Windpower and Ecotechnology
HSLU, Intensive week

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Last update: February 5, 2025

Contents

Part I

Environmental Impact Assessment

1 Environmental benefits vs. environmental impact

1.1 Environmental benefit

Benefits of windpower:

- Zero-emissions energy;
- Manutention between 10 and 20 years;
- Energy produced by wind is normally always available and free;
- Relative quick building;
- Gains in environmental (natural) services or ecological properties by certain actions.

1.2 Environmental impact

Energy sector in general:

- Energy sector as a whole is rated to have negative influence on the environment;
- Various processes involved in the energy chain generate environmental stress;
- Energy chain: Raw materials procurement → Conversion to energy/electricity → Energy/electricity use;
- Main pollutants causing environmental stress are:
  - Airborne emissions (PM and gaseous);
  - GHGs;
  - Liquid waste discharges on water and soil;
  - Solid waste;
- Not all energy sources have the same environmental impact or natural resource depletion capability;
- How to quantify/rate environmental impacts/benefits on ecosystem?
  → Environmental benefits are mainly expressed in terms of avoided environmental impacts (e.g.: gains in environmental services or ecological properties attained by using e.g. wind power)

2 Environmental impact assessment (EIA)

- Identification and qualification of impacts on ecosystems;
- Detection and reduction of environmental impacts within entire lifetime of energy systems;
- EIA should allow to compare different energy sources.

2.1 Field of use

EIA is used as a planning procedure or decision-making instrument:

- Planning procedure:
- Decision-making instrument:

EIA can help to achieve:

- 1
- 2
- 3
- 4

2.2 Definition

EIA is the formal process for:

- Identifying likely impacts (effects) of activities (projects) on the environment, human health, and economy;
- Identifying measures to mitigate and monitor these impacts.

3 Impact

3.1 Definitions

3.1.1 Impact

Impact is the deviation (change) from the baseline situation that is caused by the activity
→ Impacts can only be quantified knowing the baseline situation.

3.1.2 Baseline situation

The baseline situation is the existing environmental condition, in absence of activity.

Baseline situation is not a simple snapshot, thus natural variability and current trends need to be considered.

3.1.3 Environmental components

Various environmental components may be of interest to characterize the baseline situation:

- Water (quality, quantity, use, accessibility, ...);
- Soil (nutrient concentration, crop productivity, erosion, salinity, ...);
- Biodiversity (flora and fauna, populations, habitat, ...);
- Environmental health (existing diseases, pathogens, ...);
- Special ecosystems (key species, endangered species).

3.2 Types of impacts

EIA doesn't treat all impacts equally:
→ Focus is set on the most significant impacts which might change project outline/direction.

Some types of impacts:

- Direct vs indirect impacts:
  - Direct: What wind power plants do to the nearby environment (e.g.: noise pollution);
  - Indirect: What wind power plants do to the planet;
- Short-term vs long-term impacts;
- Adverse vs beneficial impacts;
- Cumulative impacts (synergistic effects).

3.3 Impact measure units

Impacts can be measured in numerous ways:

- Intensity (e.g.: ppm, Hertz, Watt, ...);
- Probability (occurrence);
- Spatial extent (magnitude);
- Duration:
  - 1
  - 2
  - 3

    - 4
- Reversibility.

3.4 Application fields

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4 Benefits of implementing EIA in project

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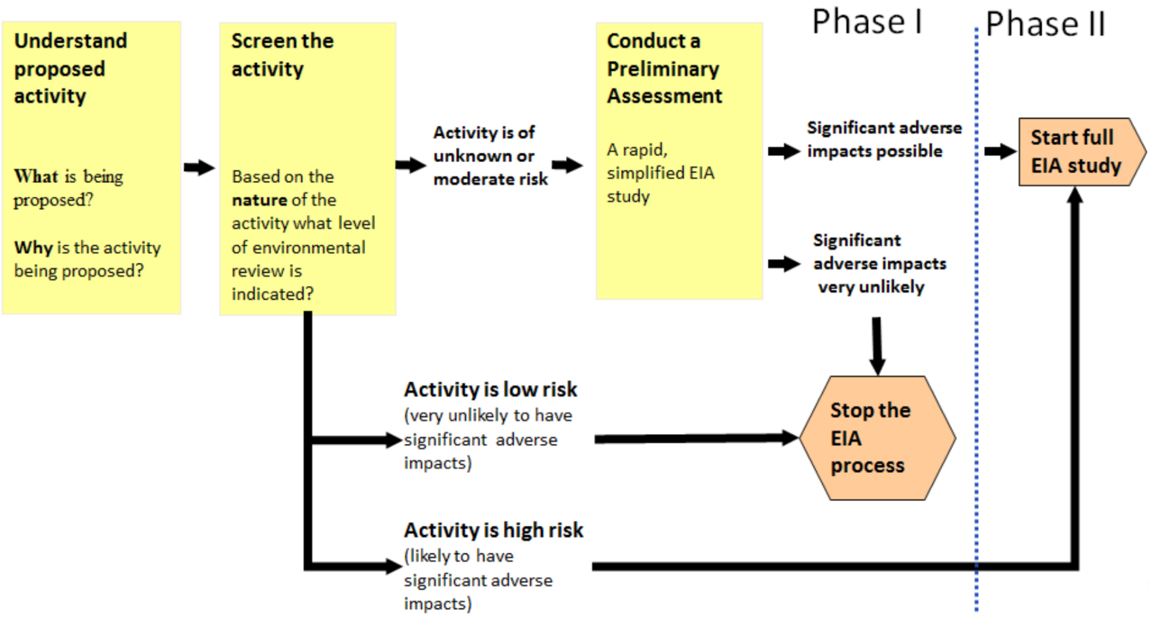
5 EIA process



5.1 Phase I - Initial inquiries

5.1.1 Understand proposed activity

1. EIA processes begin with understanding why an activity is proposed:
    - Answer requires definition of development objective (D.O.);
    - Understanding D.O. allows to identify environmentally sound alternatives.

   D.O. example:
    - Building a road → NOT a D.O.
    - Increasing access to a certain area → D.O.
2. Understanding what is being proposed including associated actions:
    - Primary activity (e.g.: construction of a road);
    - Associated actions (e.g.: clearing of forest, soil drainage, ...).

5.1.2 Screen the activity

Part II

Environmental impacts - onshore

6 Stakeholders analysis

6.1 Definition

SA is a methodology used to "facilitate institutional and policy reform processes by accounting for and often incorporating the needs of those who have a "stake" or an interest in the reforms under consideration" (World Bank)

SA is "a tool for assessing different interest groups around a policy issue or intervention, and their ability to influence the final outcome" (FAO)

SA is applied to identify and sort stakeholders that are likely to affect or be affected by a proposed action (e.g. project), according to their impact and the impact the action might have on them

6.2 Goals

1. Development of a strategic view of the human and istitutional landscape:
   - Including the relationships between different stakeholders;
   - Issues different stakeholders care about most;
2. SA can help a project to identify:
   - Interests of all stakeholders who may affect or be affected by the project;
   - Potential conflicts or risks that could jeopardise the project;
   - Opportunities and relationships that can be built on during implementation;
   - Appropriate strategies and approaches for stakeholders engagement;
   - Ways to reduce negative impacts on vulnerable and disadvantaged groups;
3. Stakeholders partecipation:
   - It's essential for sustainability;
   - Generates a sense of ownership.

6.3 Implementation

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6.4 Development

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6.5 Identifying key stakeholders and their interests

Key questions of initial identification stage:

- Who is most dependent on the resources at stake and for what reason (economically, ecologically, ...);
- Are these resources replacable by other resources?;
- Who possesses legal claims?
- Are several government/ministry departments involved?
- Are there national and/or international bodies involved?
- Are the stakeholders and their interests geographically and seasonally stable?
- Are the major events or trends currently affecting the stakeholders? (e.g.: development initiatives, migration, population growth);

- Has there been done a similar project within that region?

SA always starts with brainstorming all possible stakeholders.

6.6 Assessing influence/impact of each stakeholder

Key questions for second step:

- ...

6.6.1 Influence/impact analysis

Influence/impact analysis can be done using SA matrix:

Conduct a Stakeholder Analysis based on the given information

1. Identify the main stakeholders of the above-described offshore wind park project

   a) What are the main bodies and administrative organizations (e.g. ministry) which have responsibilities or competences for the area and the activities that might be affected by the construction of a wind farm?

   R:

   - MITECO (Ministry of EcoTrans and Demological Challenge)
   - General Directorate for Coast and Sea
   - Regional and local governments
   - Ministry of Agriculture, fishing, food
   - European Union
   - Ministry of Tourism / Industry / Commerce

   b) Which stakeholders will have influence on the project?

   R:

   - Hotel owners
   - Tourism
   - Fishers lobby
   - NGO's (WWF, REDS, Green Peace)
   - Public communities participation
   - Investors
   - Media
   - ((National) Energy providers)

   c) Which economic activities might potentially be affected by the construction of an offshore wind farm and which associations represent them?

   R:

   - Agriculture → Fishing
   - FNCP (National Federation of Fisherman's Guild)
   - Apromar
   - Tourism spanish confederation of Hotel owners
   - Transport spanish maritime cluster
   - Internal chamber of shippings
   - (Telecom activities (cables/servers))

2. Interest of stakeholders

   a) State the main interest for each stakeholder in a table

   R:

3. Identify influence / impact for each stakeholder and assign the appropriate strategy to engage stakeholder

Table 1: Stakeholder Analysis

Stakeholder	Interests and Concerns
MITECO (Ministry for the Ecological Transition and Demographic Challenge)	- Advancing renewable energy projects to meet climate goals.
	- Ensuring compliance with environmental regulations and biodiversity protection.
Ministry of Transport, Mobility, and Urban Agenda	- Ensuring maritime safety and minimal disruption to shipping routes.
	- Regulating offshore infrastructure to maintain navigational efficiency.
Ministry of Heritage (Cultural and Natural Heritage Protection)	- Protecting coastal landscapes and cultural heritage sites.
	- Evaluating potential impacts on marine ecosystems and historical landmarks.
Regional Government Body (Junta de Andalucía)	- Balancing economic growth (tourism, fishing, and renewable energy).
	- Addressing concerns of local communities and businesses.
European Union (EU)	- Promoting offshore wind energy under the European Green Deal.
	- Ensuring compliance with EU environmental and maritime regulations.
Ministry of Tourism	- Protecting the visual and economic appeal of coastal tourism.
	- Addressing hotel and tourism sector concerns regarding the wind farms impact.
Hotel Owners Association	- Maintaining an attractive coastal environment to sustain tourism.
	- Avoiding potential economic losses due to wind farm-related changes.
FNCP (National Federation of Fishermens Guilds)	- Protecting fishing grounds and tuna migration routes.
	- Ensuring fishing communities' economic viability and long-term sustainability.
International Chamber of Shipping (ICS)	- Ensuring international shipping routes remain uninterrupted.
	- Advocating for safe and efficient maritime transport infrastructure.
Local Communities	- Ensuring economic opportunities and job security.
	- Addressing concerns related to environmental impacts and quality of life.
Investors (Wind Energy Companies & Financial Backers)	- Securing profitability and financial returns on the wind farm project.
	- Mitigating regulatory and environmental risks that could delay construction.

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Stakeholder	Interests and Concerns
National Energy Provider	- Integrating offshore wind energy into the national grid.
	- Ensuring energy reliability and efficiency in distribution.
Ministry of Agriculture and Fishing	- Protecting marine biodiversity and sustainable fishing practices.
	- Assessing the potential effects of wind farms on fisheries and aquaculture.
	Engagement Methods
MITECO (Ministry for the Ecological Transition and Demographic Challenge)	- Official project proposal submission with an Environmental Impact Assessment (EIA).
	- Formal meetings and consultations with key officials.
Ministry of Transport, Mobility, and Urban Agenda	- Direct engagement through maritime regulatory bodies.
	- Joint working groups to assess navigational impact.
Ministry of Heritage (Cultural and Natural Heritage Protection)	- Formal request for an assessment of cultural and natural heritage impact.
	- Collaboration with conservation experts for compliance.
Regional Government Body (Junta de Andalucía)	- Public consultations and stakeholder forums.
	- Meetings with regional development agencies.
European Union (EU)	- Compliance reports and funding applications through EU renewable energy programs.
	- Engagement via European Commission environmental and energy departments.
Ministry of Tourism	- Collaboration meetings with tourism planning departments.
	- Impact assessment studies to address industry concerns.
Hotel Owners Association	- Industry roundtable discussions and surveys on potential impacts.
	- Meetings with association representatives to explore mitigation measures.
FNCP (National Federation of Fishermens Guilds)	- Direct dialogue with guild leaders and fishermens cooperatives.
	- Field visits to assess fishing route concerns.
International Chamber of Shipping (ICS)	- Formal submission of navigation impact reports.
	- Coordination through maritime industry conferences and workshops.
Local Communities	- Town hall meetings and public information campaigns.
	- Online platforms for feedback and concerns.
Investors (Wind Energy Companies & Financial Backers)	- Business meetings and investment pitches.

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Stakeholder	Interests and Concerns
	- Regular project updates through financial reports and stakeholder briefings.
National Energy Provider	- Technical discussions on grid integration.
	- Collaboration on energy distribution agreements.
Ministry of Agriculture and Fishing	- Joint environmental and economic impact assessments.
	- Regular dialogue with marine and fishing policy units.

7 Environmental impacts

7.1 Introduction

- Wind turbine operation does not cause any direct airborne/aquatic emissions:
  → However also operation causes negative environmental impacts;
- Manufacturing process of wind turbine creates environmental impact;
- Which direct/indirect environmental impacts occur?
- Who is effected by possible impacts? Who are the stakeholders?

7.2 Onshore wind energy

7.2.1 Visual impact (on landscapes)

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7.2.2 How do wind turbines (wind parks) change landscapes?

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7.3 Visual assessment (changes on landscape)

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7.4 Disco effect and shadow flicker

7.4.1 Disco effect – light reflections

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7.4.2 Shadow flicker

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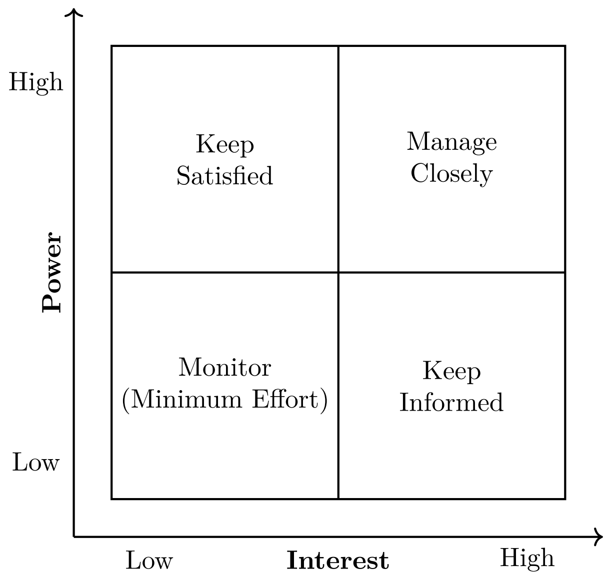
7.5 Land use



7.6 Noise impact

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7.6.1 Low frequency noise (LFN)

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7.7 Impact on birds

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7.7.1 Methods to reduce impacts on birds

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7.8 Electromagnetic interference (EMI)

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EIA exercise – 140 MW offshore wind park

Task 1

What is being proposed?

- 140 MW Offshore Park ⇒ 70 turbines (2 MW each), grid pattern
- 110 m high turbines (70 m hub height), monopole foundation rammed into seabed
- 50 km of interconnecting cables: 36 kV grid, 20 km sea cable to shore, 5 km passing through protected landscape
- 4x4 m helicopter landing pad × 70 turbines

Why?

- To increase Denmarks renewable energy capacity and reduce reliance on fossil fuels
- To harness strong wind resources in offshore shallow waters for stable electricity generation
- To contribute to national and international climate goals by reducing carbon emissions

Type of Environmental Impact Assessment (EIA)

- Full EIA required due to scale and proximity to protected area
- Impact on seabed: marine ecosystems (disruption of benthic habitats)
- Noise ⇒ interference with marine lifeforms (whales, harbor porpoises, migratory birds)
- Visual impact ⇒ minor concern (offshore location)
- Sediment movement ⇒ water quality ⇒ potential degradation
- Potential methane sink disruption

Task 2

Relevant Impact Categories

- Marine ecosystem: impact on fish, marine mammals, and benthic organisms
- Bird migration: risk of collision, displacement due to rotor movement
- Seabed disturbance: monopile foundation and cable laying altering sediment dynamics
- Water quality: increased turbidity due to construction
- Underwater noise pollution: pile driving and operational noise
- Shipping and navigation safety: potential risks to vessels
- Climate benefits: renewable energy reducing CO_2 emissions

Less Important Categories

- Soil erosion (not relevant offshore)
- Deforestation (not applicable)
- Land-use change (only minor coastal modifications)

Task 3

Installation Phase

- Harbor porpoise ⇒ hearing impacted by pile-driving noise (≈150 kHz sensitivity)
- Sediment resuspension ⇒ increased turbidity affecting marine life
- Increased vessel traffic ⇒ potential collisions with marine animals
- Temporary displacement of fish and marine mammals

Operation Phase

- Bird collisions: seabirds (e.g., gannets, gulls, kittiwakes) impacted
- Continuous noise from turbines ⇒ communication interference for marine mammals
- Creation of artificial reef structures around monopile bases (potential biodiversity benefit)
- Reduction of CO_2 emissions contributing to climate mitigation

Part III

Environmental impacts - offshore

8 Environmental impacts

8.1 Visual impact

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Threshold	
Distance	**Impact**
<13 km	possible major visual effects
13 – 24 km	possible moderate visual effects
>24 km	possible minor visual effects

8.2 Noise impact

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8.2.1 Construction phase

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8.2.2 Operation phase

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8.3 Electromagnetic fields

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8.4 Turbine foundation

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8.5 Impact on sea birds

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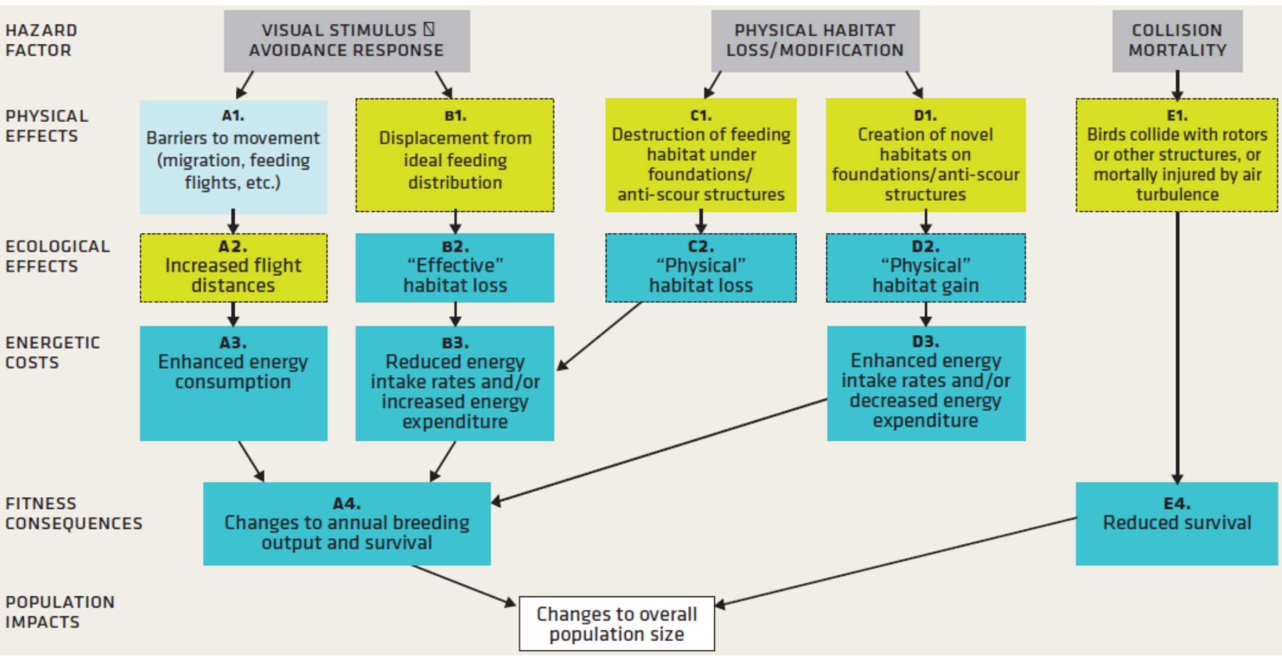

8.6 Ship collisions

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8.7 Other impacts

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8.7.1 Radar signals

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8.7.2 Shadowing (masking)

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8.7.3 Returns

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8.7.4 Scattering

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Part IV

Cost of windpower

9 Wind economics

9.1 Cost types

Cost can be measured in a number of different ways:

- Capital (initial investment/equipment) costs;
- Operation and maintenance costs;
- Levelised cost of enegy (LCOE);
- Fixed/variable costs

Cost can be measured from different perspectives:

- Private investors / Indipendent power producers → Cost/financial analysis;
- State-owned electricity generation utility → Economic analysis:
  (e.g.: incl. subsidies, taxation, incentives, CO_2 pricing, externalities, ...)

9.2 Private companies

Benefits:

- Energy price (comes from the grid operator);
- Sell of energy;
- Zero-emission energy → best air quality and life quality;
- People and families move near the area in order to get job.

9.3 Private companies

-

10 Levelised cost of electricity generation (LCOE)

- LCOE is a measure of cost effectiveness of a energ source;
- It is used to compare different methods of electricity generation on a comparable basis;
- LCOE is calculated by accounting for all of a system's expected lifetime costs devided by the system's lifetime expected power output (kWh);
- LCOE reflects minimum price at which electricity has to be sold (excl. taxes):
  - A relatively low LCOE means that electricity is being produced at a low cost;
  - Higher likely returns for investor;
- LCOE of renewable energy rechnologies varies by technology, country and project:
  - Depending on energy resource, capital/operating costs and efficiency/performance;
- Cost of energy technologies is based on discounting financial flows:
  - Discounting: multiplying an amount (cost) by a discount rate to determine its present value;
  - Discounting is the opposite of compounding;
  - (e.g.: 1'000.- compounded at annual interest rate of 10% per year for 5 years = 1'610.51.-)
  - (inverse: Present value of 1,610.51.- realized ayer 5 years discounted at 10% per year = 1,000.-)
- (e.g.: Cost structure for wind turbines → Capital costs, maintenances, deconstruction.)

10.0.1 LCOE formula

$$\text{LCOE} = \frac{\sum_{n}^{t=1} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{n}^{t=1} E_t}$$

where:

- **LCOE** = the average lifetime levelised cost of electricity generation;
- $\mathbf{I_t}$ = investment expenditures in the yeat **t**;
- $\mathbf{M_t}$ = operations and maintenance expenditures in the year **t**;
- $\mathbf{F_t}$ = fuel expenditures in the year **t**;
- $\mathbf{E_t}$ = electricity generation in the year **t**;
- **r** = discount rate;
- **n** = economic life of the system.

Example
A company has a 1mil francs as capital costs and, after 10 years, they have still 1mil francs at the end. The initial costs are higher or lower, considering a big discount rate?

Net costs: Initial Outlay − Present Value of any Return

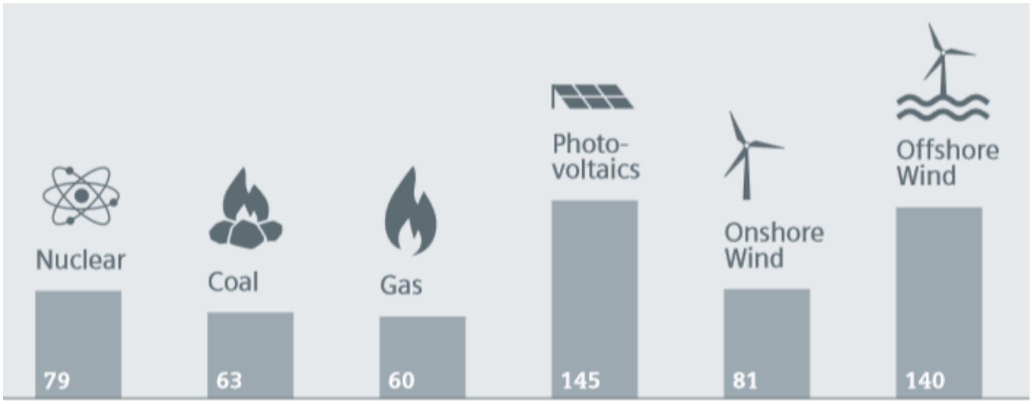
$\Rightarrow 1'000'000 - \dfrac{1'000'000}{(1+r)^{10}}$

When the discount rate is large, the 1 million francs you have at the end of 10 years is heavily discounted and not worth very much in todays terms. Effectively, that makes your net cost higher.

So, to answer the question directly:
They are effectively higher, because you are not getting much present-value "credit" for the 1 million francs you receive 10 years in the future.

10.0.2 Energy LCOE

- Quality of LCOE estimations strongly depends on quality and detail level of input data;
- LCOE estimations are tipically characterized by large uncertainity range (e.g.: maintenance costs, produced kWh);
- LCOE estimates are highly sensitive to assumed discount rate.



$$\text{LCOE} = \frac{\text{Total costs over lifetime [¤]}}{\text{Electricity produced over lifetime [kWh]}}$$

10.0.3 Guidance scheme

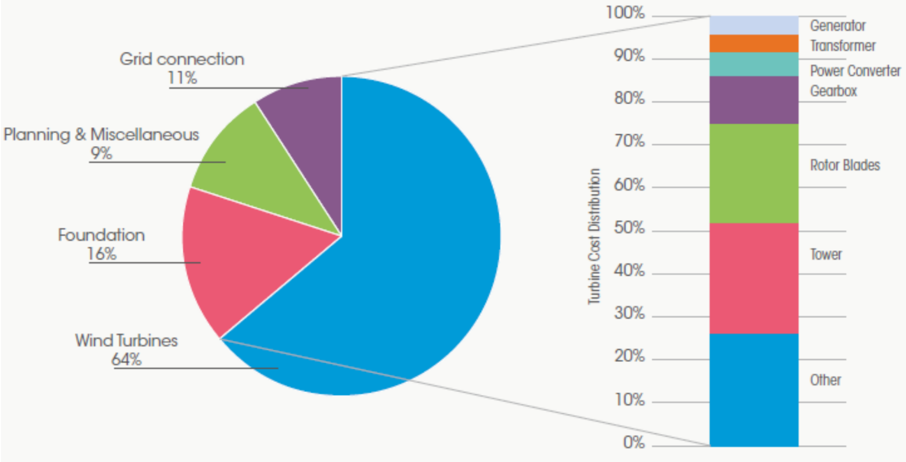
EU guidance scheme for LCOE best practice: Guidelines defines minimum cost parameters that should be included in LCOE calculation:

- ...

10.1 Capital (investment) cost

10.1.1 Investments

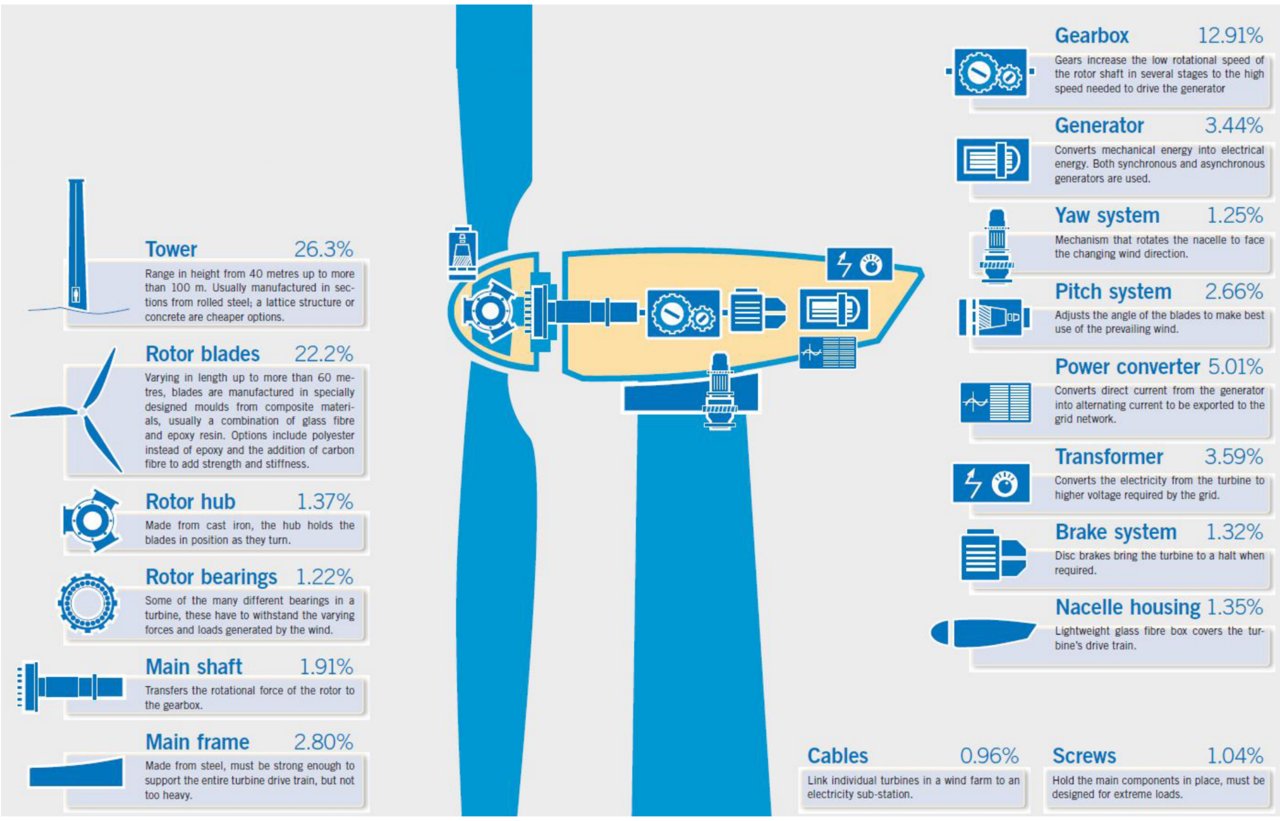
- Cost structure of a wind power project is dominated by upfront capital cost:
  - Up to 70–80% of total cost;
  - No fuel price risk during operation;
- Capital costs of a wind power project can be broken down into:
  - Turbine cost (incl. blades, tower and transformer);
  - Civil works (incl. construction costs for site preparation, foundation construction);
  - Grid connection costs (incl. transformers, substations, connection to transmission network);
  - Other capital costs (e.g.: construction of buildings, project consultancy costs, ...).



	Onshore	Offshore
Capital investment costs (USD/kW)	1 700-2 450	3 300-5 000
Wind turbine cost share (%)[1]	65-84	30-50
Grid connection cost share (%) [2]	9-14	15-30
Construction cost share (%) [3]	4-16	15-25
Other capital cost share (%) [4]	4-10	8-30

Share of different cost components varies by country and project:

- Country specific cost structure (e.g. labour cost, land cost etc.);
- Project specific cost structure (type and size of turbine, off- or onshore etc.).



- Investment cost of onshore wind power projects in developed countries:
  - Range between USD 1,700/kW - USD 2,400/kW;
  - In comparison in China capital costs are around USD 1,300/kW;
- During 1980 and 2004 capital costs steadily declined;

- Ayer 2004 installed cost increased to around USD 2,000/kW;
- Reasons for price increases are include:
  - Rising cost of commodities (e.g. steel, copper);
  - Copper and steel account for around 20-40% of total capital cost;
  - High market demand lead to shortages in certain components → higher prices;
- Capital costs for offshore wind projects in developed countries:
  - Vary between USD 3,300 - USD 5,000/kW;
  - Price variation depending on water depth - shiy from a shallow to deeper water projects.

10.2 O&M cost

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10.3 Cost reduction potential

10.3.1 Turbine components

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10.3.2 Grid connection

- Cost of grid connection is not likely to decline significantly for onshore wind farms;
- Offshore grid connection costs can be reduced by increased scale of wind parks.

10.3.3 Foundation

- Foundations accounts for 7-10% of onshore costs;
- 15% to 20% for offshore costs;
- Largest cost components are cement and steel;
- Cost reductions by reduced material consumption (more efficient design);
- Cost reductions by reduced materials cost or materials substitution;
- Cost reduction by new offshore foundation designs → Fixed seabed vs. floating foundation (in testing stage).

10.3.4 Other

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10.4 Levelised cost of electricity from wind energy

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Part V

Wind power and ecotechnology

11 Wind power generalities

11.0.1 How does a wind turbine work?

There is a wind vane (1) at the top of each turbine: this tells the turbine the speed and direction the wind is blowing.

The turbine then rotates on the tower to face into the wind, and the blades (2) rotate on their axis to create maximum resistance against the wind.

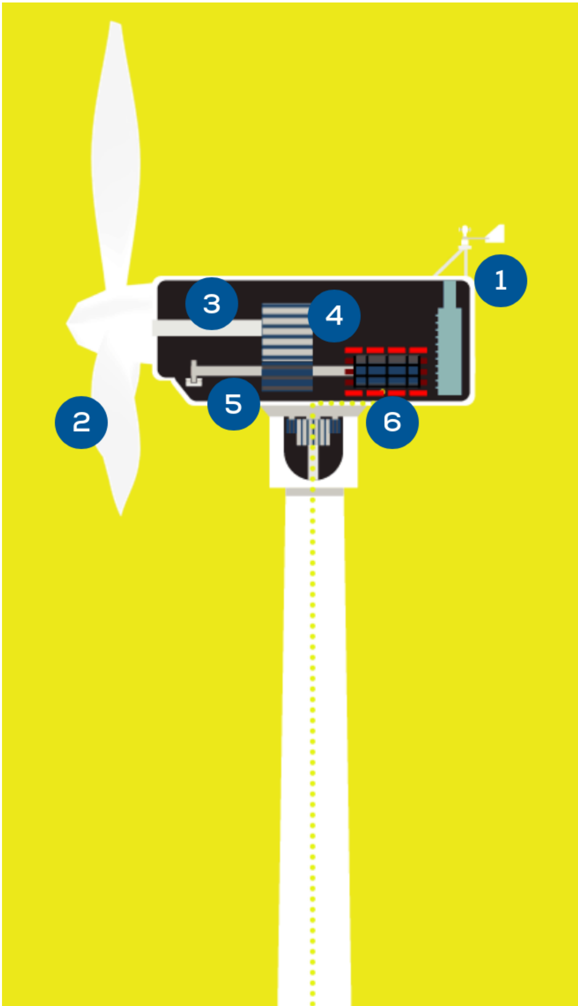
The wind starts turning the blades which are connected to a hub and a low-speed shaft (3).

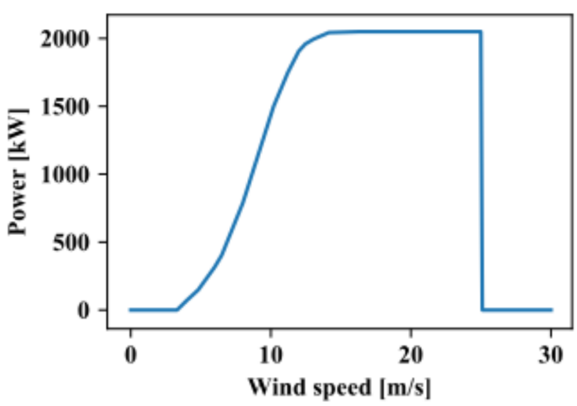
The low-speed shaft spins at the same speed as the blades (7-12 revolutions per minute). But we need a much faster rotational speed for the generator to produce electricity.

Thats why most wind turbines have a gearbox (4), which multiplies the rotational speed of the low-speed shaft by over 100 times to the high-speed shaft (5), which rotates up to 1,500 revolutions per minute.

This is connected to a generator (6), which converts the kinetic energy into electricity.

Turbines that do not have a gearbox are connected directly from the hub to the generator (6) through their axis (this is called "direct-drive").

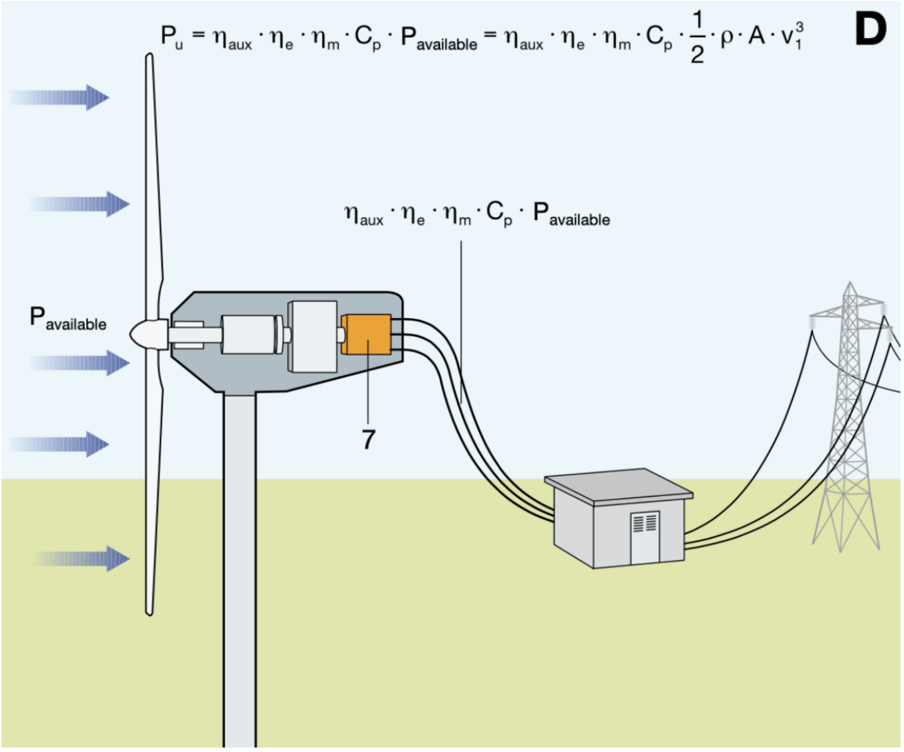




11.0.2 Power curve

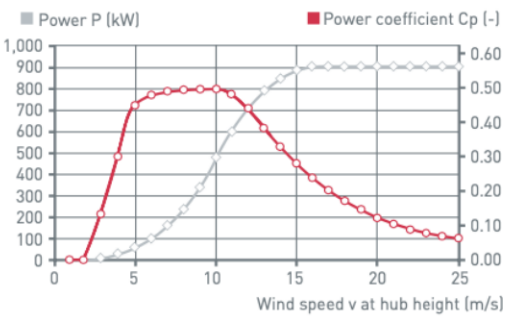
- Wind turbine electrical power output as a function of mean wind speed at hub height;
- Different operating regimes across the wind speed range:
  - cut-in wind speed: minimum wind speed at which the turbine will deliver power;
  - rated wind speed: above this value the wind turbine will produce its rated power;
  - cut-out wind speed: above this value the wind turbine will stop converting wind to electricity.

11.0.3 Wind to electricity conversion chain



11.0.4 Wind turbine technical characteristics

Calculated power curve



Wind (m/s)	Power P (kW)	Power-coefficient Cp (-)
1	0.0	0.00
2	0.0	0.00
3	4.0	0.16
4	20.0	0.34
5	50.0	0.43
6	96.0	0.48

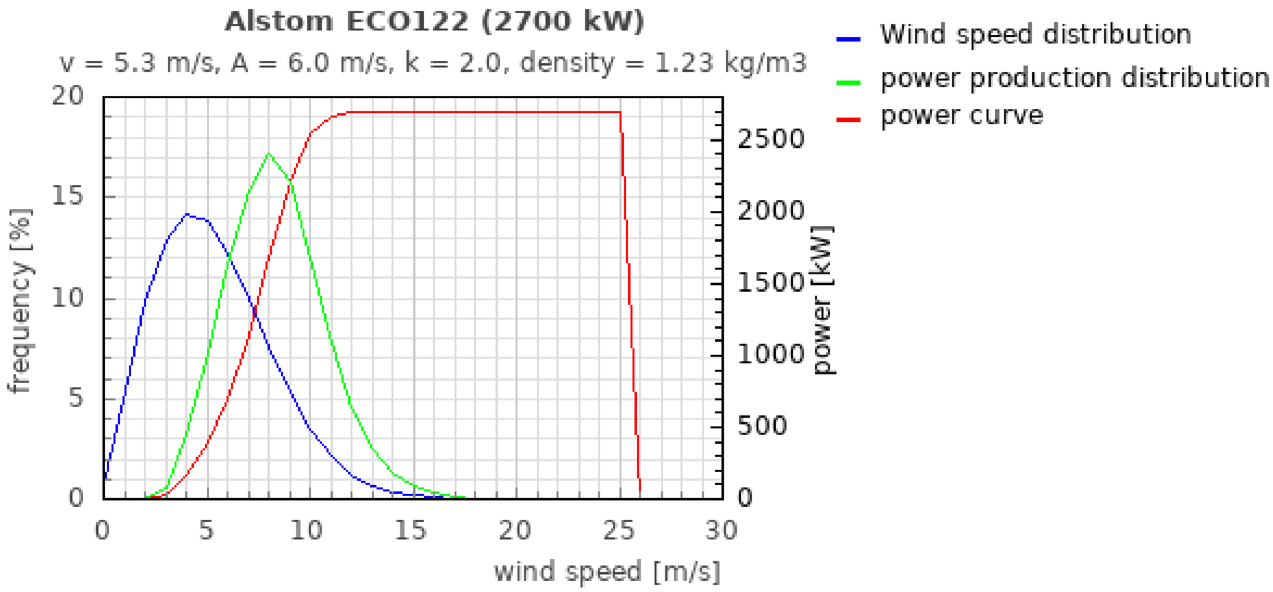
Technical specifications E-44

Rated power:	**900 kW**
Rotor diameter:	**44 m**
Hub height in meter:	**45 / 55**
Wind zone (DIBt):	**-**
Wind class (IEC):	**IEC/EN IA**
WEC concept:	Gearless, variable speed, single blade adjustment

Rotor

Type:	Upwind rotor with active pitch control
Rotational direction:	Clockwise
No. of blades:	3
Swept area:	1,521 m^2
Blade material:	GRP (epoxy resin); Built-in lightning protection
Rotational speed:	Variable, 16 - 34.5 rpm
Pitch control:	ENERCON single blade pitch system; one independent pitch system per rotor blade with allocated emergency supply

11.0.5 Wind-wave statistical distribution



Rayleigh distribution

$$p(H) = \frac{2H}{(H_{\text{rms}})^2 \exp\left(-\left(\frac{H}{H_{\text{rms}}}\right)^2\right)}$$

Root-mean-square height

$$H_{\text{rms}} = \sqrt{\sum \frac{H_i^2}{N}}$$

Cumulative probability distribution

$$P(H) = \int_0^H p(H)\, dH = 1 - \exp\left(\frac{H}{H_{\text{rms}}}\right)^2$$

12 Wind energy technology

12.1 Overview of wind energy conversion

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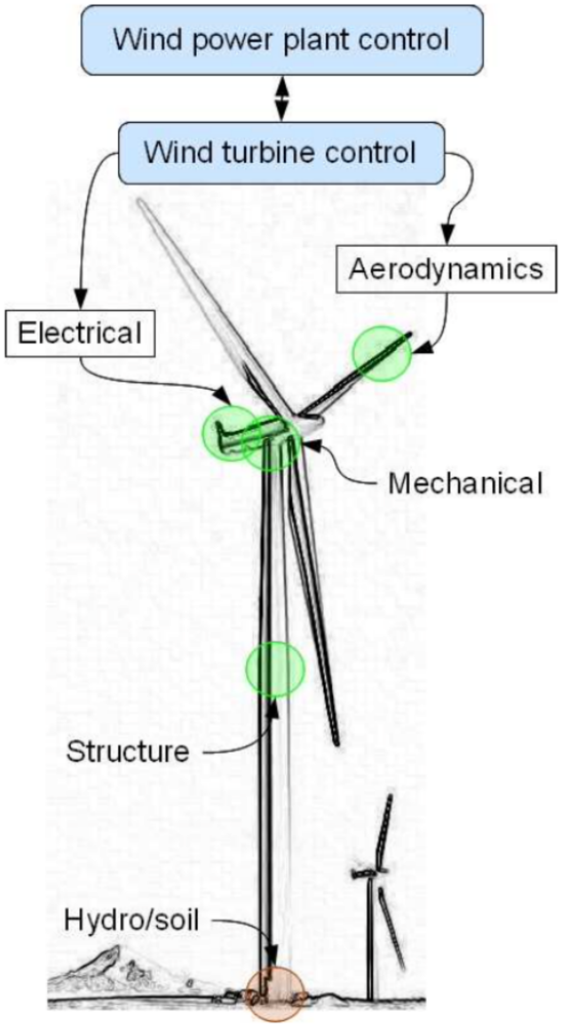
12.2 Modern wind turbines

12.2.1 Horizontal axis wind turbines (HAWT)

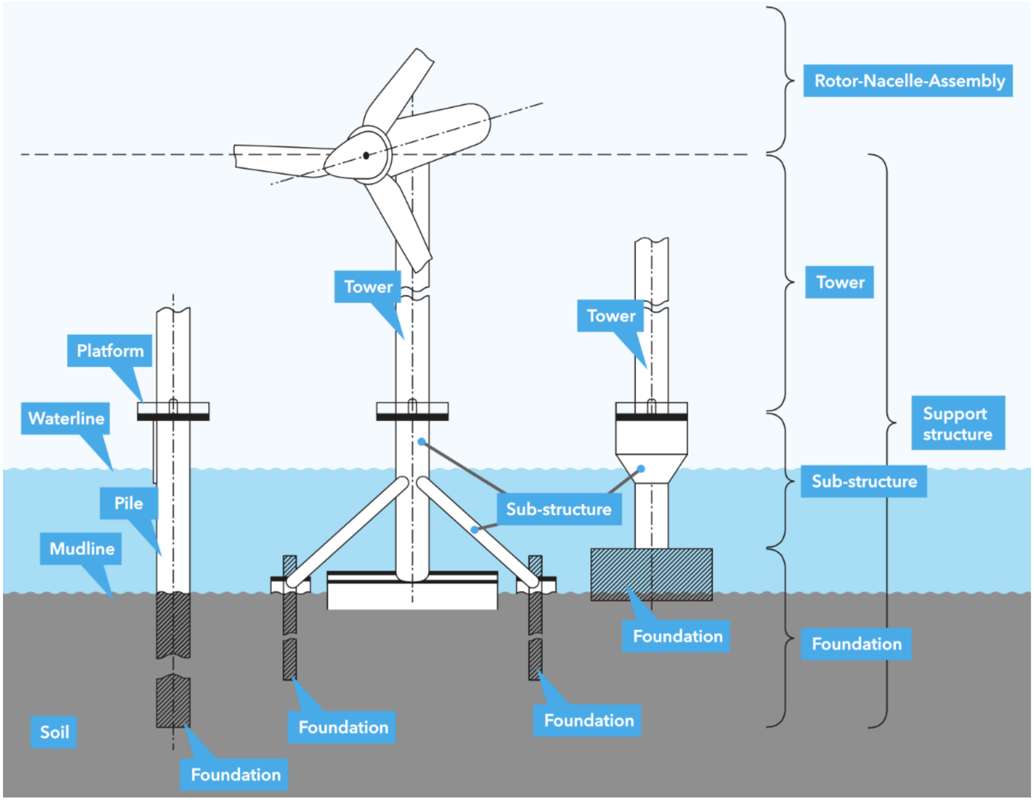
- Axis of rotation (almost) horizontal;
- Rotor in front of the tower as seen from the wind (upwind);
- 3-bladed rotor more efficient that other configurations;
- Yaw control;
- Pitch control;
- Variable speed;
- Capable of supporting greed;



12.2.2 Subsystems and components

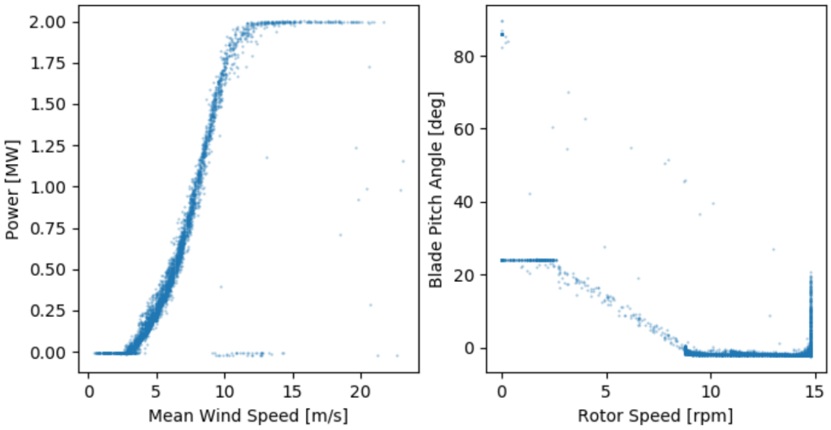
- **Rotor:** blades, hub, pitch system;
- **Nacelle:**
    - **Drive train:**

12.2.3 Components of fixed-bottom offshore wind turbine



12.2.4 Basic operation modes

- Off/standby;
- Idling;
- Start up;
- Low, mid, high-power;
- Maximum power;
- Shut down (high wind speed, large vibrations);
- Parked

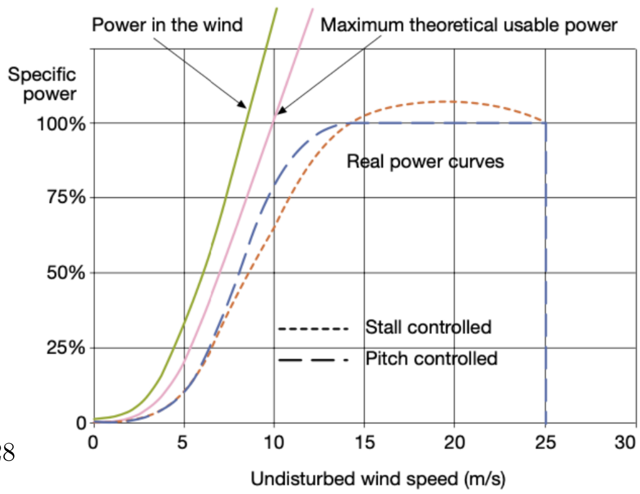


12.2.5 Operation under site-specific conditions

- Power regulation to avoid large grid unbalance: curtailment, shut-down due to storms;
- Avoid environmental impacts: reduced operation during bird migration season, noise or shadow restrictions;
- Protect turbine components under harsh environments.

12.2.6 Basic operation modes

- $P_{\text{wind}} = \frac{1}{2}\rho A u^3$
- $P_{\max} = \frac{1}{2}\rho A u^3 c_p$
- $c_p \simeq 0.59$



12.2.7 Calculate annual energy production

Annual energy production (e.g., during 8760 h) of a wind turbine, assuming that is all the time available to produce energy E [kWh/year], is given by:

$$\boxed{E = 8760 \int_{0}^{\infty} P(u) f(u)\, du}$$

where:

- $P(u)$: wind turbine power output [kWh] as a function of u;
- $f(u)$: probability density function of wind speed [s/m];
- u: wind speed [m/s].

Equivalent hours per year h_{eq} is given by:

$$\boxed{h_{eq} = \frac{E}{P_n}}$$

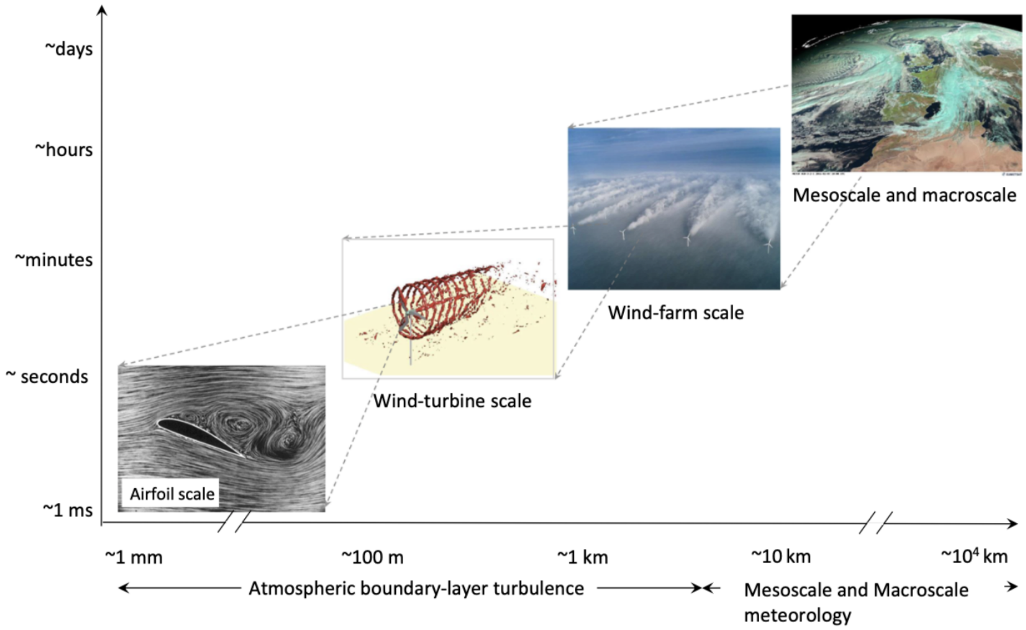
where P_n is the rated power of the wind turbine.

13 Basics of wind energy conversion

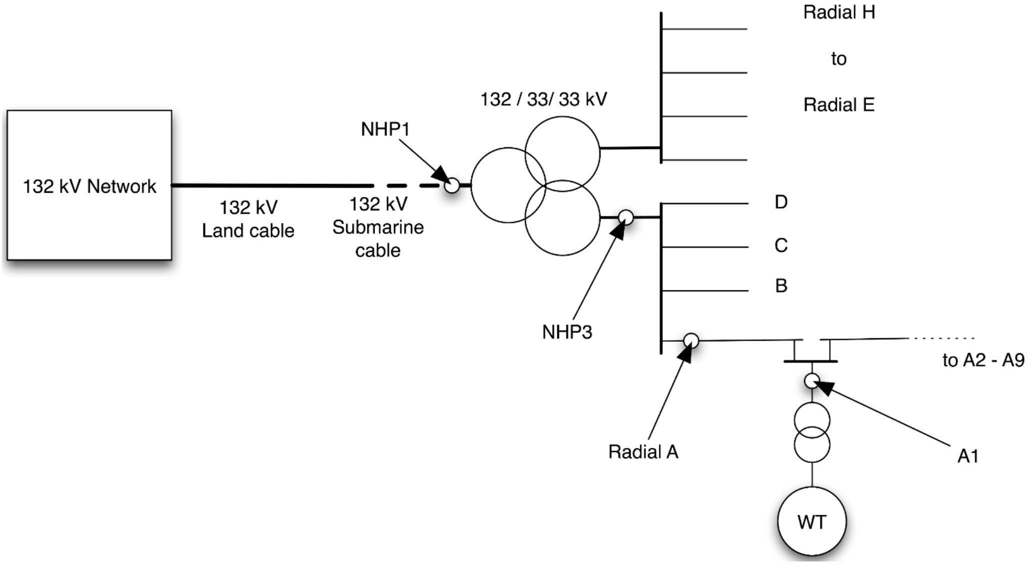
14 Wind farms

A wind farm or wind power plant is an array of wind turbines with a common connection point to the grid.

14.1 Range of flow scales relevant to wind farms



14.2 Components for connection to the grid in an offshore wind farm



14.3 Impacts on power systems

Larger wind farms can influence power systems:

- Upgrades to transmission and distribution infrastructure might be needed;
- Power quality might be influenced by distorsion to voltage and increase of harmonics;
- Grid stability may need require novel practices to balance demand and production.

15 Wind resource

15.1 Global wind patterns

...

15.2 Wind climate

...

15.2.1 Wind profile in the atmospheric boundary layer

Wind shear influences resource assessment and wind turbine design because it influences the energy production and the wind turbine structural loads.

Models of mean wind speed u as a function of height z:

Power law

$$\boxed{u(z) = U_r \left(\frac{z}{z_r}\right)^{\alpha}}$$

where:

- U_r: wind speed measured at height z_r;
- α: flow over flat terrain (tipically 0.14).
  This variable is sensitive to sourface roughness, height, and atmospheric stability.

Logarithmic law (without considering stability)

$$\boxed{u(z) = \frac{U^*}{k} \ln\left(\frac{z}{z_0}\right)}$$

where:

- U^*: friction velocity (it depends on air density and terrain roughness);
- $k = 0.4$ (von Kármán's constant)
- z_0: surface roughness length (for very smooth surfaces, $z_0 = 0.01$ mm)

15.2.2 Terrain roughness

Size and distribution of roughness elements:

- vegetation;
- buildings;
- soil surface.

Standard roughness classes:

- 0: water areas, sea fjords, and lakes $\rightarrow z_0 = 0.2$ mm;
- 1: open areas with few windbreaks $\rightarrow z_0 = 30$ mm;
- 2: farm land with scattered trees and small buildings $\rightarrow z_0 = 100$ mm;
- 3: urban areas, forest, farm land with many windbreaks $\rightarrow z_0 = 400$ mm.

15.2.3 Standard wind classes

	I **High**	**II** **Medium**	**III** **Low**	**IV** **Very low**
Reference wind speed	50	42.4	37.5	30
Annual average wind speed (Max)	**10**	**8.5**	**7.5**	**6**
50-year return gust	70	59.5	52.5	42
1-year return gust	52.5	44.6	39.4	31.5

15.3 Importance of site specific wind characteristics

15.3.1 Wind turbine design

16 Wind project development

17 Wind in the electricity mix

18 Social acceptance