Sustainable Exploitation of Renewable Energy Resources

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Sfruttamento Sostenibile di Risorse Energetiche Rinnovabili

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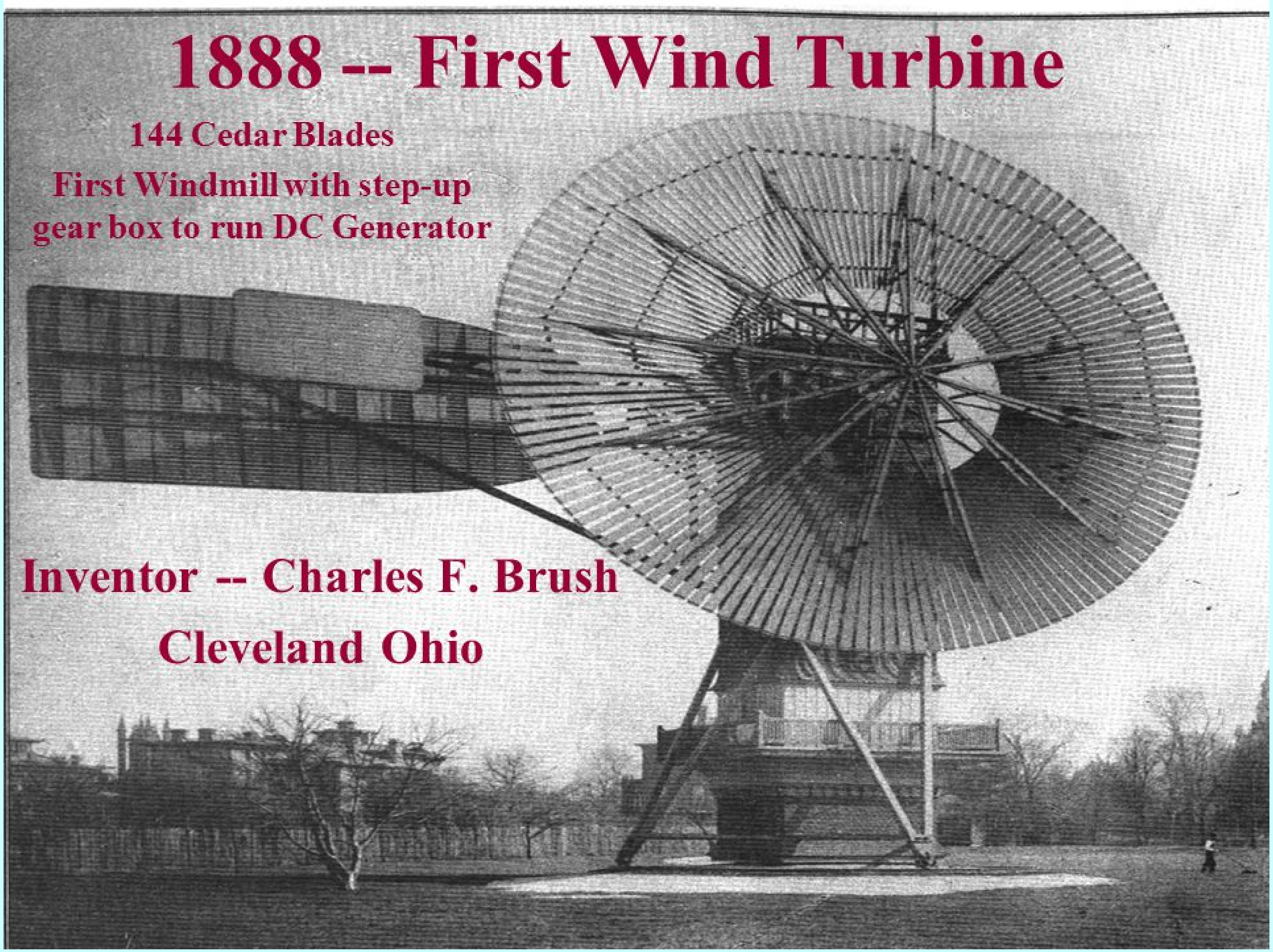
1st Part:
Wind Turbines

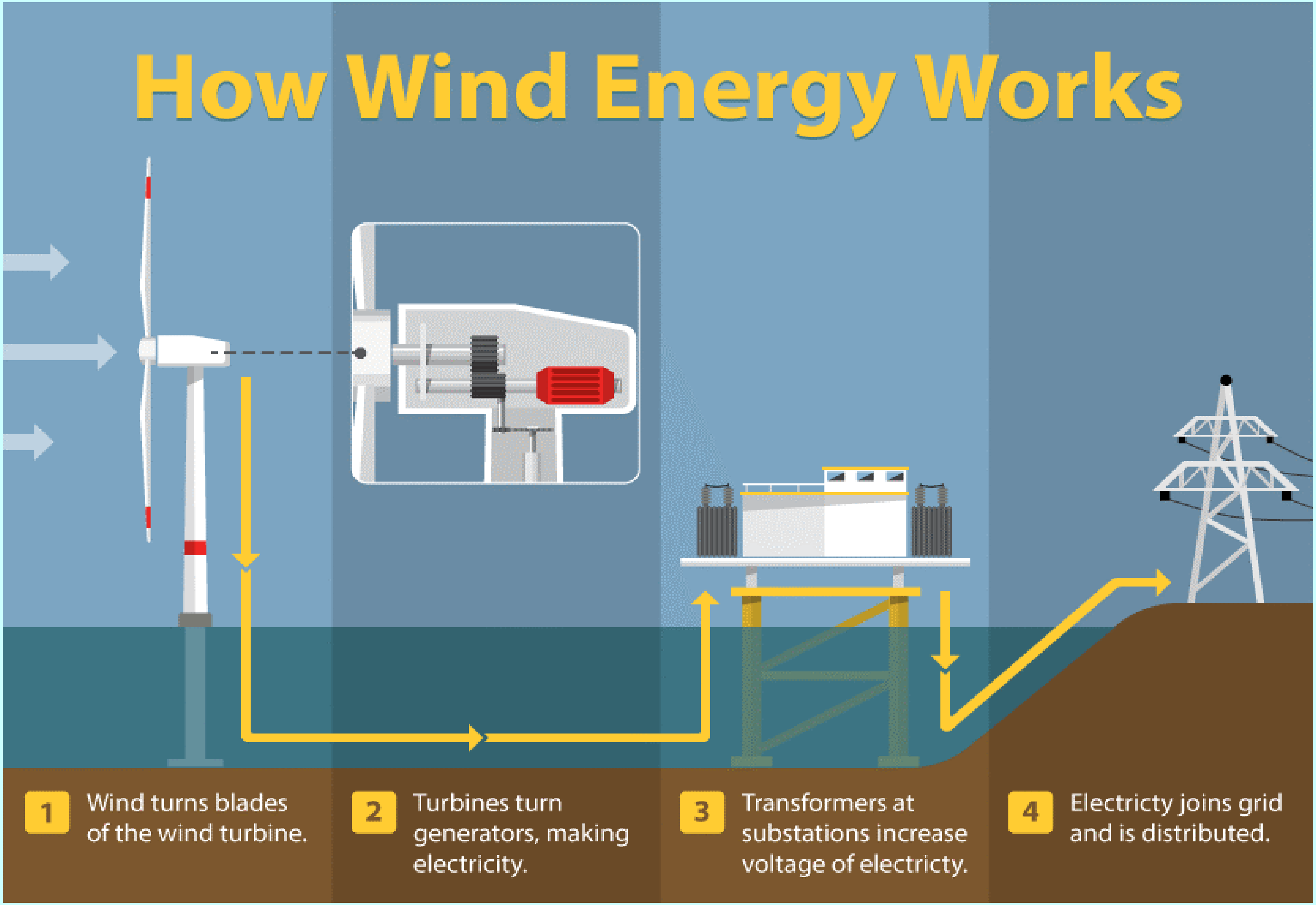
Discussion Topics

- General considerations
- Advanced control
- “Sustainable” structures
- Fault scenario
- Wind turbine modelling issues
- Concluding remarks

Early Wind Power

First Wind Turbine




How Wind Energy Works
1 Wind turns blades of the wind turbine.
2 Turbines turn generators, making electricity.
3 Transformers at substations increase voltage of electricty.
4 Electricty joins grid and is distributed.

What is Wind Energy?

- The process by which the wind is used to generate mechanical energy or electricity

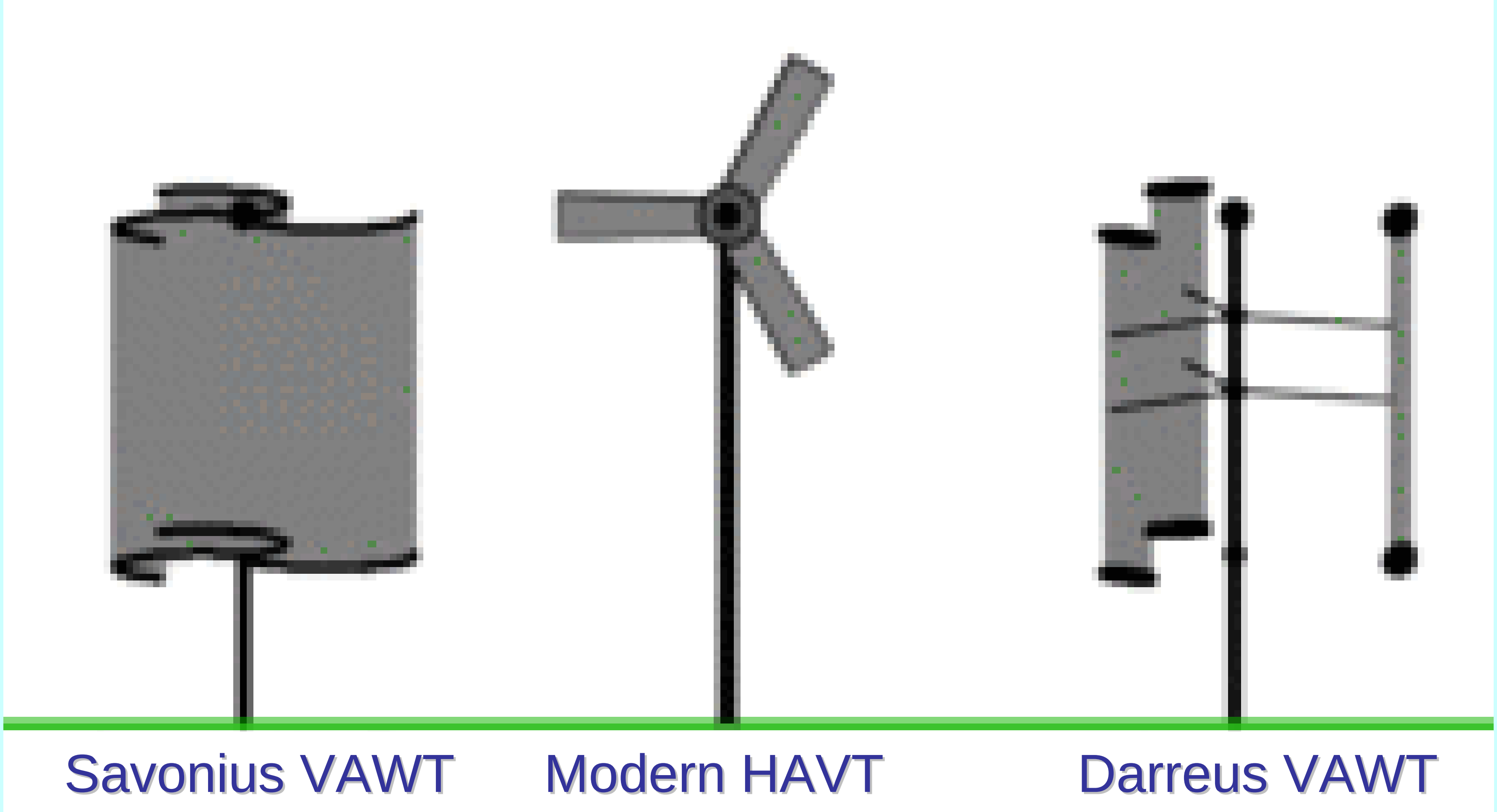
- Wind turbines convert the **kinetic energy** in the wind into **mechanical** and **electrical energy**

Many blade designs



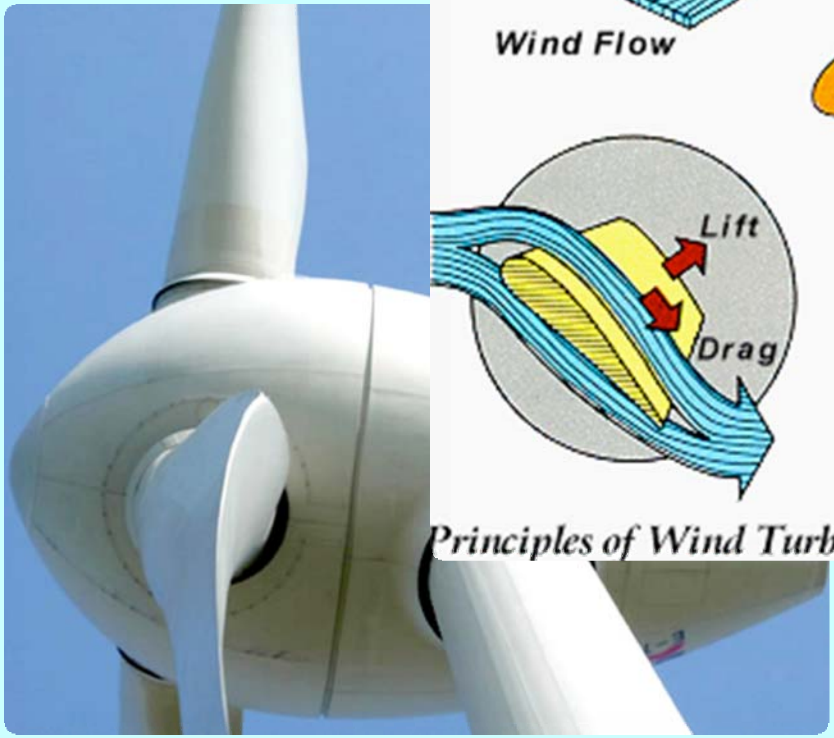


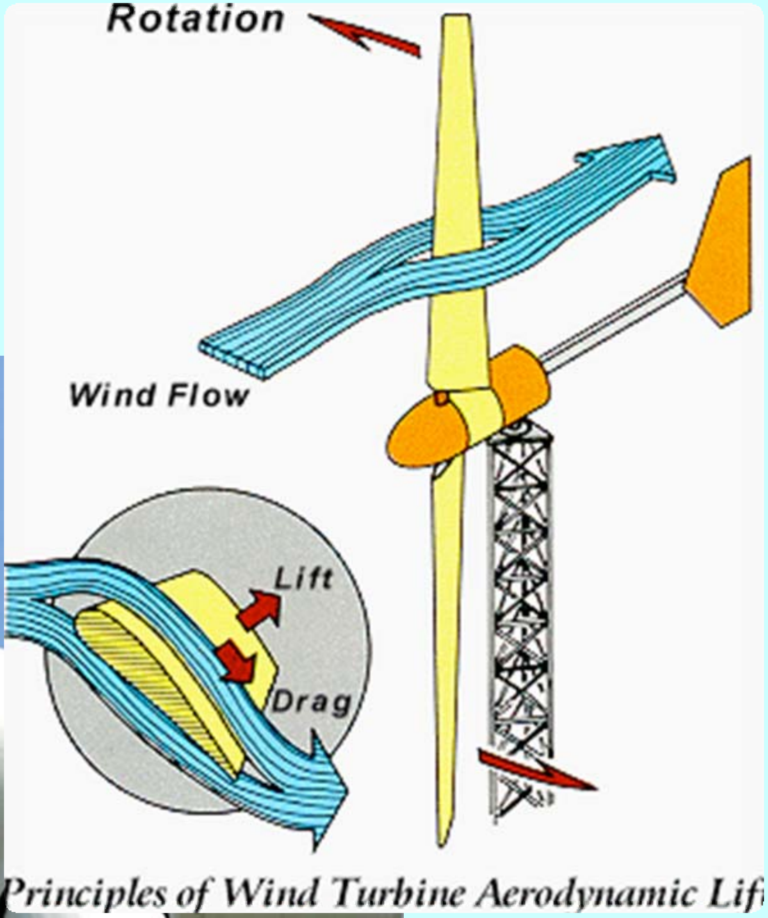

Examples



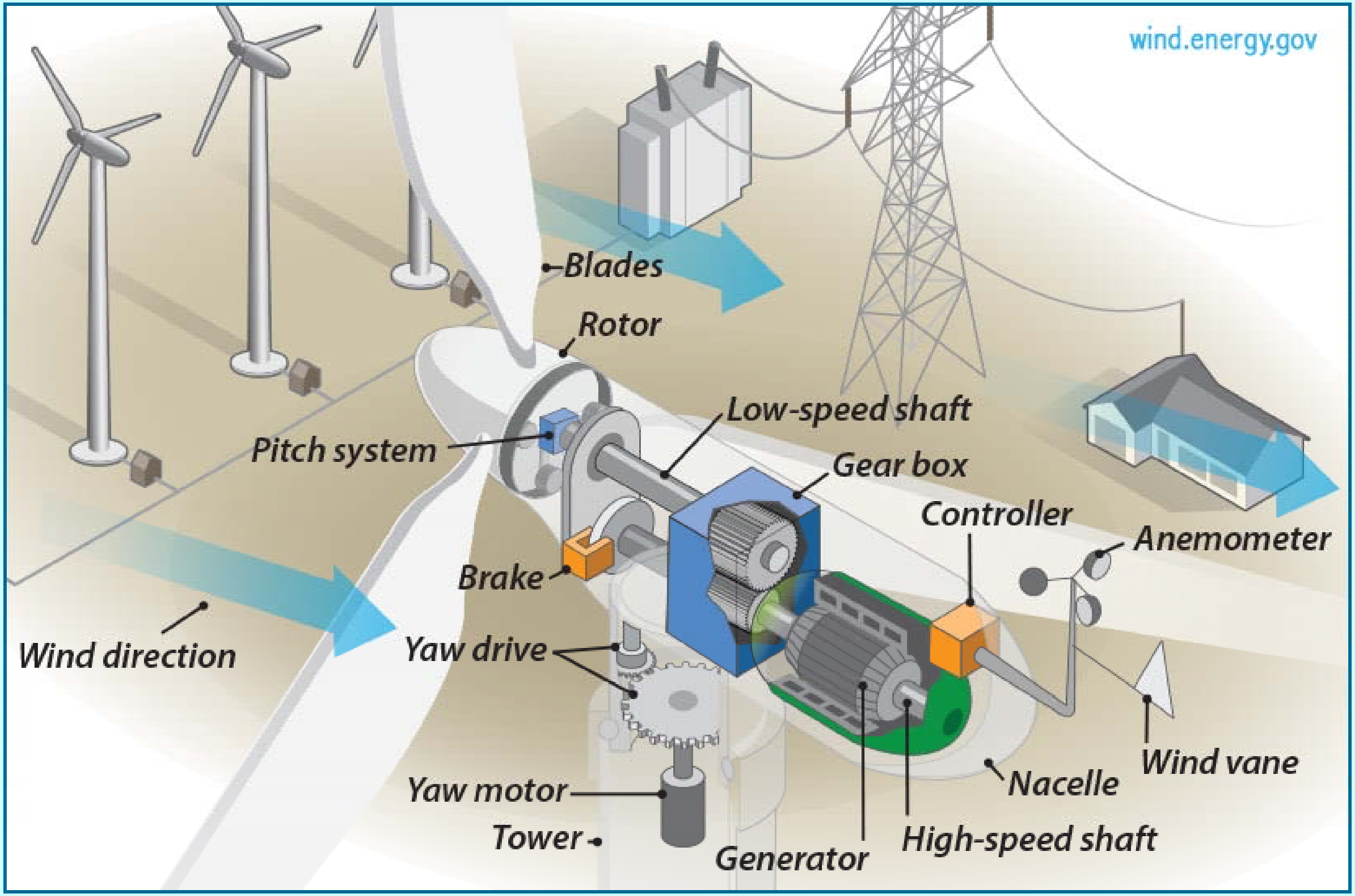
The Turbine Blade

- Operates much like an airplane wing
- Low-pressure air forms on the downwind side of the blade
- The low-pressure air pocket then pulls the blade toward it, causing the rotor to turn

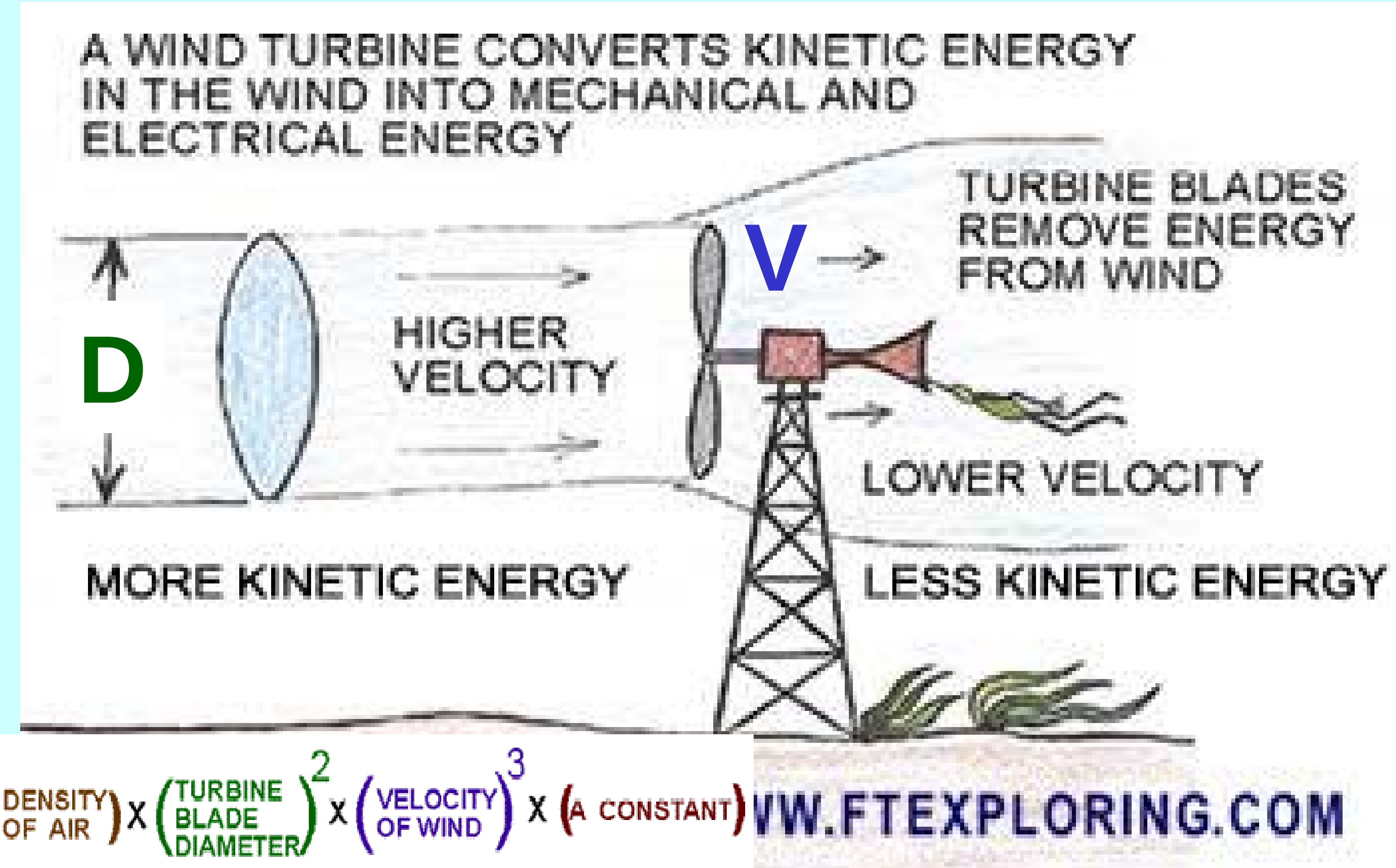


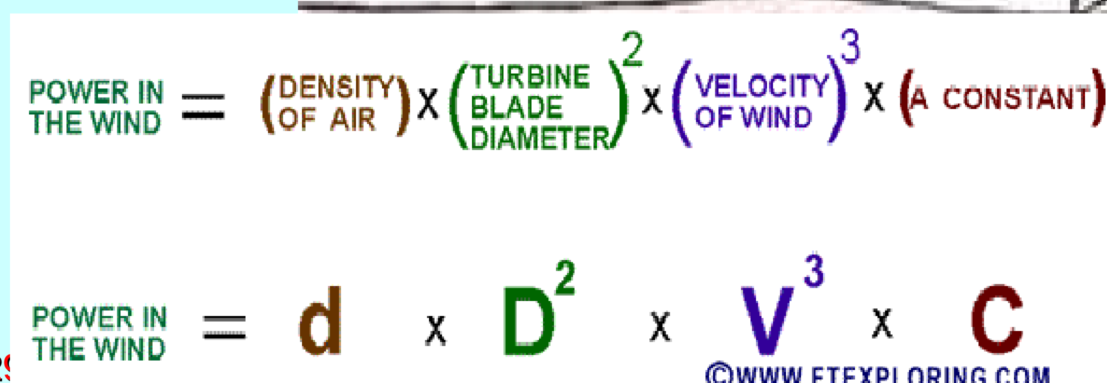


Wind Turbine Components

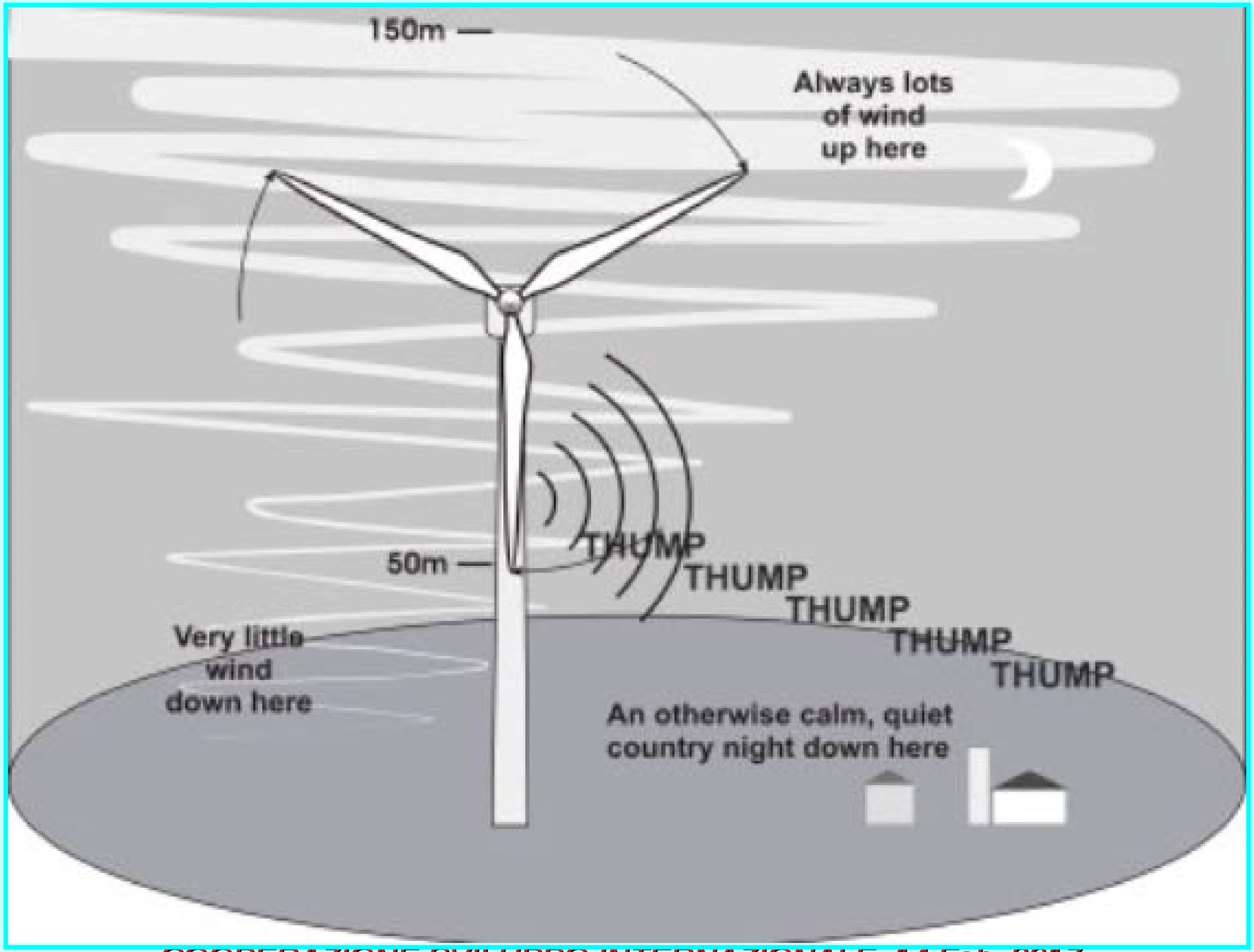


Produced Energy

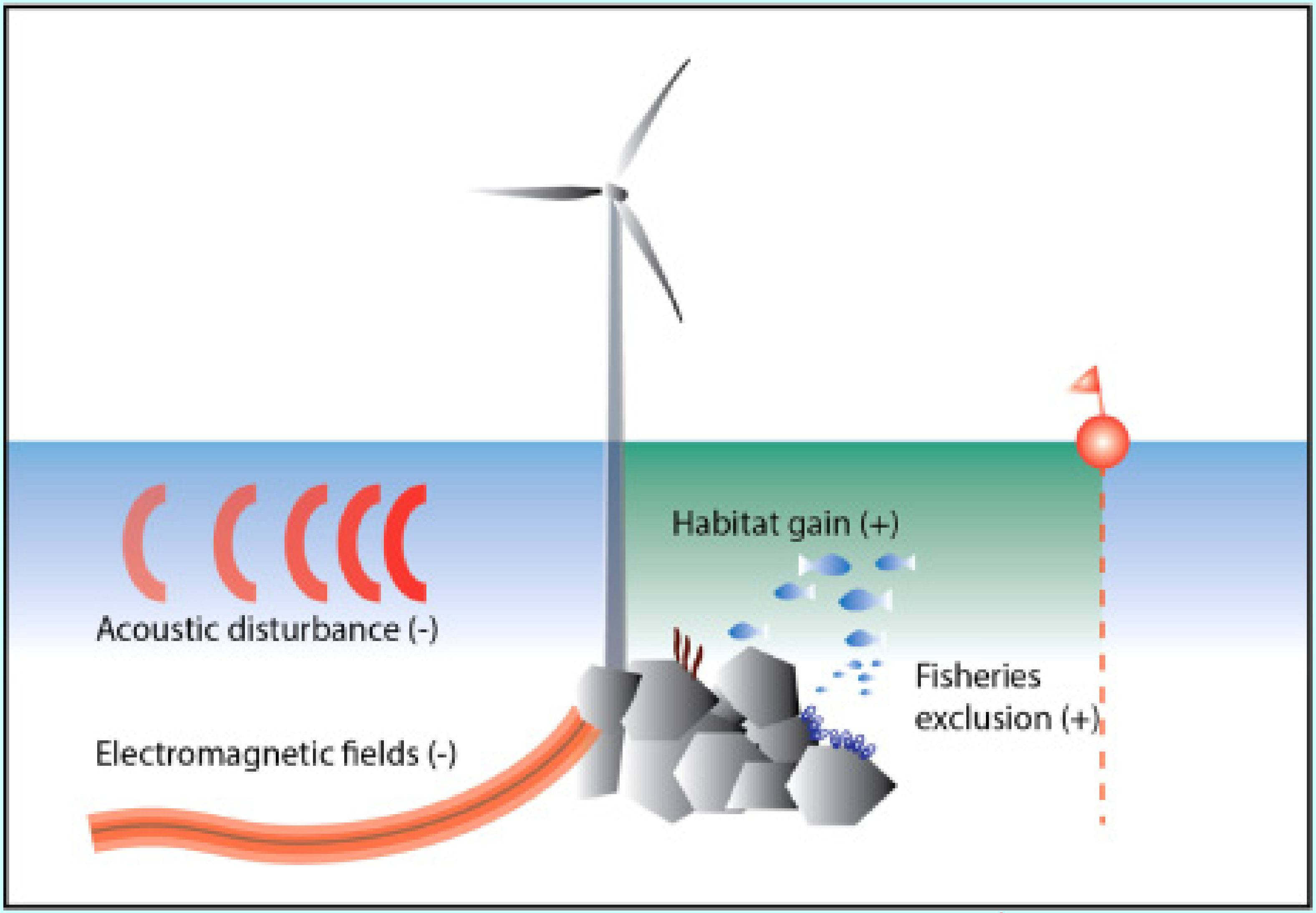




Environmental Impact 1



Environmental Impact 2



Environmental Impact 3

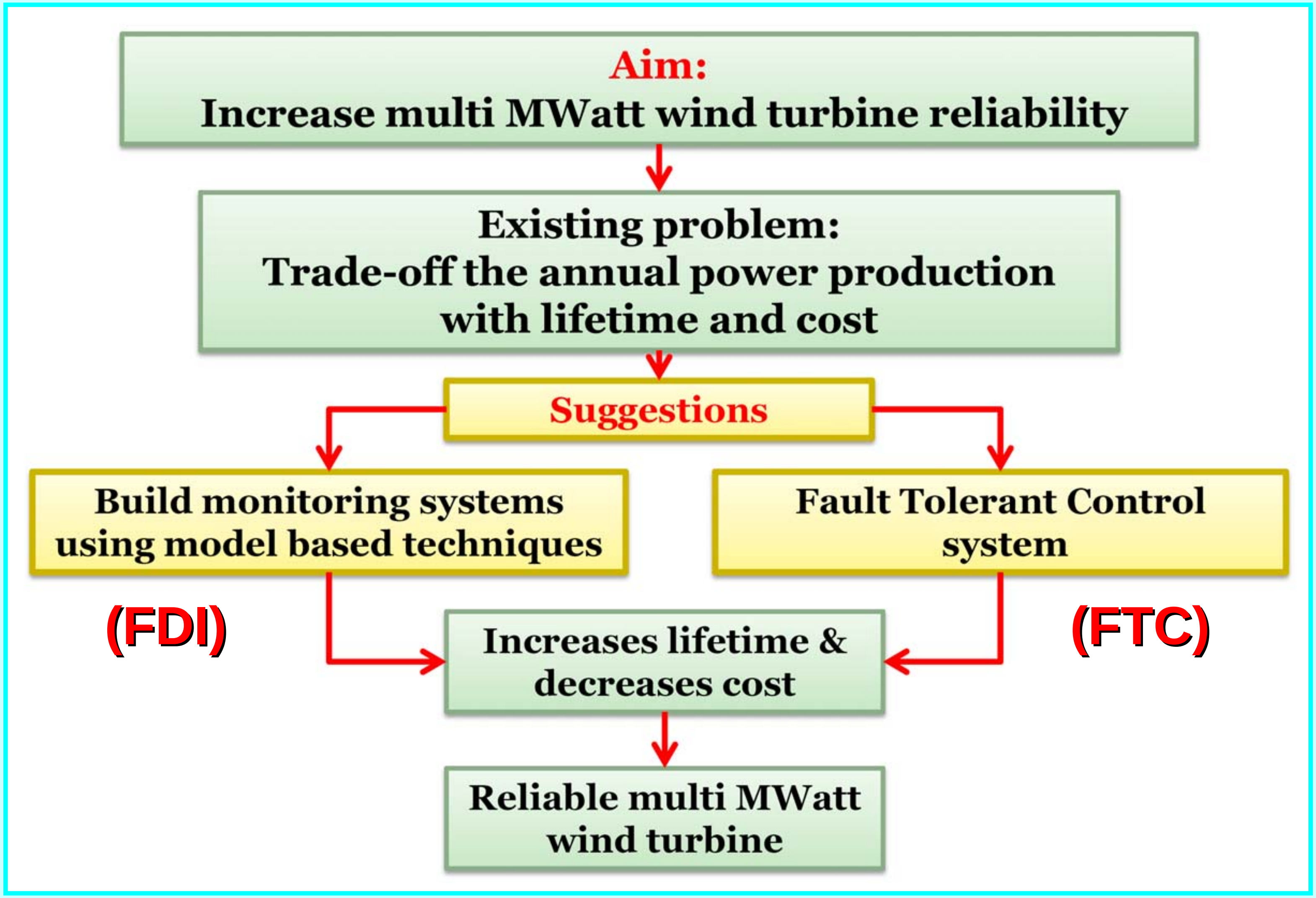
Energy and Control Issues

- ✓ Control systems have high influence on the total **cost of energy**
- ✓ Focus on **advanced control solutions**
  - **Condition monitoring**
  - **Fault diagnosis and fault tolerant control**
- ✓ The design of control solutions is enhanced by the development of **high-fidelity benchmark** models and prototypes
  - **Modelling issues**
- ✓ Solutions characterised by craftsmanship, quality, **reliability**, and proven technology

Advanced Control Solutions

“Sustainable Control”

Advanced Control



Safety-Critical Systems

- ✓ **Model-based FDI** and **FTC** are proposed as new approaches for **sustainable** (high degree of reliability and availability) wind turbine control
- ✓ Manage **loads** (storms, …) **and faults**
- ✓ ***NOTE***: *FTC was developed as aerospace topic, focussed mainly on NASA projects, motivated by advanced aircraft that could be reconfigured by control through a high degree of flight surface redundancy*

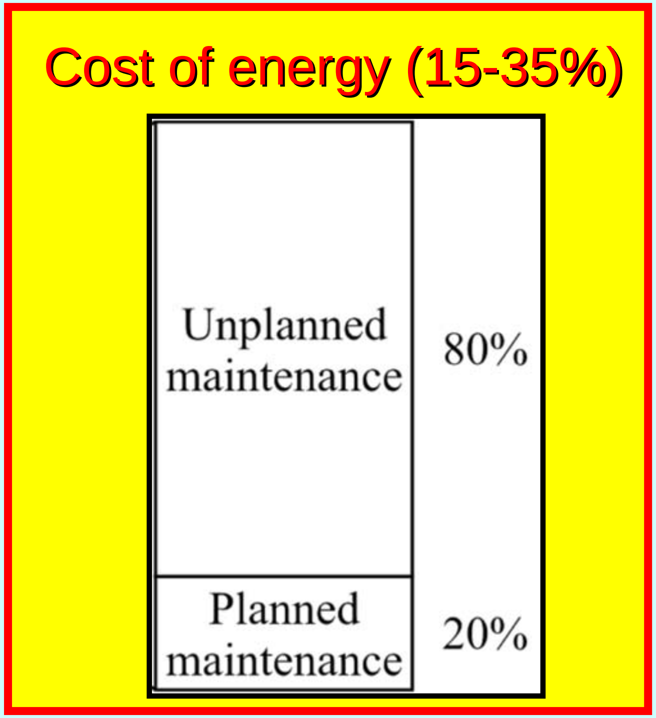
Motivations

- ✓ **Harsh** environment asks for the system to be well protected
- ➢ **Offshore wind turbines** are stand-alone power plants in inadequate service and maintenance attendance
- ✓ Safety-related control systems to help avert major incidents resulting from lightning, storms, gusts and other periodic incidents, and **faults** that affect the energy drive train and the electricity production

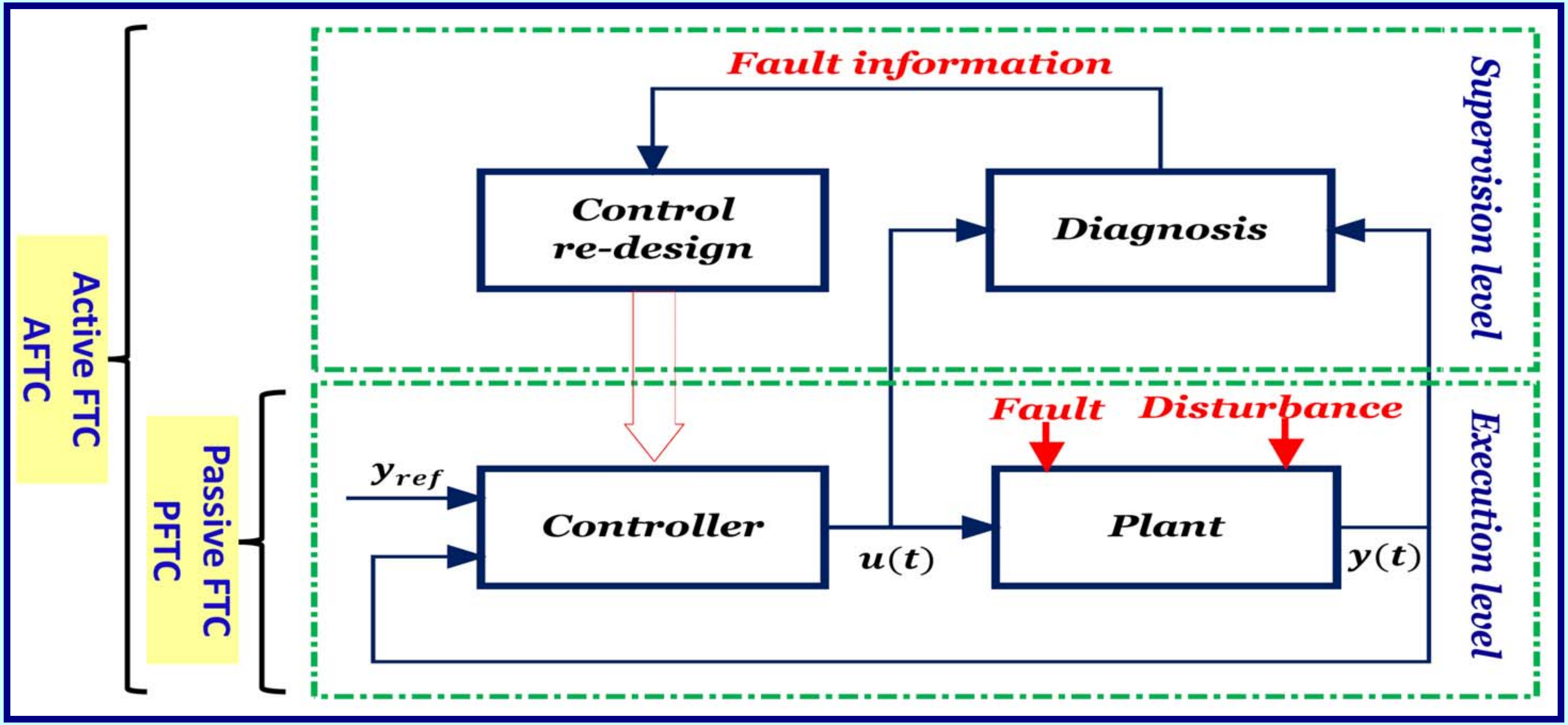
Example…

✓ A 5 MW wind turbine stopped will loose 24 MWh per day in production if 40% wind capacity is assumed

- Combine this with **difficult accessibility** at an offshore wind farm, it might take days before a fault is cleared
- Advanced **FDI** and **FTC** included in the control system **could provide information on the fault**, thus allowing for correct and faster repair if required, and/or **continued energy generation** eventually at lower level until maintenance service

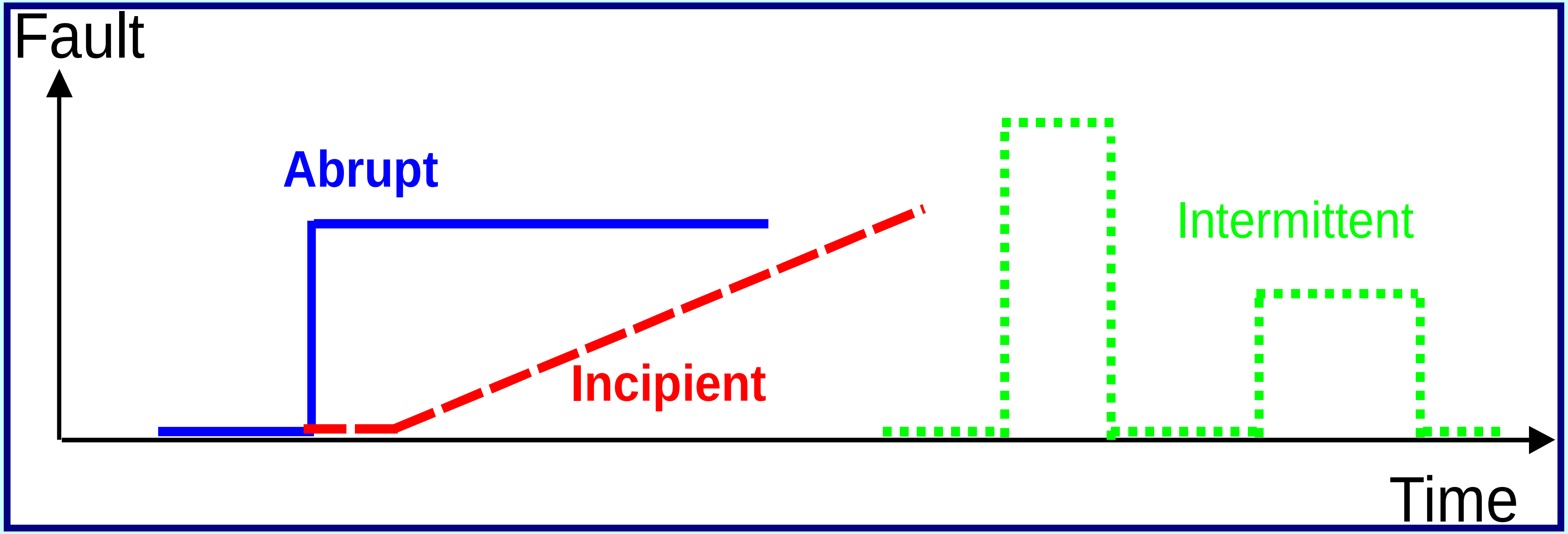



FDI / FTC
Fundamentals



- ✓ **PFTC: Robust fixed structure controller**
  - No fault information provided
- ✓ **AFTC: Real-time controller reconfiguration**
  - Fault reconstruction

General Fault Modes



- **Abrupt fault:** *e.g.* failures
- **Incipient fault:** *i.e.* hard to detect
- **Intermittent fault:** *e.g.* disconnections

Fault example…

System Requirements

- ✓ Safeguard w.r.t. all the different types of loads that inflict a wind turbine and regulate accordingly
  - **loads from the environment** (e.g. storms, waves, wind shear and wakes),
  - **loads from the wind turbine** itself (e.g. blades aerodynamic imbalances, yaw misalignments),
  - **loads from the system** (start/stop and turbine failures)
- ✓ Analyse system performance to avoid instabilities
- ✓ Balancing efficient production with lifetime considerations
- ✓ **Ensure redundant system capabilities to allow production until service and maintenance (O&M) are possible**

Wind Turbine Maintenance

- ✓ **High degree of reliability and availability (sustainability) is required and at the same expensive and safety critical maintenance work can occur**
- ✓ **Site accessibility**, system availability not always ensured, *severe weather conditions (+ sea installations)*
- ✓ FTC and FDI researches are stimulated in this application area since important aspects for **decreasing wind energy cost and increasing electrical grid penetration**
- ✓ FTC can enhance specific control actions to prevent plant damage and ensure system availability during malfunctions
- ✓ **Maintenance costs (O&M)** and **off-time** can be significantly **reduced**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International Challenge

- ✓ *kk-electronic* (Denmark) together with *MathWorks* (USA) launched a number of benchmark models for fault detection and accommodation, which allows turbine owners and researchers to find the best schemes to handle different faults.
- ✓ Based on these models, a series of competitions and challenges have been launched
  - Simple Wind Turbine FDI/FTC benchmark model
  - Advanced WT FDI / FTC benchmark model
  - Wind farm FDI/FTC benchmark model

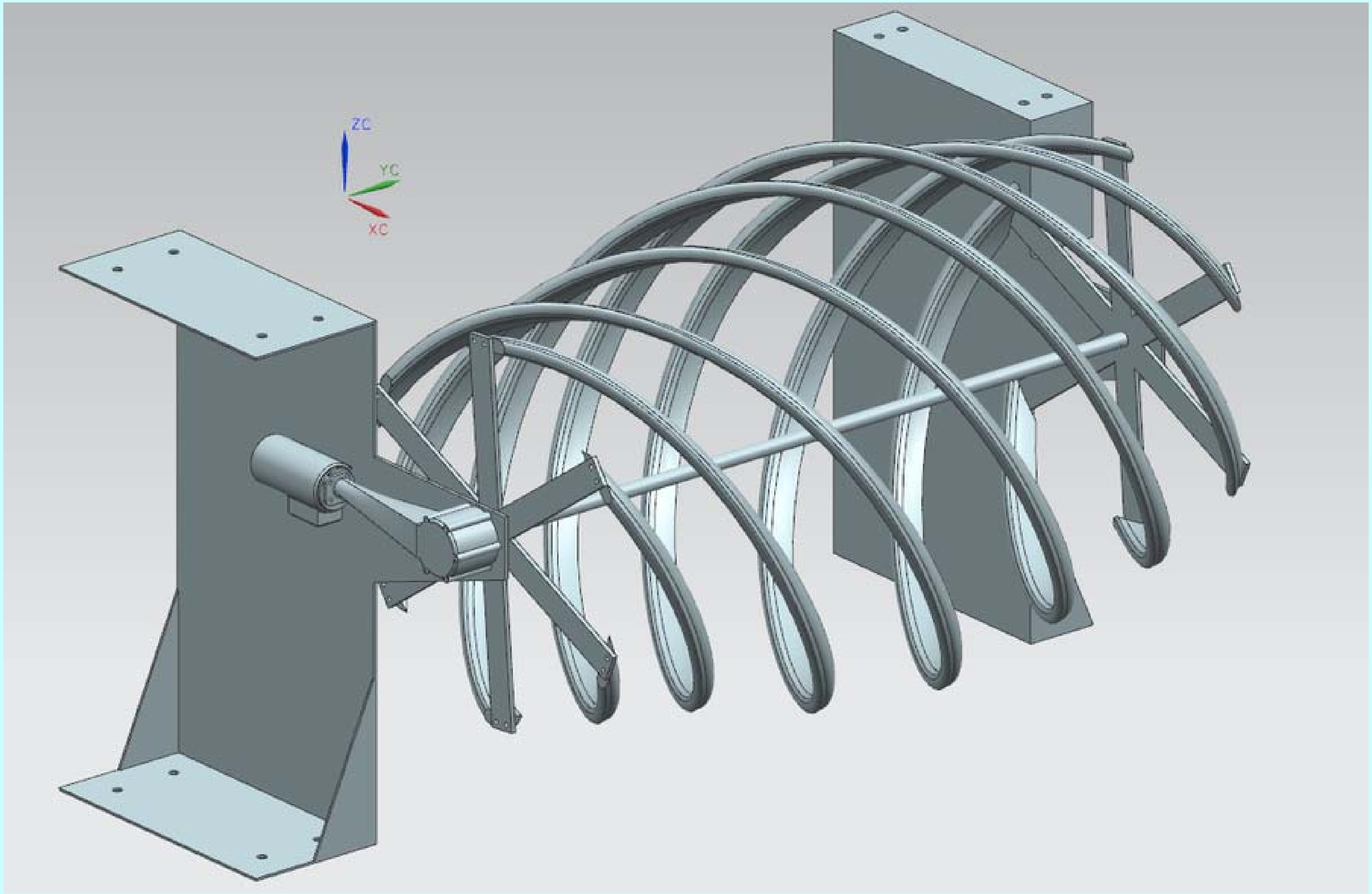
Benchmark Model Motivations

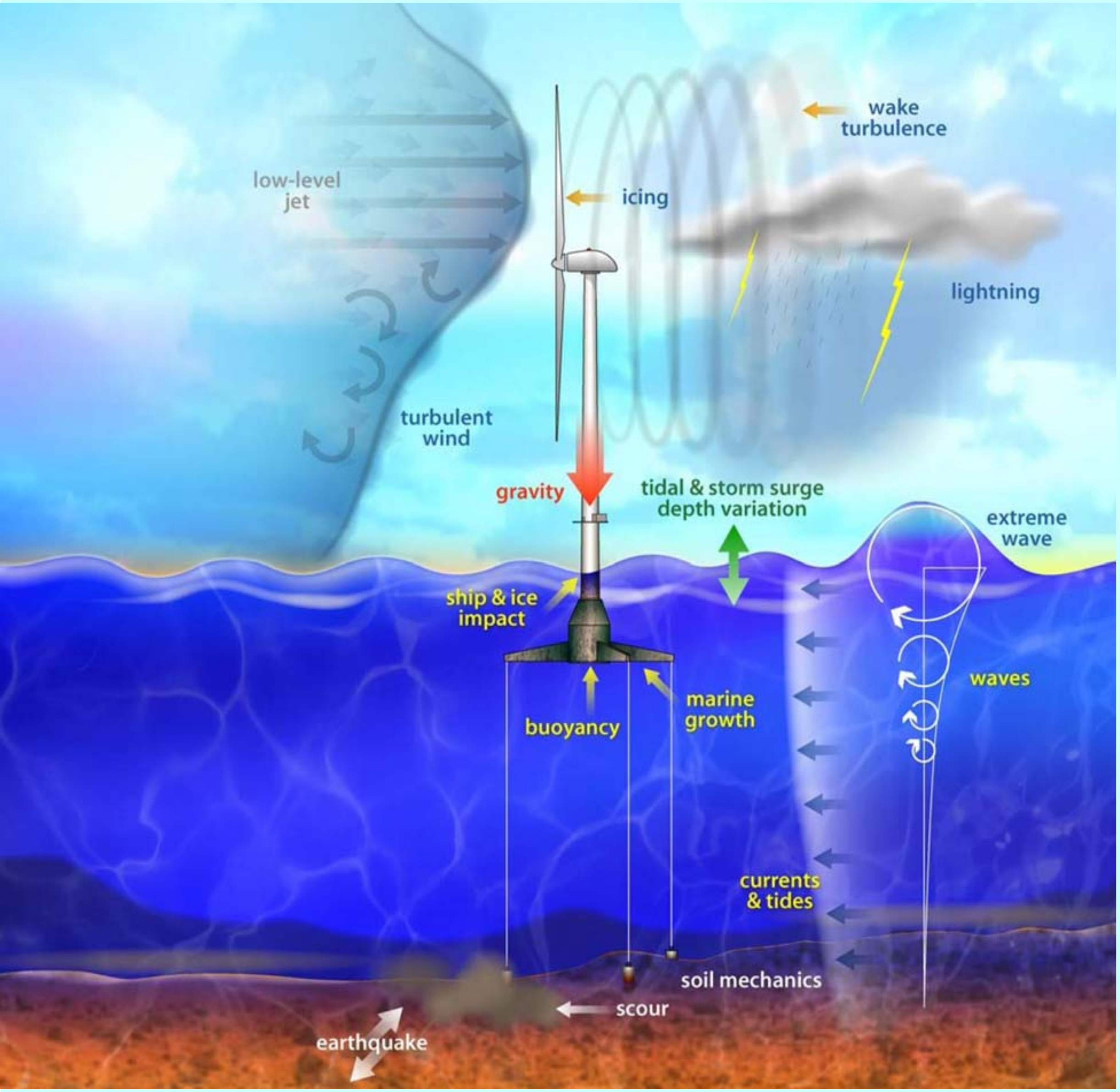
- ✓ Wind turbine benchmarks were proposed to provide generic platforms (freely available) for designing and testing different FDI and FTC solutions
- ✓ **The target was researchers in the FDI and FTC community, such that they can apply and compare their methods on wind turbine realistic installations**
- ✓ The model is generic, it can be provided to the public
- ✓ Solutions finally verified on accurate wind turbine models (confidential)

Competition Challenges

- ✓ **Fault diagnosis and fault-tolerant control scheme designs**
- ✓ Design procedure
  - Modelling
- ✓ Describe the considered system
  - Fault analysis
- ✓ Identify faults to be handled
  - Detect, isolate (and estimate faults)
  - Fault-tolerant control
- ✓ Based on signal correction
- ✓ Based on scheduling and reconfiguration of the controller

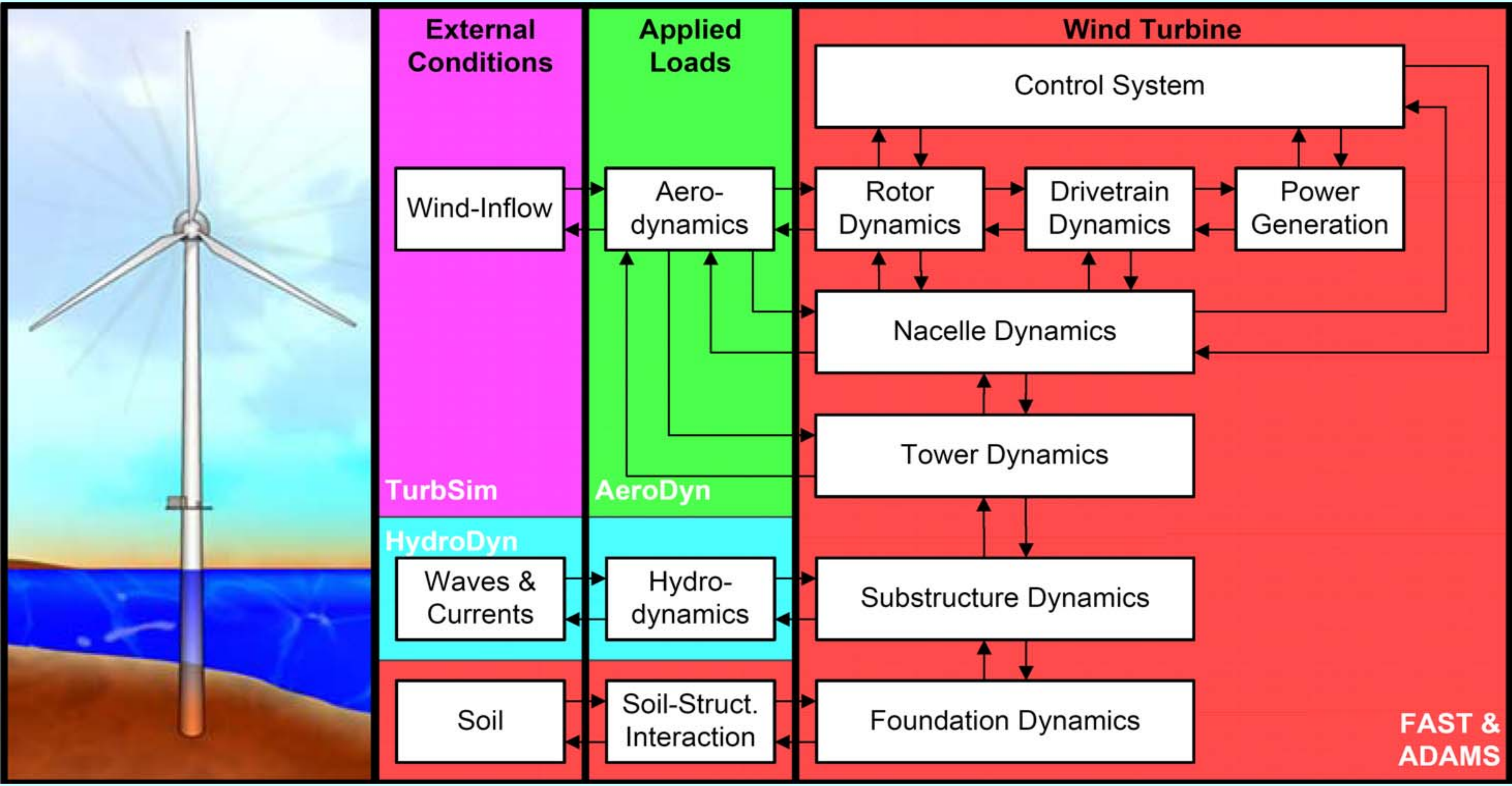
Modelling Topics





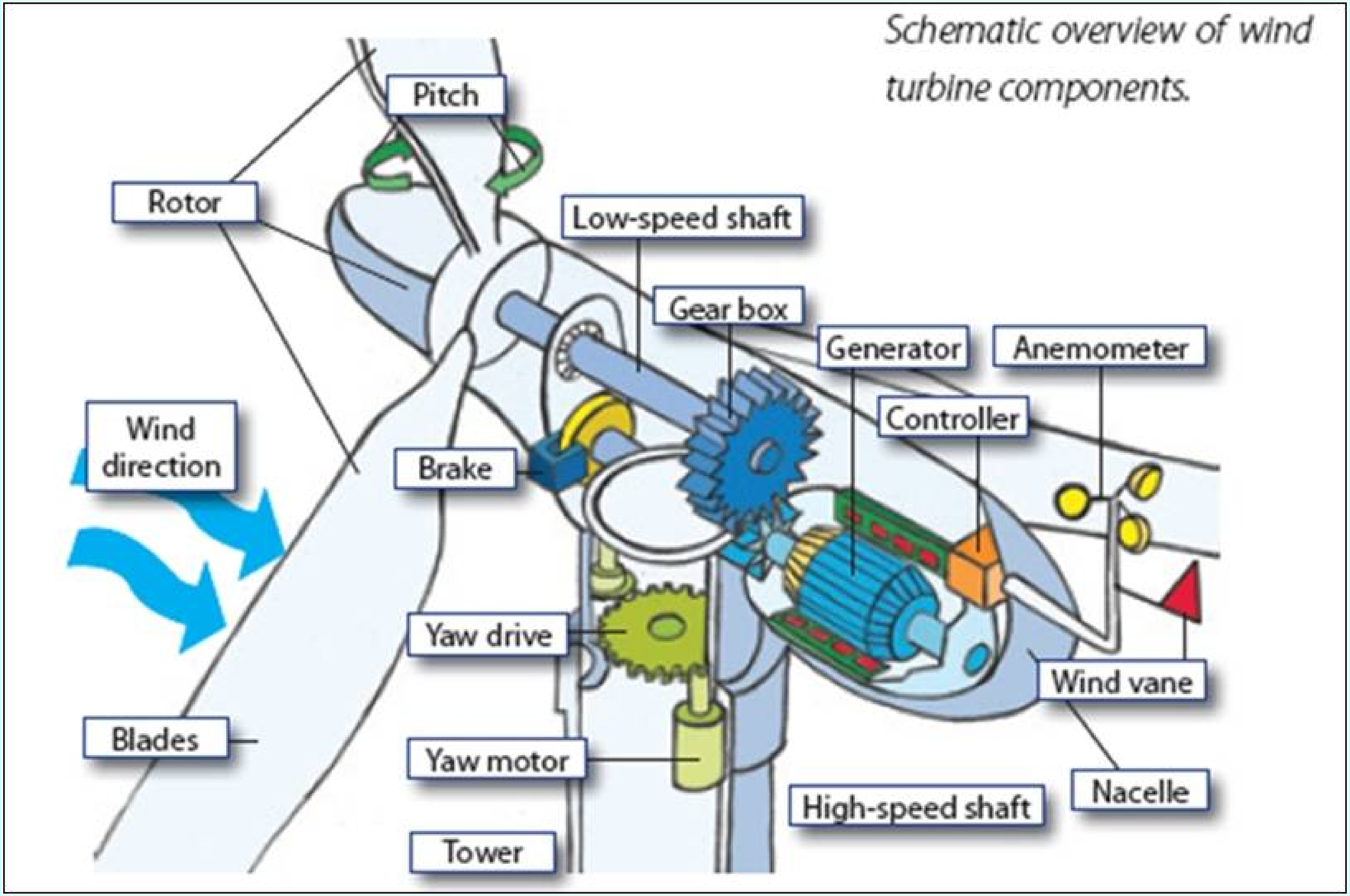
- **Coupled aero-hydro-servo-elastic interaction**
- **Models originate from different disciplines**
  - Wind-Inflow
  - Waves
  - Aerodynamics
  - Hydrodynamics
  - Structural dynamics
  - Control systems
- **Multi-Physics Simulation Tools**

Design Codes Examples

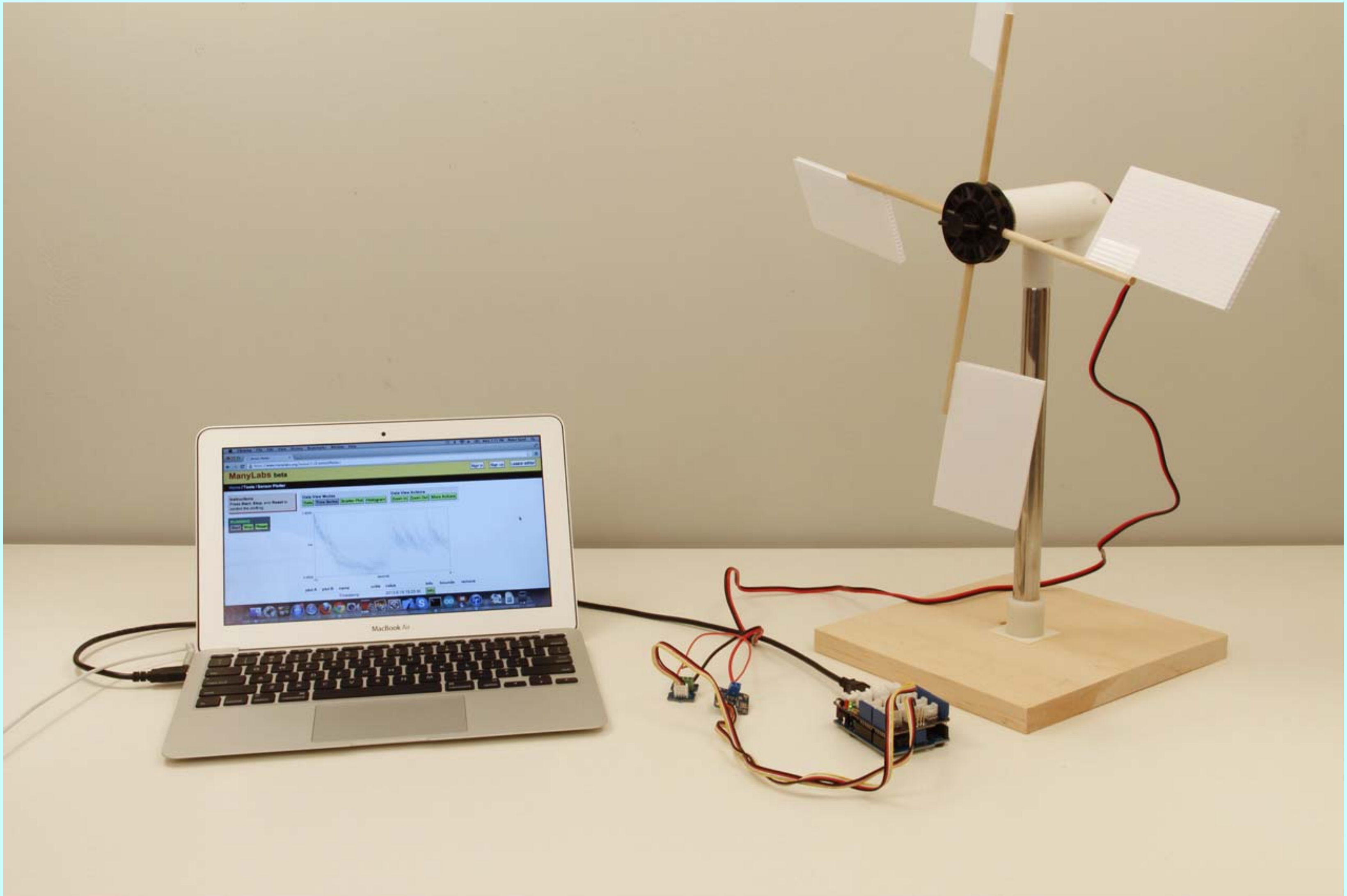


Coupled Aero-Hydro-Servo-Elastic Simulation

Wind Turbine Components



Measurement Sensors

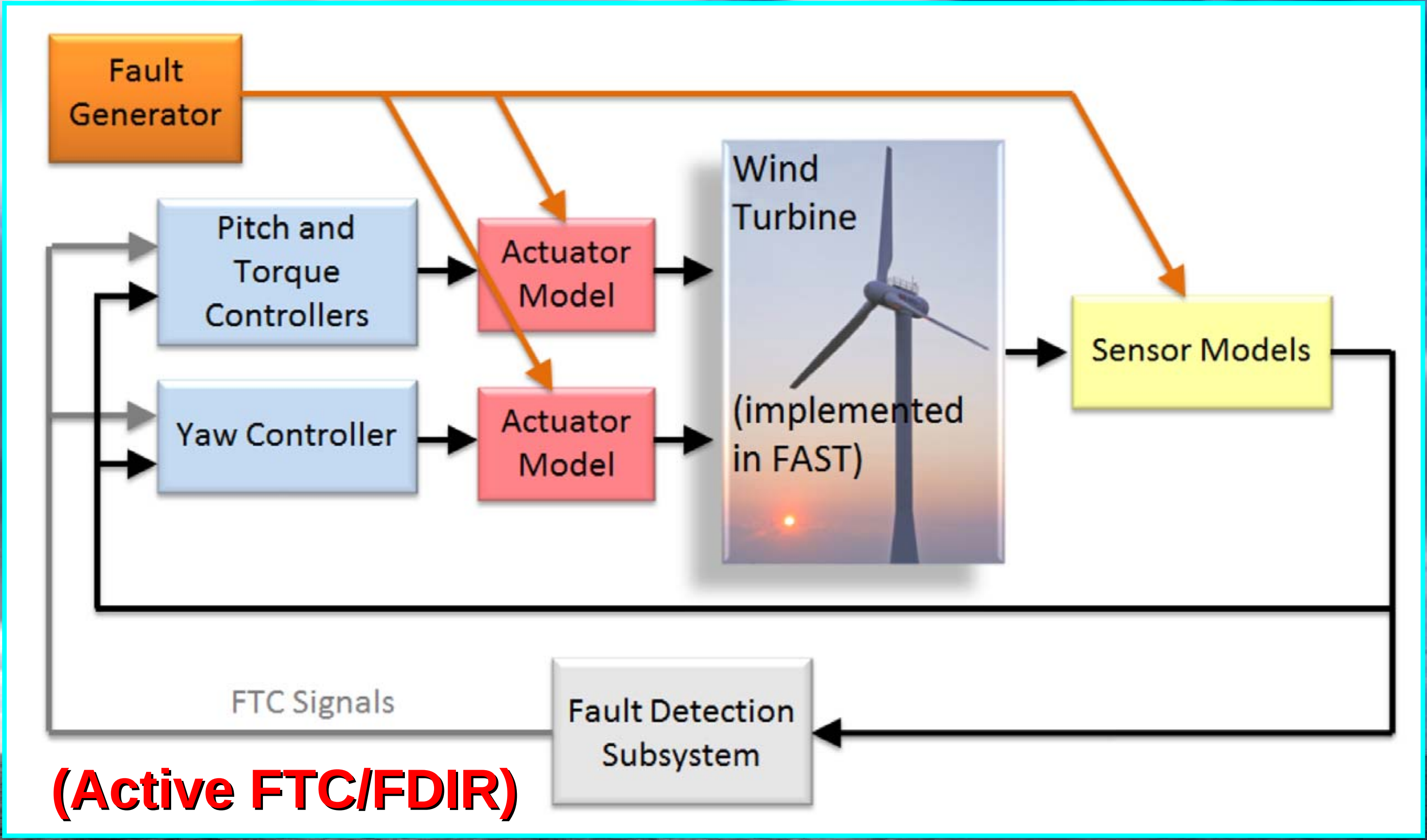


Measurements

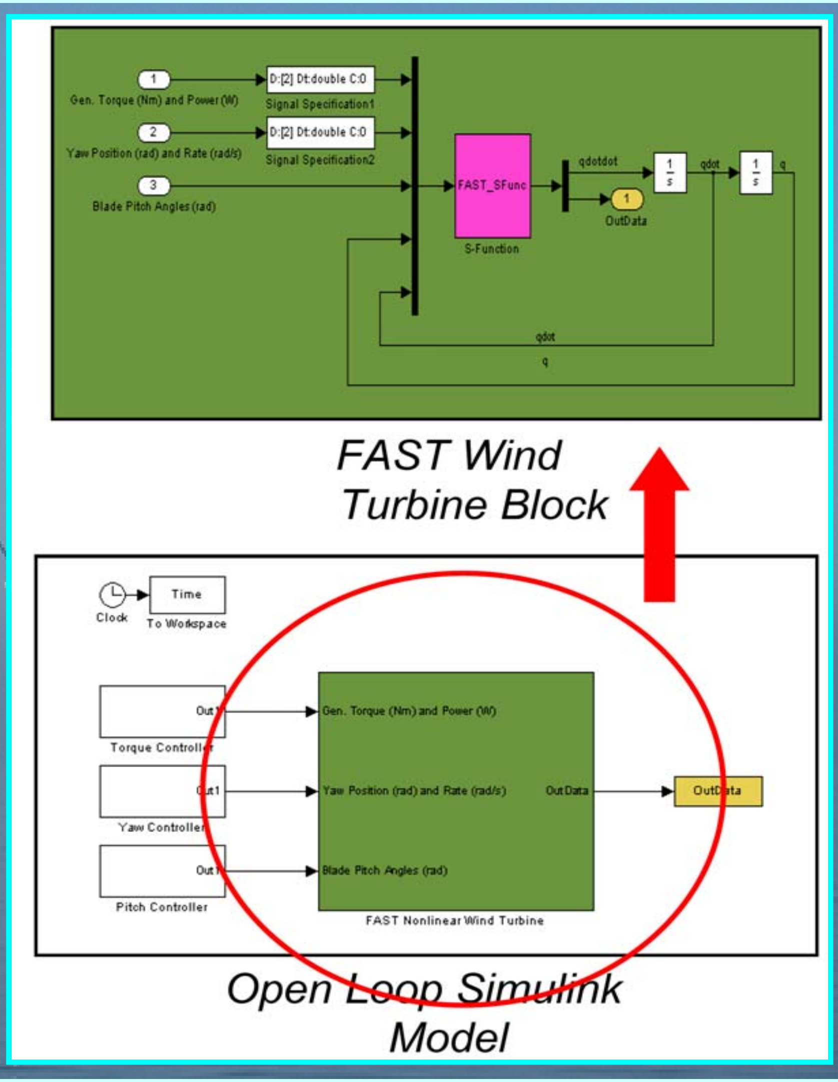
Sensor Type	Symbol	Unit	Noise Power
Anemometer - Wind speed at hub height	$v_{\mathrm{w,m}}$	m/s	0.0071
Rotor Speed	$\omega_{\mathrm{r,m}}$	rad/s	10^{-4}
Generator Speed	$\omega_{\mathrm{g,m}}$	rad/s	$2 \cdot 10^{-4}$
Generator Torque	$\tau_{\mathrm{g,m}}$	Nm	0.9
Generated Electrical Power	$P_{\mathrm{g,m}}$	W	10
Pitch Angle of i th Blade	$\beta_{i,\mathrm{m}}$	deg	$1.5 \cdot 10^{-3}$
Azimuth angle low speed side	ϕ_{m}	rad	10^{-3}
Blade root moment ith blade	$M_{\mathrm{B},i,\mathrm{m}}$	Nm	10^{3}
Tower top acceleration (x and y directions) measurement	$\begin{bmatrix} \ddot{x}_{\mathrm{x,m}} \\ \ddot{x}_{\mathrm{y,m}} \end{bmatrix}$	$\mathrm{m/s}^2$	$5 \cdot 10^{-4}$
Yaw error	$\Xi_{\mathrm{e,m}}$	deg	$5 \cdot 10^{-2}$

Wind Turbine Actuators

Simulink-based Scheme

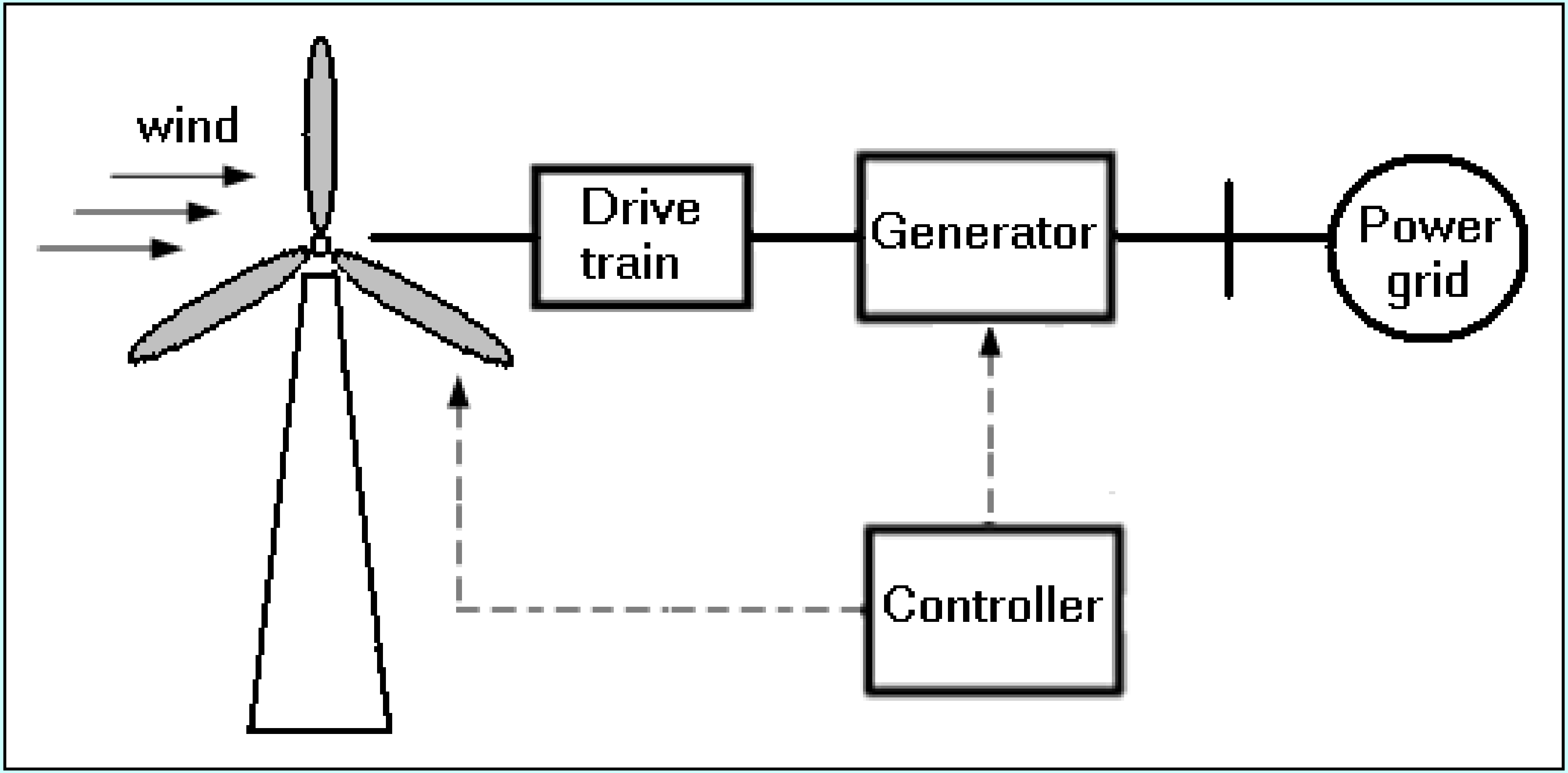


Wind Turbine Simulators



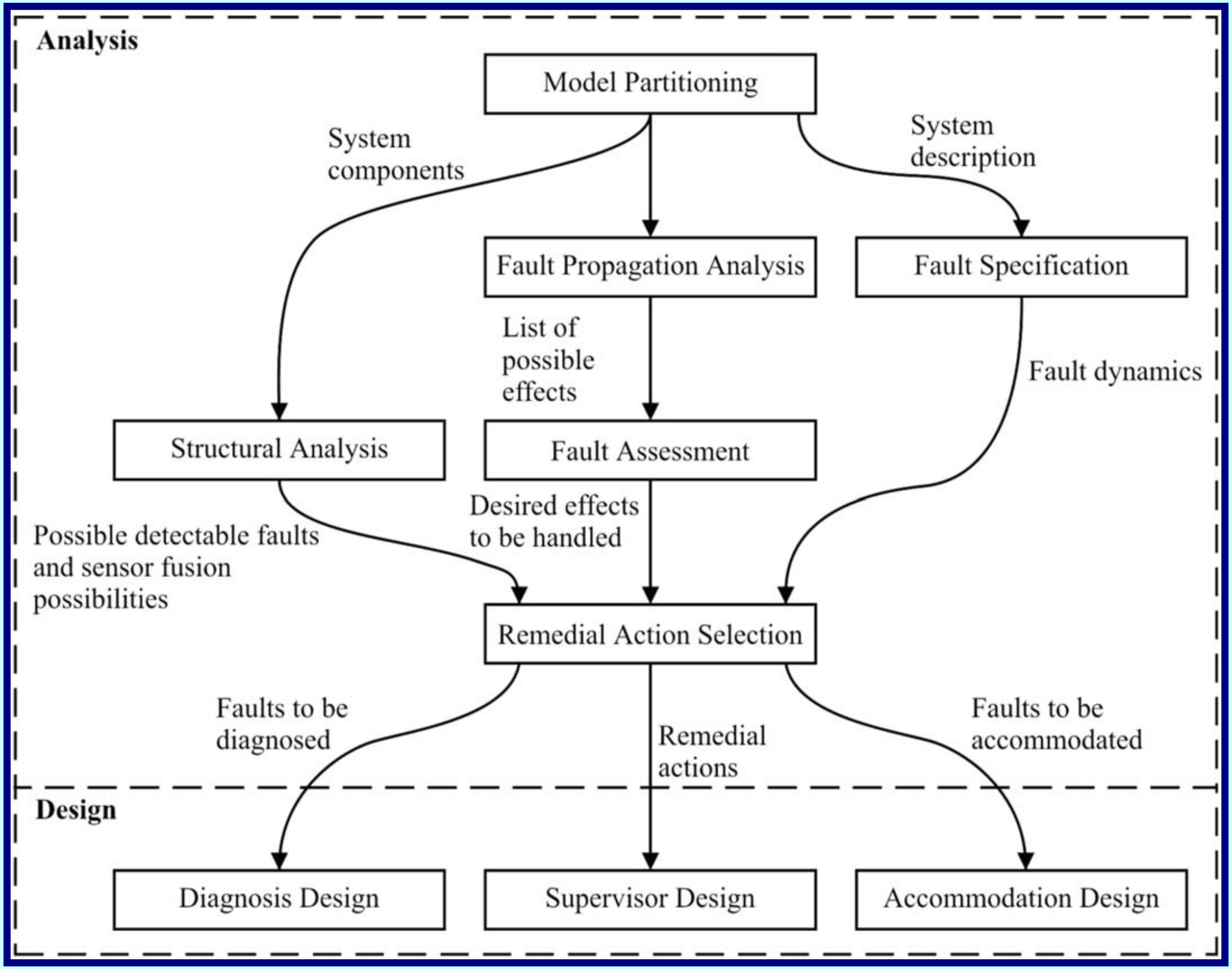
Reference Controller

Reference Controller



Fault Analysis

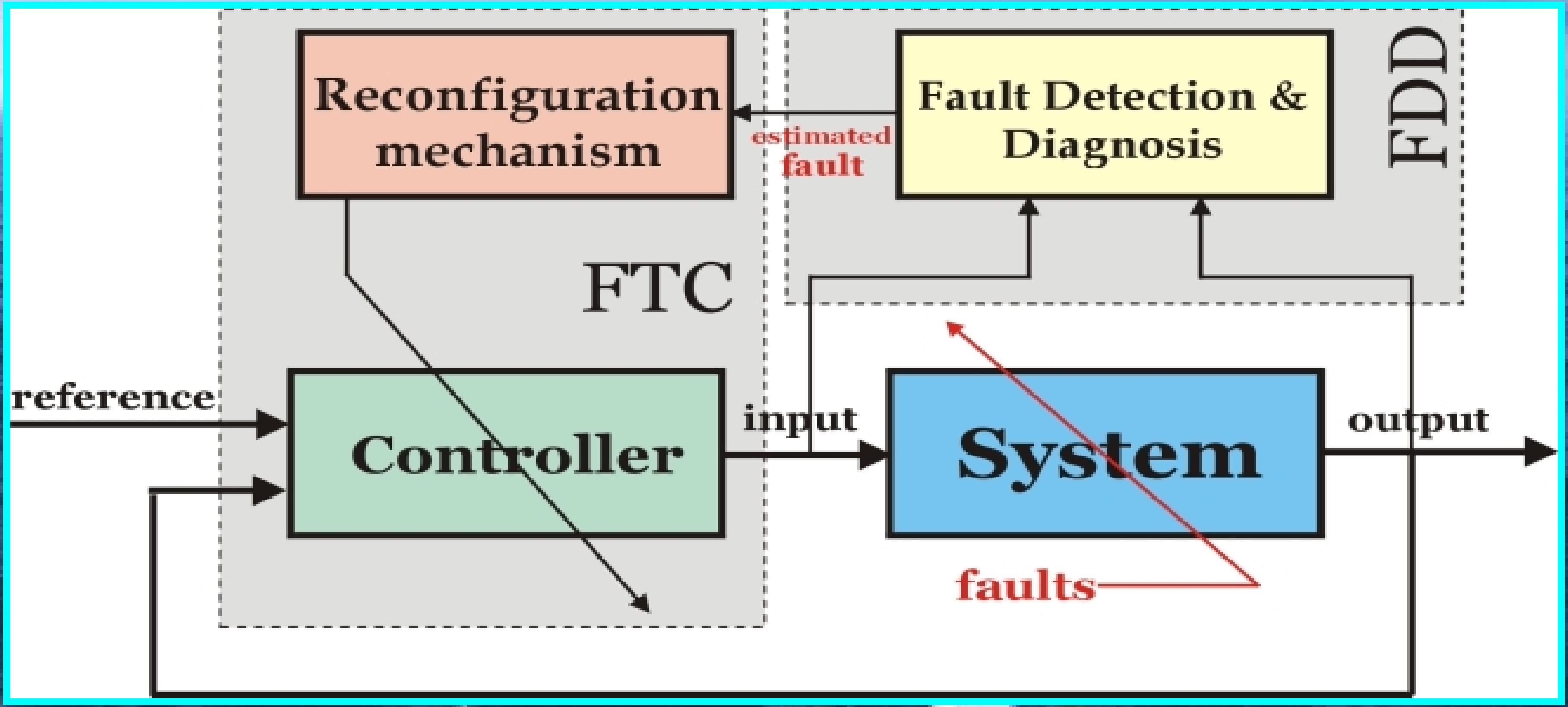
Failure Mode & Effect Analysis



Fault Scenario

Component	Fault
Pitch sensor	Biased output
Pitch actuator	Pump wear
	High air content in oil
	Hydraulic leakage
	Valve blockage
	Pump blockage
Generator speed sensor	Proportional error
	Fixed output
	No output

FTC General Structure

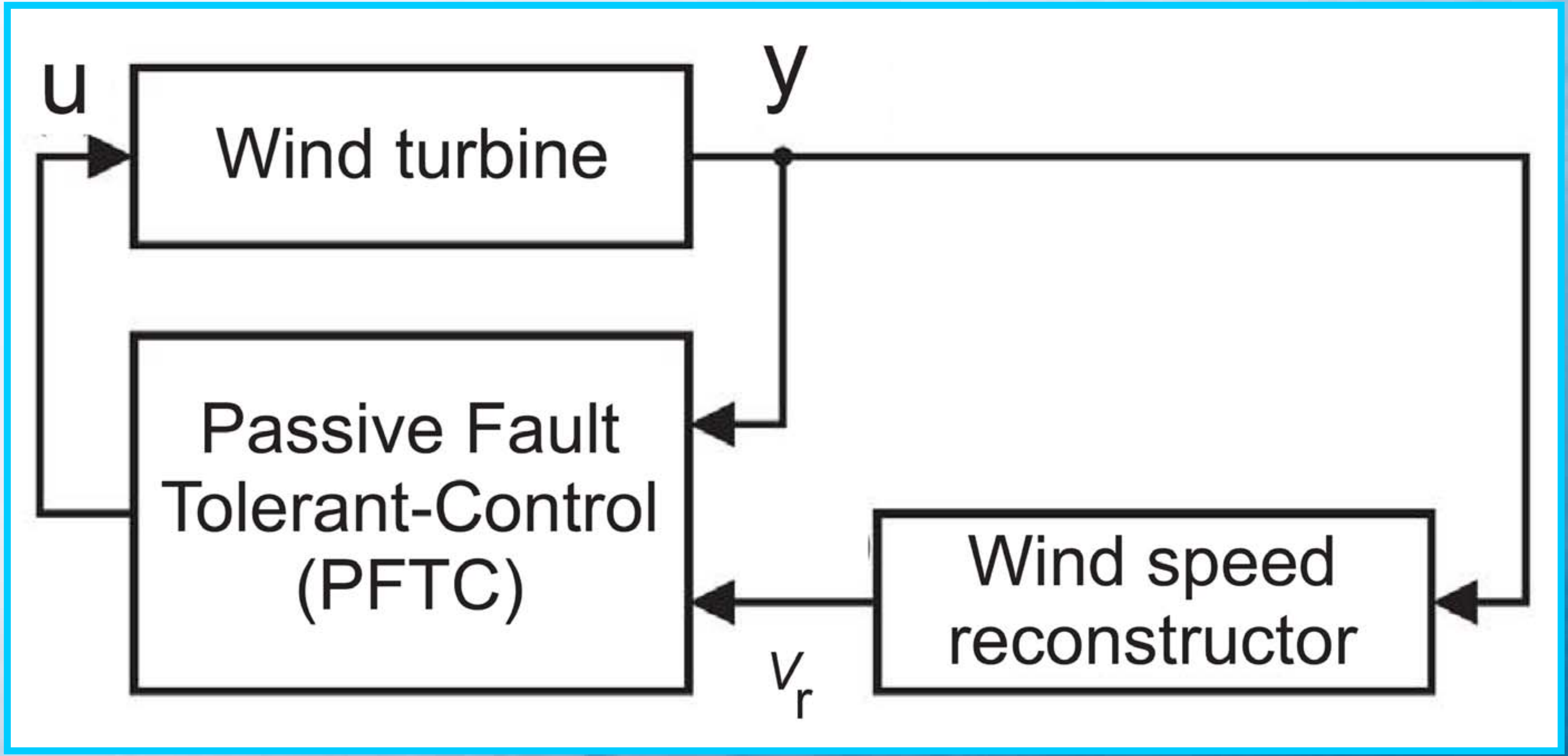


- ✓ **PFTC**: Robust fixed structure controller
- ✓ **AFTC**: Real-time controller reconfiguration

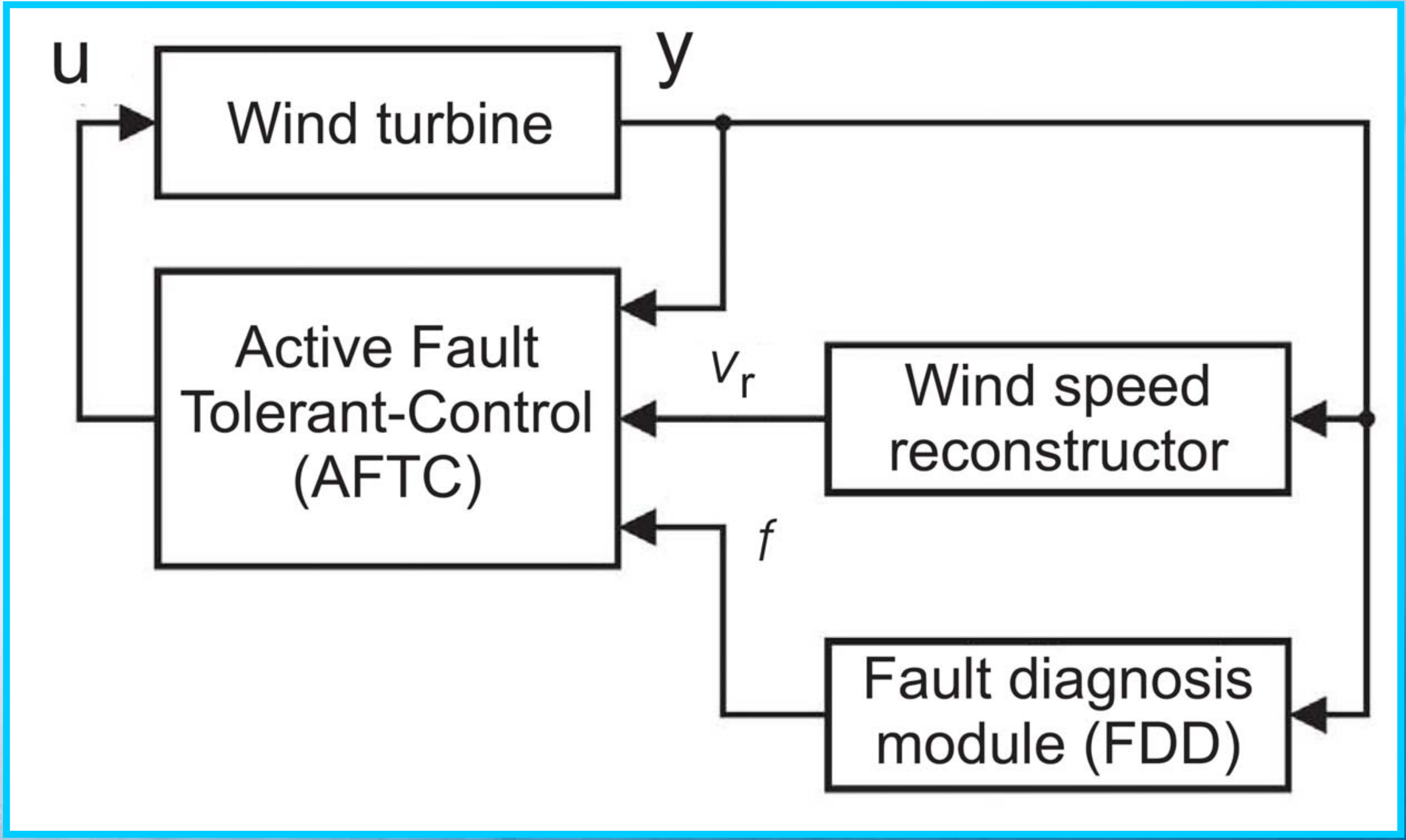
Fault Accommodation

Component	Fault	Fault Accommodation Method
Pitch sensor	Biased output	Signal correction of measurement and reference signals
Pitch actuator	High air content in oil	Active and passive fault-tolerant control
	Pump wear	
	Hydraulic leakage	Shut down the wind turbine
	Valve blockage	
	Pump blockage	
Generator speed sensor	Proportional error	Signal correction of measurement signal
	Fixed output	Signal correction of measurement signal (PL)
	No output	Active and passive fault-tolerant control (FL)

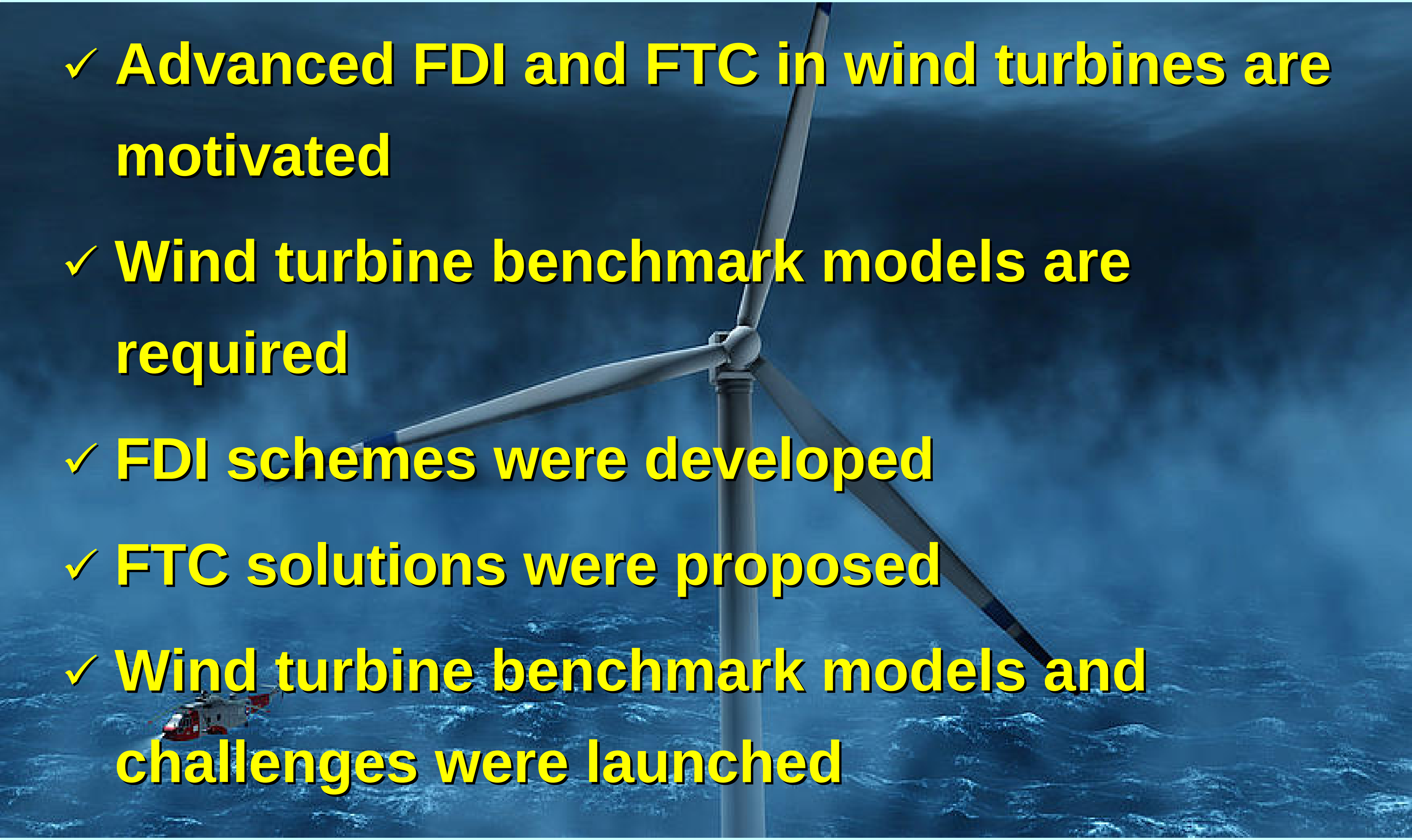
FTC Solutions: Passive



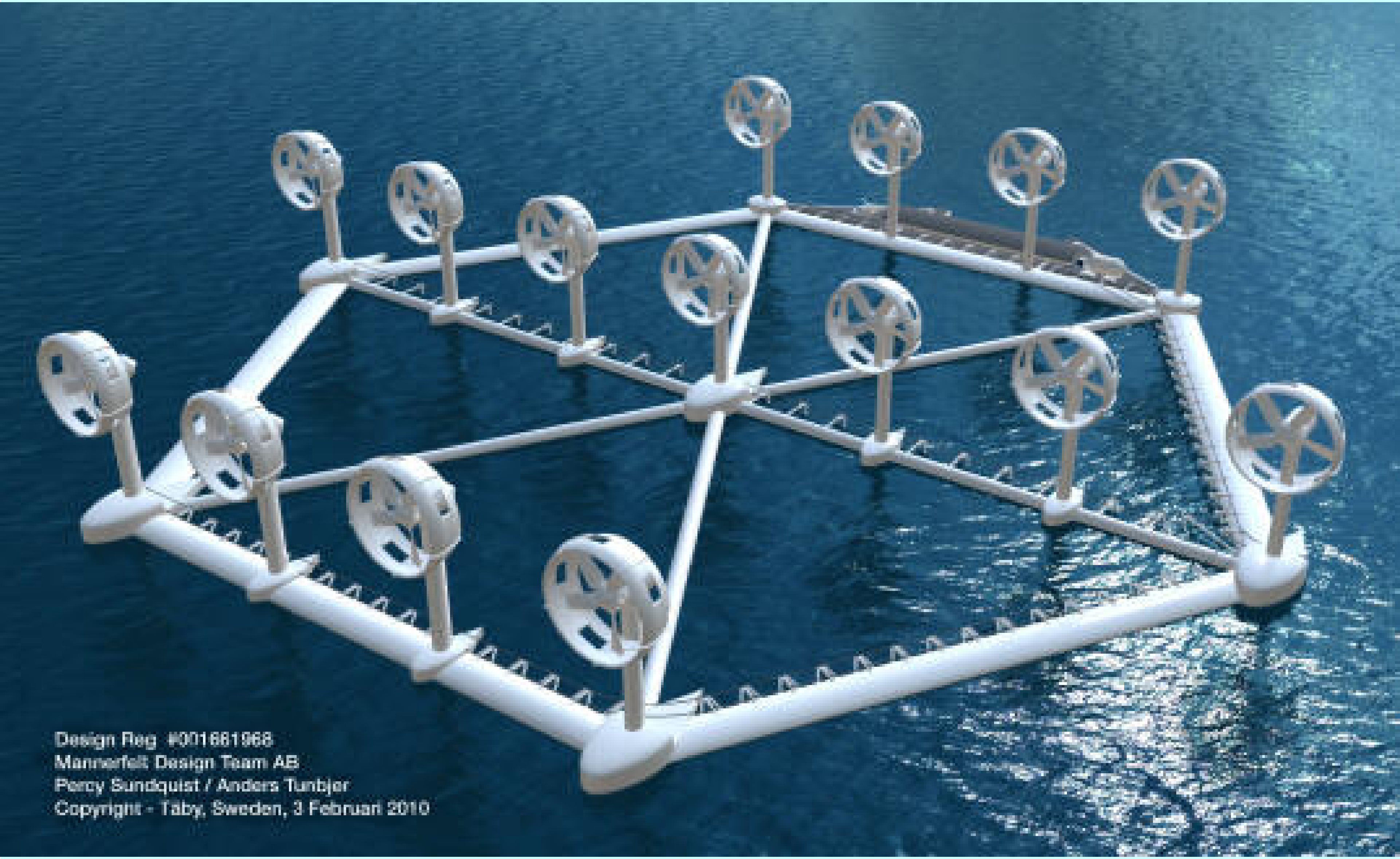
FTC Solutions: Active



Conclusion



- ✓ Advanced FDI and FTC in wind turbines are motivated
- ✓ Wind turbine benchmark models are required
- ✓ FDI schemes were developed
- ✓ FTC solutions were proposed
- ✓ Wind turbine benchmark models and challenges were launched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2nd Part: Hydroelectric Power

Discussion Topics

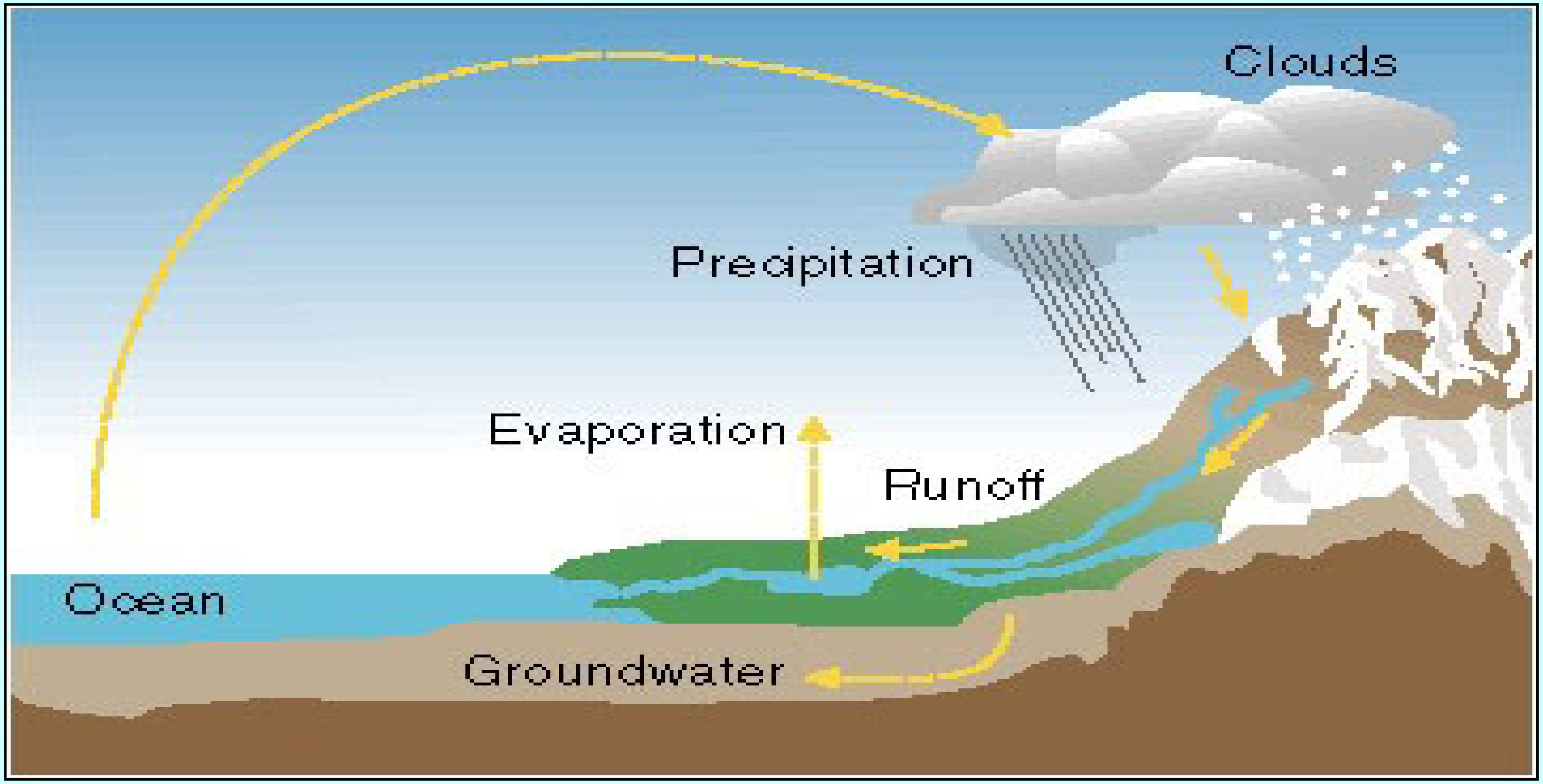
- General considerations
- Introduction
- General structures
- Hydroelectric modelling issues
- Concluding remarks

Hydroelectric power (often called hydropower) is considered a renewable energy source

A renewable energy source is one that is not depleted (used up) in the production of energy

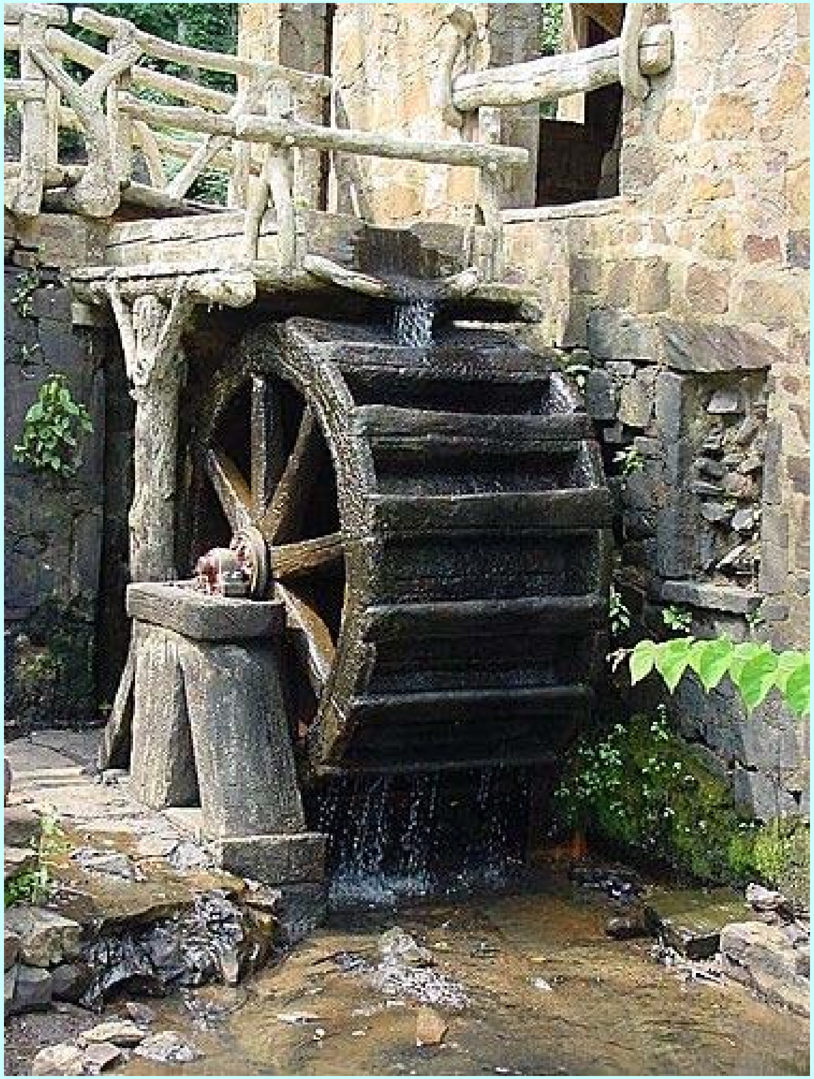
Through hydropower, the energy in falling water is converted into electricity without “using up” the water

Hydropower energy is ultimately derived from the sun, which drives the water cycle**. In the water cycle, rivers are recharged in a continuous cycle. Because of the force of gravity, water flows from high points to low points. There is** kinetic energy **embodied in the flow of water**



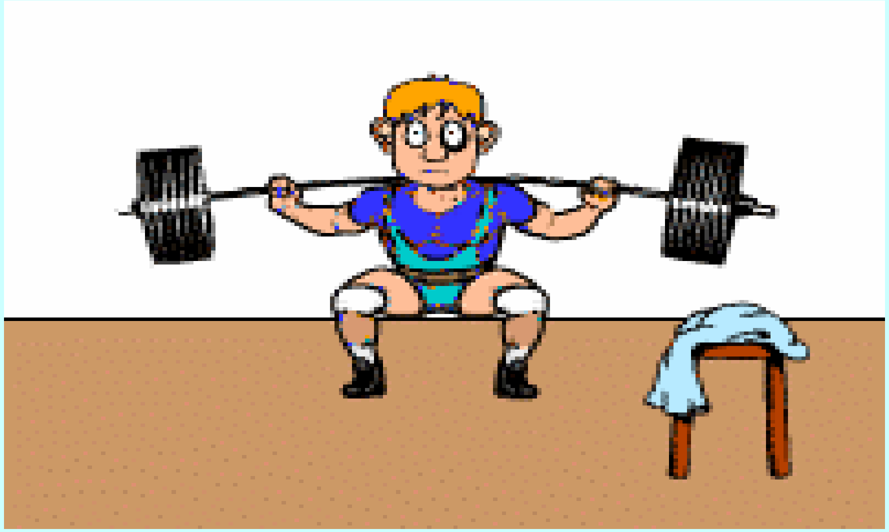
Kinetic energy is the energy of motion. Any moving object has kinetic energy

Water Wheel



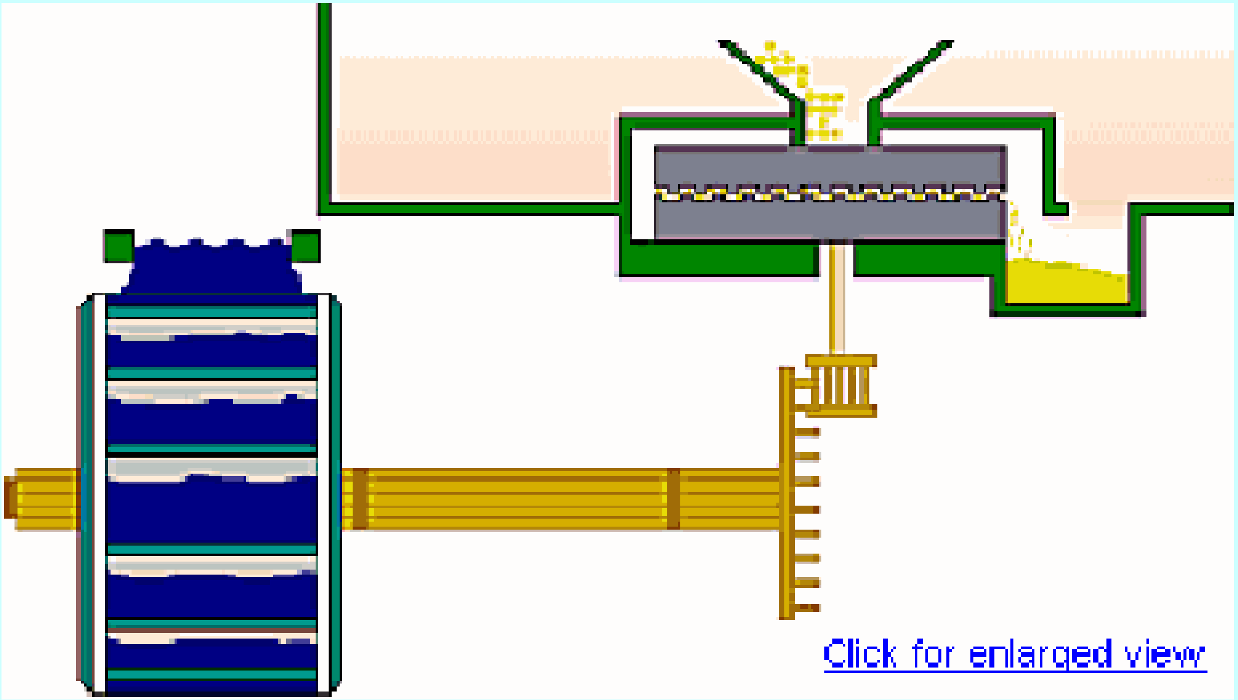
- Humans first learned to harness the kinetic energy in water by using **waterwheels**
- A waterwheel is a revolving wheel fitted with blades or vanes
- Waterwheels convert the **kinetic energy** of flowing water to **mechanical energy**

Mechanical Energy



- Mechanical energy is a form of kinetic energy, such as in a machine
- Mechanical energy has the ability to do work
- Any object that is able to do work has mechanical energy

Early Waterwheels



- Early waterwheels used mechanical energy to grind grains and to drive machinery such as sawmills and blacksmith equipment

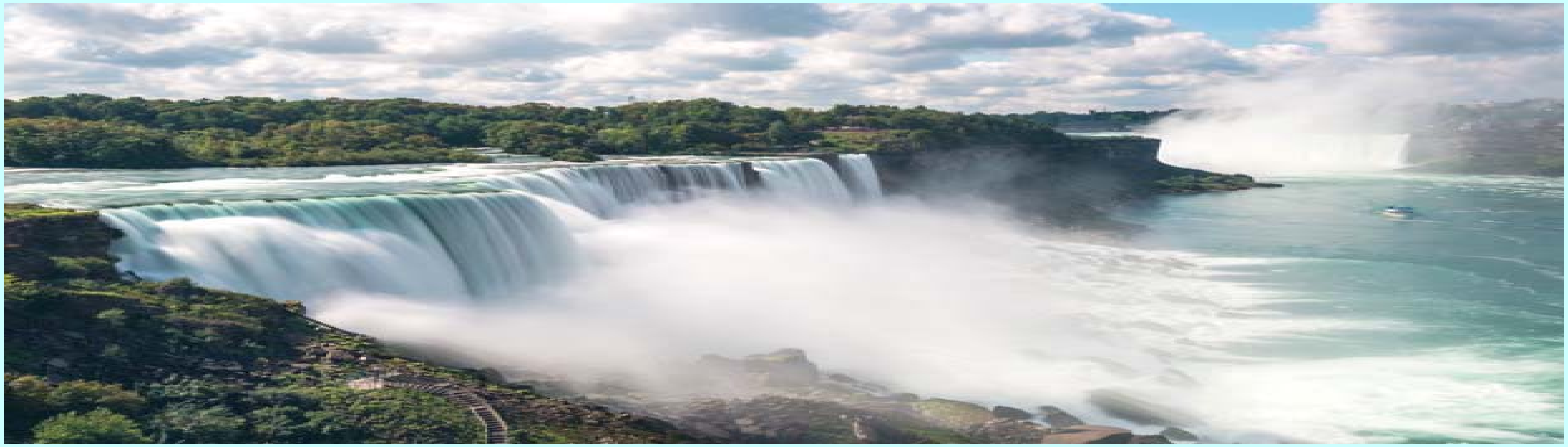
Waterwheel Technology

- Waterwheel technology advanced over time
- Turbines are advanced, very efficient waterwheels
- Often enclosed to further capture water’s energy

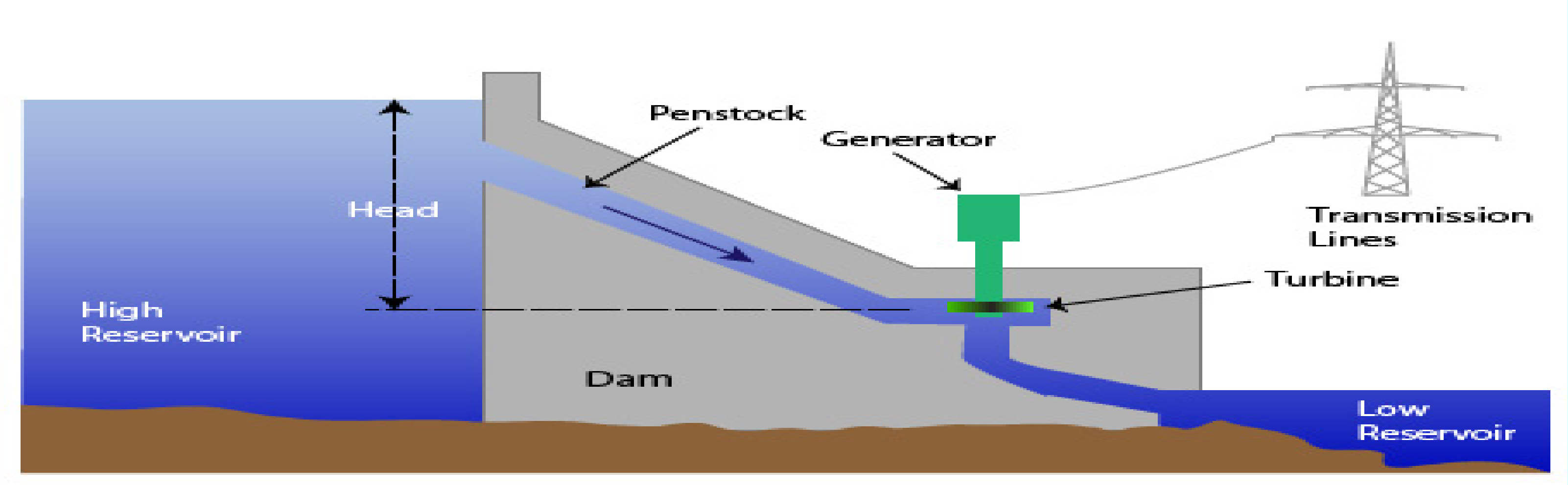
Mechanical Energy & Electricity

- Not long after the discovery of electricity, it was realized that a turbine's mechanical energy could be used to activate a generator and produce electricity
- The first hydroelectric power plant was constructed in 1882 in Appleton, Wisconsin. It produced 12.5 kW of electricity used to light two paper mills and one home

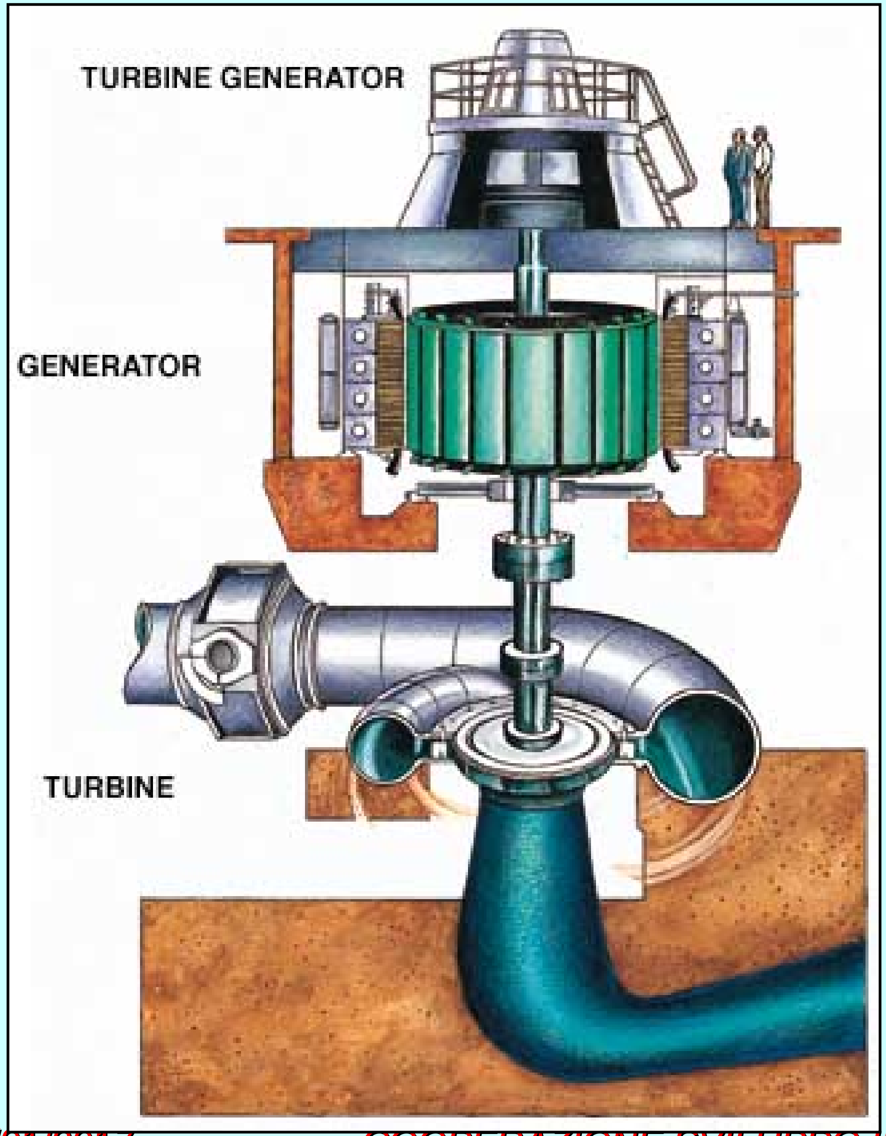
Hydroelectric Power



- Hydroelectric power (hydropower) systems convert the kinetic energy in flowing water into electric energy

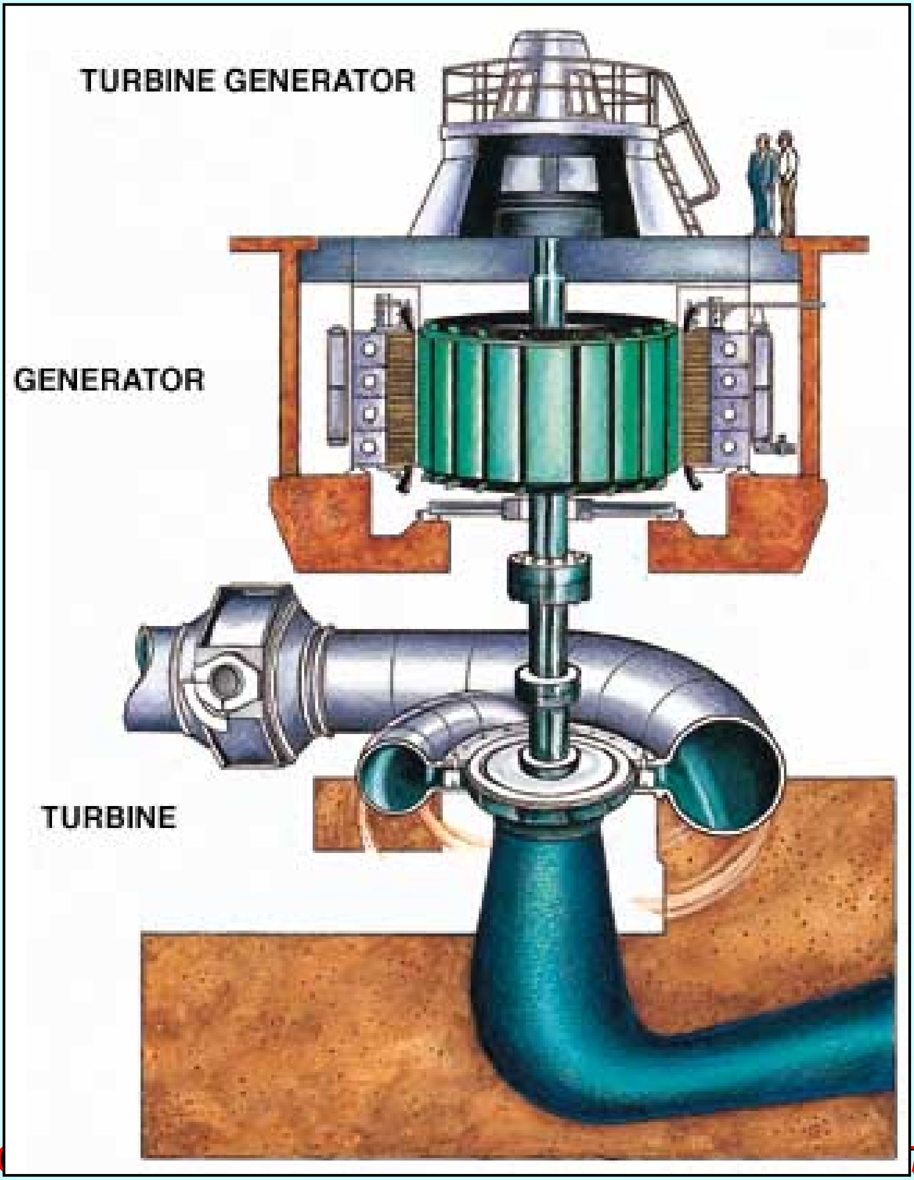


How a Hydroelectric Power System Works - Part 1



Flowing water is directed at a turbine (remember turbines are just advanced waterwheels). The flowing water causes the turbine to rotate, converting the water's kinetic energy into mechanical energy.

Hydroelectric Power System 1



- Flowing water is directed at a turbine (remember turbines are just advanced waterwheels)
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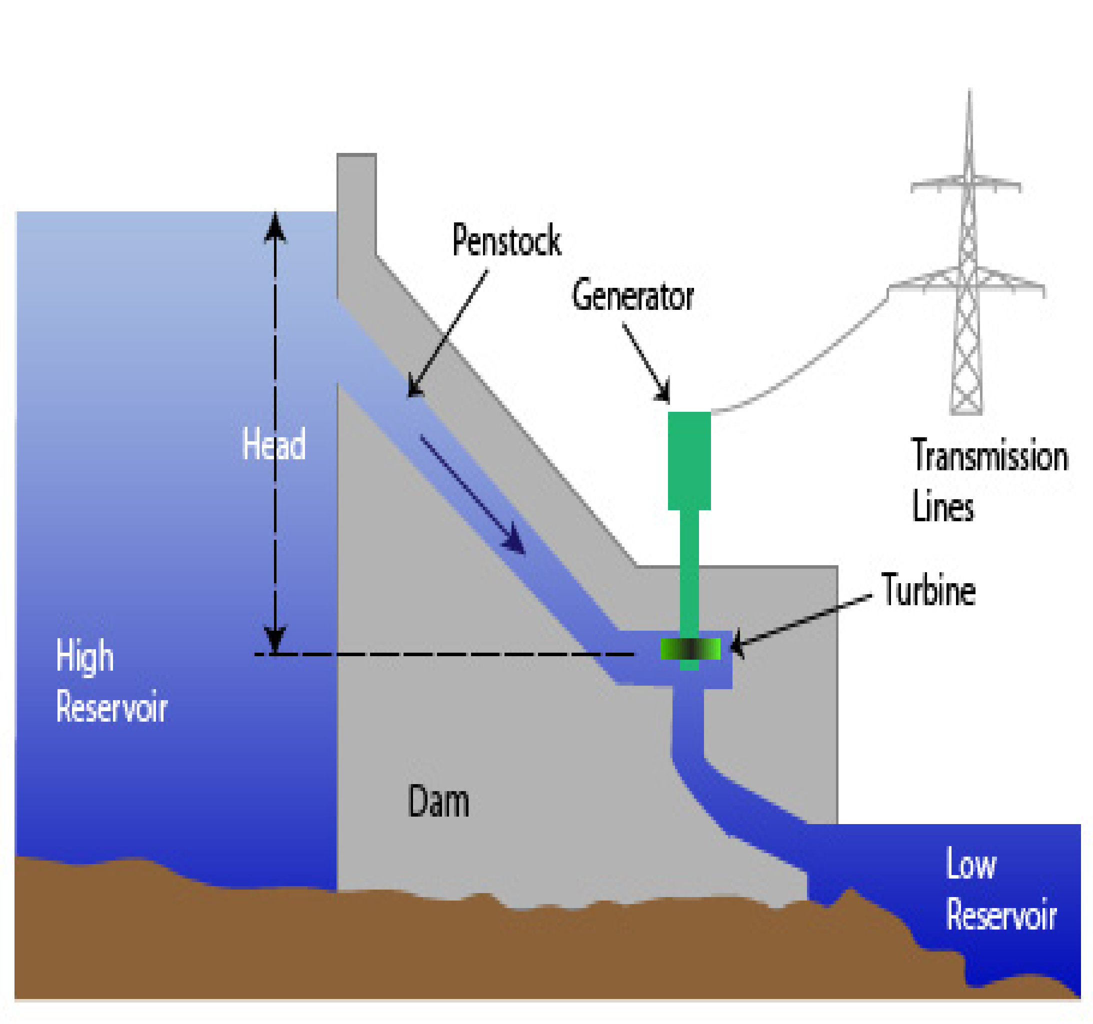
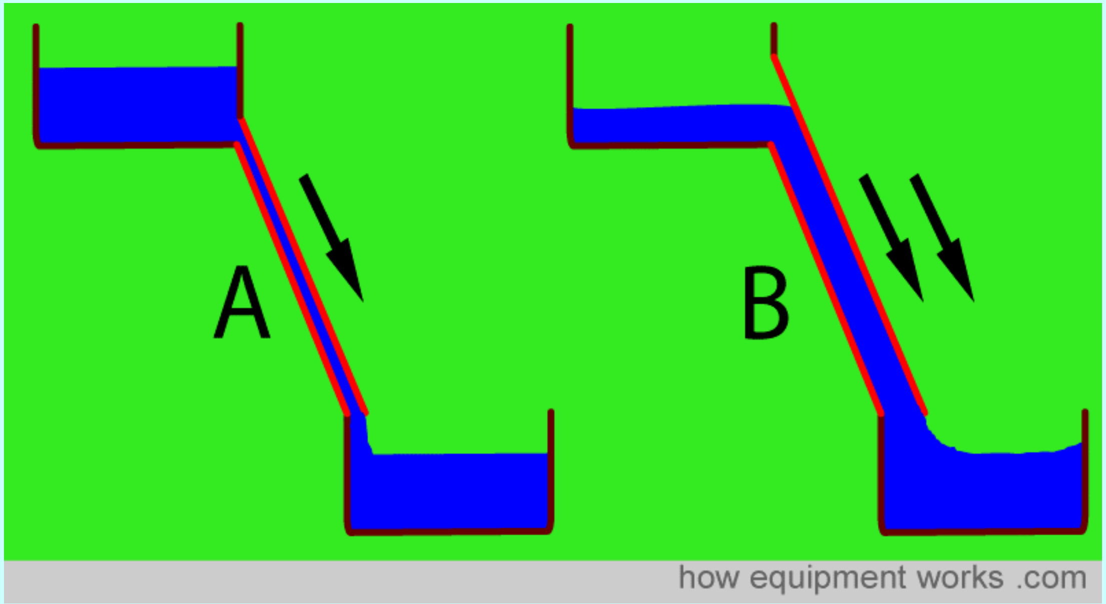
Hydroelectric Power System 2



- The mechanical energy produced by the turbine is converted into electric energy using a turbine generator
- Inside the generator, the shaft of the turbine spins a magnet inside coils of copper wire
- It is a fact of nature that moving a magnet near a conductor causes an electric current

Generated Electricity



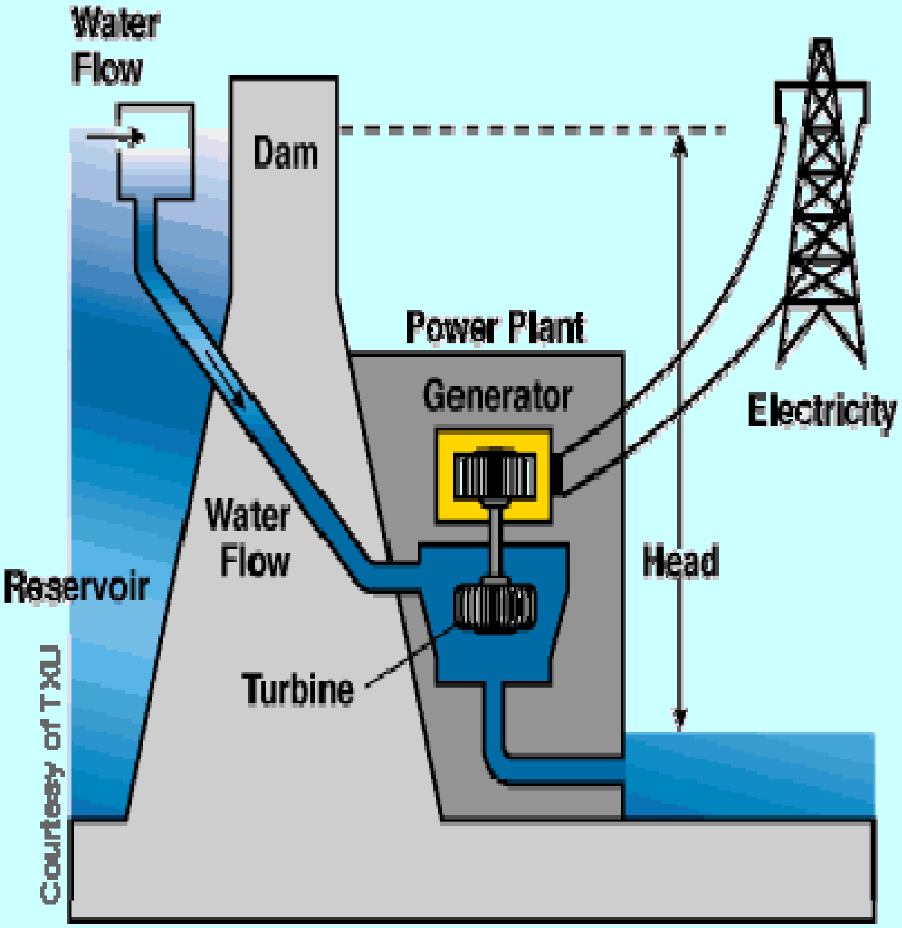
- The amount of electricity generated by a hydropower plant depends on two factors:
  - Flow rate - the quantity of water flowing in a given time
  - Head - the height from which the water falls
- The greater the flow and head, the more electricity produced

Flow Rate

- The quantity of water flowing
- When more water flows through a turbine, more electricity can be produced
- The flow rate depends on the size of the river and the amount of water flowing in it
- Power production is considered to be directly proportional to river flow

Head

- The height from which water falls
- The farther the water falls, the more power it has. The higher the dam, the farther the water falls, producing more hydroelectric power.
- Power production is also directly proportional to head. That is, water falling twice as far will produce twice as much electricity



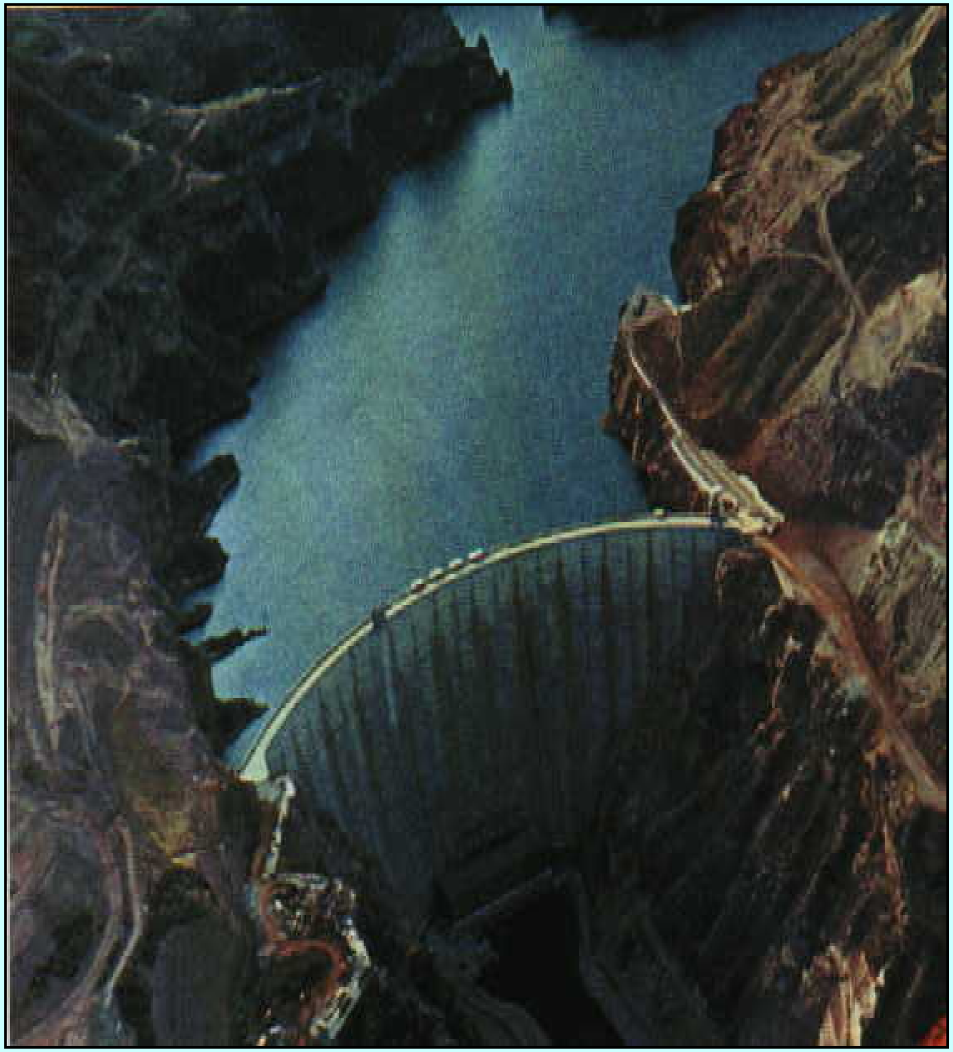
- It is important to note that when determining head, hydrologists take into account the pressure behind the water
- Water behind the dam puts pressure on the falling water

Energy Production

Power = (Head) x (Flow) x (Efficiency)

- **Power** = the electric power in kilowatts or kW
- **Head** = the distance the water falls (m)
- **Flow** = the amount of water flowing (m/s)
- **Efficiency** = How well the turbine and generator convert the power of falling water into electric power
  - This can range from 60% (0.60) for older, poorly maintained hydroplants to 90% (0.90) for newer, well maintained plants

High-head Hydropower



- Tall dams are sometimes referred to as “high-head” hydropower systems
- That is, the height from which water falls is relatively high

Low-head Hydropower

- Many smaller hydropower systems are considered “low-head” because the height from which the water falls is fairly low
- Low-head hydropower systems are generally less than 6 metres high

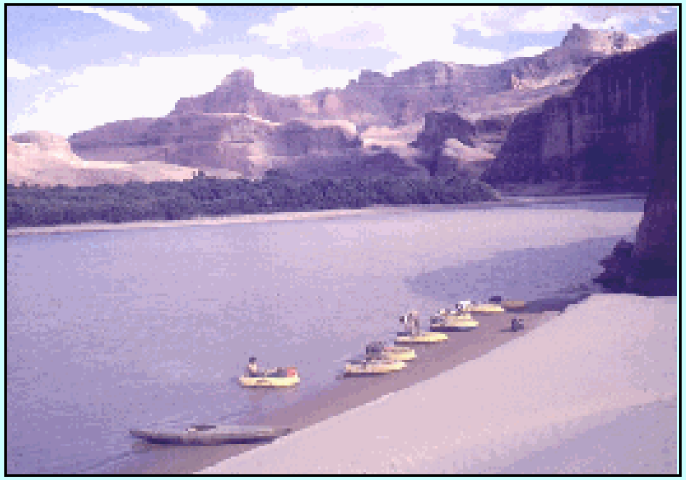
Environmental Considerations

High-head hydropower systems can produce a tremendous amount of power. However, large hydropower facilities, while essentially pollution-free to operate, still have undesirable effects on the environment

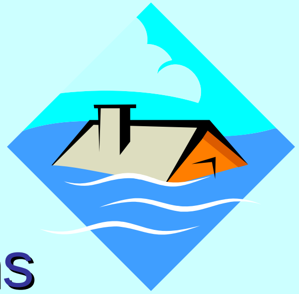
Environmental Considerations

- **High-head hydropower** systems can produce a tremendous amount of power
- However, large hydropower facilities, while essentially pollution-free to operate, still have **undesirable effects on the environment**

Installation of new large hydropower projects today is very controversial because of their negative environmental impacts. These include:

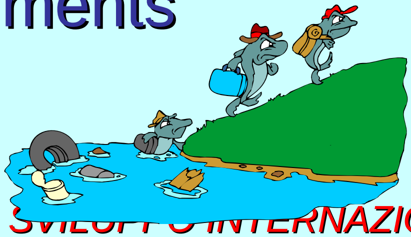


June 1962



- upstream flooding
- declining fish populations
- decreased water quality and flow
- reduced quality of upstream and downstream environments

June 1964



Low-head & Low Impact Hydropower

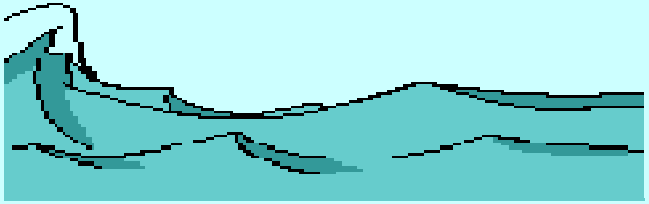
- Scientists today are seeking ways to develop hydropower plants that have less impact on the environment
- One way is through **low-head hydropower**
- These projects are usually **low impact** as well—that is, they have fewer negative effects on the environment

Low Impact Hydropower

- A hydropower project is considered low impact if it considers these environmental factors:

- River flow
- Water quality
- Watershed protection
- Fish passage and species protection
- Recreation & facilities
- Cultural resource protection

- Because the water cycle is continuous, hydropower is a renewable energy source



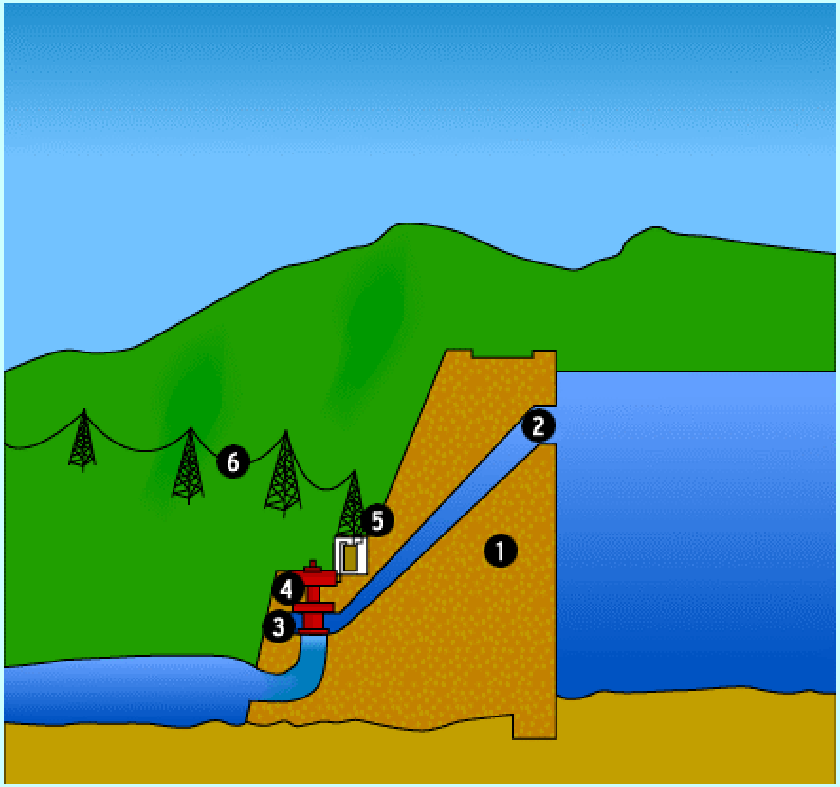
- The future of hydropower lies in technologies that are also environmental friendly

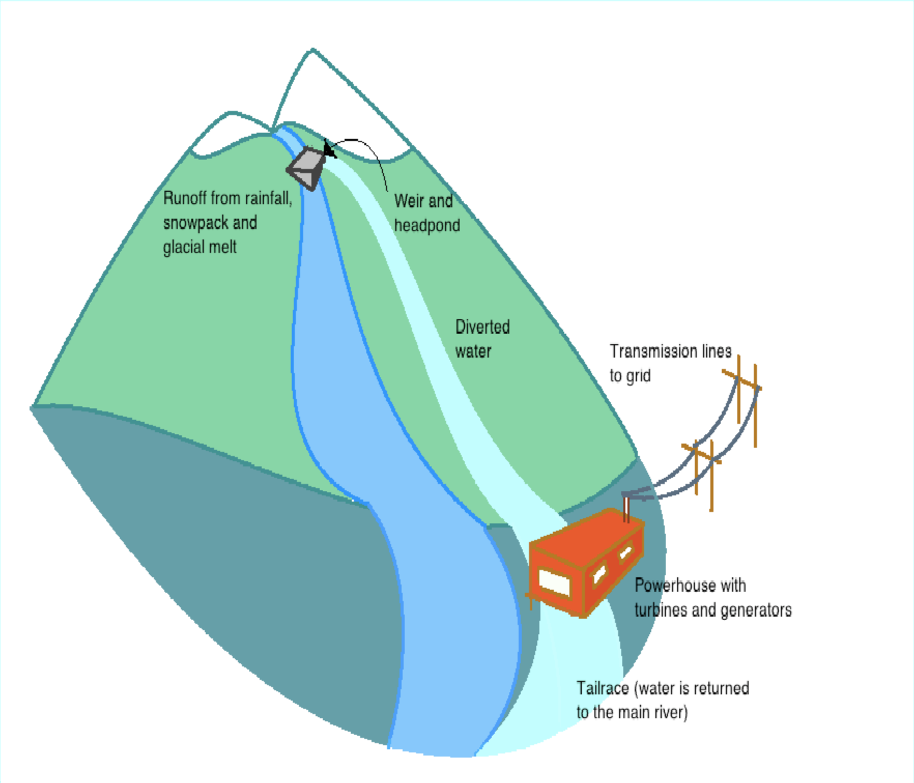
Low Impact Hydropower

- The amount of electricity produced depends upon the amount of water flowing (flow rate) and the height from which water falls (head)
- There are high-head and low-head hydropower systems. Low-head hydropower systems are generally less than 6 meters high

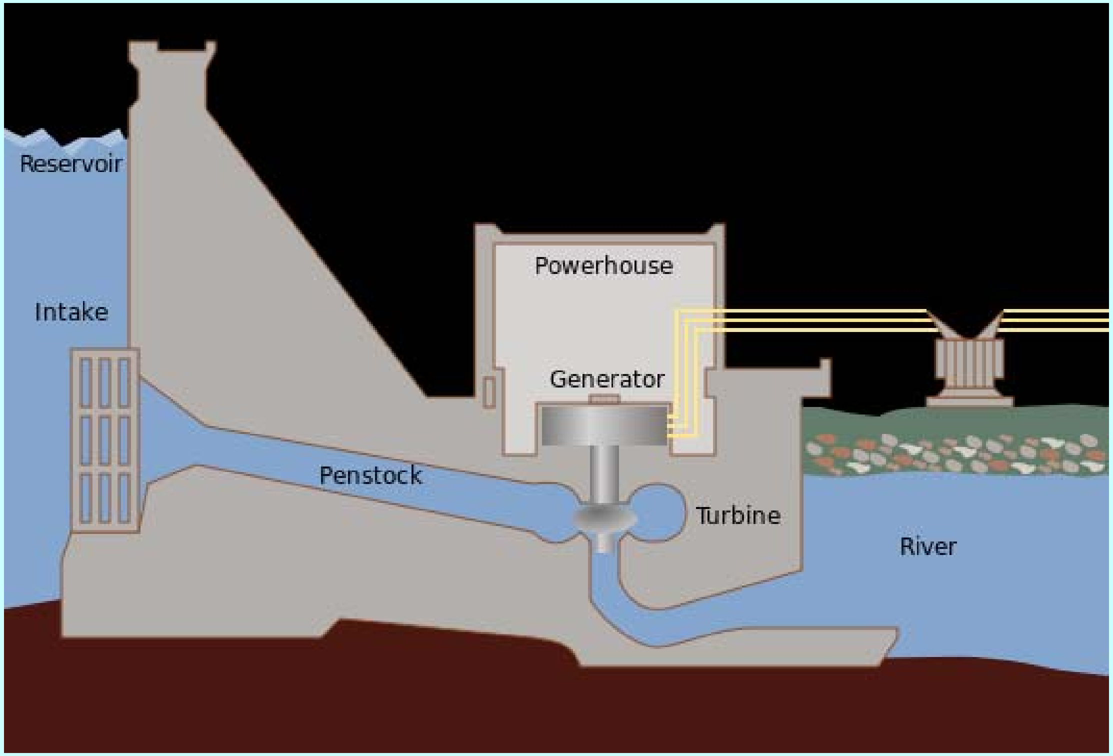
Hydropower Facilities

- 2 primary types of hydropower facilities: the **impoundment system (or dam) and the run-of-the-river system**



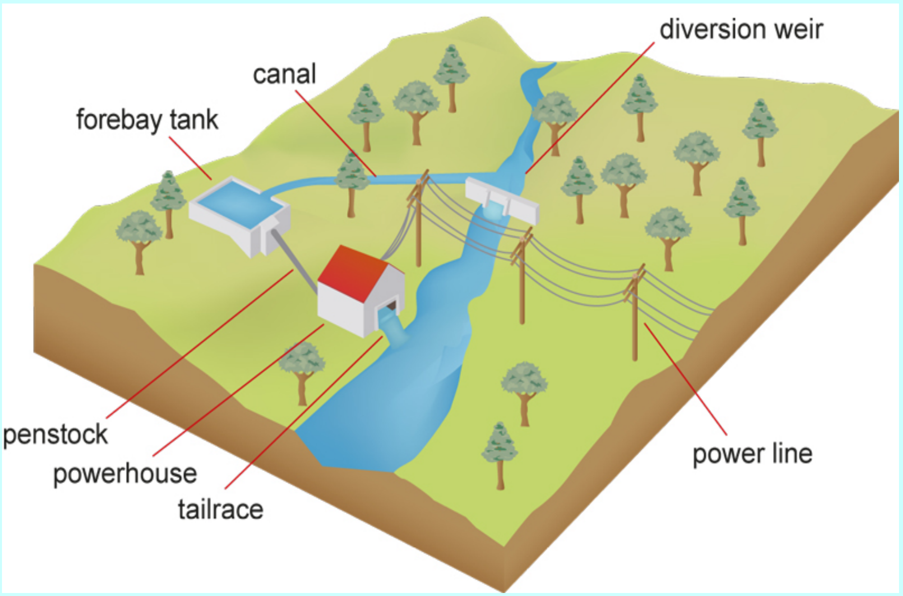


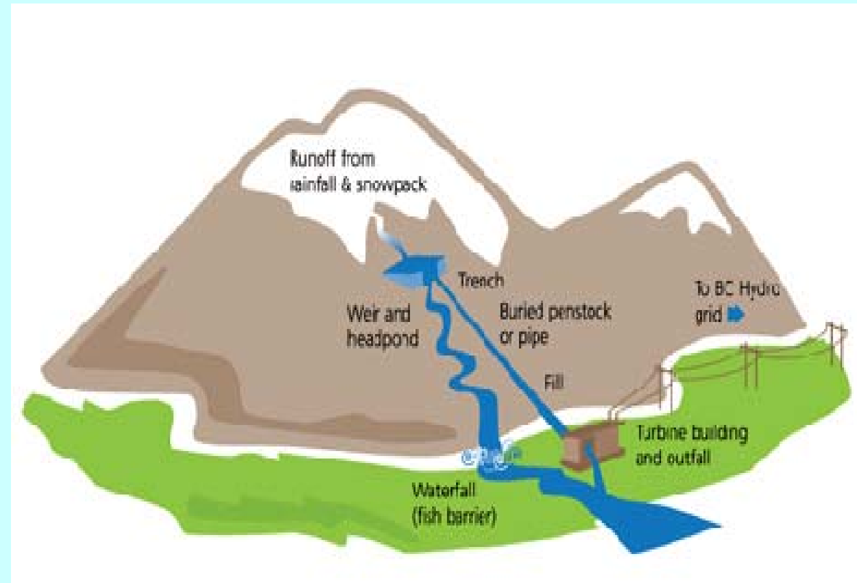
Impoundment System



- It is simply a dam that holds water in a reservoir
- Water released through a penstock to drive the turbine
- Large & high-head hydropower facilities use impoundments

Run-of-the-River Hydropower System





- It the river's natural flow and requires little or no impoundment, e.g. a diversion of a portion of the stream through a canal or penstock, or it may involve placement of a turbine right in the stream channel
- Often low-head

Hydropower Size

- There are large power plants that produce hundreds of megawatts of electricity and serve thousands of families
- There are also small and micro hydropower plants that individuals can operate for their own energy needs
- Power plants are classified by how much energy they are able to produce

Large Hydropower

- A large hydropower facility has the capacity to produce more than 30,000 kW
- Large hydropower systems typically require a dam

Small Hydropower

- They can produce 100 – 30,000 kW
- Small hydropower facilities may involve a small dam, or be a diversion of the main stream, or be a run-of-the-river system

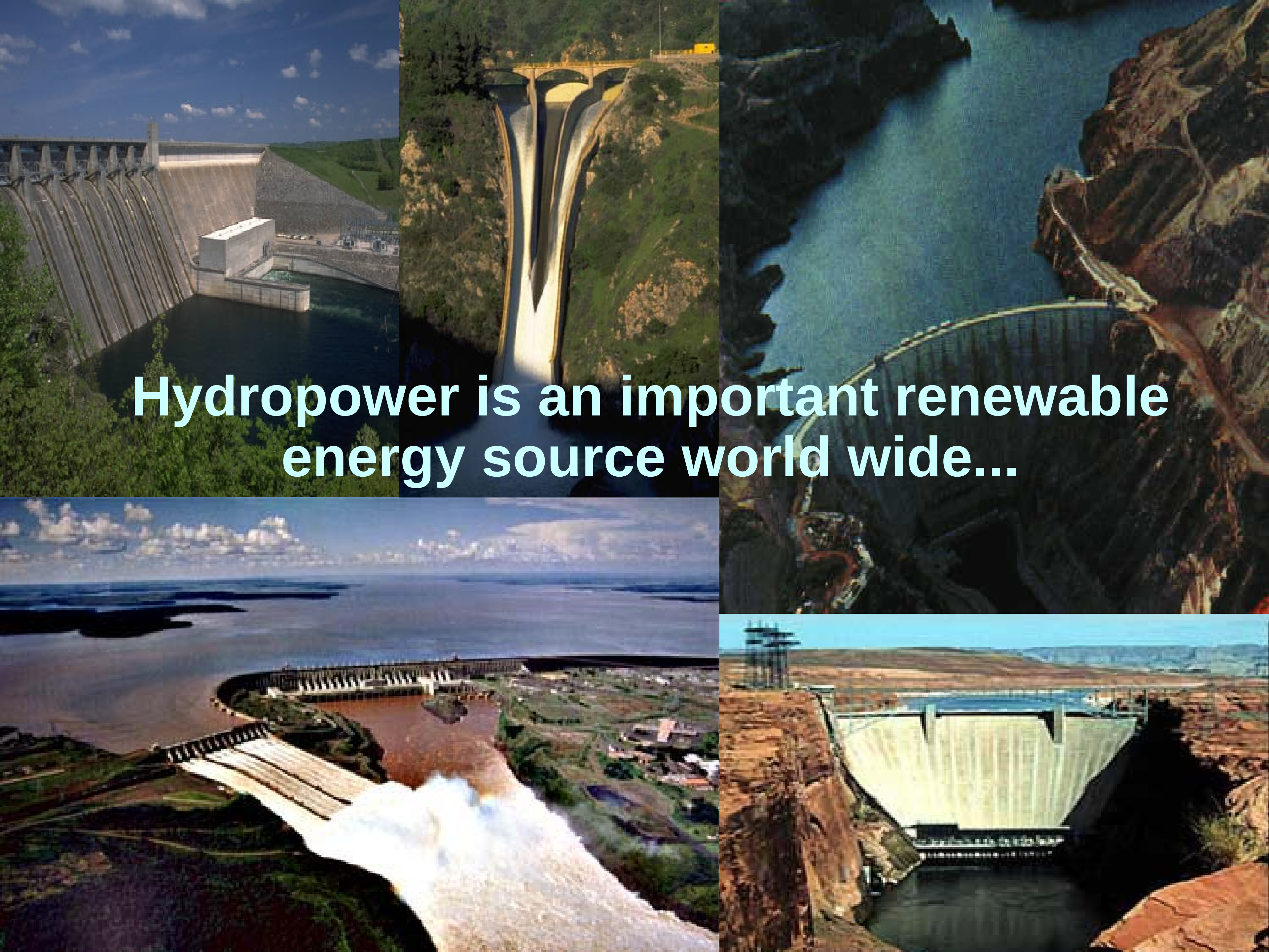
Micro Hydropower

- Micro hydropower plants have the capacity to produce 100 kilowatts (kW) or less.
- Micro-hydro facilities typically use a run-of-the-river system

Arizona Falls, a low-head hydropower system, is the Valley's newest hydroelectric generation station. An exciting example of a low impact, renewable energy source, Arizona Falls is open to the public as a place to experience water and its contribution to our energy and water needs.

Example

- Low-head hydropower system, a new hydroelectric generation station
- Low impact, renewable energy source


Hydropower is an important renewable
energy source world wide...