[1040-EL-ISA-1DA1209] Energy Conversions Lectures, group 39167	Title: Project on Supercapacitor, Flywheel, DMFC Fuelcell, LTO Battery, Wind Turbine and Gas Turbine technologies	Class 1 Electrical Engineering Group: School year: 2023/2024
Team members: Maciej Hildebrandt Zbigniew Michaluk Piotr Wasylów	Teacher conducting lab. dr hab. inż. Mariusz Kłos	Warsaw University of Technology Plac Politechniki 1, Warszawa

1.SUPERCAPACITOR

1. INTRODUCTION

Supercapacitors or ultra-capacitors or electro-chemical capacitors, uses materials with large area of surface as electrodes and low thickness dielectric electrolytes to attain capacitance of several orders higher than capacitors of conventional nature. By making this, supercapacitors obtain higher energy density with higher power density which is the characteristic feature of common capacitors.

Their unique properties bridge the gap between traditional capacitors and batteries which make them suitable for a variety of applications ranging from consumer electronics to industrial power backup systems and electric vehicles.

2. PRINCIPLE OF OPERATION

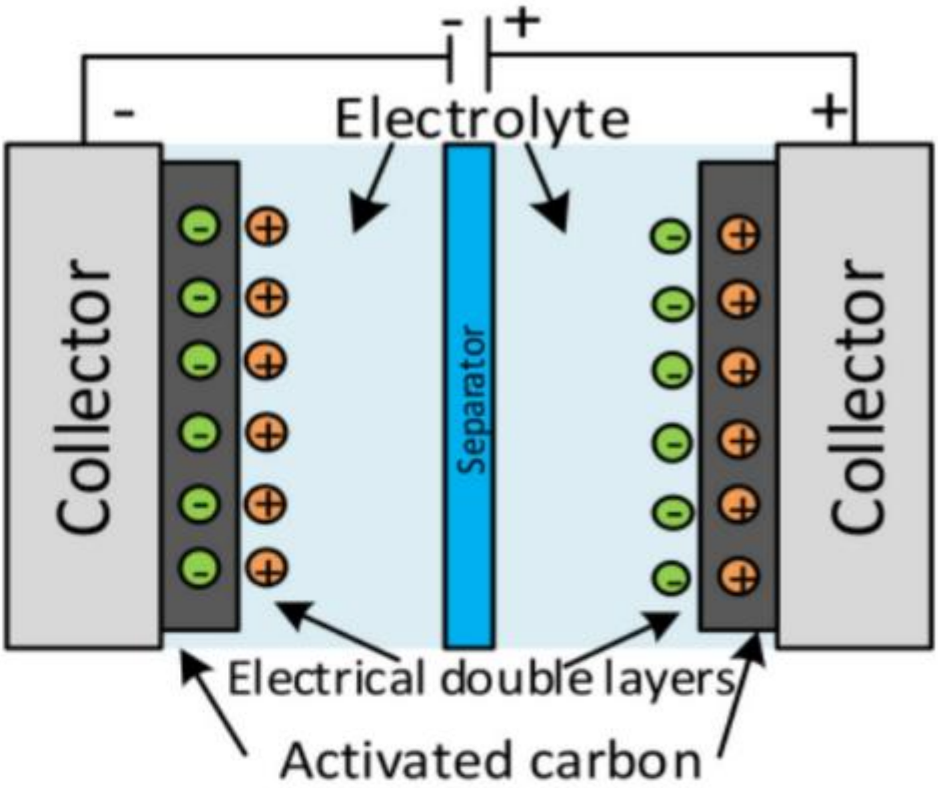
Supercapacitors operate on principles that involve electrochemical and electromagnetic phenomena depending on the type of the supercapacitor. They can be charged electrostatically or electrochemically depending on their type.

- Electrostatic Storage (Electrochemical Double-Layer Capacitors): In EDLCs, energy storage occurs via the formation of an electric double layer at the interface between the electrode and the electrolyte. When a potential is applied, ions in the electrolyte migrate to the electrode surface, forming a layer of charge. The capacitance (C) is directly proportional to the surface area (A) of the electrode and inversely proportional to the distance (d) between the charges:

$$C=(\epsilon A)/d$$

- Electrochemical Storage (Pseudocapacitors): Pseudocapacitors store energy through fast, reversible redox reactions at the electrode surface. Unlike EDLCs, which store charge purely electrostatically, pseudocapacitors involve faradaic processes. These reactions contribute additional capacitance and energy density beyond what is achievable with electrostatic storage alone.

Charging electrostatically invoves generating electric fields between the electrodes during charging, creating an electric double layer in EDLCs.



(b)

Figure 1. diagram of a supercapacitor

The basic structure of a supercapacitor involves 3 main elements visible on figure 1:

- **Electrodes:** Typically made of high surface area materials like activated carbon.
- **Separator:** Prevents electrical shorting while allowing ionic movement.
- **Electrolyte:** Facilitates ion migration between electrodes.

3. MATERIALS OF CONSTRUCTION

The performance of supercapacitors is mainly dependent on materials used in construction. The high capacitance as opposed to conventional capacitors comes from high quality materials in electrolytes, electrodes and separators.

Electrode

- The performance of supercapacitors depends largely on the nature and type of electrode material used.
- Carbon nanomaterials will bring out higher surface areas and exhibit higher specific capacitance.
- Transition metal oxides are known for their better electrochemical properties.

Electrode materials for supercapacitors: A comprehensive review of advancements and performance, ISSN 2352-152X

ACTIVATED CARBON

- **Properties:** High surface area, good conductivity, relatively low cost.
- **Applications:** Widely used in EDLCs due to its ability to form extensive electric double layers.

GRAPHENE

- **Properties:** Exceptional electrical conductivity, very high surface area, flexibility.
- **Applications:** Used in advanced supercapacitors to achieve high energy and power densities.

METAL OXIDES (E.G., RUO2, MNO2)

- **Properties:** High pseudocapacitance, good conductivity, reversible redox properties.
- **Applications:** Used in pseudocapacitors to provide additional capacitance through faradaic reactions.

Electrolyte

The electrolyte provides the medium for ion transport and determines the voltage window and ionic conductivity of the supercapacitor.

AQUEOUS ELECTROLYTES

- Common Compounds: KOH, H2SO4, Na2SO4.
- Properties: High ionic conductivity, low cost, safe.

- Limitations: Limited voltage window (typically ~1.2 V).

ORGANIC ELECTROLYTES

- Common Compounds: TEABF4 in acetonitrile or propylene carbonate.
- Properties: Wider voltage window (2.5-3.0 V), moderate ionic conductivity.
- Limitations: Higher cost, flammability, environmental concerns.

IONIC LIQUIDS

- Common Compounds: EMIMBF4, BMIMPF6.
- Properties: Wide voltage window (up to 4 V), high thermal stability.
- Limitations: High cost, viscosity can affect ion transport.

Supercapacitor electrode energetics and mechanism of operation: Uncovering the voltage window

SEPARATOR MATERIALS

Separators prevent electrical shorting between electrodes while allowing ion passage.

POLYPROPYLENE (PP)

- Properties: Good chemical resistance, mechanical strength, thermal stability.
- Applications: Commonly used in supercapacitors and batteries.

POLYETHYLENE (PE)

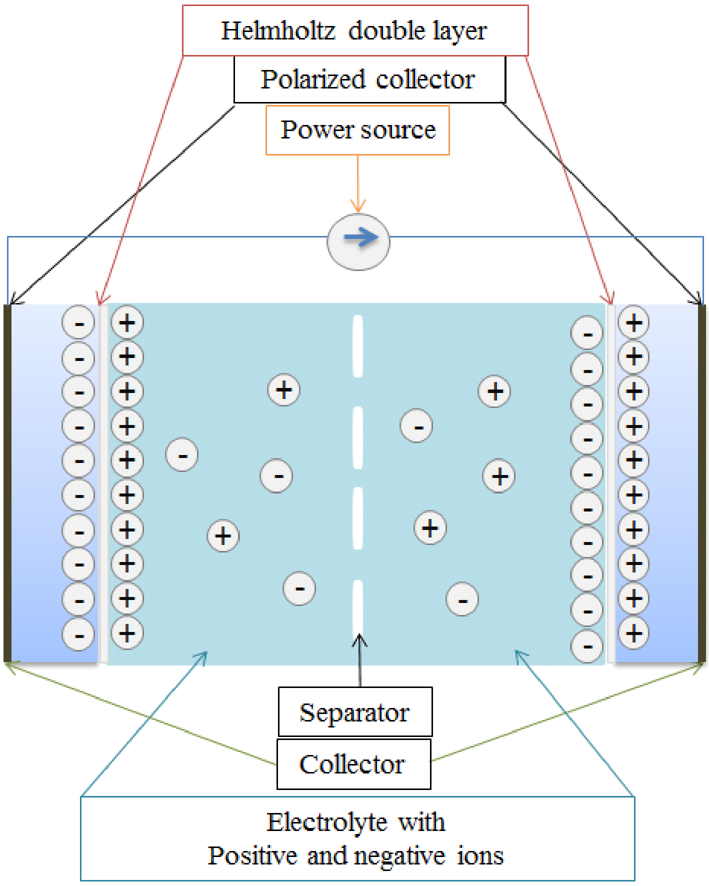
- Properties: High chemical resistance, flexibility, low cost.
- Applications: Often used in combination with PP for enhanced properties.

CELLULOSE

- Properties: Biodegradable, good ionic conductivity, natural abundance.
- Applications: Eco-friendly alternative for separators.

Separators in SCs enable ionic flow and isolate electronic flow. The design and fabrication decide the structure and properties of separators which in turn play a vital role in determining the performance of a SC including energy and power densities by regulating the cell kinetics, cycle life and safety. The material that exhibits high specific surface area, excellent mechanical properties and high thermal stability greatly improves overall performance of the SC.

4. IDEA DIAGRAM



Ashraf, Abdullah. (2016). NITROGEN AND SULFUR– DOPED CARBON NANOFIBER MIXED OXIDES COMPOSITES FOR SUPERCAPACITOR APPLICATIONS. 10.13140/RG.2.2.17783.32168.

ELECTRODE

Electrodes store energy through the formation of electric double layers (in EDLCs) or via redox reactions (in pseudocapacitors). They have high surface area for charge storage, good electrical conductivity, and are chemically stable.

ELECTROLYTE

Facilitates ion transport between electrodes during charging and discharging cycles. The choice of electrolyte affects the voltage window, ionic conductivity, and overall performance.

SEPARATOR

The separator prevents electrical shorting between electrodes while allowing ion movement which allows energy storage.

5. PERFORMANCE CHARACTERISTIC

ENERGY EFFICIENCY

Typical Range: 85-98%.

Losses and Phenomena Causing Them:

• Internal Resistance: Causes resistive heating and energy loss during charge and discharge cycles.

• Leakage Current: Small current that flows through the electrolyte, leading to energy loss over time.

• Self-Discharge: The gradual loss of stored charge when the supercapacitor is not in use.

TEMPERATURE RANGE

Operating Range: -40°C to +70°C.

Effects of Temperature:

High Temperatures: Can accelerate electrolyte decomposition and electrode degradation, reducing lifespan and performance.

Low Temperatures: Increase internal resistance and reduce ion mobility, leading to lower efficiency and power output.

POWER DENSITY

Typical Range: 10,000 to 20,000 W/kg.

Factors Influencing Power Density:

• Electrode Material: High conductivity materials like carbon nanotubes and graphene increase power density.

• Electrolyte Conductivity: Higher ionic conductivity in the electrolyte enhances power output.

ENERGY DENSITY

Typical Range: 5 to 10 Wh/kg for EDLCs; up to 30 Wh/kg for pseudocapacitors.

Factors Influencing Energy Density:

• Electrode Material: Higher surface area and pseudocapacitive materials increase energy storage capacity.

• Electrolyte Voltage Window: Wider voltage windows enable higher energy storage.

CYCLE LIFE

Typical Range: 500,000 to 1,000,000 cycles.

Factors Influencing Cycle Life:

• Electrode Stability: Materials that can withstand repeated charge/discharge cycles without degradation.

• Electrolyte Stability: Electrolytes that do not degrade over time or with temperature changes.

Charge/Discharge Time

Typical Range: Seconds to minutes.

Factors Influencing Charge/Discharge Time:

• Electrode Surface Area: Higher surface area allows for faster charge and discharge.

• Electrolyte Conductivity: Higher conductivity reduces resistance and speeds up ion movement.

4. CURRENT R&D GOALS

Current R&D in supercapacitors focuses on improving electrode materials, developing better electrolytes, optimizing manufacturing processes, and enhancing performance for applications in electric vehicles, public transportation, and renewable energy storage.

Flywheels: The Ultimate Green Energy Storage Solution

Zbigniew Michalak

Flywheel and kinetic energy storage systems (FESS) possess unique advantages such as extremely long life-cycles, high power density, minimal environmental impact, fast response, frequency and voltage stability. There is noticeable progress in FESS, especially in utility, large-scale deployment for the electrical grid, and renewable energy applications. Several studies have forecast a sizeable increase in power regulation requirements as more wind and solar resources are deployed. When compared to batteries, they are less damaging to the environment, being largely made of inert or benign materials.

Most modern flywheels are typically sealed devices that need minimal maintenance throughout their service lives. Magnetic bearing flywheels in vacuum enclosures, such as the NASA model depicted above, do not need any bearing maintenance and are therefore superior to batteries both in terms of total lifetime and energy storage capacity, since their effective service lifespan is still unknown. Flywheel systems with mechanical bearings will have limited lifespans due to wear.

PRINCIPLE OF OPERATION

Flywheel energy storage systems (FESS) store energy in the form of rotational kinetic energy of a spinning mass (rotor or flywheel). The kinetic energy stored in the flywheel is proportional to its moment of inertia and the square of its rotational speed, as given by the equation:

E = (1/2) * I * ω^2

where "E" is the kinetic energy, "I" is the moment of inertia of the flywheel, and "ω" is the rotational speed.

MAIN COMPONENTS OF A FESS

1. FLYWHEEL/ROTOR

The rotating mass that stores kinetic energy.

2. BEARING SYSTEM

Supports the flywheel during operation, typically magnetic bearings to reduce friction losses.

3. POWER CONVERTER SYSTEM

Consists of an electric machine (motor/generator) and power electronics for charging (converting electrical energy to kinetic energy) and discharging (converting kinetic energy to electrical energy).

4. AUXILIARY COMPONENTS

Vacuum enclosure, cooling system, catcher bearings, etc.

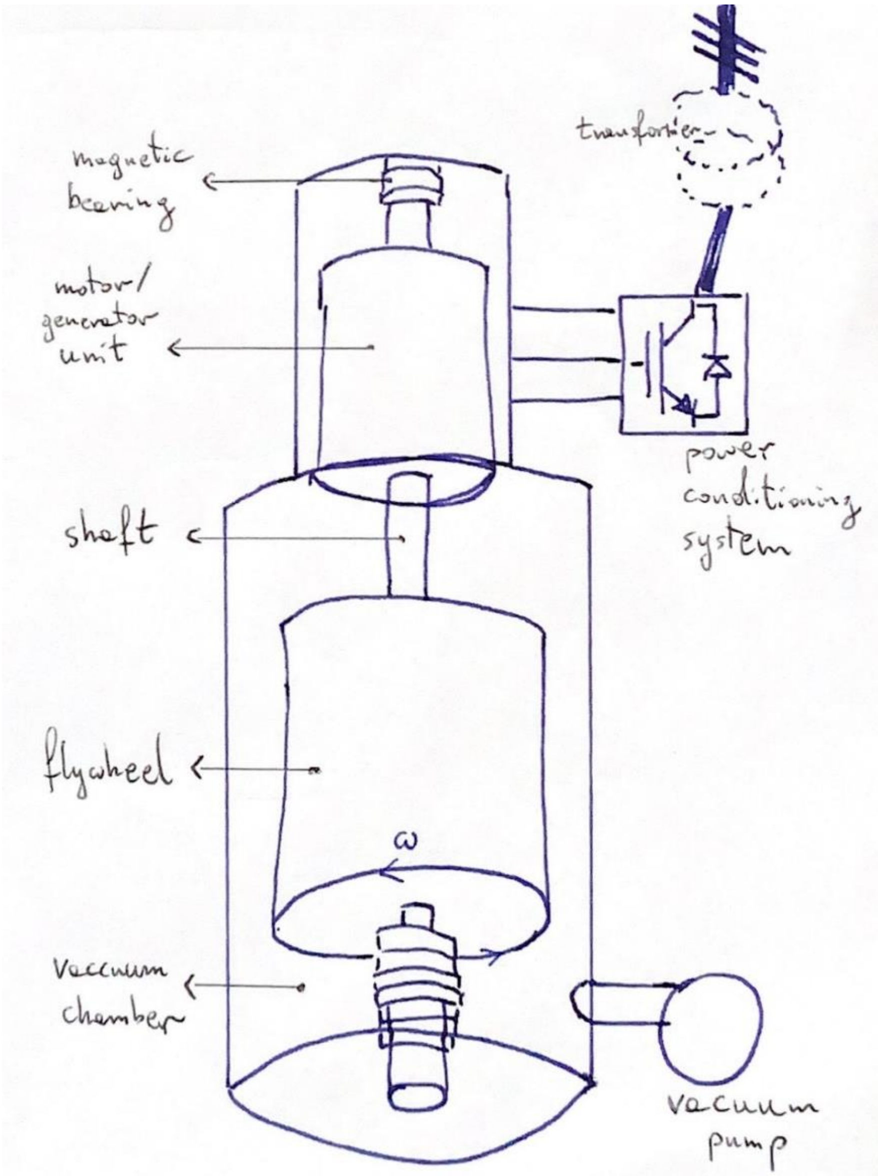


Fig. Hand-drawn schematic of a typical FESS (own work)

THERMODYNAMIC AND OTHER PHENOMENA

The primary phenomenon utilized in FESS is the conversion of electrical energy into rotational kinetic energy during charging, and the reverse conversion during discharging. The energy conversion process involves electromechanical and electromagnetic phenomena.

During charging, the electric machine (motor) converts electrical energy into mechanical rotational energy, accelerating the flywheel. During discharge, the flywheel's kinetic energy is converted back into electrical energy by the electric machine (generator).

Advanced FES systems have rotors made of high strength carbon-fiber composites, suspended by magnetic bearings, and spinning at speeds from 20,000 to over 50,000 rpm in a vacuum enclosure. Such flywheels can come up to speed in a matter of minutes – reaching their energy capacity much more quickly than some other forms of storage.

Other phenomena involved include:

- Windage losses due to air friction on the spinning flywheel (mitigated by operating in a vacuum enclosure).
- Bearing losses, and in the case of magnetic bearings - hysteresis and eddy current losses.
- Electrical losses in the power converter system.

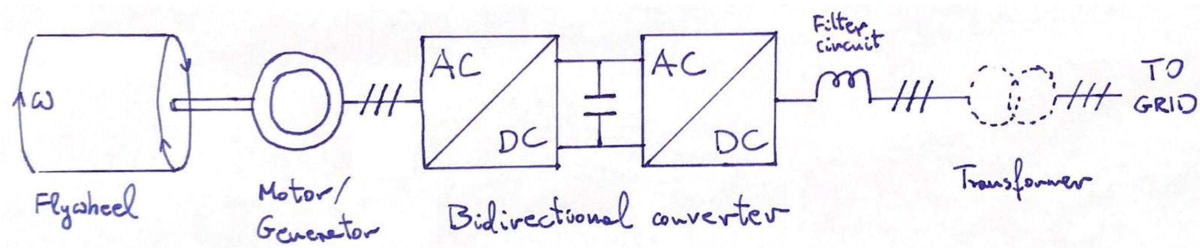


Fig. Flywheel energy flow diagram - energy flows both ways (own work)

ENERGY CARRIER

The energy carrier in FESS is the rotating flywheel/rotor, which stores kinetic energy in the form of its rotational motion.

MATERIALS

1. FLYWHEEL/ROTOR

- Composite materials (carbon fiber, glass fiber, epoxy) for high strength-to-weight ratio and high specific energy.

- High-strength steels for high energy density, low cost, and better recyclability.

- Emerging materials like graphene for potential higher specific energy.

2. BEARING SYSTEM

- Active magnetic bearings (AMBs) using electromagnets and feedback control.

- Passive magnetic bearings or hybrid bearings (combination of magnetic and mechanical bearings).

- Magnetic materials like permanent magnets or electromagnets.

3. POWER CONVERTER SYSTEM

- Permanent magnet synchronous machines (PMSMs) for high power density and efficiency.

- Induction machines for lower cost and robustness.

- Switch reluctance machines (SRMs) for fault-tolerance and no demagnetization risk.

- Power electronics components like inverters, converters, and controllers.

4. AUXILIARY COMPONENTS

- Vacuum enclosure (typically steel or aluminum).

- Cooling system (air or liquid cooling).

- Catcher bearings (typically ball bearings).

Materials	Density (kg/m^3)	Tensile strength MPa	Specific energy Wh/Kg	Material cost $/Kg
Steel 4340	7700	1520	50	1
E-glass 2000	100	1520	14	11
S2-glass	1920	1470	210	24.6
Carbon T1000	1520	1950	350	101.8
Carbon AS4C	1510	1650	300	31.3

Fig. Comparison of different flywheel materials

DISC SHAPES

Different disc shape designs for the flywheel can significantly impact the energy density and specific energy of the flywheel energy storage system (FESS). One of the papers (Xiaojun Li & Alan Palazzolo, 2021) discusses some of these designs:

1. CONVENTIONAL ANNULUS/THICK RIM DESIGN

- The most common design, where the flywheel is a thick annular ring with a central bore for the shaft.

- Shape factor (K) up to 0.3, limiting the energy density.

- Stress concentrations due to the shrink-fitted shaft.

2. LAVAL DISC

- An ideal disc shape with a cylindrical body and two conical ends.
- Shape factor (K) of 1, providing the maximum theoretical energy density.
- Challenging to manufacture and suspend magnetically.

3. SHAFTLESS FLYWHEEL

- A single-piece flywheel without a central bore or shaft.
- Shape factor (K) close to 0.6, almost double the energy density of conventional designs.
- Requires specialized magnetic bearing and control systems.

4. THIN RIM/SHELL FLYWHEEL

- A thin, hollow cylindrical shell as the flywheel rotor.
- Shape factor (K) up to 0.5, providing higher energy density.
- Allows integration of other components (bearings, electric machine) inside the shell for compactness.
- Also requires specialized magnetic bearing and electric machine designs.

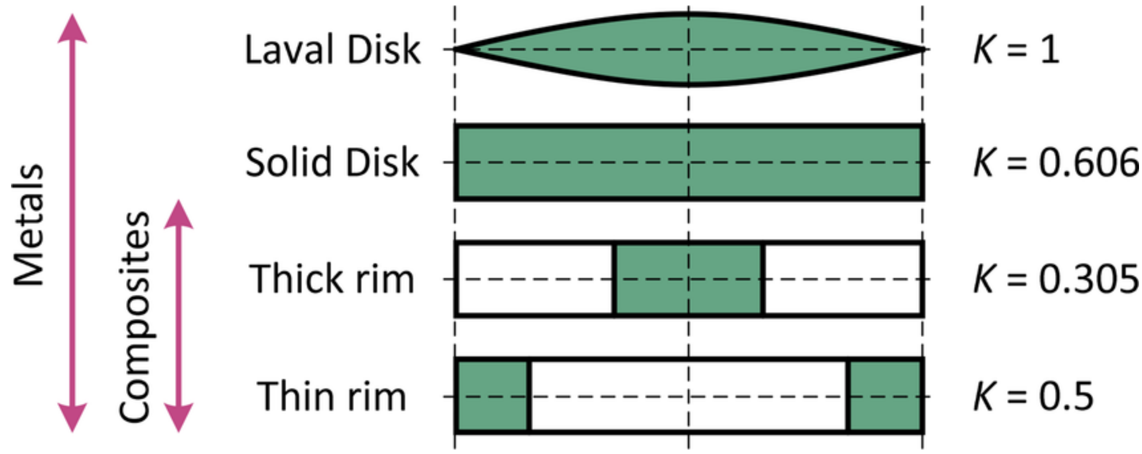


Fig. Shape factors of typical flywheel designs

The potential of these alternative disc shapes lies in their ability to achieve higher energy densities and, consequently, higher specific energies for the same material and rotational speed. The shaftless and thin rim/shell designs are particularly promising, as they can nearly double the energy density compared to conventional thick rim designs.

However, these alternative designs also introduce additional complexities in manufacturing, magnetic bearing design, and control systems. Ongoing research efforts aim to address these challenges and realize the full potential of these advanced flywheel disc shapes for higher performance and more compact FESS designs.

PERFORMANCE CHARACTERISTICS

1. POWER DENSITY

In the range of hundreds of kW/m^3 to several MW/m^3, depending on design and materials.

2. ENERGY DENSITY

Composite flywheels can achieve around 50-100 Wh/kg, while steel flywheels have lower specific energy but higher energy density (volume-based) due to their higher mass density.

3. EFFICIENCY

Above 90%, with some systems reporting efficiencies higher than 95%.

4. LIFETIME

Designed for hundreds of thousands to millions of charge-discharge cycles, with potential lifetimes of 20-30 years or more.

5. RESPONSE TIME

Very fast response time, typically in the range of milliseconds to seconds, making FESS suitable for applications like frequency regulation and power quality improvement.

6. TEMPERATURE RANGE

Typically operate within a wide temperature range, from -40°C to 50°C or higher, depending on the design and materials used.

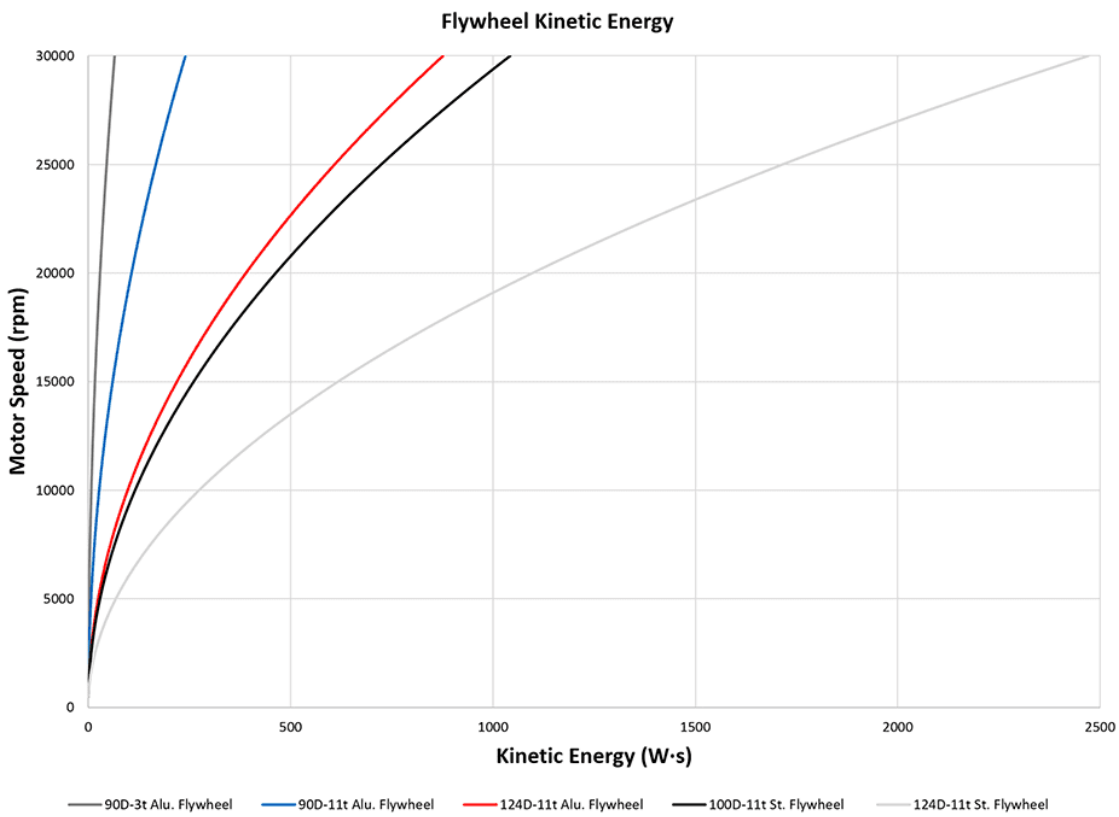


Fig. Flywheel kinetic energy in relation to rpm for some commonly used materials

RESEARCH AND DEVELOPMENT

1. NEW MATERIALS

Exploring advanced materials like graphene for higher specific energy and strength-to-weight ratios.

2. COMPACT AND INTEGRATED DESIGNS

Developing more compact and integrated FESS designs, combining components like bearings and electric machines for space and weight savings.

3. HYBRID ENERGY STORAGE SYSTEMS

Integrating FESS with other energy storage technologies like batteries or supercapacitors to leverage their complementary strengths.

4. ADVANCED CONTROL STRATEGIES

Improving control algorithms for better performance, efficiency, and reliability.

5. FAILURE MODE ANALYSIS AND CONTAINMENT

Investigating potential failure modes and developing effective containment strategies for safety.

6. NEW APPLICATIONS

Exploring new applications beyond traditional energy storage, such as attitude control in aerospace and robotics.

AREAS OF APPLICATION

1. RENEWABLE ENERGY INTEGRATION

Smoothing power output from intermittent renewable sources like wind and solar.

2. FREQUENCY REGULATION

Providing fast response and maintaining grid frequency stability.

3. UNINTERRUPTIBLE POWER SUPPLY (UPS)

Ensuring continuous power supply during grid outages or disturbances.

4. TRANSPORTATION

Energy recovery and power boost in electric and hybrid vehicles, rail systems, and marine applications.

5. PULSED POWER APPLICATIONS

Providing high-power pulses for electromagnetic launching systems, lasers, and other defense applications.

6. AEROSPACE

Attitude control and energy storage for satellites and space systems.

7. INDUSTRIAL APPLICATIONS

Energy recovery and storage in cranes, robots, and other industrial machinery.

EXAMPLES OF PILOTED OR INDUSTRIAL INSTALLATIONS

1. FREQUENCY REGULATION IN THE ELECTRICAL GRID

A utility-scale 20 MW flywheel energy storage plant in Hazle Township, Pennsylvania (the Hazle Facility) using flywheel technology developed by its affiliate, Beacon Power, LLC (Beacon Power). The Hazle Facility provides frequency regulation services to the regional transmission organization, PJM Interconnection, LLC (PJM), through its participation in PJM's Regulation Market (a market-based system for the purchase and sale of the Regulation ancillary service). The zero emission Hazle Facility is designed for a 20 year-life over which it is capable of performing at least 100,000 full depth of discharge cycles. To achieve its 20 MW capacity, the Hazle Facility is comprised of two hundred of Beacon Power's 100 kilowatt (kW)/25 kilowatt/hour (kWh) flywheels connected in parallel. It can fully respond to a signal from PJM in less than 2 seconds.

Hazle Spindle – Hazle Township, PA

Beacon POWER.

Fig. Hazle FESS facility

2. LOS ANGELES METRO WAYSIDE ENERGY STORAGE SYSTEM

A 2 MW FESS system installed for energy recovery and storage in the Los Angeles metro system, using steel flywheels (Calnetix/Vycon). The REGEN technology, which captures energy regenerated by trains as they brake into passenger stations, will allow Metro to reduce its total energy consumption and peak power demand from the utility. To date, the data collected shows Metro is realizing 20% in energy consumption. It is estimated the project will have an annual savings of 541 megawatt hours based on recent data, which could provide 100 average California homes with power.

3. HITACHI ABB 2 MW FLYWHEEL SYSTEM (KODIAK ISLAND, USA)

A 2 MW FESS system installed for renewable energy integration and grid stabilization on Kodiak Island, Alaska. The island is 99% powered by renewable energy, mostly hydroelectric. The FESS system enabled the grid to forgo the use of oil for times when renewable sources don't provide enough power.

Fig. Kodiak Island, Alaska (powered by 99% renewable energy)

4. ACTIVE POWER UPS SYSTEMS

Commercial FESS systems developed by Active Power in Austin, Texas for uninterruptible power supply applications, using steel flywheels with capacities up to 2.8 kWh and 675 kW.

5. AIRCRAFT LAUNCHING SYSTEMS

The Gerald R. Ford-class aircraft carrier will use flywheels to accumulate energy from the ship's power supply, for rapid release into the electromagnetic aircraft launch system (EMALS). The shipboard power system cannot on its own supply the high power transients necessary to launch aircraft. Each of the four rotors will store 121 MJ (34 kWh) at 6400 rpm. They can store 122 MJ (34 kWh) in 45 secs and release it in 2–3 seconds. The flywheel energy densities are 28 kJ/kg (8 W·h/kg); including the stators and cases this comes down to 18.1 kJ/kg (5 W·h/kg), excluding the torque frame.

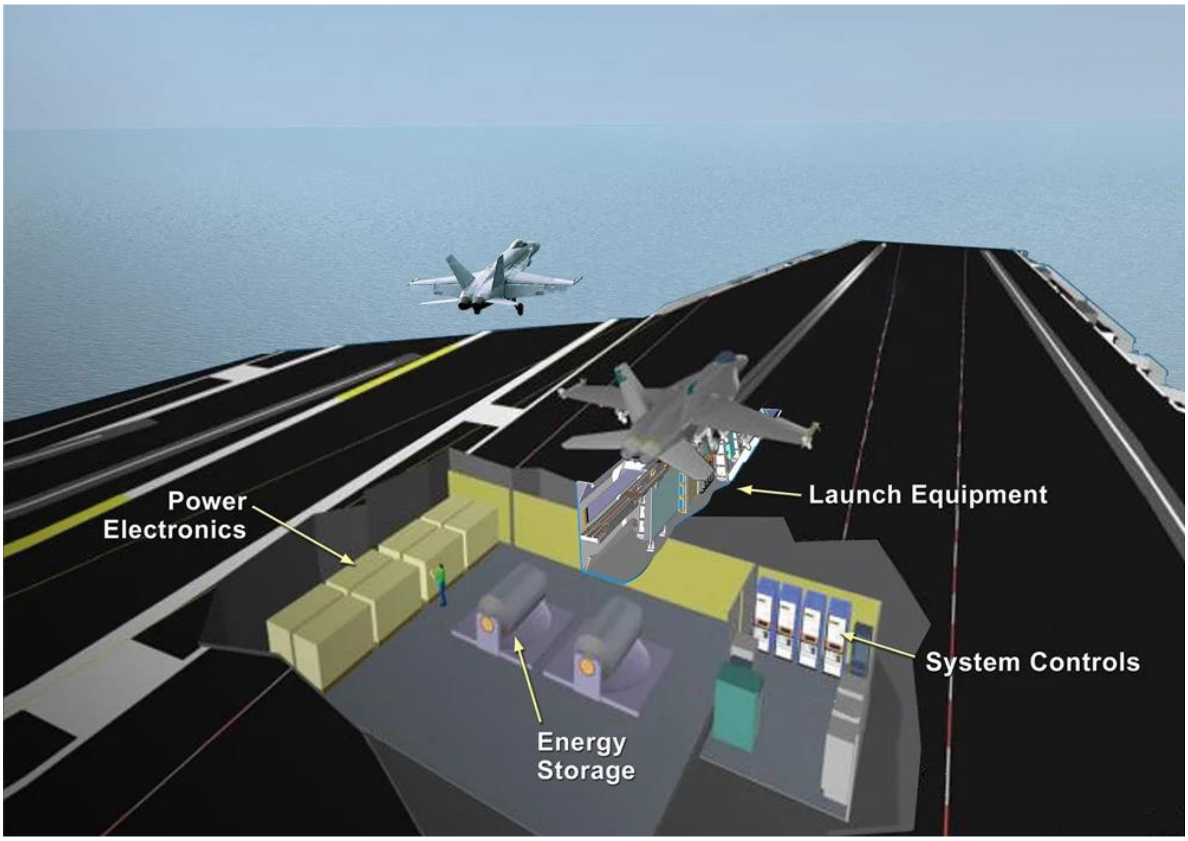


Fig. The electromagnetic rail aircraft launch system diagram with flywheels indicated as energy storage

Fig. F-18 preparing to launch with the EMALS system on the deck of USS Gerald R. Ford aircraft carrier

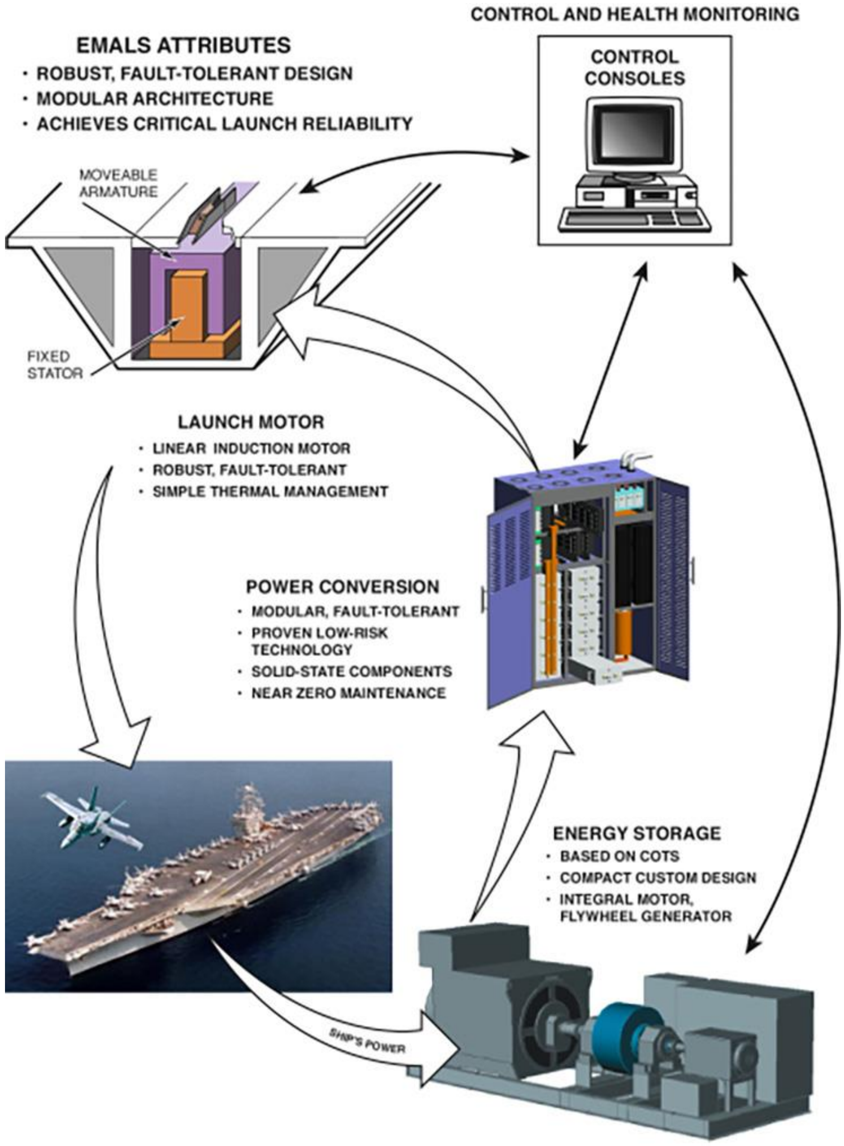


Fig. The electromagnetic rail aircraft launch system components

EMALS MAJOR FUNCTIONAL BLOCKS

1. The Prime Power Interface, which is the interconnect to the ship's electrical distribution system (which is sourced by nuclear reactors) and delivers power to drive the energy-storage rotors
2. The Launch Motor (a linear-induction motor)
3. The Power-Conversion Electronics, which takes the energy stored in the rotors and converts it to the carefully timed wave to energize the series of windings of the launch motor. The power switches which control the windings are located below deck; the

switching for each winding is controlled by a module built of solid-state SCR and IGBT devices
4. The Launch Control, which manages the current delivered to the launch motor windings for smooth, tailored acceleration, with closed-loop feedback for precision as conditions vary
5. The Energy Storage motor-generator rotors (flywheels)
6. The Energy Distribution System, which includes the cables, disconnects, and terminations needed to deliver the energy from the power-conversion system to the launch motor

POTENTIAL DISADVANTAGES

There is a possibility of high-speed flywheels breaking and exploding, releasing shrapnel fragments. However, they can be installed below ground to reduce this risk. Chemical batteries can be designed to match a wide variety of sizes and dimensions, but a flywheel must occupy a certain volume - the energy it stores is proportional to its rotational inertia. As a flywheel gets smaller, its mass also decreases, so the speed must increase, and so the stress on the materials increases. In applications with constrained dimensions, like a car or a train, flywheels may not be a viable solution.

COMPARISON WITH OTHER ENERGY STORAGE SOLUTIONS

Technology	Power Achieved	Power Density	Energy Density	Lifetime	Efficiency	Unit Costs
Flywheels	High	High	Moderate	>20 years	85-95%	Moderate to High
Lithium-Ion Battery	Moderate/High	Moderate	High	5-10 years	90-95%	Moderate
Supercapacitors	Very High	Very High	Low	>10 years	90-95%	Very High
Pumped hydro	Low	Low	Low	Very long	75-80%	Low
Compressed air	Medium	Medium	Medium	Long	60-65%	Low/ location dependent

LIST OF TECHNOLOGY COMPANIES WITH MATURED MARKET PRODUCTS

1. ACTIVE POWER (UNITED STATES)

One of the pioneering companies in flywheel energy storage systems, Active Power has been developing and selling flywheel-based uninterruptible power supply (UPS) and frequency regulation systems since the 1990s. (https://www.activepower.com/)

2. BEACON POWER (UNITED STATES)

Beacon Power was a company that developed and deployed large-scale flywheel energy storage plants for frequency regulation services. (https://beaconpower.com/)

3. AMBER KINETICS (UNITED STATES)

A California-based company that has developed and commercialized flywheel energy storage systems for various applications, including grid-scale energy storage, backup power, and frequency regulation.

They have developed a steel rotor flywheel design that operates at low speeds (around 8,000 RPM) compared to traditional flywheels. This allows for a longer lifespan and improved safety. In addition to utility-scale projects, Amber Kinetics has targeted commercial & industrial customers for backup power and peak shaving applications.

The company has received funding from investors like Bill Gates, Honeywell, and GE, among others. (https://amberkinetics.com/)

5. KINETIC TRACTION SYSTEMS (UNITED STATES)

Kinetic Traction Systems has developed flywheel-based energy recovery and storage systems for use in rail and other transportation applications. (https://kinetictraction.com/)

6. TEMPORAL POWER (CANADA)

Temporal Power produces flywheel-based energy storage systems for various applications, including power quality, ride-through power, and grid frequency regulation.

3.DMFC FUELCELL

1. PRINCIPLE OF OPERATION

Direct Methanol Fuel Cells (DMFCs) operate by directly converting the chemical energy of liquid methanol into electrical energy through an electrochemical process. This process involves the oxidation of methanol at the anode and the reduction of oxygen at the cathode, facilitated by a proton-conducting membrane.

2. THERMODYNAMIC, ELECTROMAGNETIC, ELECTROCHEMICAL PHENOMENA

Thermodynamic Phenomena: The primary thermodynamic principle involved in DMFC operation is the Gibbs free energy change associated with the methanol oxidation reaction. The efficiency of the DMFC is influenced by the temperature and pressure conditions, which impact the cell potential and reaction kinetics.

Electromagnetic Phenomena: Electromagnetic fields play a role in the movement of charged species within the cell. The electric field within the electrolyte drives protons from the anode to the cathode, while electrons flow through an external circuit, generating electrical power.

Electrochemical Phenomena: At the anode, methanol is oxidized to carbon dioxide, producing protons and electrons:

$$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$$

At the cathode, oxygen is reduced to water:

$$\frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$$

The overall reaction is:

$$CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2 + 2H_2O$$

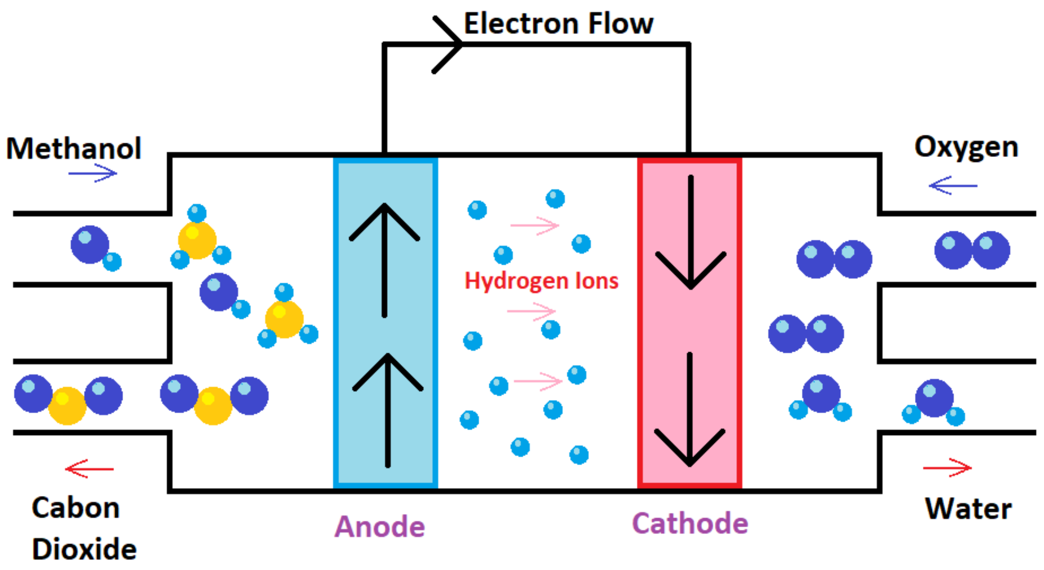
3. ENERGY CARRIERS

The primary energy carriers in a DMFC are:

- **Gases:** Oxygen (O_2) at the cathode.
- **Liquids:** Methanol (CH_3OH) mixed with water at the anode.
- **Solids:** The proton-conducting membrane (usually Nafion).

4. DRAWINGS, PHOTOS, AND IDEA DIAGRAMS

- A schematic of a DMFC showing the flow of methanol and oxygen.



5. MATERIALS OF CONSTRUCTION

Major Components:

- **Membrane Electrode Assembly (MEA):** Typically uses Nafion as the proton-conducting membrane.
- **Catalysts:** Platinum (Pt) and ruthenium (Ru) for the anode; Platinum (Pt) for the cathode.
- **Bipolar Plates:** Usually made from graphite or coated metals to conduct electrons and separate gases.
- **Gaskets and Seals:** Made from chemically resistant polymers to prevent leakage.

Auxiliary Components:

- **Pump and Blower:** For methanol and air supply, respectively.
- **Heat Exchanger:** For thermal management.
- **Gas Separator:** To manage CO_2 production.

6. PERFORMANCE CHARACTERISTICS

- **Potential:** Typically around 0.5 to 0.7 V per cell.
- **Efficiency:** Approximately 30-40% due to various losses including methanol crossover and heat generation.

- **Temperature:** Operates optimally at 60-120°C.
- **Power Density:** Around 50-100 mW/cm².
- **Energy Density:** Higher than hydrogen fuel cells due to the liquid fuel.
- **Lifetime:** Dependent on operational conditions, typically 1,000-5,000 hours.

7. CHARACTERISTICS DESCRIBING OPERATION

Thermodynamic Efficiency: Illustrated using Sankey diagrams to show energy losses. **Current-Voltage (I-V) Curves:** Show the cell potential as a function of current density. **Power-Voltage (P-V) Curves:** Indicate the power output relative to the voltage. **Temperature-Entropy (T-S) and Enthalpy-Entropy (H-S) Diagrams:** Useful for understanding the thermodynamic properties and losses.

8. CURRENT RESEARCH DIRECTIONS

Research focuses on:

- Reducing methanol crossover through advanced membrane materials.
- Improving catalyst performance and durability.
- Enhancing thermal management systems.
- Developing more efficient and compact auxiliary components.

9. AREAS OF APPLICATION

DMFCs are used in:

- Portable power sources for electronics.
- Backup power for telecommunication and remote sensors.
- Military applications for portable power units.
- Transportation, including auxiliary power units in vehicles.

10. EXAMPLES OF INDUSTRIAL INSTALLATIONS

1. **Oorja Protonics:** Utilizes DMFCs for telecom towers and backup power, with installations in 27 African countries.
2. **EFOY Pro:** Used in oil and gas pipelines in Canada and remote telecom stations.
3. **Sim ark Control:** Integrates DMFCs with SCADA systems for pipeline monitoring.
4. **SFC Energy:** Provides DMFC systems for military applications and communication networks.
5. **Toyota Tsuho:** Implements DMFCs in transportation for clean energy solutions.

11. SUMMARY COMPARISON OF TECHNOLOGIES

Parameter	DMFC	PEMFC	SOFC
Power Density (mW/cm²)	50-100	500-1,000	200-500
Efficiency (%)	30-40	40-60	50-60
Lifetime (hours)	1,000-5,000	5,000-10,000	10,000-20,000
Energy Density	High	Medium	High
Operating Temperature	60-120°C	60-80°C	500-1,000°C
Cost per Unit	Moderate	High	High

13. LIST OF TECHNOLOGY COMPANIES

These companies offer mature market products and have significant installations in various applications globally

- **Oorja Protonics**
- **SFC Energy**
- **EFOY Pro**
- **Simark Control**
- **Toyota Tsuho**

4.LTO BATTERY

Lithium-titanate batteries (LTO) have gained widespread attention as a promising negative electrode material for high-power lithium-ion batteries due to their excellent safety performance and long cycle life. This article provides a comprehensive overview of the development status and application prospects of nanotechnology in LTO batteries.

1. PRINCIPLE OF OPERATION

Principle of Operation of LTO Batteries: Lithium-titanate batteries (LTO) are a type of lithium-ion battery where the anode material is made of lithium-titanate ($Li_4Ti_5O_{12}$) instead of graphite. The use of LTO allows for faster charging and discharging, longer cycle life, and enhanced safety.

Thermodynamic, Electromagnetic, and Electrochemical Phenomena:

- **Thermodynamic:** Energy transformations during charging and discharging cycles.
- **Electromagnetic:** Movement of electrons through the external circuit.
- **Electrochemical:** Lithium ions move between the anode (LTO) and the cathode (usually lithium manganese oxide or lithium iron phosphate).

2. ENERGY CARRIERS

Energy Carriers in LTO Batteries:

- **Solids:** Lithium-titanate ($Li_4Ti_5O_{12}$) anode, cathode material ($LiMn_2O_4$ or $LiFePO_4$).
- **Liquids:** Electrolyte, typically a lithium salt in an organic solvent.
- **Gases:** Minimal, but could include evolved gases under extreme conditions (e.g., oxygen, CO_2).

3. MATERIALS OF CONSTRUCTION

Materials of Construction:

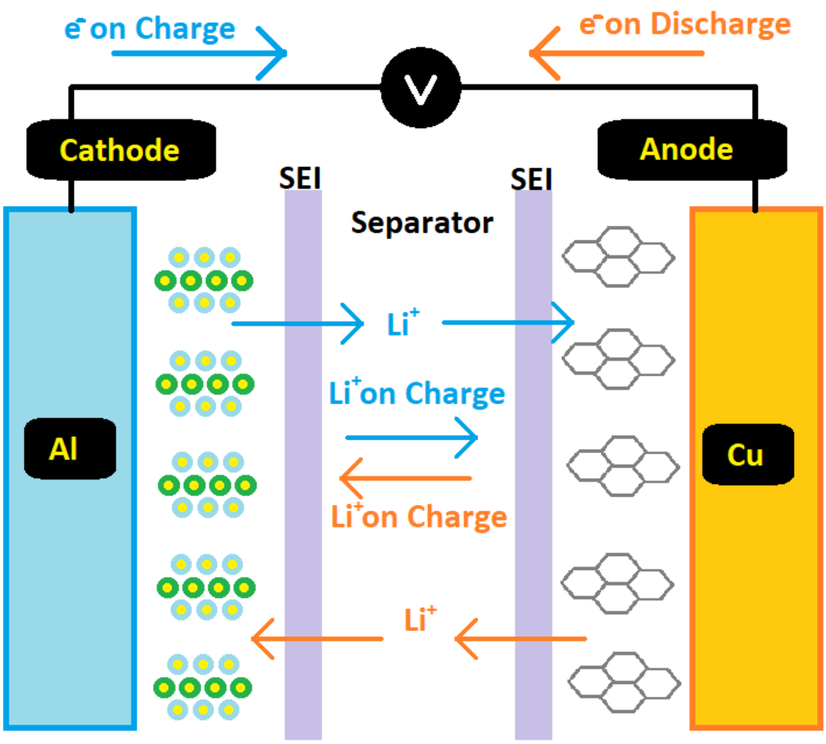
- **Anode:** Lithium-titanate ($Li_4Ti_5O_{12}$)
- **Cathode:** Lithium manganese oxide ($LiMn_2O_4$), lithium iron phosphate ($LiFePO_4$)
- **Electrolyte:** Lithium salt (e.g., $LiPF_6$) in organic solvent (e.g., ethylene carbonate, dimethyl carbonate)
- **Separator:** Polyethylene or polypropylene
- **Current Collectors:** Aluminum (cathode side), Copper (anode side)

4. FUNCTIONAL DIAGRAMS OF COMPONENTS

Idea Diagrams and Functionality:

- **Anode:** Stores lithium ions during charging.
- **Cathode:** Releases lithium ions during charging and accepts them during discharging.
- **Electrolyte:** Medium for ion transfer between anode and cathode.
- **Separator:** Prevents short-circuiting while allowing ion flow.

Diagrams:



5. PERFORMANCE CHARACTERISTICS

Current Performance Characteristics:

- **Potential:** 2.3V to 2.4V nominal
- **Efficiency:** Around 90-95%
- **Temperature Range:** -30°C to 55°C
- **Power Density:** Up to 10,000 W/kg
- **Energy Density:** 50-80 Wh/kg
- **Lifetime:** Over 10,000 cycles

Phenomena Causing Losses:

- **Internal Resistance:** Causes heat and reduces efficiency.
- **Side Reactions:** Degrade materials over time.

6. ADVANTAGES OF LTO BATTERIES

- **High Safety**: LTO batteries are known for their excellent thermal stability and lower risk of thermal runaway.
- **Long Cycle Life**: They can withstand many more charge-discharge cycles compared to traditional lithium-ion batteries.
- **Fast Charging**: The ability to charge and discharge at very high rates.
- **Wide Temperature Range**: Operate effectively in a broader range of temperatures.

CHALLENGES

- **Lower Energy Density**: LTO batteries generally have lower energy density compared to other lithium-ion batteries, which can limit their use in applications where space and weight are critical.
- **Higher Cost**: The materials and manufacturing processes for LTO batteries are more expensive.

7. RESEARCH AND DEVELOPMENT

Current R&D Directions:

- **Enhancing Energy Density:** Research on new cathode materials and electrolytes.
- **Improving Cycle Life:** Developing coatings and additives to reduce degradation.
- **Cost Reduction:** Scaling up production and finding cheaper materials.

8. AREAS OF APPLICATION

Applications of LTO Batteries:

- **Electric Vehicles (EVs):** Fast charging and long cycle life make them ideal for EVs.
- **Grid Storage:** Reliable performance and safety for energy storage systems.
- **Portable Electronics:** Safety and fast charging for high-demand applications.

9. INDUSTRIAL INSTALLATIONS

Examples of Industrial Installations:

1. **China Aviation Lithium Battery Co., Ltd:** EV applications.
2. **Altairnano:** Grid storage systems.
3. **Leclanché:** Renewable energy integration.
4. **Yinlong Energy:** Electric buses.
5. **Toshiba SCiB:** Various industrial and consumer applications.

10. SUMMARY AND COMPARISON

Tabular Comparison:

Technology	Power (W)	Power Density (W/kg)	Energy Density (Wh/kg)	Lifetime (cycles)	Efficiency (%)	Unit Cost ($/kWh)
LTO	10,000	10,000	50-80	10,000+	90-95	600-1000
Li-ion (NMC)	5,000	250-700	150-250	1,000-3,000	85-90	150-250
Lead-acid	300-500	100-200	30-50	300-500	70-80	100-150

12. TECHNOLOGY COMPANIES

List of Companies:

1. **Altairnano**
2. **Yinlong Energy**
3. **Toshiba SCiB**
4. **Leclanché**
5. **China Aviation Lithium Battery Co., Ltd**

Wind Turbines: Harnessing the Power of Wind

Zbigniew Michalak

Wind turbines are fascinating machines that harness the kinetic energy of wind and convert it into electrical energy. Their basic principle of operation is remarkably simple and their use getting more popular with time as costs are decreasing and demand for renewable energy grows.

PRINCIPLE OF OPERATION

The primary component of a wind turbine is the rotor, which consists of two or more blades attached to a hub. As the wind blows across the blades, it creates a lift force that causes the rotor to spin. This spinning motion is then transferred to a generator, typically located in the nacelle (the housing at the top of the tower), which converts the mechanical energy into electrical energy.

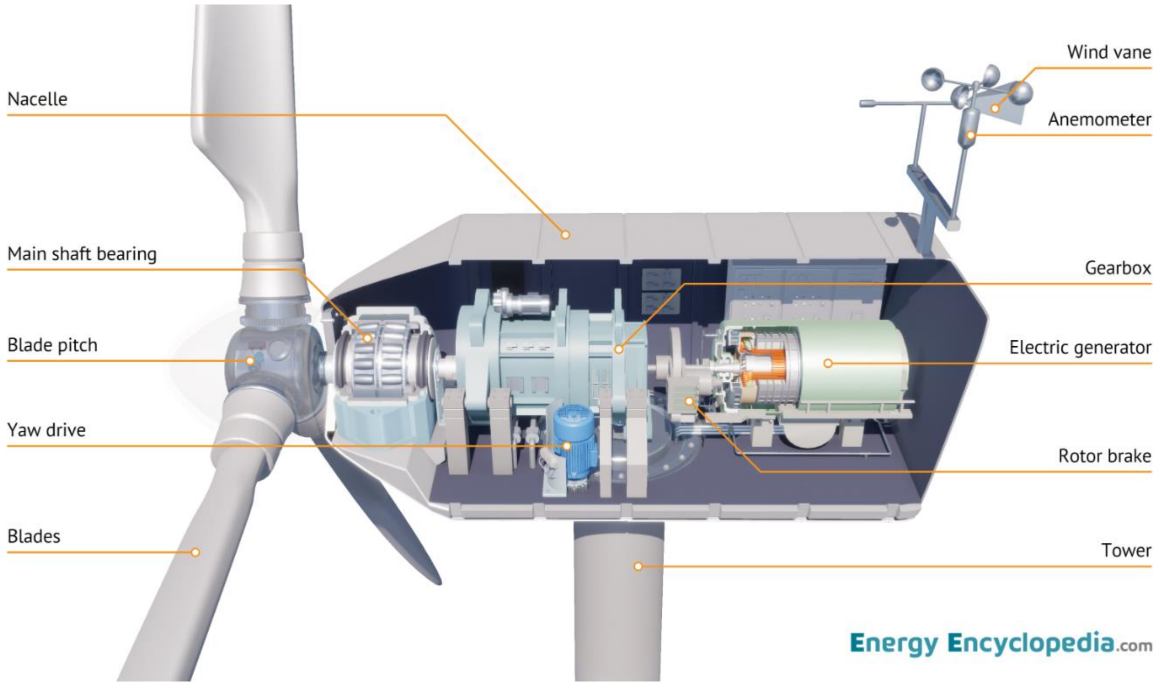


Fig. Schematic of the turbine, Credit: EnergyEncyclopedia.com

THERMODYNAMIC AND OTHER PHENOMENA

The aerodynamic principles behind wind turbine operation are based on the laws of fluid dynamics and the Bernoulli principle. As the wind flows over the curved surface of the blades, it creates a pressure differential, with lower pressure on the upper surface and higher pressure on the lower surface. This pressure difference generates lift, causing the blades to rotate.

ENERGY CARRIER

The energy carrier in wind turbines is the wind itself, which is essentially moving air. The kinetic energy of the wind is captured by the rotor blades and converted into rotational mechanical energy, which is then transformed into electrical energy by the generator.

Betz Law – theoretical limit of energy extraction from a stream of fluid. It results from the fact that if we extracted the entire energy, the stream of air behind the turbine would stop and there would be no more flow to keep the turbine spinning. Betz losses are about 40.7%.

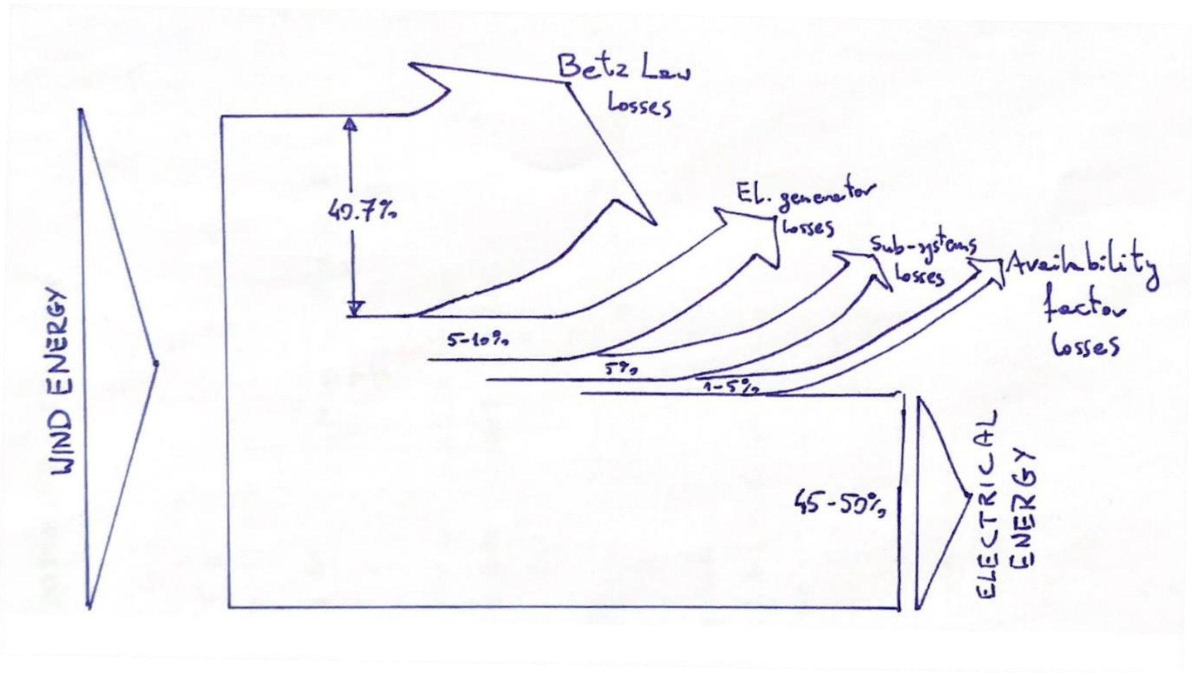


Fig. Sankey diagram for wind energy (own work)

MATERIALS OF CONSTRUCTION

1. ROTOR BLADES

Typically made of lightweight yet strong materials like fiberglass-reinforced plastics, carbon fiber-reinforced plastics, or advanced composites. These materials provide the necessary strength and flexibility to withstand the extreme forces exerted by the wind.

2. TOWER

Commonly constructed from steel or concrete, providing a sturdy foundation and support for the nacelle and rotor.

3. NACELLE

It consists of various components, including the generator, gearbox (if applicable), and control systems, which are made from a combination of metals, alloys, and electronic components.

4. GENERATOR

Depending on the design, wind turbines may use permanent magnet generators or induction generators, which incorporate magnetic materials like rare-earth magnets or copper windings.

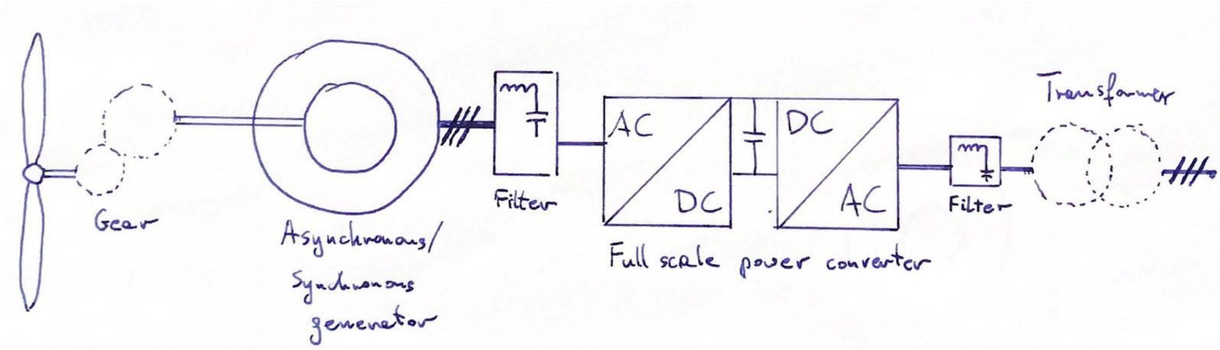


Fig. Simplified electrical diagram (own work)

THE POWER CURVE OF THE WIND TURBINE

A power curve depicts the output power of a wind turbine at different wind speeds. Understanding and optimizing the power curve is crucial for maximizing the annual energy production of a wind turbine.

1. Cut-in wind speed: This is the minimum wind speed at which the wind turbine starts generating power. Below this wind speed, the turbine does not rotate or produce electricity.

2. Cut-out wind speed: This is the maximum wind speed at which the wind turbine is designed to operate. Above this wind speed, the turbine is shut down to prevent excessive stress and damage to its components.

The lower the cut-in wind speed and the higher the cut-out wind speed, the more energy the wind turbine will produce on an annual basis. This is because the turbine can operate and generate electricity over a wider range of wind speeds, thereby increasing its overall energy yield.

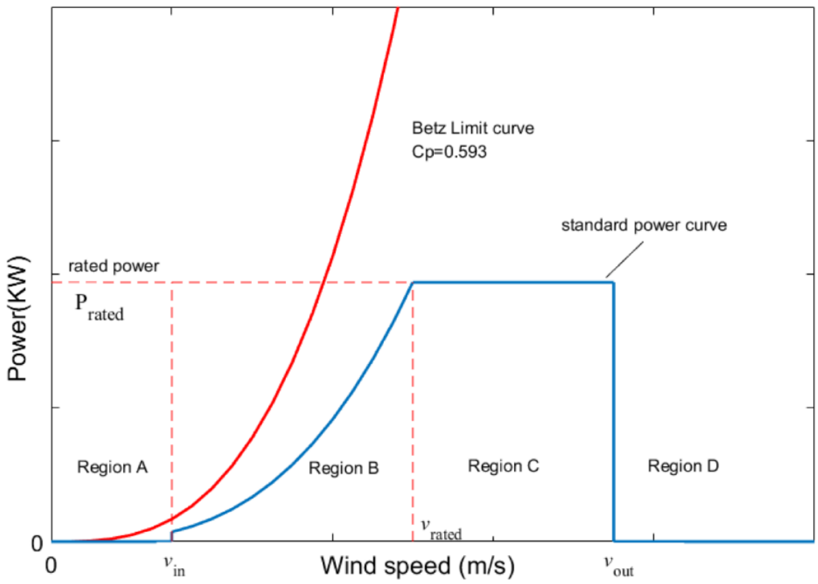


Fig. Power curve of a theoretical turbine (Vin – cut in, Vout – cut out speed)

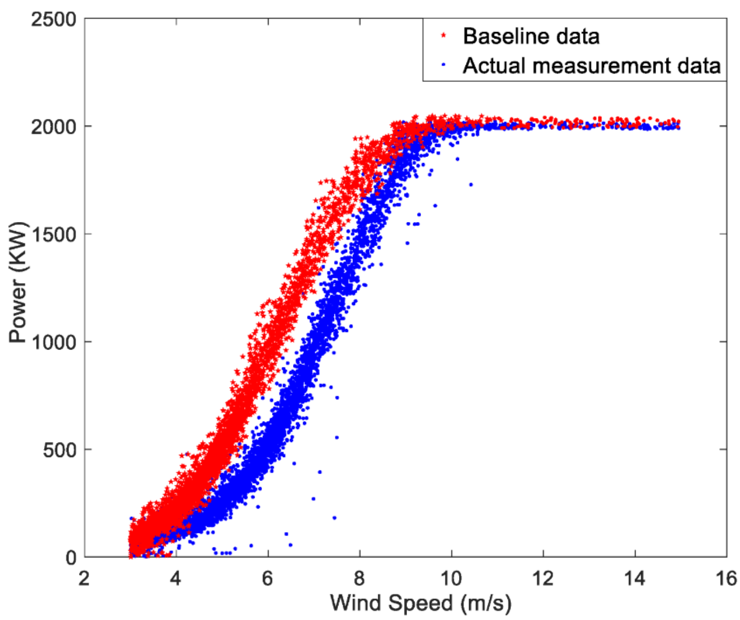


Fig. Real world measurements

One new approach is to design wind turbines that can generate energy at lower wind speeds, which expands the possibility of constructing wind farms in areas with lower average annual wind speeds.

There are also ongoing efforts to extend the power curve to higher wind speeds, allowing wind turbines to continue producing electricity in extremely strong winds. This can be achieved through control system updates or by incorporating aerodynamic braking systems, such as chord slots on the blades, to control overspeed conditions.

CURRENT PERFORMANCE CHARACTERISTICS

Wind turbines have come a long way in terms of performance and efficiency. Some key performance characteristics include:

1. POWER OUTPUT

Modern utility-scale wind turbines can generate power outputs ranging from a few megawatts (MW) to over 15 MW for some offshore wind turbines.

2. CAPACITY FACTOR

The capacity factor represents the actual output of a wind turbine compared to its theoretical maximum output. Typical capacity factors range from 25% to 50%, depending on wind conditions and turbine design.

3. EFFICIENCY

The efficiency of wind turbines is determined by factors such as aerodynamic design, mechanical losses, and electrical conversion losses. Modern wind turbines can achieve efficiencies of 35% to 45%.

4. LIFETIME

Wind turbines are designed to have a lifespan of 20 to 25 years, although with proper maintenance and refurbishment, their lifetime can be extended.

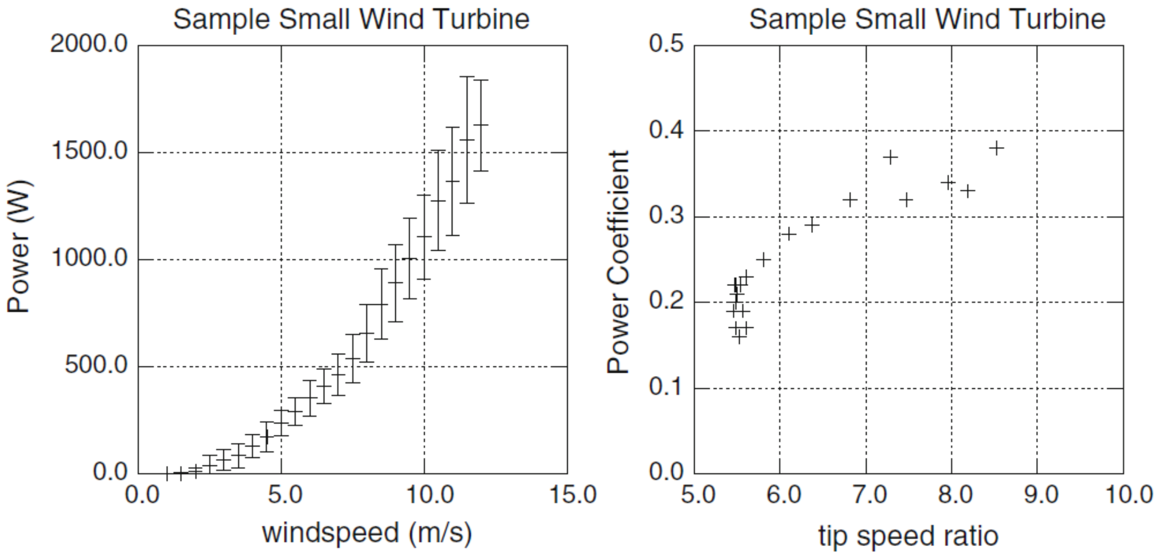


Fig. Example of power characteristics of wind turbines

CLASSIFICATION OF OFFSHORE WIND TURBINES

1. MONOPILE FOUNDATIONS

Monopile foundations are currently the most common type of offshore wind turbine foundation, accounting for about 80% of installed foundations. A monopile is a single, large-diameter steel pile that is driven into the seabed to support the turbine tower. The PDF states that monopiles typically have a diameter of 6 to 8 meters and extend 20 to 30 meters below the seabed. Suitable for less than 15m depth.

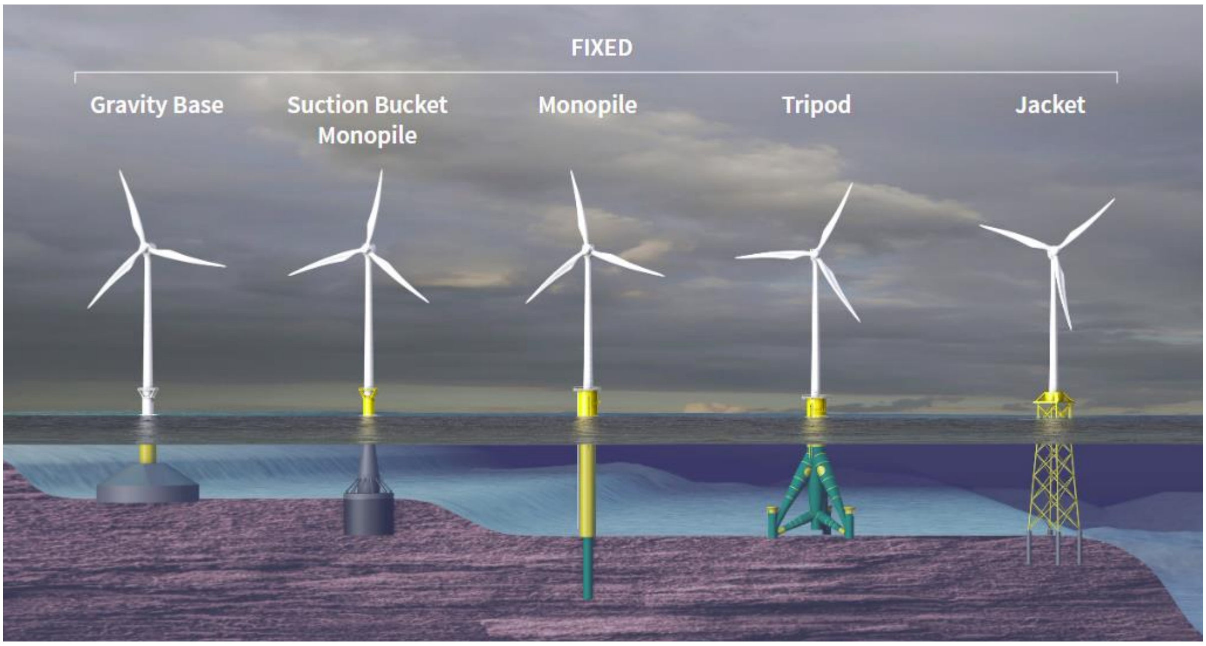


Fig. Foundations of offshore wind turbines

2. JACKET FOUNDATIONS

Jacket foundations are lattice-type structures with multiple legs or piles that are secured to the seabed. The use of jacket foundations is expected to increase more than quadruple in future offshore wind farm projects, particularly in deeper waters where monopiles may not be feasible. They can reach a total length of 60 meters (over 30 meters below sea level). Suitable for different types of soils.

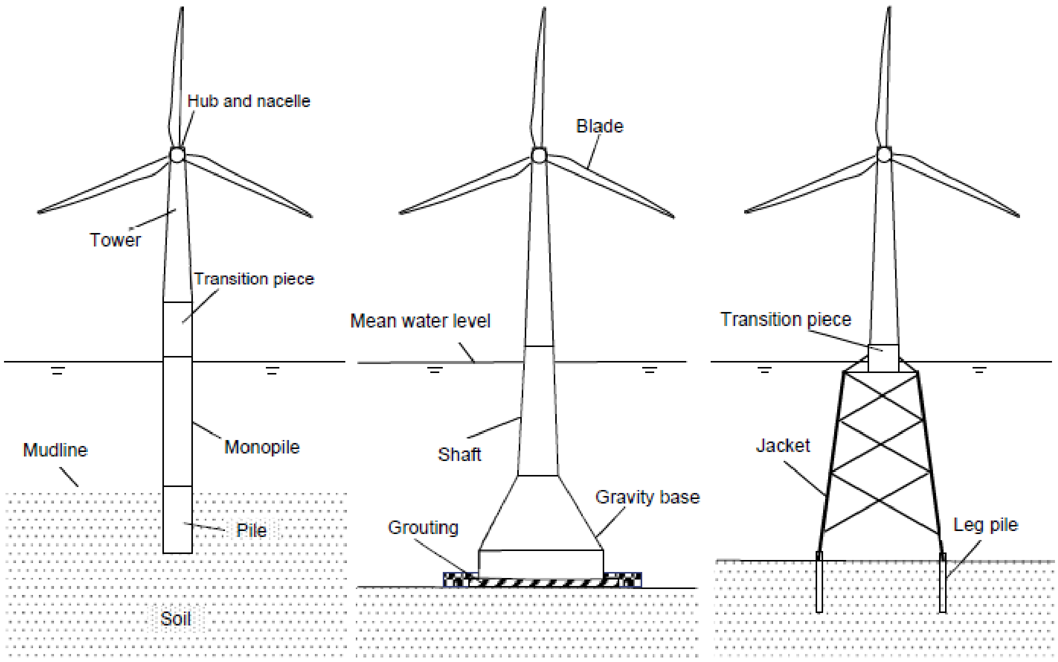


Fig. Fixed-bottom foundations

3. GRAVITY FOUNDATIONS

Gravity foundations are another type of offshore wind turbine foundation. These are massive concrete or steel structures that rely on their sheer weight and size to remain stable on the seabed. Gravity foundations are better suited for rocky or uneven seabed conditions where it is difficult to drive piles. Constructed at depths of up to 30 meters.

4. FLOATING FOUNDATIONS

For deeper water locations, where fixed-bottom foundations like monopiles or jackets are not suitable, the use of floating foundations is growing. These foundations allow wind turbines to be installed in water depths where conventional foundations are not feasible. Floating foundations offer environmental advantages over fixed ground structures and are being planned for deployment in regions like Southeast Asia, Oceania, and Northern Europe.

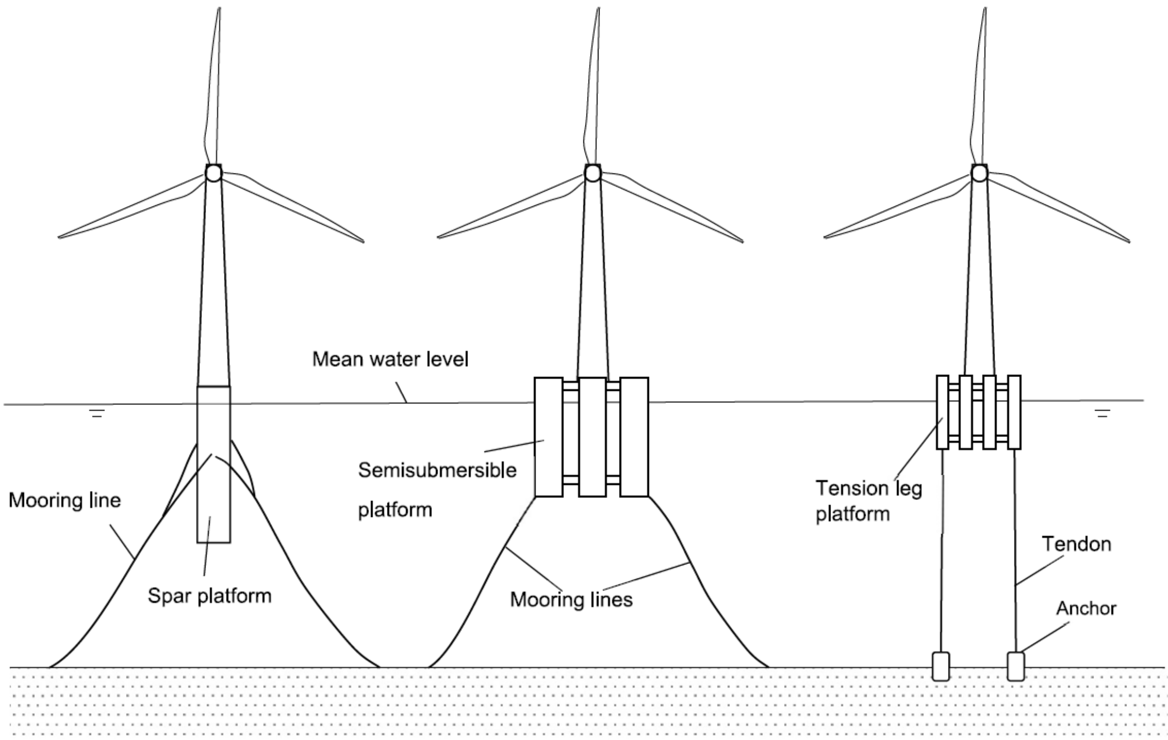


Fig. Floating foundations

The choice of foundation type depends on factors such as water depth, seabed conditions, and project-specific requirements. While monopiles are currently the most prevalent, the industry is shifting towards more jacket foundations and exploring floating foundations to access deeper water locations and expand offshore wind energy generation.

AREAS OF APPLICATION AND EXAMPLES

Wind turbines are primarily used for generating electricity, with applications ranging from small-scale residential or commercial installations to large-scale utility wind farms. Some examples of wind energy installations include:

OFFSHORE WIND FARMS

1. The London Array offshore wind farm in the UK, with a capacity of 630 MW, and the Hornsea One offshore wind farm in the UK, with a capacity of 1.2 GW, are among the largest offshore wind farms in operation.


Fig. London Array offshore wind farm

2. A 3.6 GW capacity Dogger Bank Wind Farm is being constructed in UK waters 70 nautical miles (130km) off the coast of Yorkshire and in the UK's North Sea. Dogger Bank sits approximately 130km (80 miles) off the coast of Yorkshire and will occupy an area almost as large as Greater London and nearly twice the size of New York City.

   It will comprise 277 offshore turbines capable of producing enough energy to power the equivalent of six million British homes annually. It will eventually have 277, 260-meter-tall turbines. Dogger Bank will be the world's largest offshore wind farm, more than two and a half times the size of the largest offshore wind farm currently in operation. Full operation is scheduled to begin in 2026.

   It uses GE Vernova's Haliade-X 13 MW turbines, one of the largest and most powerful globally. This is the first time Haliade-X units have been energized offshore anywhere in the world. Each rotation of the 107m long blades can produce enough energy to power an average British home for two days.

   Power from the offshore wind farm is being transmitted to the UK's national grid via Dogger Bank's high-voltage direct current (HVDC) transmission system, marking the first-time use of HVDC technology on a UK wind farm.

Fig. The 3.6 GW Dogger Bank Wind Farm (one of GE Vernova’s Haliade-X 13 MW turbines)

ONSHORE WIND FARMS

1. The Gansu Wind Farm in China is the largest wind farm in the world, with a projected capacity of 20,000 MW at the cost of $17.5bn.

Fig. The Gansu Wind Farm

2. The Shepherd's Flat Wind Farm in Oregon, USA, with a capacity of 845 MW, and the Jaisalmer Wind Park in Rajasthan, India, with a capacity of 1.6 GW, are examples of large-scale onshore wind farms.

Figure. The Shepherd's Flat Wind Farm in Oregon, USA

DISTRIBUTED WIND

Small-scale wind turbines are increasingly being used for residential, agricultural, and commercial applications, providing on-site renewable energy generation.

WIND TURBINE TECHNOLOGY TRENDS

1. INCREASING WIND TURBINE SIZE AND CAPACITY

There is a trend towards upscaling wind turbines for offshore installations, with larger turbines capable of capturing more wind energy and achieving higher power outputs. The PDF mentions that the largest operating wind turbine in the world is the prototype GE Haliade-X in Rotterdam, with a capacity of 13 MW. Manufacturers prefer larger turbines over multiple smaller ones for the same output, as it reduces the cost per installed kilowatt of power.

Fig. Nacelle for a GE Haliade-X turbine

2. DEEPER WATER AND FLOATING FOUNDATIONS

To access locations with deeper water depths, where traditional fixed-bottom foundations are not feasible, researchers are exploring floating foundation designs for offshore wind turbines. Floating foundations not only facilitate turbine placement but also offer environmental advantages over fixed ground structures. The use of floating wind turbines is planned in regions like Southeast Asia, Oceania, and Northern Europe.

3. MONOPILE AND JACKET FOUNDATIONS

While monopile foundations (a single pile driven into the seabed) currently account for about 80% of installed offshore wind turbine foundations, there's an increase in the use of jacket foundations (a lattice-type structure) for future projects in deeper waters (Bošnjaković, Mladen, et al., 2022). However, monopiles may remain the dominant foundation type due to their low cost and the industry's ability to adapt them to deeper waters.

4. LARGER OFFSHORE WIND FARMS

There is a steady increase in the global offshore wind turbine capacity, with significant growth in large offshore wind farms in Europe (Figure). This continuous growth in rated capacity is one of the factors contributing to the reduction in the cost of offshore wind farms.

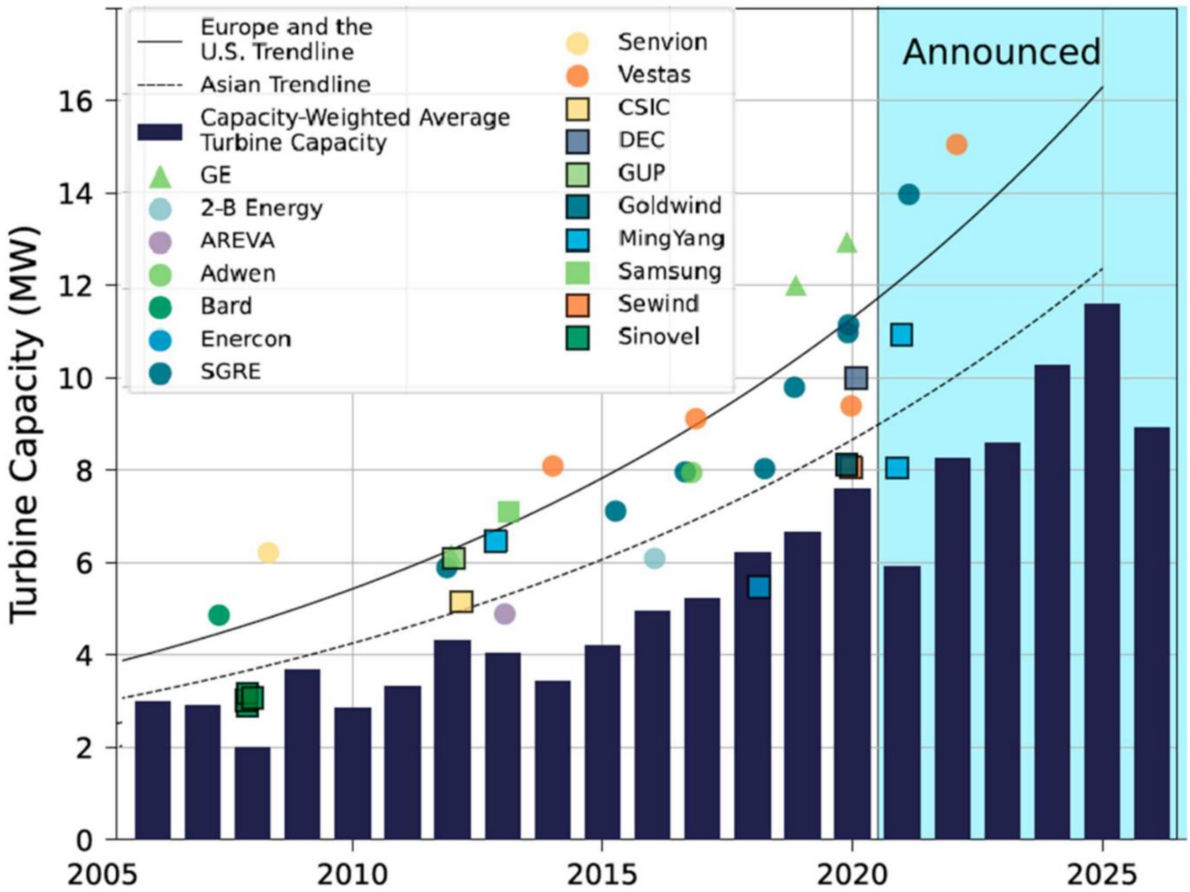


Fig. Current and projected turbine capacities

5. FLOATING OFFSHORE WIND CAPACITY

The cumulative deployment of floating offshore wind turbines is expected to reach 3,688 MW by 2026, with major contributions from countries like South Korea, Saudi Arabia, Spain, and France.

6. MAINTENANCE AND GRID INTEGRATION

Improving maintenance strategies, including remote monitoring and predictive maintenance, is crucial for reducing downtime and operational costs of offshore wind farms. Additionally, upgrading and modernizing power grids is necessary to accommodate the increasing share of renewable energy from offshore wind farms.

7. HYDROGEN PRODUCTION

There is great potential for offshore wind farms to play a role in the transition towards a hydrogen economy, with plans to utilize the generated electricity for the production of "green" hydrogen through electrolysis from water.

SUMMARY

Characteristic	**Wind Turbines**
Power Achieved	Up to 15 MW for offshore turbines, typically 2-5 MW for onshore turbines
Power Density	Moderate to high, depending on wind conditions
Energy Density	N/A (*dependent on wind*)
Lifetime	20-25 years (*can be extended with refurbishment*)
Efficiency	35-45% (*less important since wind is a free and renewable resource*)
Unit Costs	\$2.6 – \$4 million per average-sized commercial wind turbine (GE Haliade-X 14 costs between \$11-\$13M)
Energy cost	Around \$1,000,000 USD per megawatt

Table. Comparative summary of wind turbine technology

Wind turbine technology has come a long way, and ongoing research and development efforts aim to further improve performance, efficiency, and cost-effectiveness. As we strive towards a sustainable energy future, wind energy will undoubtedly play a crucial role in the global energy mix.

LIST OF WIND TURBINE TECHNOLOGY COMPANIES WITH MATURED MARKET PRODUCTS

1. VESTAS (DENMARK)

Founded in 1945, one of the largest wind turbine manufacturers in the world, Vestas has a diverse portfolio of onshore and offshore wind turbines ranging from 2 MW to 15 MW capacities. (https://www.vestas.com/en)

2. SIEMENS GAMESA (SPAIN)

Formed by the merger of Siemens Wind Power and Gamesa, this company is a leading supplier of offshore and onshore wind turbines, with models up to 14 MW. (https://www.siemensgamesa.com/en-int)

3. GE VERNOVA (UNITED STATES)

It has a comprehensive range of wind turbines, including the Haliade-X offshore turbine with a capacity of 13-14 MW, and onshore turbines up to 5.8 MW. (https://www.gevernova.com/)

4. GOLDWIND (CHINA)

Goldwind is a major Chinese wind turbine manufacturer with a strong presence in both domestic and international markets, offering turbines up to 8 MW. (https://www.goldwind.com/en/)

5. ENERCON (GERMANY)

Known for its gearless wind turbine designs, Enercon has a portfolio of onshore turbines ranging from 2 MW to 7.5 MW capacities. (https://www.enercon.de/en)

6. ENVISION ENERGY (CHINA)

Envision is a Chinese company that produces both onshore and offshore wind turbines, with models up to 5.7 MW. (https://www.envision-group.com)

7. MINGYANG SMART ENERGY (CHINA)

Mingyang is a leading Chinese wind turbine manufacturer, offering onshore and offshore turbines up to 16 MW in capacity. (https://www.myse.com.cn/en/)

6.GAS TURBINE

1. INTRODUCTION

Gas turbines, also known as combustion turbines, are a type of internal combustion engine that convert natural gas or other liquid fuels to mechanical energy. This mechanical energy then drives a generator that produces electrical energy. Gas turbines are widely used in various applications, including power generation, aviation, marine propulsion, and industrial processes. Their efficiency, reliability and impressive power to weight ratio made them commonly used in aviation, and later in modern power systems.

2. PRINCIPLE OF OPERATION

These machines operate on the principle of the Brayton cycle, which involves three main stages: compression, combustion, and expansion.

COMPRESSION:

Air is drawn into the compressor, where it is compressed to a high pressure. This is typically achieved using axial or centrifugal compressors.

As the air is compressed, its temperature increases.

COMBUSTION:

The high-pressure air enters the combustion chamber, where it is mixed with fuel (usually natural gas, kerosene, or diesel).

The fuel-air mixture is ignited, causing the temperature of the mixture to rise dramatically, resulting in high-energy, high-pressure combustion gases.

EXPANSION:

The high-pressure, high-temperature gases expand through the turbine section.

As the gases expand, they pass through turbine blades, causing the turbine to spin. This rotational energy is used to drive the compressor (in a closed loop system) and can also be used to generate electricity or provide mechanical power for other applications.

The expanding gases exit the turbine at a lower pressure and temperature.

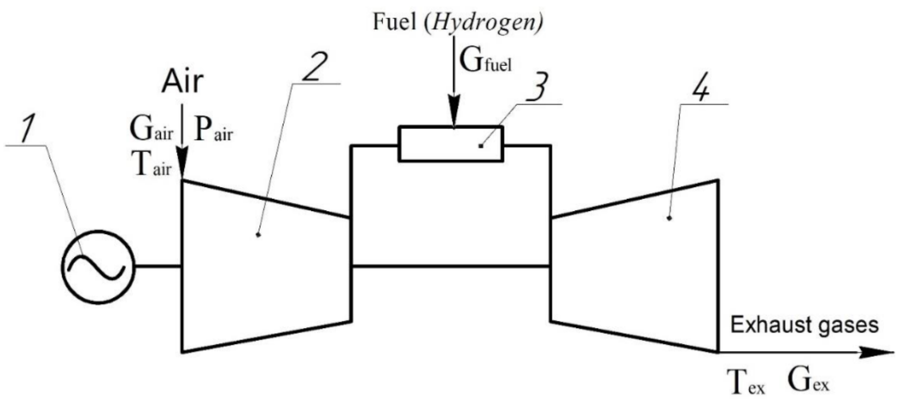


Figure 3. The schematic diagram of the investigated installation. 1 — a gas turbine generator; 2 — a multistage compressor; 3 — a combustion chamber; 4 — a gas turbine; P_{air} – an air pressure at the inlet (kPa), T_{air} – an air temperature at the inlet, (^{0}C), G_{air} – a mass air flow at the inlet to the gas turbine, (kg/s), G_{fuel} – a hourly fuel consumption, (kg/h), G_{ex} - flue gas flow rate (kg/s), T_{ex} – a flue gas temperature, (^{0}C)

G E Marin et al 2021 J. Phys.: Conf. Ser. 1891 012055

Figure 3 describes a diagram of a basic gas turbine connected to a generator (1). Each of the Brayton cycle stages occur in a diffrent part of the turbine. The air is compressed in the multistage compresor (2) for it to be then mixed with fuel and ignited in the combustion chamber (3). The expanding exhaust gases then escape through the blades of the gas turbine (4) in turn powering the compressor and generating power.

Gas turbines are also known for their flexibility in terms of the types of fuel they can use. While natural gas is the most common fuel due to its clean-burning properties and widespread availability, gas turbines can also operate on a variety of other fuels, including liquid fuels like diesel and jet fuel, biogas, syngas, and even hydrogen.

3. MATERIALS OF CONSTRUCTION

The materials used in the construction of gas turbines must withstand extreme conditions, including high temperatures, high pressures, and corrosive environments. The performance and efficiency of gas turbines are significantly influenced by the materials used in their construction. Advancements in material science have played a crucial role in enhancing the capabilities of gas turbines, enabling higher operating temperatures, better efficiency, and longer service life.

COMPRESSOR

The compressor section of a gas turbine compresses incoming air to high pressures before it enters the combustion chamber. Materials used in compressors need to possess high strength and fatigue resistance due to the mechanical stresses involved.

- Titanium Alloys: Commonly used in the front stages of the compressor where temperatures are lower. Titanium alloys offer a good strength-to-weight ratio and excellent corrosion resistance.

- Nickel-Based Alloys: Used in the rear stages of the compressor where temperatures are higher. Nickel-based alloys provide superior high-temperature strength and resistance to oxidation and corrosion.

COMBUSTOR

The combustor is where the fuel-air mixture is ignited and burned, producing high-temperature gases. Materials in the combustor must withstand high temperatures and thermal cycling.

- Nickel-Based Superalloys: Widely used due to their ability to retain strength and resist oxidation at high temperatures. Examples include Inconel, Hastelloy, and Rene alloys.

- Ceramic Matrix Composites (CMCs): Emerging materials that offer superior thermal resistance and lower density compared to metals. CMCs can operate at temperatures higher than those possible with metal alloys, enhancing turbine efficiency.

TURBINE

The turbine section extracts energy from the high-temperature gases produced in the combustor. Materials used in turbines must withstand the highest temperatures and mechanical stresses in the gas turbine.

- Single-Crystal Superalloys: Used for turbine blades and vanes. These materials are cast as single crystals to eliminate grain boundaries, which enhances high-temperature creep resistance and mechanical strength.
- Thermal Barrier Coatings (TBCs): Applied to the surface of turbine blades and vanes to protect the underlying metal from extreme temperatures. TBCs are typically made of ceramic materials such as yttria-stabilized zirconia (YSZ).

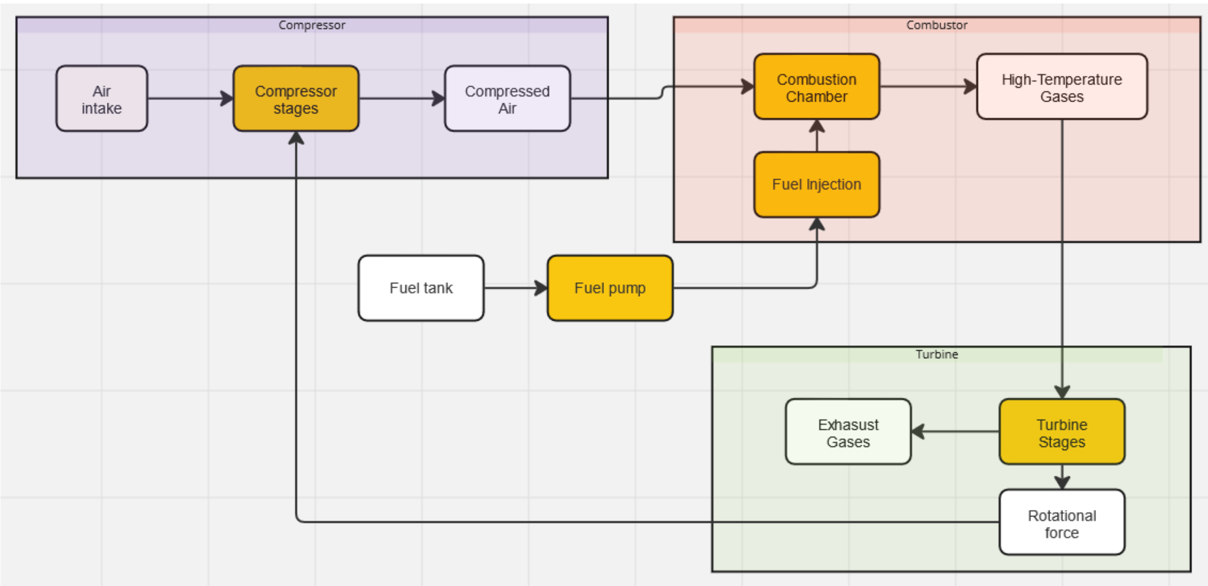
AUXILIARY SYSTEMS

Auxiliary systems, including cooling systems, lubrication systems, and control systems, also require specialized materials to ensure reliability and performance.

Stainless Steels: Used in various components for their excellent corrosion resistance and good mechanical properties at moderately high temperatures.

Polymer-Based Composites: Used in components that do not experience the highest temperatures but require good mechanical properties and resistance to chemical attack.

4. IDEA DIAGRAM



5. PERFORMANCE CHARACTERISTICS

POWER OUTPUT

Gas turbines have a wide range of power outputs, from small turbines producing a few hundred killowatts to large industrial turbines generating over 400 MW. The potential output of a gas turbine depends mainly for application it is intended for.

POWER DENSITY

Power density refers how powerfull the source realtive to its size or mass. Gas turbines achieve very high power densities, making them suitable for applications where space and weight are critical, such as in aviation. The power density of advanced gas turbines can exceed 10 MW per cubic meter.

THERMAL EFFICIENCY

The thermal efficiency of a gas turbine measures how effectively it converts fuel energy into mechanical energy. Simple cycle gas turbines typically achieve thermal efficiencies between 30% and 40%. This figure can be improved by using waste heat from the gas turbine to drive a steam turbine (CCGT), wich in turn can achieve efficiencies over 60%.

LOSSES AND CAUSES

Several phenomena contribute to the inefficiencies in gas turbines:

Inefficiency in combustion: Incomplete combustion leads to unburnt fuel and residue, reducing efficiency.

Heat Losses: Heat loss to the environment reduces the thermal energy of expanding gasses leading to decrease in the overall efficiency.

Mechanical friction: Friction and wear in rotating components, such as bearings and seals, reduce the mechanical efficiency of the turbine.

OPERATING TEMPERATURE

The operating temperature of a gas turbine, particularly in the combustor and turbine sections, significantly impacts its efficiency and performance. Advanced gas turbines operate at temperatures exceeding 1500°C (2732°F). Higher operating temperatures improve thermal efficiency but require advanced materials and cooling technologies to manage thermal stresses.

ENERGY DENSITY

Energy density refers to the energy in a given fuel in relation to its volume. Gas turbines typically use fuels with high energy densities, such as jet fuel and diesel. The energy density of jet fuel, for example, is 34.7 MJ/L, which contributes to the high power output and efficiency of gas turbines.

LIFETIME

The operational lifetime of gas turbines is influenced by factors such as operating conditions, maintenance practices, and materials used.

Typical Lifetimes: Gas turbines are designed for lifetimes of 20 to 30 years or more, with regular maintenance and periodic overhauls.

Maintenance Intervals: Regular inspections, including minor inspections every 8,000 to 12,000 operating hours and major overhauls every 25,000 to 50,000 operating hours, are essential to ensure reliability and longevity.

6. CURRENT R&D GOALS

Current research and development efforts in gas turbine technology are focused on improving performance, efficiency and reliability.

Performance and efficiency can be improved by using higher working temperatures which creates the need for advanced materials.

High-Temperature Alloys:

Developing alloys capable of withstanding higher temperatures to increase efficiency and power output.

Exploring the use of high-entropy alloys (HEAs) and intermetallic compounds for improved strength and corrosion resistance.

Aerodynamics and Turbomachinery

Advanced Turbomachinery Design:

Developing advanced aerodynamic designs to improve efficiency and reduce losses in compressor and turbine stages.

Investigating novel blade and vane geometries, such as swept blades and 3D airfoils, to enhance performance across a range of operating conditions.

Active Flow Control:

Exploring active flow control techniques, such as boundary layer suction and blowing, to mitigate aerodynamic losses and improve overall efficiency.

7. AREAS OF APPLICATION

Gas turbines, due to their high efficency and power density find their use in wide range of apliances ranging from power plants to helicopters.

POWER GENERATION

Electricity Generation:

Gas turbines are widely used in both centralized and decentralized power generation facilities, including combined cycle power plants, peaking plants, and distributed generation systems

AVIATION

Gas turbines, due to their high power to weight ratio, power most of today's aircrafts, providing thrust for propulsion. They are used in both turbojet and turbofan engines, allowing efficient high-speed air travel.

AUXILARY POWER SOURCE

Auxilary power unit is a device that provides power for other means than propulsion. Gas engines can weight less than 100kg while providing more power than a car engine making it usefull in portable aplications of APUs.

MILITARY

High reability and performance allows the use of gas turbine in military applications, most notable beeing Abrams M1 tank using the Avco-Lycoming AGT1500 gas turbine engine. The relativly lightweight engine allows the tank to be more armoured, and flexibility of fuel types proves helpful when supply is limited.

8. EXAMPLES OF PILOTED OR INDUSTRIAL INSTALLATIONS OF THE TECHNOLOGY

EDF BOUCHAIN POWER PLANT (BOUCHAIN, FRANCE)

Application: Power Generation

Gas turbine model: General Electric (GE) 9HA.01

Tehnology: Combined Cycle Power Plant

Power output: 605 MW

The Bouchain Power Plant features a GE 9HA.01 gas turbine, one of the most efficient gas turbines in the world, with a net efficiency exceeding 62%.

The combined cycle configuration includes a heat recovery steam generator (HRSG) and a steam turbine, which together enhance the overall efficiency of the plant.

The plant provides flexible, reliable, and efficient power to the French grid, supporting both baseload and peak demand requirements.

ABRAMS M1 TANK

Application: Military Ground Vehicle Propulsion

Gas Turbine Model: Honeywell AGT1500

Technology: Simple Cycle Gas Turbine Engine

Power Output: 1,500 hp (1,120 kW)

Description:

The Abrams M1 tank is powered by a Honeywell AGT1500 gas turbine engine, which provides high power-to-weight ratio and exceptional mobility for the tank.

The AGT1500 is a multi-fuel engine capable of operating on diesel, kerosene, and jet fuel, offering operational flexibility.

The gas turbine engine allows the Abrams M1 to achieve speeds of up to 45 mph (72 km/h) and operate efficiently in a variety of environmental conditions.

BOEING 787 DREAMLINER

Technical Description:

Application: Commercial Aviation

Gas Turbine Model: Rolls-Royce Trent 1000 and General Electric GEnx

Technology: Turbofan Jet Engines

Thrust: Approximately 64,000 to 78,000 pounds-force (lbf)

Description:

The Boeing 787 Dreamliner is equipped with advanced turbofan engines, the Rolls-Royce Trent 1000 or the GE GEnx, both offering high efficiency and reduced emissions.

These engines incorporate advanced materials and aerodynamic designs to improve fuel efficiency and reduce noise levels.

The Dreamliner benefits from these engines' high bypass ratios and low specific fuel consumption, making it one of the most fuel-efficient long-haul aircraft.

REFERENCES

SUPERCAPACITOR

1. Karthikeyan, S., et al. "Supercapacitor: Evolution and review." *Materials Today: Proceedings* 46 (2021): 3984-3988.
2. Ahankari, Sandeep, Dylan Lasrado, and Ramesh Subramaniam. "Advances in materials and fabrication of separators in supercapacitors." *Materials Advances* 3.3 (2022): 1472-1496.
3. Al Ashraf, Abdullah. *Nitrogen and sulfur-doped carbon nanofiber mixed oxides composites for supercapacitor applications*. Diss. Qatar University (Qatar), 2016.
4. Phor, Lakshita, Ashok Kumar, and Surjeet Chahal. "Electrode materials for supercapacitors: A comprehensive review of advancements and performance." *Journal of Energy Storage* 84 (2024): 110698.

FLYWHEEL

5. Nkomo, N. Z., and A. A. Alugongo. "Flywheel Energy Storage Systems and Their Applications: A Review." (2024).
6. Li, Jiansong, et al. "Design and energy analysis of a flywheel-based boom energy regeneration system for hydraulic excavators." Frontiers in Energy Research 11 (2023): 1202914.
7. Wang, Pengwei, et al. "Design and Performance Analysis of Super Highspeed Flywheel Rotor for Electric Vehicle." World Electric Vehicle Journal 13.8 (2022): 147.
8. Choudhury, Subhashree. "Flywheel energy storage systems: A critical review on technologies, applications, and future prospects." International transactions on electrical energy systems 31.9 (2021): e13024.
9. Li, Xiaojun, and Alan Palazzolo. "A review of flywheel energy storage systems: state of the art and opportunities." *Journal of Energy Storage* 46 (2022): 103576.

DMFC FUELLCELL

10. Madaswamy, Suba Lakshmi, et al. "Polyaniline-based nanocomposites for direct methanol fuel cells (DMFCs)-A Recent Review." Journal of Industrial and Engineering Chemistry 97 (2021): 79-94.
11. Alias, M. S., et al. "Active direct methanol fuel cell: An overview." International Journal of Hydrogen Energy 45.38 (2020): 19620-19641.
12. Li, Xianglin, et al. "Experimental measurements of fuel and water crossover in an active DMFC." International Journal of Hydrogen Energy 46.5 (2021): 4437-4446.

LTO BATTERY

13. Ilyas ANDIK, Fatma Yasemin ARSLAN, Ali UYSAL et al. Comparison of Prediction Performance of Lithium Titanate Oxide Battery Discharge Capacity with Machine Learning Methods, 20 November 2023.
14. Lu, Fan, et al. "A Study on Low-Temperature Model Parameter Identification of LTO Battery by Cuckoo Search." 2020 15th IEEE Conference on Industrial Electronics and Applications (ICIEA). IEEE, 2020.
15. Zhou, Yanhu. "Advantages and Application of Nano LTO battery." Highlights in Science, Engineering and Technology 32 (2023): 186-192.
16. Novak, Martin, and Zdenek Novak. "Modeling and Experimental Validation of a LTO Battery Cell for a Hydrogen Hybrid Bus." 2023 IEEE 32nd International Symposium on Industrial Electronics (ISIE). IEEE, 2023.

WIND TURBINE

17. Porté-Agel, Fernando, Majid Bastankhah, and Sina Shamsoddin. "Wind-turbine and wind-farm flows: a review." *Boundary-layer meteorology* 174.1 (2020): 1-59.
18. Bošnjaković, Mladen, et al. "Wind turbine technology trends." *Applied Sciences* 12.17 (2022): 8653.
19. Jiang, Zhiyu. "Installation of offshore wind turbines: A technical review." *Renewable and Sustainable Energy Reviews* 139 (2021): 110576.
20. Nejad, Amir R., et al. "Wind turbine drivetrains: state-of-the-art technologies and future development trends." *Wind Energy Science* 7.1 (2022): 387-411.
21. Veers, Paul, et al. "Grand challenges in the design, manufacture, and operation of future wind turbine systems." *Wind Energy Science* 8.7 (2023): 1071-1131.
22. Ren, Zhengru, et al. "Offshore wind turbine operations and maintenance: A state-of-the-art review." Renewable and Sustainable Energy Reviews 144 (2021): 110886.

GAS TURBINE

23. Marin, G. E., D. I. Mendeleev, and B. M. Osipov. "A study on the operation of a gas turbine unit using hydrogen as fuel." *Journal of Physics: Conference Series*. Vol. 1891. No. 1. IOP Publishing, 2021.