

REIES – Lesson 4b: Motion Delivery

Exercise Sheet

Complete the exercises below to practise the concepts from Lesson 4b. Show all working for calculation questions.

Section A – Knowledge Questions

Exercise 1

Knowledge

The lesson introduces five motion delivery technologies: combustion engine, gas turbine, steam turbine, water turbine, and wind turbine.

- For each technology, state (a) the primary energy input form, (b) the motion output type (linear thrust or shaft rotation), and (c) whether motion is the final product or an intermediate step to electricity. Complete the table.

Technology	Primary energy input	Output type	Motion final / intermediate?
Combustion engine			
Gas turbine (power plant)			
Gas turbine (aircraft)			
Steam turbine			
Water turbine			
Wind turbine			

- The lesson states that in a gas turbine power plant, part of the turbine output is used to drive the compressor. Explain why this internal 'parasitic' use of energy is necessary, and what happens to the remainder of the shaft power.

Exercise 2

Knowledge

The lesson describes the four-stroke cycle of a combustion engine.

- Name the four strokes in the correct order and describe what physically happens during each one.
- During which stroke is useful mechanical work produced?
- Combustion engines have an efficiency of only 25–30 %. Where does the remaining 70–75 % of the fuel energy go? Give two specific loss pathways.

Exercise 3

Knowledge

The lesson explains the Betz limit for wind turbines and the wind speed profile with height.

- What is the Betz limit? State its numerical value and explain physically why 100 % of the wind's kinetic energy can never be captured by a turbine.
- The wind power formula is $P = C_p \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v^3$. Explain in words what each term represents and why the relationship between power and wind speed is cubic rather than linear.
- The wind speed profile power law is $v_2 = v_1 \cdot (z_2/z_1)^\alpha$. What does the shear exponent α represent? From the table in the lesson, which terrain type has the highest α and which has the lowest? What are the practical implications for wind turbine tower height?
- Tidal turbines and wind turbines work on similar principles but operate in different fluids. Water is about 800 times denser than air. Using the power formula $P = C_p \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v^3$, explain why tidal turbines can generate significant power at much lower current speeds than wind turbines need.

Exercise 4

Knowledge

The lesson discusses pumped hydro storage as a way to balance intermittent renewable energy, using the El Hierro island system as an example.

- Describe the charging and discharging cycle of a pumped hydro storage system. Which energy conversions take place in each direction?
- The lesson lists cogeneration (CHP) as a way to improve gas turbine efficiency from ~40 % to 70–80 %. Explain what waste energy is captured in a CHP system and how it is used. Why does the efficiency jump so significantly?
- The lesson mentions that large steam turbines divide steam expansion into high-pressure (HP), intermediate-pressure (IP), and low-pressure (LP) stages. Give two engineering reasons why this staged approach is preferred over a single expansion stage.

Section B – Calculation Questions

Exercise 5

Calculation

Kinetic energy and velocity conversions. A car with mass 1 400 kg travels at 120 km/h on a motorway.

1. Convert 120 km/h to m/s.
2. Calculate the kinetic energy of the car in Joules. Use: $KE = \frac{1}{2} \cdot m \cdot v^2$
3. Convert this kinetic energy to kWh. (1 kWh = 3 600 000 J)

Exercise 6

Calculation

Wind turbine power. A wind turbine has a rotor diameter of 126 m, a power coefficient $C_p = 0.42$, and operates at a hub-height wind speed of 10 m/s. Use air density $\rho = 1.225 \text{ kg/m}^3$.

1. Calculate the swept area A of the rotor. Use: $A = (\pi/4) \cdot D^2$
2. Calculate the power output of the turbine in kW and MW. Use: $P = C_p \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v^3$
3. If the wind speed increases from 10 m/s to 12 m/s (a 20 % increase), by what factor does the power change? Calculate the new power output and compare. What does the cubic relationship imply for wind turbine siting?
4. This turbine operates for 2 500 full-load hours per year (capacity factor $\approx 29 \%$). Calculate its annual energy production in MWh and GWh.

Exercise 7

Calculation

Wind speed profile. A met mast measures wind speed at 10 m height as 6 m/s over open, flat terrain (shear exponent $\alpha = 0.16$). A wind turbine will be installed with its hub at 100 m height.

1. Use the wind profile power law to estimate the wind speed at 100 m hub height. Use: $v_2 = v_1 \cdot (z_2/z_1)^\alpha$
2. Using the turbine from Exercise 6 ($D = 126 \text{ m}$, $C_p = 0.42$, $\rho = 1.225 \text{ kg/m}^3$), calculate the power output at the corrected hub-height wind speed from part (1).
3. Now repeat using $\alpha = 0.30$ (suburban terrain) while keeping $v_1 = 6 \text{ m/s}$ at $z_1 = 10 \text{ m}$. What is the hub-height wind speed, and how does the power output compare? What

does this tell you about the importance of terrain roughness for wind energy assessment?

Exercise 8

Calculation

Water turbine power. A run-of-river hydropower plant has a flow rate of $80 \text{ m}^3/\text{s}$ and a head (height difference) of 25 m. The turbine efficiency is 88 %. Use $\rho = 1\,000 \text{ kg/m}^3$ and $g = 9.81 \text{ m/s}^2$.

1. Calculate the hydraulic power available from the water (before turbine losses). Use:
 $P_{\text{hydraulic}} = \dot{V} \cdot \rho \cdot g \cdot H$
2. Calculate the actual electrical power output of the turbine. Use: $P_{\text{turbine}} = \eta \cdot P_{\text{hydraulic}}$
3. During a drought the flow rate drops to $40 \text{ m}^3/\text{s}$ while the head remains at 25 m. What is the new power output? By what percentage has output dropped?
4. Compare this hydro plant with a wind turbine farm needed to produce the same average power (from Ex 6, each turbine produces $\sim 3.9 \text{ MW}$ at 10 m/s wind). How many wind turbines from Ex 6 would be needed? Comment on the difference in land use and predictability.

Exercise 9

Calculation

Gas turbine efficiency and cogeneration. A gas turbine power plant burns natural gas and has an electrical efficiency of 38 %. It consumes 500 MW of fuel (thermal input).

1. Calculate the electrical power output in MW.
2. How much thermal power (MW) is rejected as waste heat in the exhaust gases?
3. In a cogeneration (CHP) configuration, 60 % of the exhaust waste heat is captured and used for district heating. Calculate: (a) the useful thermal power recovered, and (b) the overall efficiency of the CHP system (electrical + thermal useful output / fuel input).
4. The lesson states CHP systems can reach 70–80 % efficiency. Does your calculated value fall within this range? What percentage of the original fuel energy is still wasted?

Exercise 10

Calculation

Multi-step chain: wind to pumped hydro to electricity. A wind farm generates 200 MW on a windy night when electricity demand is low. This surplus electricity is used to pump water into an upper reservoir 300 m above the lower reservoir. Use $g = 9.81 \text{ m/s}^2$, $\rho = 1\,000 \text{ kg/m}^3$, pump efficiency = 85 %, turbine efficiency = 90 %.

1. The pumping system uses all 200 MW. Calculate the mass flow rate of water being pumped uphill (kg/s). Use: $P_{\text{pump}} = \dot{m} \cdot g \cdot H / \eta_{\text{pump}} \rightarrow \dot{m} = P_{\text{pump}} \cdot \eta_{\text{pump}} / (g \cdot H)$
2. The wind farm runs for 6 hours, storing water in the upper reservoir. Calculate the total mass of water stored (kg) and its gravitational potential energy (in GJ and MWh).
3. The stored water is released through turbines ($\eta_{\text{turbine}} = 90 \%$) to generate electricity during peak demand. Calculate the electrical energy recovered (MWh).
4. Calculate the round-trip efficiency of this pumped hydro system: $\eta_{\text{round-trip}} = E_{\text{out}} / E_{\text{in}}$. Comment on the result.

Section C – Internet Exploration

Exercise 11

Internet Exploration

The Netherlands is building offshore wind capacity rapidly. The Gemini Wind Park — visible in the lesson slides — is one of the largest in the country.

- Visit <https://www.geminiwindpark.nl> or search for 'Gemini wind park Netherlands'. Find and report: (a) the total installed capacity (MW), (b) the number of turbines, (c) the rated power per turbine, and (d) approximately how many Dutch households it supplies.
- Visit the Global Wind Energy Council site (<https://gwec.net>) or search for 'global wind capacity 2024'. Find: (a) the total global installed wind capacity (GW), (b) which country has the most installed capacity, and (c) how much new capacity was added in the most recent reported year.
- Based on what you find, write 3–5 sentences explaining why offshore wind is particularly well-suited for the Netherlands compared to onshore wind, referring to the wind speed profile concepts from the lesson.

Exercise 12

Internet Exploration

The El Hierro island (Canary Islands, Spain) system is mentioned in the lesson as a real-world example of wind-powered pumped hydro storage.

- Visit <http://www.goronadelviento.es/en/> or search for 'El Hierro Gorona del Viento'. Find: (a) the installed wind capacity (MW), (b) the pumped hydro storage capacity (MW and MWh if available), and (c) what percentage of the island's electricity was supplied by renewables in recent years.
- Search for 'tidal energy Orbital Marine Power O2' or visit <https://orbitalmarine.com>. Find: (a) the rated power of the O2 floating tidal platform, (b) the rotor diameter, and (c) in which location it is deployed. Compare this to the wind turbine from Exercise 6 — which produces more power per unit of swept area, and why?
- Search for 'IEA hydropower report 2024' or visit <https://www.iea.org/energy-system/renewables/hydropower>. Find: what share of global electricity generation does hydropower currently provide? Write 3–5 sentences on the main challenges to expanding hydropower globally.

Section D – Home Experiments

Exercise 13

Home Experiment – Kinetic Energy on a Bicycle (or by Walking)

In this experiment you will measure your own kinetic energy at different speeds, directly applying the formula $KE = \frac{1}{2} \cdot m \cdot v^2$ from the lesson. No special materials are needed beyond a measuring tape (or GPS app) and a stopwatch.

Materials needed:

- A phone with a GPS speed app (e.g. Google Maps navigation, Strava, or a free speedometer app) OR a measured 20 m distance marked on a flat surface and a stopwatch
- Your body weight in kg (or use a bathroom scale)
- A bicycle (optional — the experiment also works on foot at walking, jogging, and running speeds)

Procedure:

1. Measure or estimate your mass (including bike if cycling) in kg.
2. Move at three different speeds: slow (walking ~5 km/h), medium (jogging or cycling ~15 km/h), and fast (running or cycling ~30 km/h). Use your GPS app to read the speed, or time yourself over a 20 m distance and calculate speed from $v = \text{distance} / \text{time}$.

- Record each speed in km/h and convert to m/s.
- Calculate the kinetic energy at each speed using $KE = \frac{1}{2} \cdot m \cdot v^2$.
- When you brake to a stop, this kinetic energy must be removed. Estimate how far you coast (without pedalling or walking) from each speed before stopping: measure the coasting distance in metres.

Record your results:

Speed (km/h)	Speed (m/s)	KE (J)	Coasting distance (m)
~5 (walk)			
~15 (jog/cycle)			
~30 (run/cycle)			

Reflection questions:

- When you doubled your speed (e.g. from 15 to 30 km/h), did kinetic energy double or quadruple? Explain using the formula.
- In a conventional car with friction brakes, kinetic energy is converted to heat and wasted. How does regenerative braking in an electric vehicle recover some of this energy? Which component performs the energy conversion during braking?
- The lesson states that combustion engines have efficiency of 25–30 %. If a car engine uses 60 kJ of fuel energy to accelerate to 30 m/s, but only 28 % reaches the wheels, how much kinetic energy does a 1 200 kg car actually gain? Is this consistent with your formula?

Exercise 14



Home Experiment – Build a Simple Wind Turbine Anemometer

In this experiment you will build a cup anemometer — the standard instrument used to measure wind speed — from household materials, and use it to explore the relationship between wind speed and rotation rate that underpins wind turbine design. You will also verify the wind profile concept by measuring at two heights.

Materials needed (low cost, most at home):

- 4 small paper or plastic cups (e.g. espresso cups or yoghurt pots)
- 2 strips of stiff cardboard or thin wooden sticks (~30 cm each)
- A sharp pencil or thin wooden skewer (acts as the vertical axis)
- Sticky tape and scissors
- A marker pen to mark one cup (to count revolutions)
- A stopwatch
- Optional: a ruler to measure mounting heights

Assembly:

1. Cross the two cardboard strips at right angles and tape them together at the centre to form a plus (+) shape.
2. Tape one cup to each end of the four arms, all facing the same rotational direction (all open ends facing the same way around the circle). One cup should be marked with a dot.
3. Push the pencil through the centre of the cross so it can spin freely as a vertical axis (you can hold it between two fingers or rest it in a bottle neck).

Measurements:

4. Hold or mount the anemometer outdoors (or near an open window) at approximately 1 m height. Count how many revolutions (times the marked cup passes a fixed point) in 30 seconds. Record as RPM_1 .
5. Raise the anemometer to approximately 2 m height (hold it above your head, or mount on a longer stick). Count revolutions again for 30 seconds. Record as RPM_2 .
6. Repeat both measurements three times and average the results.

Record your results:

Height	Trial 1 (RPM)	Trial 2 (RPM)	Trial 3 (RPM)	Average RPM
~1 m				
~2 m				

Reflection questions:

- Did you observe a higher RPM at 2 m than at 1 m? Is this consistent with the wind profile power law? Note that your measurements may be noisy — explain why repeating trials and averaging improves reliability.
- Each cup has an open side and a curved back. Explain why this asymmetry causes the anemometer to spin. (Hint: consider which side has more drag.)
- A real wind turbine blade uses lift (like an aircraft wing) rather than drag to generate rotation. Look up 'wind turbine blade aerodynamics lift vs drag'. Briefly explain in your own words why lift-based designs are more efficient than drag-based cups.