WIND ENERGY

2.1 Technology Description

Wind results from the movement of air caused by atmospheric pressure gradients. The uneven heating of the atmosphere causes expansion of warmer air, making less pressure where it is warmer than where it is cooler. The wind blows from higher-pressure zones to lower-pressure locations. The greater the air pressure gradient, the higher the wind speed and, as a result, the more wind power that can be captured.

A wind turbine is an energy-converting machine to convert wind's kinetic energy into mechanical energy and, in turn, into electrical power.

Wind turbine classification

• Horizontal-axis (HAWT) and vertical-axis wind turbines (VAWT)

HAWT in which the rotating axis of blades is parallel to the wind stream. In contrast, the blades of VAWT rotate with respect to their vertical axes that are perpendicular to the ground.

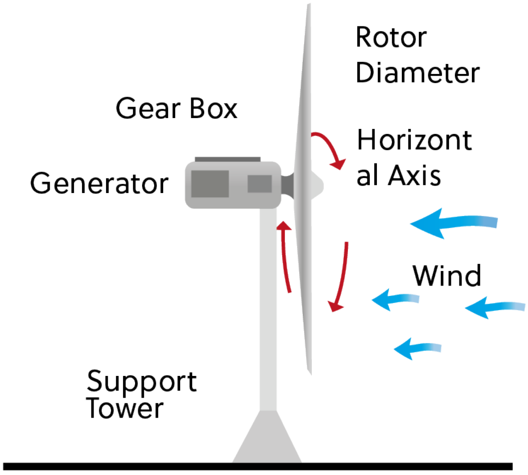
VAWT can receive and process wind from any direction to perfectly suit areas with turbulent winds; however, HAWTs need to be placed in the wind direction. A yaw meter is used in large wind turbines to keep the wind rotor position aligned with the wind stream.

HAWT design is more complex and expensive as the generator and gearbox are placed at the top of the tower. While in VAWT, the generator, gearbox, etc., can be installed at the bottom of the tower, hence the maintenance is more manageable with lesser cost.

HAWTs show outstanding performance due to sufficient starting speed, and consistent wind flows. VAWTs start at a lower wind speed which results in less productive performance.

• Upwind and downwind wind turbines

HAWTs are further subdivided into upwind and downwind wind turbines. The vast majority of horizontal-axis wind turbines now in service are upwind turbines, in which the wind rotors face the wind. The primary benefit of upwind designs is that they eliminate flow field distortion as the current travels through the wind tower and nacelle.



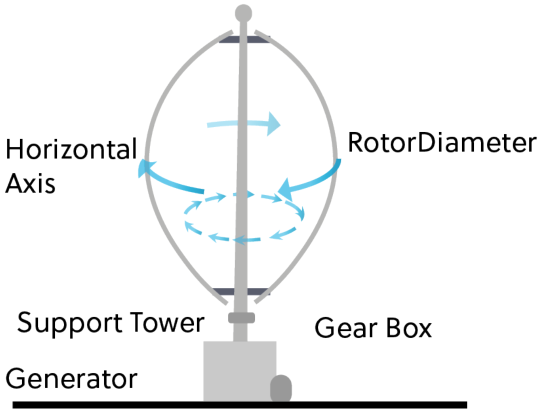


Figure 32: HAWT vs. VAWT[37]

Wind Turbine components

The major components of the horizontal wind energy system are the following:

• Rotor with 2 or 3 blades converts the energy in the wind into mechanical energy. The blades are linked to the hub, which in turn is attached to the main shaft. The blades are designed to operate either on drag or lift principle; the drag force tries to push the blades away, and the lift force moves it at right angles, as illustrated below.

(37) Ebeed, Mohamed. (2013). Enhancement Protection and Operation of The Doubly Fed Induction Generator During Grid Fault.

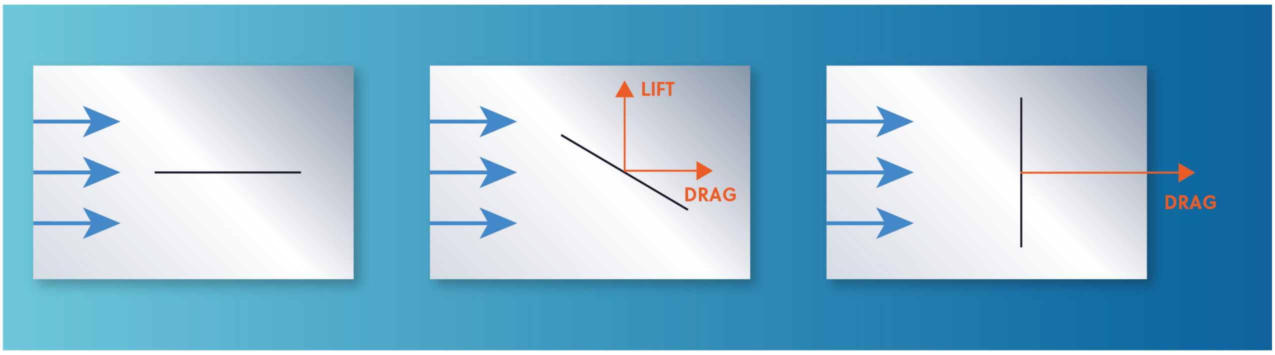


Figure 33: Drag and lift forces on a thin plate in a steady wind[38]

• The tall tower is not just a support structure; it raises the wind turbine high above the ground, so the blades are safely clear and can reach the stronger winds at higher elevations.

• The nacelle generally houses a set of gears in case of geared type, and a generator mounted on the top of the tower.

• The gearbox helps increase the slow rotational speed of the rotor (blades) to a high-speed motor to generate electricity.

• The generator is what converts the rotational motion of the wind turbine's blades into electricity.

• The solid foundation prevents the wind turbine from blowing over in high winds and icing conditions.

• Control system for starting and stopping the wind turbine as well as monitoring the machinery's proper operation.

• The yaw drive is utilized to maintain the rotor orientation facing the wind as the direction of the wind influences the amount of energy generated.

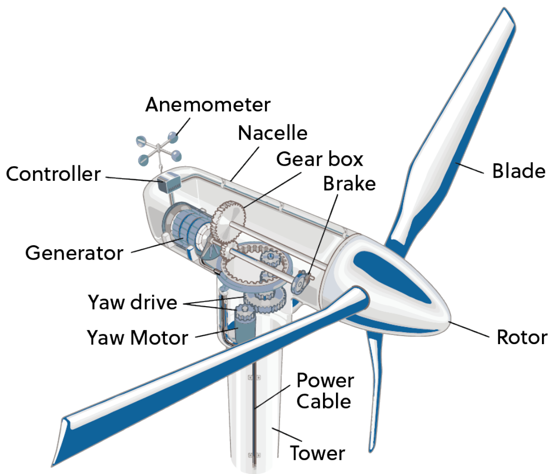


Figure 34: Wind turbine schematic diagram[39]

Wind Energy Generation Process

Wind flows across the blades of the horizontal wind turbine, which causes the air pressure on one of the sides to decrease. Therefore, the air pressure difference across the two sides of the blades creates lift and drag forces. Due to the strong lift force, the rotor, which is connected directly to a gearbox, spins the shaft; thus, it speeds up the rotation convenient for a small generator.

The generator converts this mechanical power into electricity. Lastly, a transformer steps up the voltage to be exported to the National Grid or used by a local site.

Harvested mechanical power depends on wind speed and the blades swept area; faster wind speed and larger rotor blades yield more extractable energy.

Wind Turbine Size and Power Ratings

Wind turbines can be divided into several categories, given their rated capacities: micro, small, medium, and large wind turbines.

Before 1985, the capacity of wind turbines was under 1 MW with rotor diameters of around 15 meters. In 2012, the average size was 2.5 MW with rotor diameters of 100 meters.

Onshore turbines are currently manufactured in sizes ranging from 2.5 to 3 MW, with blade lengths of roughly 50 meters.

7.5 MW turbines are the largest today, with blades about 60 meters. 15 MW turbines are planned, and 20 MW turbines are considered to be theoretically possible.[40]

(39) Lynn, Paul A. 2012. Onshore and Offshore Wind Energy. United Kingdom: John Wiley & So
(40) https://www.ewea.org/wind-energy-basics/faq/#:~:text=How%20big%20is%20a%20wind,than%203%2C312%20average%20EU%20 households.

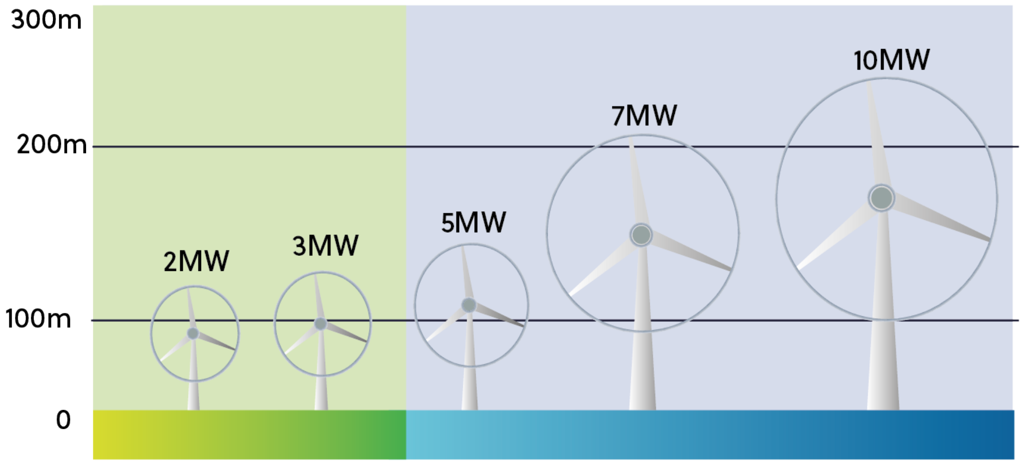


Figure 35: Typical dimensions for horizontal wind turbine[41]

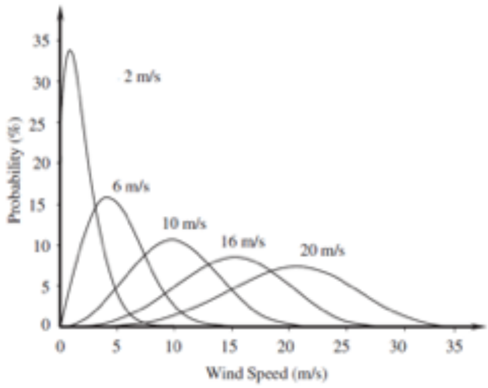
2.2 Design Considerations

Resource Assessment

• Wind speed and statistics

Wind speed is the most critical characteristic of wind power generation. Wind speed varies in both time and space, determined by many factors such as geographic and weather conditions. Because wind speed is a random parameter, measured wind speed data are usually dealt with using statistical methods.
The Weibull distribution function, which depicts the probability of different mean wind speeds occurring at the site over time, is the best choice to characterize wind speed variance at a specific location.

Wind results from the movement of air caused by atmospheric pressure gradients. The uneven heating of the atmosphere causes expansion of warmer air, making less pressure where it is warmer than where it is cooler. The wind blows from higher-pressure zones to lower-pressure locations. The greater the air pressure gradient, the higher the wind speed and, as a result, the more wind power that can be captured.



A wind turbine is an energy-converting machine to convert wind's kinetic energy into mechanical energy and, in turn, into electrical power.

A wind map based on historical wind data is a long-term forecast that assumes past information can predict the future. However, we generally reserve the word 'forecasting' for relatively short-term predictions covering hours or days.

Wind resource assessment determines the project's feasibility by identifying available wind resource data and the highest potential locations.

After site identification, a detailed wind resource site assessment should be performed. The level of detail of the study depends on the size of the intended project. Moreover, long-term weather data could be collected over ten years or more to account for long-term production estimates.

Equipment selection

• Operation characteristics of wind turbine

The power curve displayed in the figure below constrains the relationship between wind speed and the generator output power. No output power will be produced until the blade's rotational speed exceeds cut-in speed.

Cut-in speed represents the minimum speed required to generate sufficient force to overcome friction and accelerate the rotor and generator to start producing power.

Above cut-in speed, the generator produces electrical power proportional to the cube wind speed (V3) until it reaches its maximum rated power output. Beyond rated speed, the rotor blades approach the electrical machine's full strength, and the generator will be producing its rated power output. The rated power of a wind

(41) Lynn, Paul A. 2012. Onshore and Offshore Wind Energy. United Kingdom: John Wiley & Sons Ltd.

turbine shows a discrepancy from several hundred watts to megawatts.

If the wind speed further increases, the wind turbine generator stalls after to prevent mechanical and electrical damage. A mechanical or electrical speed sensor can be used to apply a brake to prevent the generator from damage. Thus, beyond cut-out speed, the generation drops to zero.

Figure 36: Wind Turbine Power Curve[42]

• *Betz limit*

The kinetic energy of the wind is converted into mechanical energy through the spinning blades. However, there is a theoretical maximum amount of energy that can be extracted from the wind, which is equal to 0.59; this is called the "power coefficient or efficiency" and is defined as:

$$C_p = \frac{\text{Power generated by wind turbine}}{\text{Theoretical max power available in wind}}$$

where $C_{p\,Max} = 0.59$

• *Wind Power*

The following equation describes the relationship between wind speed and the generated power:

$$P = \frac{1}{2}\, pAV^3\, C_p$$

p: Air density (kg/m³).
A: Swept area by the blades (m²).
V: Wind speed (m/s).

C_p : Power efficiency.

Blade swept area

$$A = \pi r^2 \,(m^2)$$

• *Capacity factor*

Because of the intermittent nature of wind, turbines do not make power all the time. Thus, a capacity factor of a wind turbine is used to provide a measure of the wind turbine's actual power output in a given period divided by its power output if the turbine has operated the entire time. A reasonable capacity factor would be 0.25–0.30, and a very good capacity factor would be around 0.40. Wind turbine capacity factor is very sensitive to the average wind speed.

• *Rated power*

Therefore, the required wind turbine(s) capacity can be evaluated after estimating **the electricity demand** using the following equation:

Wind turbine rated power (W)

$$\frac{\text{Annual energy output required (w.h)}}{365 \text{ days} \times 24 \text{ hours} \times \text{Capacity Factor}}$$

Structural Design

A wind turbine's structural design is comprised of two major components: tower and foundation. The tower design primarily depends on wind and ice loads and loads acting from the rotor, nacelle, blades, and extra equipment at the top of the tower. The foundation is constructed based on the moment and axial loads generated by the tower design and the properties of the supporting soil.

2.3 Advantages and Disadvantages

Wind power is one of the world's fastest-growing energy sources. The latest research efforts aim to address the barriers to broader wind energy usage, offering many advantages.

Advantages

• Renewable and sustainable technology that does not release pollutants and emissions, unlike depleting fossil fuels.

• Wind turbines have a small footprint, although a large landscape is required to build a wind farm. The land below the vanes of the turbines can be simultaneously for crops growing, animal grazing, or anything else.

• Its capability to serve domestic and industrial loads in remote areas, from small to large wind farms to off-grid and on-grid applications.

• Wind power is cost-effective, one of the lowest-priced energy sources available today, and mitigates the price uncertainty associated with traditional fuels.

(42) https://www.energy.gov/eere/articles/how-do-wind-turbines-survive-severe-storms

Disadvantages

- Wind power is characterized by low variable costs and relatively high fixed costs.
- Poorly sited wind energy facilities threaten wildlife; some birds and even bats have been injured and killed. In addition to disturbing the flight patterns of migratory birds and predatory birds' disturbances, they create visual and sound pollution. The impact of wind turbine noise on surrounding residents is a serious issue that must be addressed. Wind turbine noise consists of aerodynamic noise from rotating blades and mechanical vibration noise from gearboxes and generators.
- The best locations wind farms are rural areas, which require transporting electricity over long cable distances, imposing additional costs.
- The wind is a highly intermittent energy source, and the expected growth in wind power capacity could exceed the current capability of grids. Integrating large wind energy shares presents unique challenges that must be adequately addressed.

2.4 Applications

Water pumping

Small turbines with a power range of 20 to 100 kilowatts (kW) are commonly used to charge batteries in recreational vehicles and sailboats; 1 to 10 kW turbines have been used in different applications, including pumping water.

For centuries, wind energy has been primarily employed for pumping water and grinding grain, providing an economical option for pumping water in low-wind areas. However, wind-electric pumping is more versatile and can pump twice the volume for the same initial investment. Besides, mechanical windmills must be placed directly above the well; whereas, wind-electric pumping systems can be located in the best wind resource area and separated from the pump motor. But they have proven their efficiency in areas with low wind resources, as mechanical windmills provide more feasible water pumping.

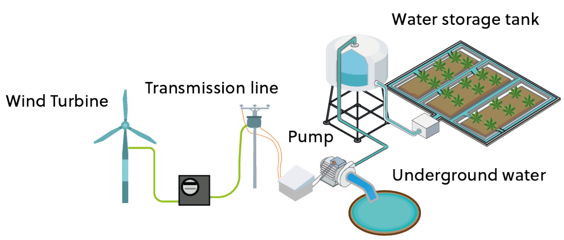


Figure 37: Wind turbine pumping station[43]

Water pumps rely on electrical power generated by a wind turbine to carry water from under to above ground.

Residential applications

Turbines range from 400 Watts to 100 kW are used depending on the energy demand and the available budget.

Figure 38: Wind Turbines for Residential Applications[44]

Off-grid applications

Small wind power systems are convenient for applications in rural areas where storing and shipping fuel is unfeasible, including telecommunications, radar, pipeline control, navigational aids, and weather stations/seismic monitoring as well as air traffic control. Such applications require robust wind machines against extreme weather with very minimal maintenance.

The stand-alone system provides power to homes and businesses remote from an established grid at the least cost. Wind power has proved to be less costly than diesel generators at any remote site to operate small household appliances; refrigeration and freezing, heating, cooling, and lighting.

Figure 39: Off-grid wind application

(43) Parigi, F. et al., 2009. Wind for irrigation application. 2009 IEEE Power Electronics and Machines in Wind Applications.
(44) REN21. 2021. Renewables 2021 Global Status Report

Building a larger system to provide power for a centralized community center, health clinic, or school. Extending the distribution lines to individual homes and creating a "mini-grid" increases the convenience of the power system to the community.

On-grid application

Mainly utilized in large-scale wind power applications, since the power output is dependent on the wind speed, differences in one meter per second can mean differences in the cost per kWh.

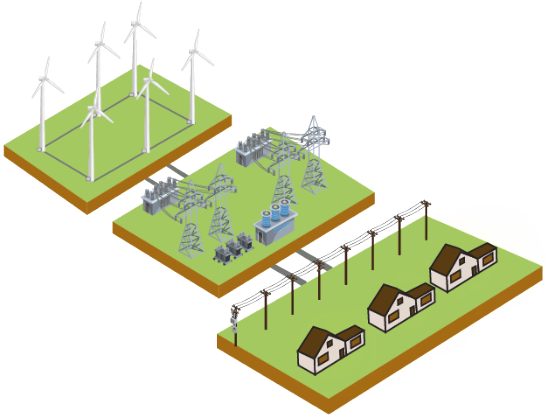


Figure 40: On-grid wind application

Large scale applications

Large scale applications are used to create power plants to support the system and reduce the operating cost and their capability to provide a feasible power for rural areas.

Large-scale private utilities may also revert to such wind farms to reduce their electric bill and the dependability on the grid of huge plants like a factory.

Along with the size, the interconnection with the central or national grid plays a vital role. On-grid applications are tied to the grid, allowing bi-directional power transfer depending on the self-sufficiency between the available generation and the current load at each instant.

Figure 41: Large-scale wind project[45]

2.5 Projects

Nouadhibou Wind Farm

Location: Mauritania

Capacity: 4.4 MW

Project Brief[46]

- The facility is powered by a 16 MW diesel plant equipped with four diesel gen-sets.
- Powering motors essentially for ore conveyors and crushers.
- Considering the powerful wind potential of the Nouadhibou site (8.78m/s at hub height), they decided to diversify on-site power generation through the development and installation of a wind farm.
- Specific wind turbine technology was also required to address the near-shore location, arid and warm climate, and highly corrosive environment.

Status: Operational

2.6 Further Readings

Technology

Lynn, Paul A. 2012. Onshore and Offshore Wind Energy. United Kingdom: John Wiley & Sons Ltd.
Link: https://digilib.bppt.go.id/sampul/9781119954613.pdf

Guide to Off-Grid Systems
Link: https://sd-windenergy.com/files/9315/5956/9091/SD_Guide_to_Off_Grid_Systems.pdf

Online Resources

Wind Resource Assessment
https://www.windustry.org/community_wind_toolbox-4-wind-resource-assessment
https://www.intechopen.com/chapters/38933

(45) https://www.kisr.edu.kw/en/gi/3/details/
(46) http://www.vergnet.com/wp-content/uploads/2016/01/Case_study-NOUADHIBOU-WIND-FARM-bbu.pdf

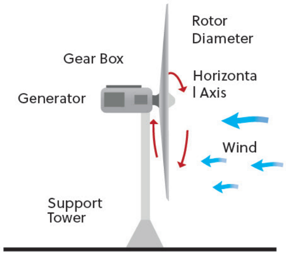
RENEWABLE ENERGY TECHNOLOGY
WIND ENERGY

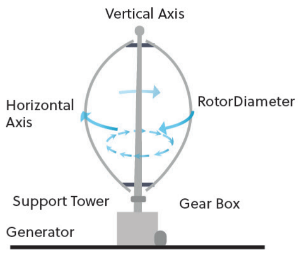
TECHNOLOGY DESCRIPTION

Wind results from the movement of air caused by atmospheric pressure gradients. The uneven heating of the atmosphere causes the expansion of warmer air. The wind blows from higher-pressure to lower-pressure zones. The wind turbine is an energy-converting machine to convert wind's kinetic energy into mechanical energy and, in turn, into electrical power.

WIND TURBINE CLASSIFICATION

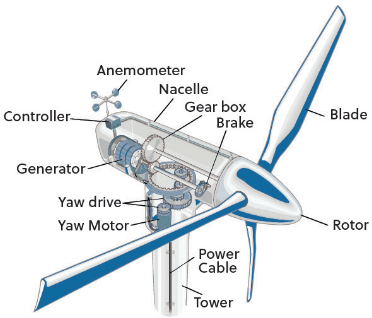
HORIZONTAL-AXIS (HAWT)	POINTS TO CONSIDER
• The rotating axis of blades is parallel to the wind stream	• Rotate with respect to their Vertical-Axis (VAWT) that are perpendicular to the ground.
• It needs to be placed in the wind direction	• Can receive and process wind from any direction
• The design is more complex and expensive	• The maintenance is more manageable with lower cost
• Outstanding performance due to sufficient starting speed	• Start at a lower wind speed which results in less productive performance





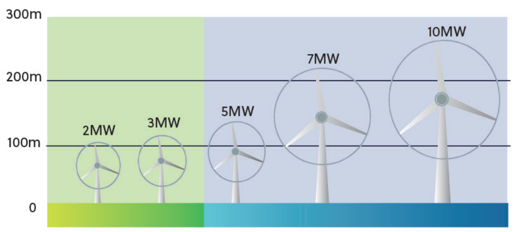
WIND TURBINE COMPONENTS

- The tall tower supports the structure and raises the wind turbine high above the ground, so the blades are safely clear and can reach the stronger winds at higher elevations.
- The nacelle generally houses a set of gears mounted on the top of the tower.
- The gearbox helps increase the speed of the rotor (blades) to generate electricity.
- Control system for starting, stopping, and monitoring the wind turbine operation.
- The yaw drive is utilized to maintain the rotor orientation facing the wind.



WIND ENERGY GENERATION PROCESS

Wind flows across the blades of the horizontal wind turbine, which causes the air pressure on one of the sides to decrease. Therefore, the air pressure difference across the two sides of the blades creates lift and drag forces. Due to the strong lift force, the rotor, which is connected directly to a gearbox, spins the shaft; thus, it speeds up the rotation convenient for a small generator.



WIND TURBINE SIZE AND POWER RATINGS

DESIGN CONSIDERATIONS

- **Wind speed and statistics**

A detailed wind resource site assessment should be performed for the selected sites.

- **Operation characteristics of wind turbine**

The power curve identifies the relationship between wind speed and the generator output power.

Cut-in speed represents the minimum speed to start producing power.

Rated power output: the generator produces electrical power proportional to the cube wind speed (V3) until it reaches its maximum rated power output.

The cut-out speed: limit speed where sensor can be used to apply a brake to prevent generators' damage

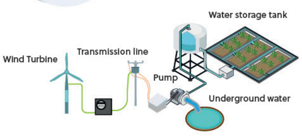
Rated power

$$W = \frac{(w \times h)}{(365 \text{ days} \times 24 \text{ hours} \times \text{Capacity Factor})}$$

(W) Wind turbine rated power
(wxh) Annual energy output required

ADVANTAGES	POINTS TO CONSIDER
• Does not release pollutants and emissions • Have a small footprint • Can serve off-grid and on-grid applications • Cost-effective	• Low variable costs and relatively high fixed costs • Poorly sited facilities threaten wildlife • Create visual and sound pollution • Best fit in rural areas, which require transporting electricity over long cable distances

APPLICATIONS



• Water pumping

• Residential applications

• Off-grid applications

• On-grid application

• Large scale applications