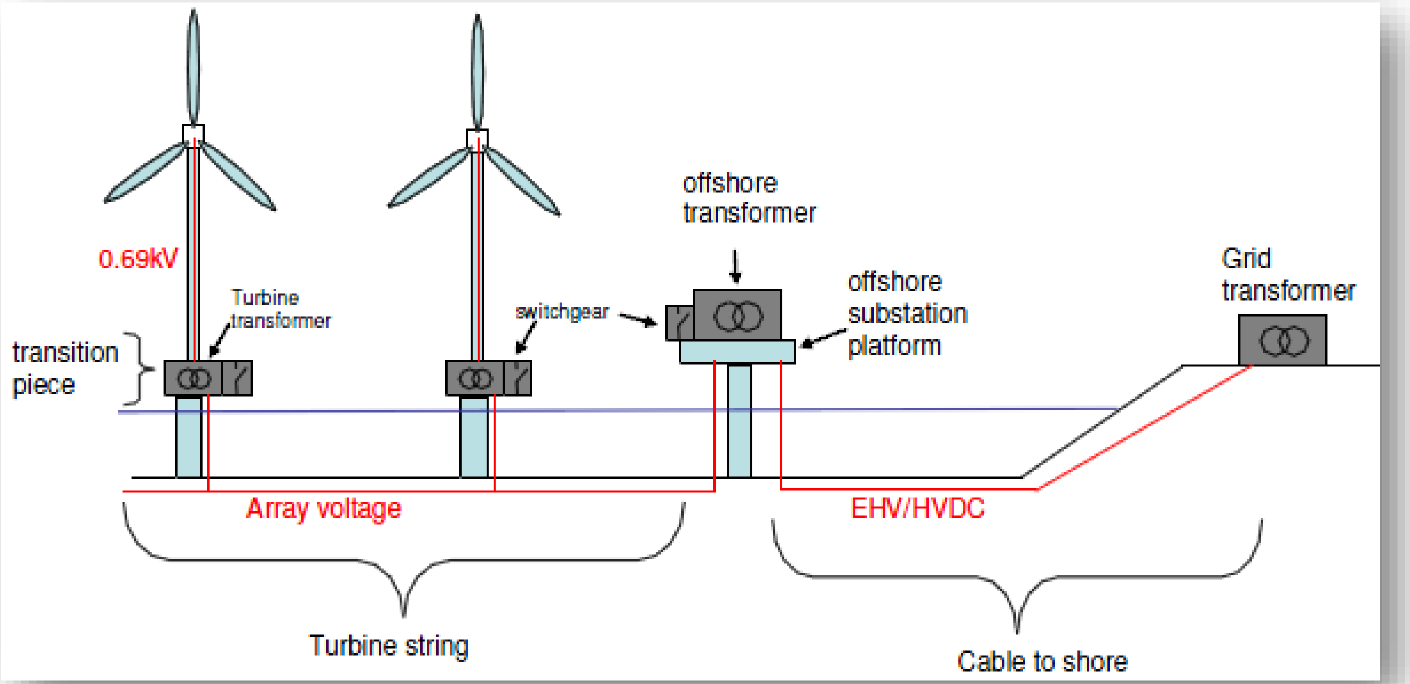
Arup Inspect
Digital inspections

Consistent data architecture

Cable Design

Inter-array Cable and Export Cable Study

- Cable Architecture
- Selection of Subsea Cable Routings
- Cable Laying Method and Landing Approach



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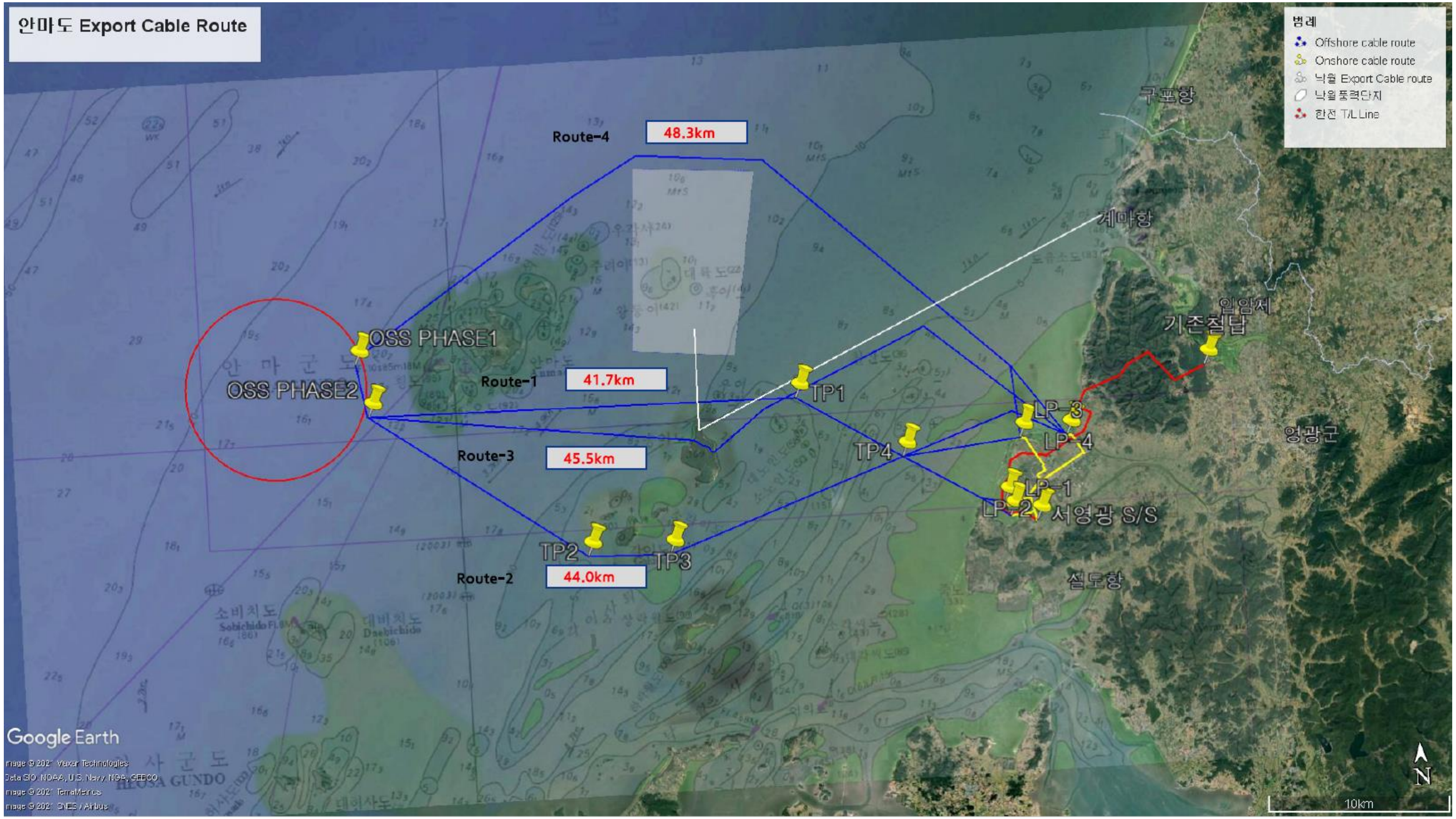
Selection of Subsea Cable Routings

Proposed Routes



Selection of Subsea Cable Routings

Proposed Export Cable Routes – Route 1 and Route 2

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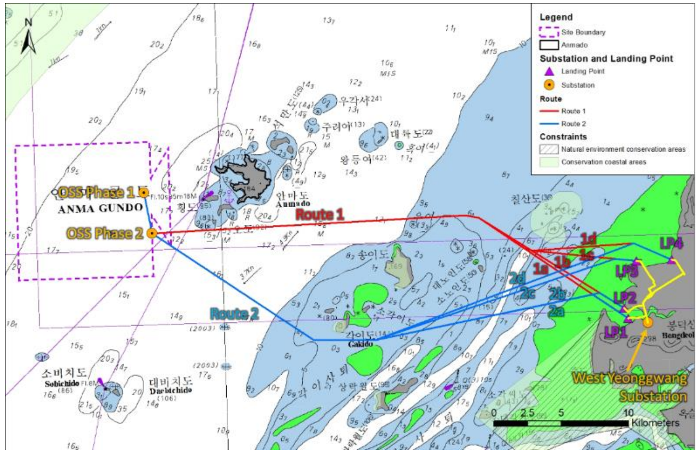
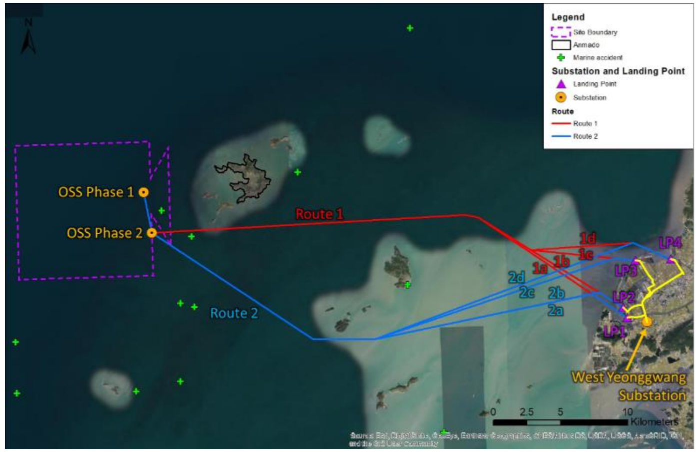
Selection of Subsea Cable Routings

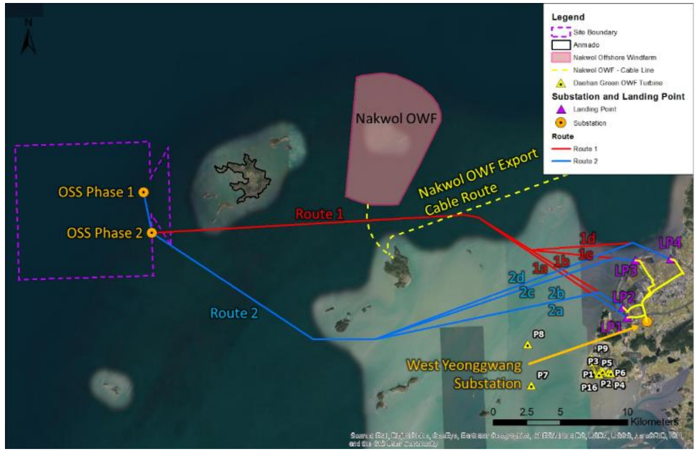
Consideration for Export Cable Routes – Route 1 and Route 2



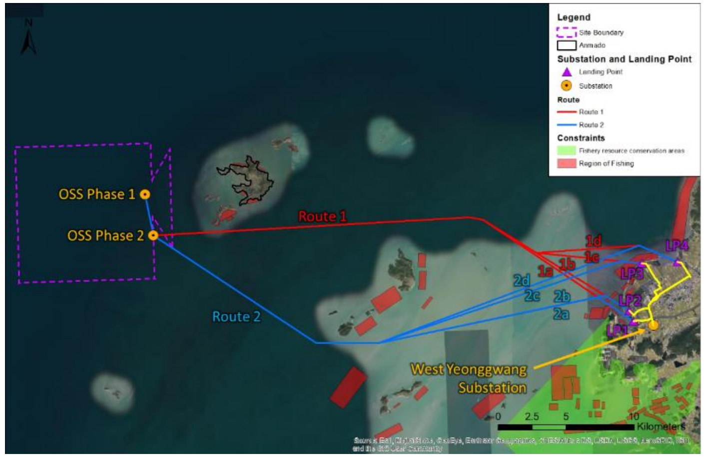
Bathymetry and Slopes



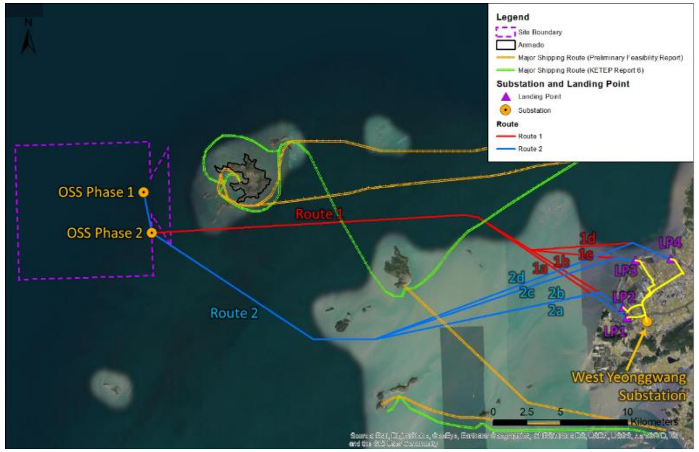
Marine Accident Investigations



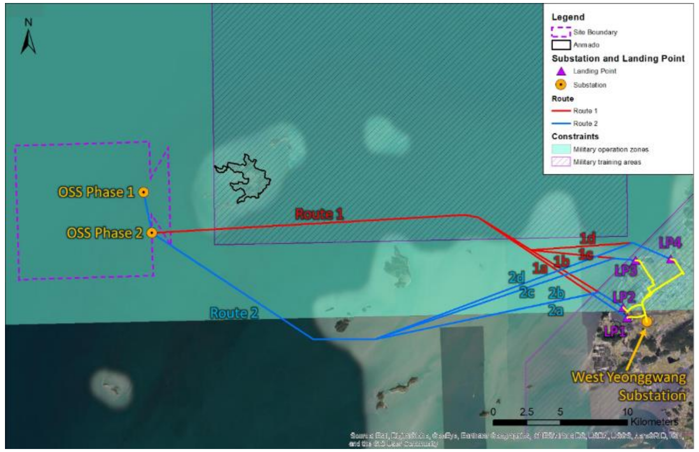
Other Offshore Windfarm Locations



Fishing Zones



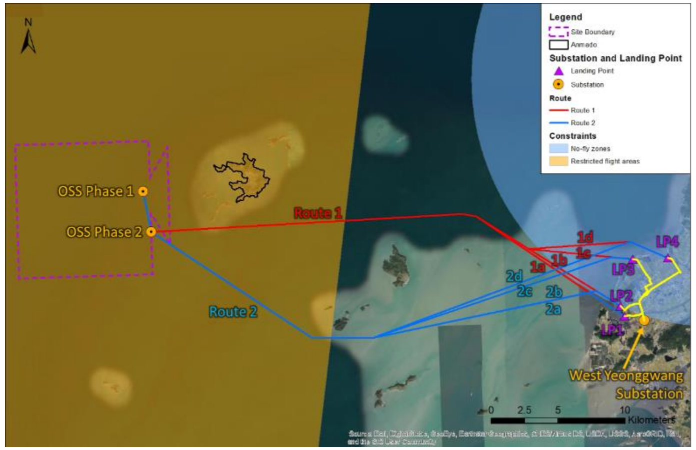
Shipping Routes



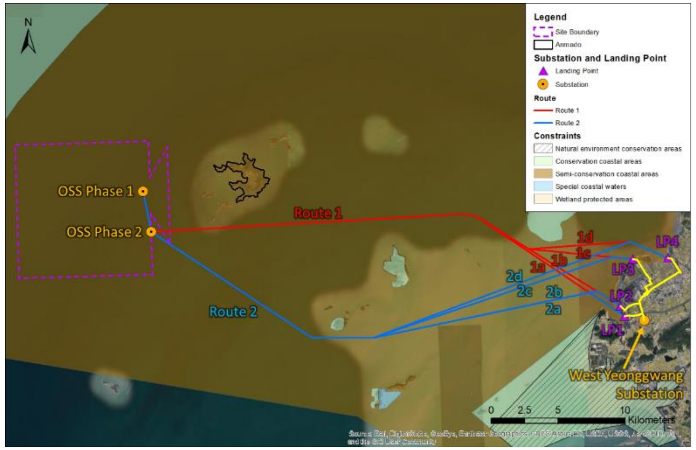
Military Zones

Selection of Subsea Cable Routings

Consideration for Export Cable Routes – Route 1 and Route 2



Flight Restricted Areas



Environmental Sensitive Areas

UNESCO World Heritage Sites

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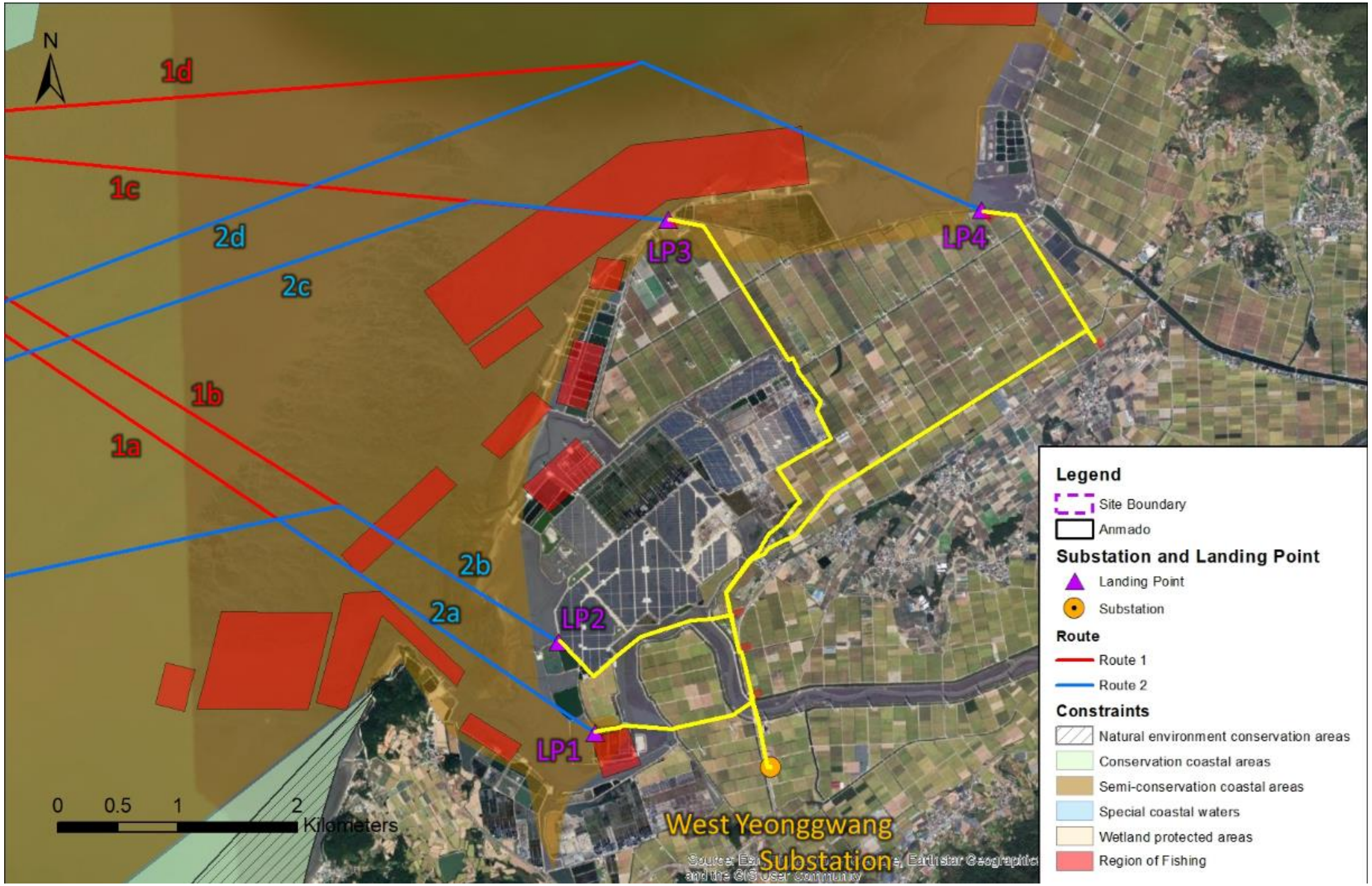
Selection of Subsea Cable Routings

Landing Points

- **Four Landing Points** are suggested after their site survey
- Onshore cables from landing points to Substation
- These routes overlap with a few fishing zones, and consequently compensation for fisheries would be necessary.



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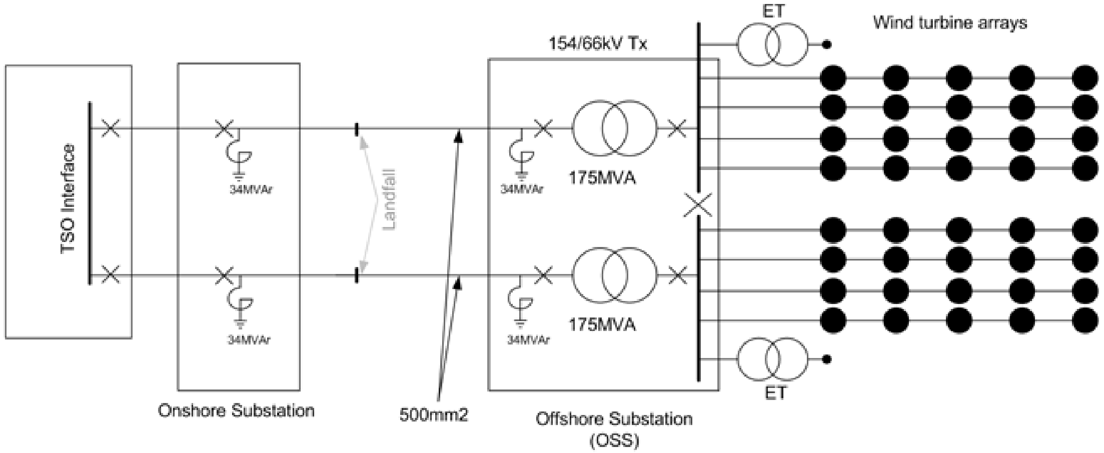
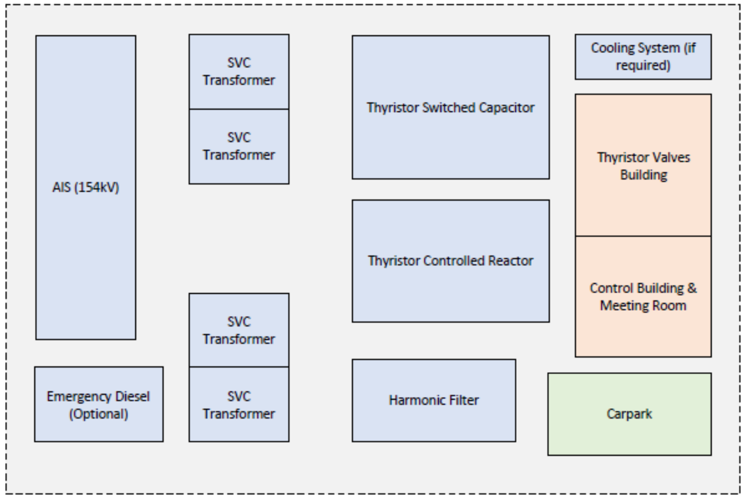
Substation and Cabling Design

Electrical Considerations

- Selection of Export Cable Voltage
- Cost Benefit Analysis
- Assessment of Substation Location
- Electrical Equipment Spatial Requirements



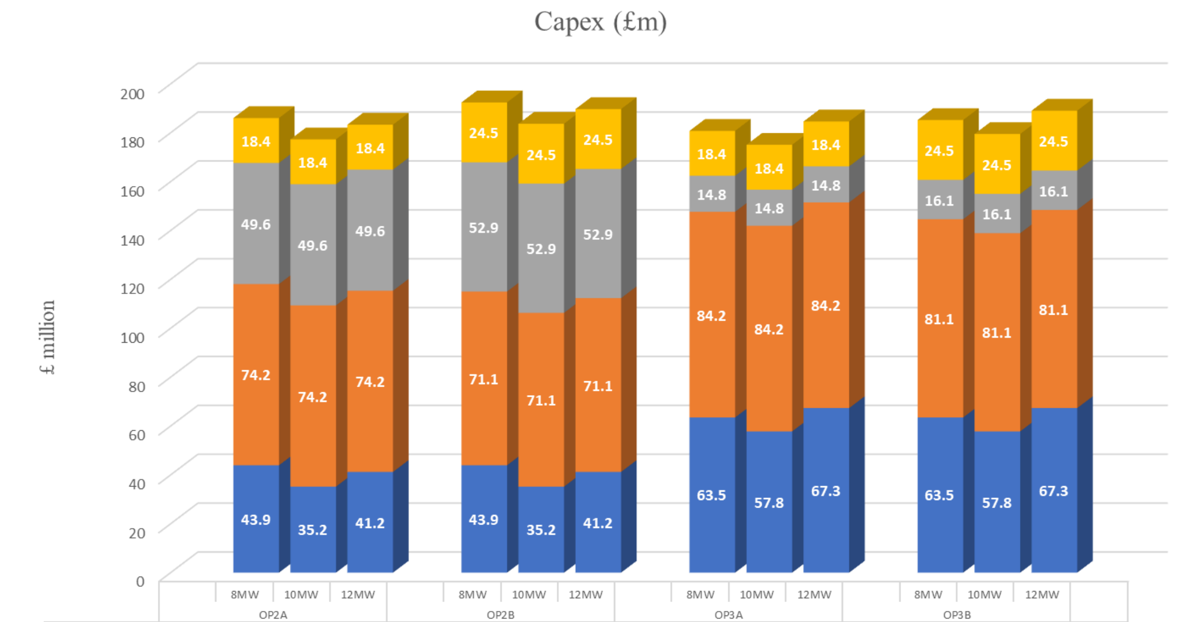
Single Line Diagram



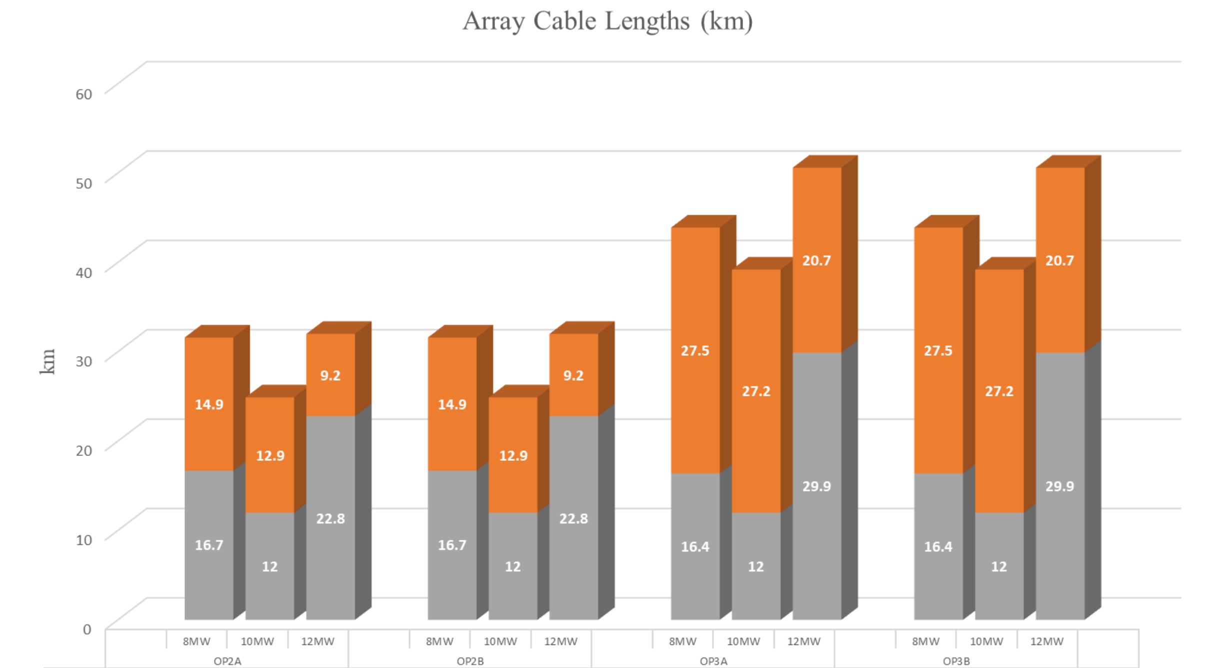
Onshore Substation Layout

Cable Design

Cost Benefit Analysis

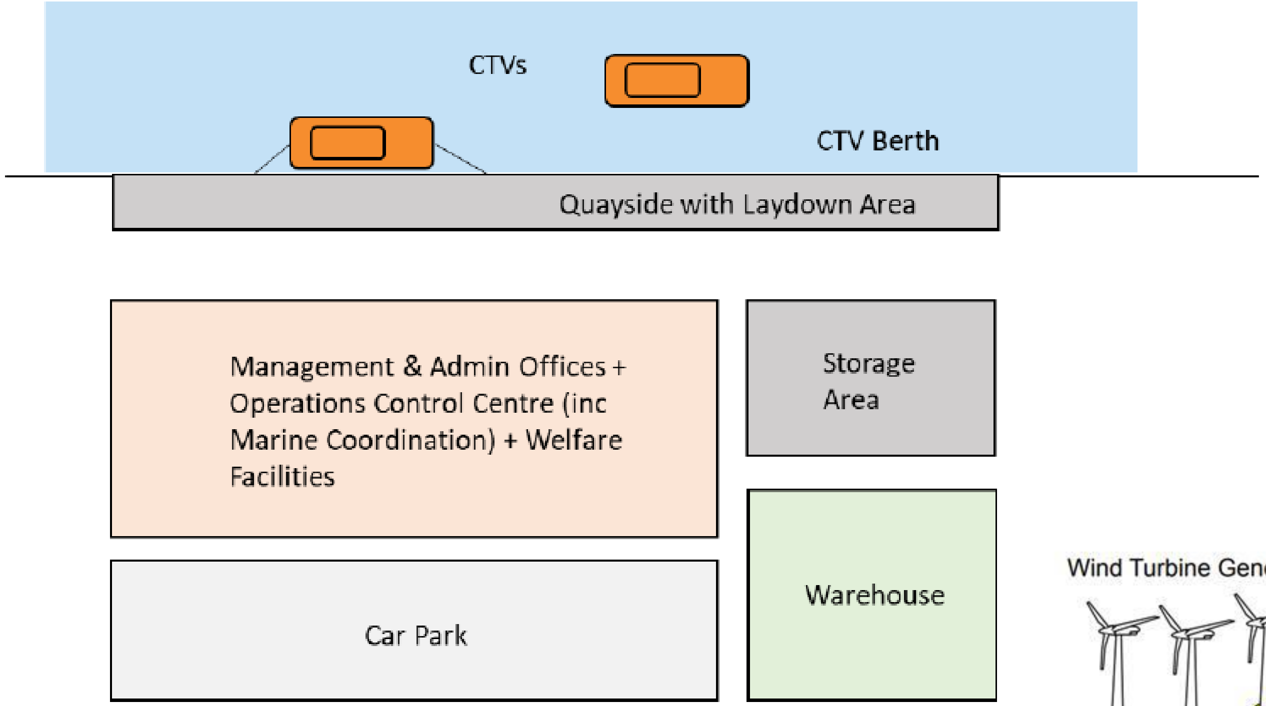


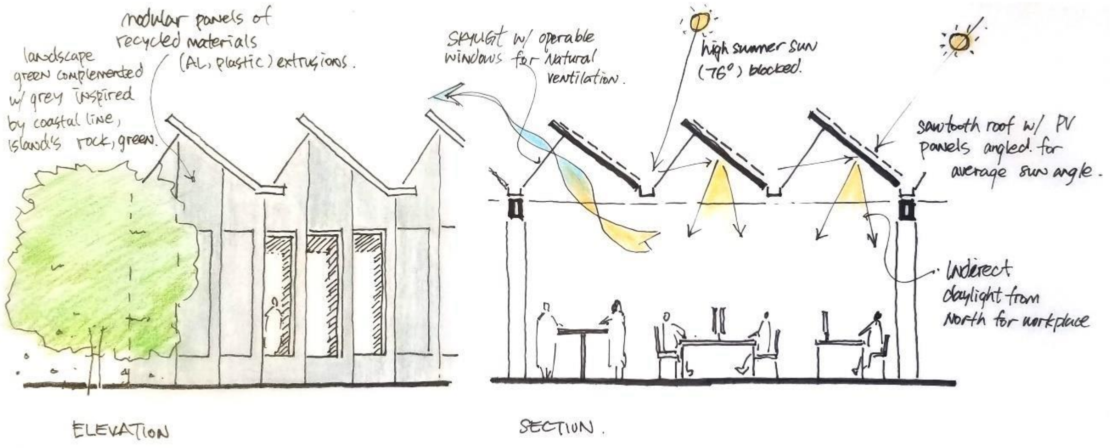
	OP2A 8MW	OP2A 10MW	OP2A 12MW	OP2B 8MW	OP2B 10MW	OP2B 12MW	OP3A 8MW	OP3A 10MW	OP3A 12MW	OP3B 8MW	OP3B 10MW	OP3B 12MW
Total	186.0	177.3	183.3	192.4	183.7	189.7	180.8	175.1	184.6	185.2	179.5	189.0
Onshore Sub	18.4	18.4	18.4	24.5	24.5	24.5	18.4	18.4	18.4	24.5	24.5	24.5
Offshore Sub	49.6	49.6	49.6	52.9	52.9	52.9	14.8	14.8	14.8	16.1	16.1	16.1
Transmission Cable	74.2	74.2	74.2	71.1	71.1	71.1	84.2	84.2	84.2	81.1	81.1	81.1
Array Cable	43.9	35.2	41.2	43.9	35.2	41.2	63.5	57.8	67.3	63.5	57.8	67.3

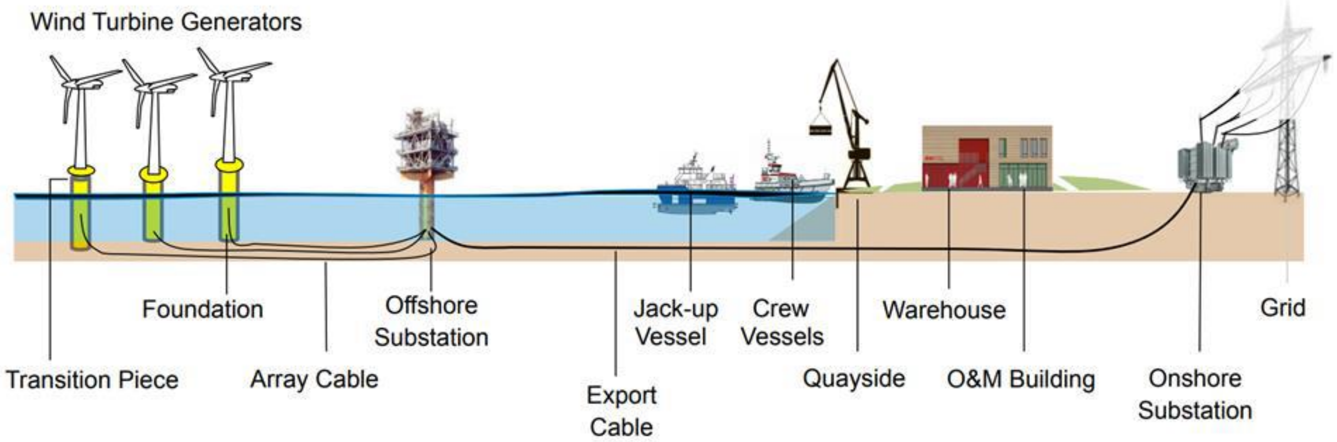


	OP2A 8MW	OP2A 10MW	OP2A 12MW	OP2B 8MW	OP2B 10MW	OP2B 12MW	OP3A 8MW	OP3A 10MW	OP3A 12MW	OP3B 8MW	OP3B 10MW	OP3B 12MW
Total	31.6	24.9	32	31.6	24.9	32	43.9	39.2	50.6	43.9	39.2	50.6
800mm2	14.9	12.9	9.2	14.9	12.9	9.2	27.5	27.2	20.7	27.5	27.2	20.7
240mm2	16.7	12	22.8	16.7	12	22.8	16.4	12	29.9	16.4	12	29.9

Operation & Maintenance Base Design







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Supporting Clients in a Changing Industry

Enhancing design through digital solutions

Accelerating deployment through digital

We've developed a data led approach - automating processes across the entire development lifecycle to enhance project outcomes.

Unlocking design solutions

Exploring the future of offshore wind infrastructure, we're designing for each unique site location and local market conditions.

Navigating future markets

Supporting clients to enter new markets - from developing business models to investor funding for infrastructure and developing supply chain relationships.

Managing and extending assets

Working to enhance the lifetime extension – our digital approach enhances return on investment of an asset, whether the development is being sold as an investment or maintained.

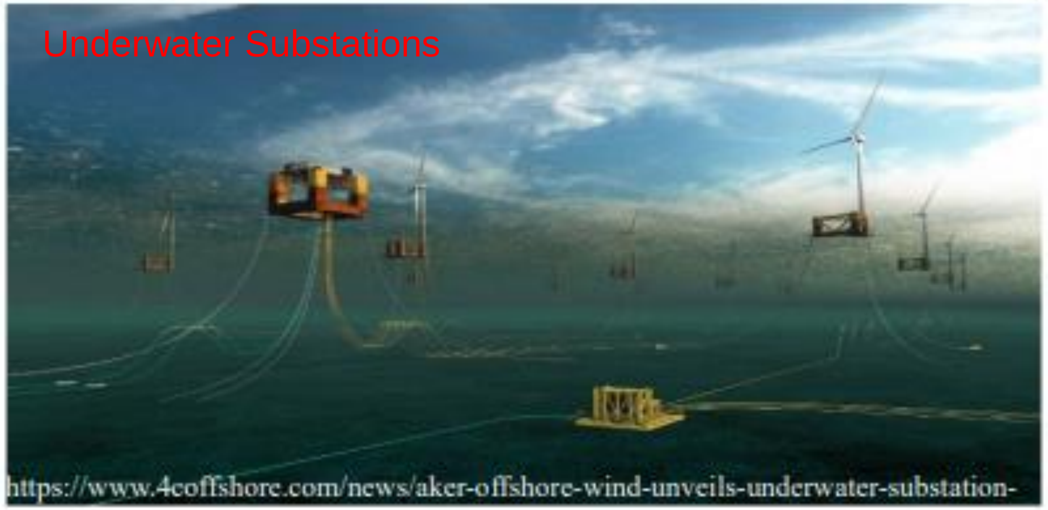
Digital Future

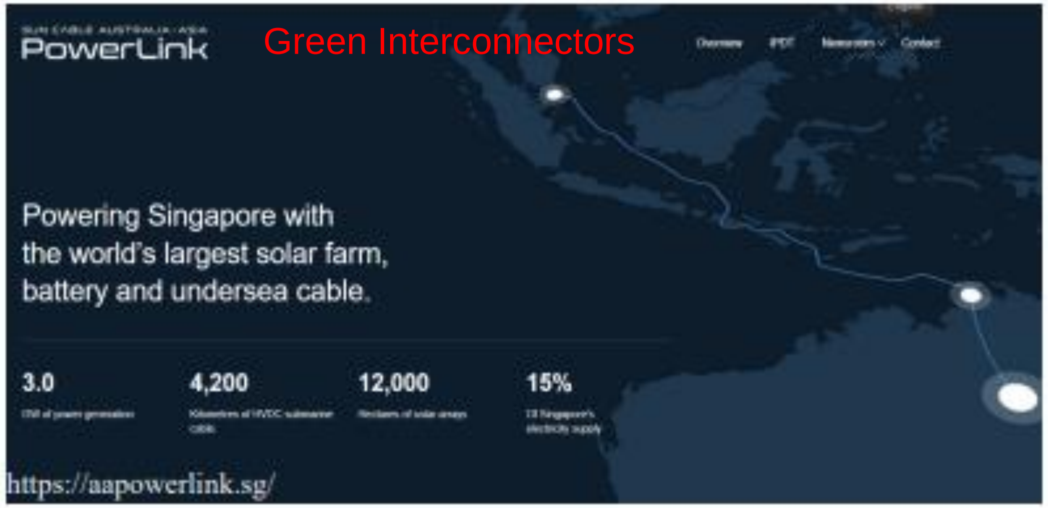
Enhancing design through digital solutions

- Digital technologies are transforming projects across a wide range of industries and sectors.
- Digital innovation is the only way to achieve success in deploying offshore wind at the scale that is needed to mitigate climate change

What’s Next

Future Developments for Offshore Wind





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