

Transcript Lesson 4b. Motion

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Welcome to Module 4b, Motion Delivery, part of the course Renewable Energy Integration in the Energy System, developed by The Hague University of Applied Sciences.

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In this module, we explore the main systems used to deliver motion. In some cases, motion is the final energy form — for example, when a combustion engine powers a car or a jet engine propels a plane. In other cases, motion is an intermediate step in a chain of energy conversions that ultimately produces electricity, as is the case for the turbines covered in this module.

Before looking at how these systems work and comparing their advantages and disadvantages, we will first review some basic concepts about motion energy. Understanding these concepts will help us better understand how the different motion delivery systems operate.

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Motion energy refers to the energy associated with movement. In physics, this is formally called kinetic energy. The greater the speed and mass of a moving object, the more kinetic energy it has.

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Velocity is a measurement of speed in a specific direction. When an object moves in a straight line, we use linear velocity. The standard unit in the international system is metres per second, though kilometres per hour is common for road transport, and miles per hour is used in the United Kingdom and the United States.

When something rotates around a centre — like a wind turbine rotor or a car engine — we use angular velocity instead. Angular velocity can be expressed in radians per second, the international system unit, or in revolutions per minute, which is more common in engineering.

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With those basic concepts in place, let us now look at the energy converters themselves. The first one is the combustion engine, which transforms chemical energy — mainly from fossil fuels — into mechanical motion. Combustion engines can also run on alternative fuels such as biofuels or hydrogen.

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Inside a combustion engine, a piston moves up and down within a cylinder, converting the energy from burning fuel into mechanical motion through a four-stroke cycle.

During the intake stroke, the piston moves downward, drawing in a mixture of air and fuel. In the compression stroke, it moves back up, compressing the mixture to make it more volatile. The power stroke follows: a spark plug ignites the compressed mixture, causing a rapid expansion of gases that forces the piston down — this is the stroke that produces useful work. Finally, in the exhaust stroke, the piston moves up again, pushing the combustion gases out. This cycle repeats continuously to produce power.

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The up-and-down motion of the pistons is converted into rotation by the crankshaft. This rotational motion is then transmitted through the gearbox and driveshaft, which adjust speed and torque, and finally reaches the wheels through the axles, propelling the vehicle forward.

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Combustion engines are valued because they convert fuel into mechanical power quickly and with high output. They are compact relative to the power they deliver, can be refueled in minutes, and rely on a well-established global infrastructure, making them practical and versatile for transport and machinery.

However, they are relatively inefficient — much of the fuel's energy is lost as heat — and they produce carbon dioxide and other air pollutants. They also involve many moving parts, leading to wear, maintenance requirements, and noise. Their dependence on fossil fuels makes them less sustainable compared to alternatives such as electric motors powered by renewable energy.

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The next energy converter is the gas turbine. Gas turbines are used both when motion is the final product — as in aircraft — and as an intermediate step to generate electricity using a generator.

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A gas turbine converts chemical energy into mechanical motion through a continuous flow process. Air is drawn in and compressed to high pressure by a compressor. This compressed air is mixed with fuel — typically natural gas — and ignited in a combustion chamber, producing a high-temperature, high-pressure gas stream. As this gas expands, it drives turbine blades to spin.

The turbine shaft is connected to both the compressor and a generator. Part of the turbine's output keeps the compressor running; the rest drives the generator to produce electricity. Unlike a piston engine, a gas turbine operates continuously, enabling smooth and efficient large-scale power generation.

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Some power plants use cogeneration — also known as combined heat and power, or CHP — to make better use of the fuel's energy. In a conventional plant, a large share of the energy is lost as waste heat. In a cogeneration system, this heat is captured and used for purposes such as heating buildings, supplying hot water, or driving industrial processes.

This significantly increases overall efficiency: cogeneration systems can reach efficiencies of 70 to 80 percent, compared to around 40 percent in conventional plants, because the same fuel provides both electricity and useful heat.

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A gas turbine in an aircraft — commonly called a jet engine — works on the same principle as in a power plant, but with a different goal. Compressed air is mixed with fuel and ignited, producing hot, high-pressure gases. These gases spin the turbine blades, which in turn drive the compressor to keep the process going.

The key difference is what happens to the remaining energy. In an aircraft engine, the goal is to produce thrust: the exhaust gases are expelled at high speed through a nozzle, pushing the aircraft forward. In a power plant, the goal is to extract as much energy as possible from the gases to spin a generator, so the exhaust is much slower.

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Gas turbines offer several strengths: they can produce large amounts of power smoothly, they have fewer moving parts than piston engines, and their high power-to-weight ratio makes them especially suitable for aviation. When combined with steam cycles in combined-cycle power plants, they can achieve high overall efficiencies.

Their limitations include lower efficiency at partial loads, a need for advanced materials due to extreme operating temperatures, and sensitivity to fuel quality and environmental conditions. They still produce emissions, including carbon dioxide and nitrogen oxides, and involve high manufacturing and maintenance costs.

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We now turn to steam turbines, which are used in a wide range of power plants — including geothermal, nuclear, and combustion plants — and can work with many different heat sources and fuels.

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A steam turbine converts thermal energy into mechanical motion using high-pressure steam. Water is heated in a boiler — by burning fuel, nuclear reactions, or other heat sources — until it becomes high-pressure steam. This steam is directed onto turbine blades, causing the shaft to spin, which drives a generator to produce electricity.

After passing through the turbine, the steam is cooled in a condenser and returns to liquid water, which is pumped back to the boiler, completing a continuous cycle. Compared to gas turbines, the use of an intermediate steam cycle allows steam turbines to efficiently generate large amounts of power, particularly at scale.

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In large steam turbines, the expansion of steam is divided into high-pressure, medium-pressure, and low-pressure stages to extract energy more efficiently. High-pressure steam from the boiler enters the first stage and expands, losing energy as it spins the blades. It is then often reheated in the boiler — increasing its temperature without significantly raising pressure — before entering the medium-pressure stage. Finally, in the low-pressure stage, the steam expands to its lowest pressure and temperature, extracting the remaining energy.

This staged approach improves efficiency, reduces mechanical stress on the blades, and prevents excessive moisture formation, which could otherwise cause damage. Like gas turbines, steam turbines can also operate in cogeneration mode to make use of waste heat.

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Steam turbines are well suited for large-scale, continuous power generation. They are highly efficient under steady operating conditions, have relatively few moving parts compared to piston engines, and are flexible in terms of energy sources — any process that generates high-pressure steam can drive them.

Their limitations include the need for a complete supporting system of boiler, condenser, and pumps, which makes installations large and expensive. They are not suited for rapid start-up or variable loads, significant heat is rejected in the condenser, and large amounts of cooling water are often required.

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We now move to water turbines, which convert the flow of water into rotational motion that can be used to generate electricity. The water source can be a reservoir behind a dam, a flowing river, or tidal movement.

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In a dam-based hydro system, water stored at a higher elevation is released and flows down through large pipes called penstocks. As it descends, its potential energy is converted into kinetic energy, which strikes the turbine blades and causes them to spin. The rotating turbine drives a generator to produce electricity.

The power output depends on two factors: the head — the height difference the water falls through — and the flow rate. Because no combustion is involved, hydro turbines are highly efficient and can operate continuously as long as sufficient water is available.

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Pumped hydro storage uses two reservoirs at different heights to store and release energy. When excess electricity is available — for example, from wind or solar — it is used to pump water to the upper reservoir, storing energy as gravitational potential energy. When electricity demand rises, the water is released back down through turbines to generate electricity.

A well-known example is the system on the island of El Hierro, where excess wind energy is used to pump water uphill, and the stored water is released when wind production drops, helping to maintain a stable electricity supply. This approach is one of the most practical ways to balance intermittent renewable energy sources.

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The power produced by a water turbine can be calculated using the following formula: $P = \eta \cdot \phi \cdot \rho \cdot g \cdot H$.

In this formula, ϕ is the volumetric flow rate — the volume of water passing through the turbine per second. The term $\rho \cdot g \cdot H$ represents the potential energy per unit volume of water, where ρ is the water density, g is gravitational acceleration, and H is the head — the height difference the water falls through. Multiplying the flow rate by this energy density gives the total available hydraulic power. Finally, η is the turbine efficiency, which accounts for real-world losses and gives the actual usable power output.

In simple terms: the more water you have, the higher it falls from, and the more efficient your turbine, the more power you generate.

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Tidal energy is a renewable energy source derived from the gravitational interaction between the Earth, the Moon, and the Sun, which causes the regular rise and fall of sea levels. These tidal movements displace large volumes of water, creating predictable and powerful flows that can be harnessed to generate electricity.

A key advantage of tidal energy is its high predictability compared to wind or solar, since tidal patterns follow regular astronomical cycles. Water is also much denser than air, meaning that tidal currents carry significant energy even at relatively low speeds.

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Tidal energy can be harvested in different ways. Tidal barrages are dam-like structures built across a bay or estuary; as the tide rises and falls, water flows through built-in turbines to generate electricity. Tidal stream systems use underwater turbines placed in fast-moving tidal currents, working on a similar principle to wind turbines but submerged.

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An interesting development in this area is the floating tidal platform developed by Orbital Marine Power. The system consists of a large floating structure moored to the seabed in areas with strong tidal currents. Long arms extend from the platform with underwater rotors at their ends, which spin as tidal water flows past them.

A key advantage of this design is that it simplifies installation and maintenance: the platform can be anchored without heavy underwater construction, and the rotor arms can be raised above the water surface for easier access and repair. This reduces operational costs and makes the technology more adaptable to different locations.

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Water turbines are highly efficient energy converters that use the flow of water to produce electricity. They rely on renewable resources, produce no direct emissions during operation, and can have long operating lifetimes with relatively low running costs. Hydropower systems offer fast response to demand changes, while tidal systems provide highly predictable output due to regular tidal cycles.

Their main limitations are geographical: suitable sites for dams, run-of-river plants, or tidal installations are not universally available. Large dams can be costly and may have significant environmental and social impacts. Tidal technologies are still maturing and face challenges in harsh marine environments. Hydropower output can also vary with seasonal water availability.

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The final energy converter in this module is the wind turbine, which converts the kinetic energy of wind into rotational motion and then into electricity. Wind is mainly harvested in areas with strong and consistent winds, so before examining how a wind turbine works, it is useful to understand what drives wind in the first place.

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Wind is the movement of air caused by differences in air pressure, which arise from uneven heating of the Earth's surface by the Sun. When the ground is heated, the air above it warms, expands, and rises, creating a low-pressure area. Cooler, denser air forms high-pressure areas, and air flows from high-pressure to low-pressure regions — this movement is what we experience as wind.

On a larger scale, wind patterns are also shaped by the rotation of the Earth — which deflects wind through the Coriolis effect — as well as the distribution of land and sea, and variations in terrain such as mountains and valleys.

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At a local level, geography has a strong influence on wind. In coastal areas, temperature differences between land and water create sea breezes during the day and land breezes at night. In mountainous regions, valleys experience daily wind cycles: during the day, sun-heated slopes cause warm air to rise up the valley — an anabatic or valley wind — while at night, the slopes cool and dense cold air flows downward — a katabatic or mountain wind.

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Wind speed also varies with height. Close to the ground, obstacles such as buildings, trees, and rough terrain create drag and turbulence that slow the wind. As altitude increases, the influence of surface friction decreases and wind flows more freely. This is why wind turbines are built on tall towers — to access the stronger and more consistent winds at greater heights.

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The variation of wind speed with height can be estimated using the wind profile power law. The formula is: v_2^2 equals v_1^2 times the quantity z_2^2 divided by z_1^2 , raised to the power of a .

Here, v_1 is the wind speed measured at a known height z_1 , and v_2 is the wind speed to be estimated at a new height z_2 . The exponent a — called the shear exponent — depends on the roughness of the terrain: smoother terrain gives a lower value of a , while rougher terrain gives a higher value.

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A wind turbine converts the kinetic energy of moving air into electricity. Wind pushes against the turbine blades, causing them to rotate. The blades are connected to a rotor, which turns a shaft inside the nacelle — the housing at the top of the tower. In most turbines, this shaft passes through a gearbox that increases rotational speed before driving a generator, where mechanical energy is converted into electrical energy.

The turbine is mounted on a tall tower to access stronger winds at height, and it is oriented to face into the wind for maximum efficiency. Modern turbines also include control systems that adjust blade angle and rotation speed to optimise energy capture and protect the system during extreme wind conditions.

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The power that a wind turbine can extract from the wind is given by the formula: P equals C_p times one-half times ρ times A times v^3 .

In this formula, one-half times ρ times v^3 represents the kinetic energy available in the wind per unit area, where ρ is the air density and v is the wind speed. The cubic relationship with wind speed is important: even a small increase in wind speed leads to a much larger increase in power. The term A is the swept area of the rotor — the circular area covered by the spinning blades — so larger turbines intercept more wind and extract more energy.

The coefficient C_p is the power coefficient, which represents how efficiently the turbine converts wind energy into mechanical power. Not all the energy in the wind can be captured, because the air must continue moving past the turbine. The theoretical maximum is known as the Betz limit, which is approximately 59 percent. In practice, modern turbines achieve power coefficients of around 35 to 45 percent.

Note that the wind speed v in the formula refers to the speed at hub height — the height of the rotor centre. Since wind speed increases with altitude, the wind profile formula from the previous slide is useful for estimating the correct wind speed at that height, which is essential for accurately calculating power output.

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Wind turbines transform the kinetic energy of moving air into electricity using a renewable and abundant resource, producing no direct emissions during operation. They are scalable — from small installations to large wind farms — and can be deployed both onshore and offshore.

Their main limitation is that wind is variable and not fully controllable, which requires integration with storage systems or other energy sources to ensure a reliable supply. Wind turbines can also have visual and environmental impacts, including effects on landscapes, noise, and potential risks to birds and bats. Initial investment and site selection can be challenging, particularly for offshore installations. Despite these limitations, wind energy is one of the most widely deployed and fastest-growing renewable energy technologies.

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If you would like to explore any of the topics covered in this lesson further, the next slide provides a selection of videos that go deeper into each of the technologies presented in this module.

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These are the references used in this lesson. Additional references are included on the individual slides.

Thank you for your attention, and see you in the next module.