

REIES – Lesson 5: Integration

Answer Key

You have completed the final lesson of the course — well done! This lesson brings together everything covered in Modules 1–4 and places it in the wider context of the energy transition. Use this document to check your answers, deepen your understanding, and reflect on how all the pieces fit together.

Section A – Knowledge Questions

Answer – Exercise 1

Knowledge

Renewable or not – assessment using the lesson's definition:

Source	Renewable?	Explanation
Solar energy	Yes	Sunlight is continuously replenished by nuclear fusion in the Sun on timescales vastly exceeding human lifespans. It is effectively inexhaustible on a human timescale.
Fossil fuels	No	Coal, oil, and gas were formed over hundreds of millions of years. They replenish on a geological timescale – completely incompatible with human energy use rates.
Biomass	Borderline	Biomass replenishes faster than fossil fuels (years to decades) but current consumption rates in many countries exceed regrowth rates. Legally classified as renewable in some jurisdictions but does not strictly meet the definition if net deforestation or land-use change occurs.
Nuclear fission	No	Fission depends on uranium (and thorium), which are finite mineral resources. Although uranium reserves will last centuries, they are not self-replenishing on a human timescale.

No golden solution: (1) No single source is available everywhere in sufficient quantity – solar is strongest near the equator, wind is strong offshore and in flat regions, geothermal is location-specific. Energy demand is global and geographically distributed, while renewable resources are concentrated. (2) Different energy needs require different energy carriers – high-temperature industrial processes, aviation, and shipping cannot easily be served by the same technology that heats a home or charges a phone. A mix of sources and conversion technologies is always required.

PESTEL examples (one per dimension):

Dimension	Example from the lesson or course
Political	EU Green Deal sets 2050 climate neutrality target; national governments must enact binding plans and permitting reforms.
Economic	LCOE of wind and solar has fallen 80–90 % in a decade; grid and storage investment requires additional trillions of euros.

Social	NIMBY opposition to wind farms; energy equity concerns for low-income households facing higher bills.
Technological	Intermittency and grid balancing challenges; need for storage, smart grids, and multi-commodity integration.
Environmental	Lifecycle emissions of wind and solar are 10–50× lower than gas; end-of-life panel and blade disposal is a growing challenge.
Legal	Permitting delays are a major barrier; third-party grid access rules; harmonised international energy trade frameworks needed.

Answer – Exercise 2



Knowledge

Six technical grid challenges:

Challenge	Why it arises from variable renewables
Intermittency	Wind and solar only generate when wind blows or sun shines; output cannot be scheduled on demand.
Load balancing	Supply and demand must match in real time; variable output means generation can suddenly exceed or fall below demand.
Peak demand mismatch	Solar peaks at midday; wind peaks overnight or in winter; neither aligns well with morning/evening demand peaks.
Frequency regulation	Any supply-demand imbalance changes grid frequency (50/60 Hz); variable renewables cause more frequent and rapid imbalances requiring fast-responding reserves.
Voltage stability	Many small distributed generators (rooftop PV) inject power locally, creating voltage rises in low-voltage networks not designed for this.
Grid congestion	Existing transmission lines were built for one-way flows from large central plants; distributed and offshore renewables create bidirectional flows that exceed line capacity in some areas.

Multi-commodity grid – three carriers and their advantages:

Energy carrier	Advantage for renewable integration
Electricity (electric grid)	Backbone of the system; direct use for most end-uses; enables real-time balancing through interconnection.
Heat (district heating/cooling)	Seasonal thermal storage bridges summer solar surplus and winter demand; reuses industrial waste heat; lower transport losses for heat at large scale.
Hydrogen (gas network)	Seasonal and long-distance energy carrier; can use repurposed gas pipelines; decarbonises hard-to-electrify sectors (industry, shipping).

Storage technology matching table:

Storage technology	Timescale	Primary function
Battery storage	Minutes to hours	Short-term grid balancing; frequency regulation; peak shaving at distribution level.

Pumped hydro	Hours to days	Large-scale daily balancing; store overnight surplus, discharge at peak demand.
Hydrogen (power-to-gas)	Days to months	Seasonal and long-distance storage; reconversion to electricity or use as fuel/feedstock.
Thermal storage	Hours to seasons	Heat network buffering; stores excess heat/cold for district heating and industrial use.

Answer – Exercise 3

Knowledge

Prosumer: a consumer who also produces energy, typically through rooftop solar PV panels. Traditionally, electricity flows one way: from large central power plants, through the high-voltage grid, down through transformers to low-voltage distribution networks and into homes. When households become prosumers and export solar electricity, the flow reverses at the local level – electricity flows from homes back into the low-voltage grid and sometimes up into the medium-voltage network. This bidirectional flow requires upgraded protection relays, transformers, cables, and metering systems that can handle two-way power.

Demand response examples:

- **Residential:** a smart EV charger automatically delays charging from 18:00–20:00 (high evening demand, low solar output) to 23:00–05:00 (low demand, excess wind at night) – or to midday (high solar output). The car owner sets departure time; the smart system optimises charging timing.
- **Industrial:** a large industrial refrigeration plant (e.g. a food cold-store) is programmed to pre-cool its products to -25°C instead of -20°C when surplus wind power is available. The refrigeration compressors then switch off during the evening demand peak, drawing down the ‘cold energy’ stored in the product mass. This is thermal demand response.

Cybersecurity: a smart grid relies on continuous real-time data exchange between millions of smart meters, sensors, grid control systems, and energy trading platforms. Each connected device is a potential entry point for malicious actors. A cyberattack on a grid's energy management system (EMS) could manipulate demand signals, cause deliberate frequency imbalances, or take substations offline – potentially causing blackouts. For example, the 2015 Ukraine power grid cyberattack (by the group Sandworm) cut power to approximately 230 000 customers by remotely switching off substations through compromised SCADA systems.

Answer – Exercise 4

Knowledge

NIMBY (‘Not In My Back Yard’): broad public support for renewable energy coexists with local opposition when specific projects are sited near residential areas. People who support renewables in principle often object when they are planned near their own homes.

Examples: (1) Onshore wind farms – objections based on noise, shadow flicker, visual impact on landscape, and perceived property value reduction. (2) High-voltage transmission lines and substations – concerns about visual impact, electromagnetic fields, and proximity

to homes. NIMBY opposition can delay or block projects for years, even when all technical and legal requirements are met.

Energy equity: energy equity means that the costs and benefits of the energy transition are distributed fairly across all income groups and communities. Low-income households are more vulnerable because: (1) energy costs represent a larger share of their income (energy poverty); (2) they are less likely to own their home, so they cannot install solar panels or benefit from investment subsidies; (3) they often live in less energy-efficient housing stock and cannot afford upgrades. **Policy measures:** income-based subsidies for heat pump installation; social tariffs that exempt low consumption from levies; regulated social electricity tariffs; targeted insulation programmes for social housing.

LCA measures the total environmental impact of a technology across its entire life: raw material extraction, manufacturing, transport, operation, and end-of-life disposal or recycling. The lesson states that renewables become 'net positive' (i.e. the carbon saved exceeds the carbon emitted in production) within 1–4 years of operation. End-of-life challenge mentioned: solar panels and wind turbine blades (made partly of composite materials that are difficult to recycle) and lithium-ion batteries all create waste streams that need dedicated recycling infrastructure – which does not yet exist at the scale needed.

Section B – Calculation Questions

Answer – Exercise 5

Calculation

Levelised Cost of Energy (LCOE)

ONSHORE WIND (5 MW, capacity factor 30 %):

Annual energy: $5\,000\text{ kW} \times 8\,760\text{ h/yr} \times 0.30 = 13\,140\,000\text{ kWh/yr}$

Lifetime energy: $13\,140\,000 \times 25\text{ yr} = 328\,500\,000\text{ kWh}$

Total lifetime cost: $\text{€}5\,000\,000 + (\text{€}80\,000 \times 25) = \text{€}7\,000\,000$

LCOE = $\text{€}7\,000\,000 / 328\,500\,000\text{ kWh} = \text{€}0.0213/\text{kWh} \approx \text{€}0.021/\text{kWh}$

GAS PEAKER (5 MW, capacity factor 10 %):

Annual energy: $5\,000\text{ kW} \times 8\,760\text{ h/yr} \times 0.10 = 4\,380\,000\text{ kWh/yr}$

Lifetime energy: $4\,380\,000 \times 25\text{ yr} = 109\,500\,000\text{ kWh}$

Total lifetime cost: $\text{€}2\,000\,000 + (\text{€}150\,000 \times 25) + (\text{€}0.08 \times 109\,500\,000)$
 $= \text{€}2\,000\,000 + \text{€}3\,750\,000 + \text{€}8\,760\,000 = \text{€}14\,510\,000$

LCOE = $\text{€}14\,510\,000 / 109\,500\,000\text{ kWh} = \text{€}0.1325/\text{kWh} \approx \text{€}0.133/\text{kWh}$

COMPARISON:

Wind LCOE: $\text{€}0.021/\text{kWh}$ vs Gas peaker LCOE: $\text{€}0.133/\text{kWh}$

Wind is 6.3× cheaper per kWh generated

10 years ago at +80–90 % higher cost: $\text{€}0.021 \times (1 + 0.85) \approx \text{€}0.039/\text{kWh}$
(using midpoint 85 % reduction)

This calculation illustrates the dramatic cost competitiveness of modern wind energy. The gas peaker's LCOE is dominated by fuel cost – if gas prices rise, its LCOE rises proportionally. Wind has near-zero fuel cost, giving it stable and predictable lifetime costs. The lesson's statement that renewables offer 'stable long-run marginal costs' is confirmed numerically here.

Answer – Exercise 6

Calculation

Grid frequency and power balance

Generation before wind surge: 2 000 MW (demand) = balanced

After wind surge: generation = 2 000 + 500 = 2 500 MW

Surplus = 2 500 - 1 800 = 700 MW

Surplus as % of demand: 700 / 1 800 = 38.9 %

Battery absorption time:

Battery power: 200 MW | Battery capacity: 400 MWh

Time to fill: 400 MWh / 200 MW = 2.0 hours = 120 minutes

(Enough time for conventional plant to ramp down – gas turbines can ramp at ~10–15 MW/min, so 700 MW takes ~50–70 min.)

Curtailement scenario:

Wind curtailed: 500 MW → 300 MW

New generation: 2 000 + 300 = 2 300 MW vs 1 800 MW demand

New surplus: 500 MW (still above demand, but manageable with battery)

Additional curtailement needed to balance: cut wind to 1 800 - 2 000 + 500 = -200 MW

[If no other plant is running: wind output limited to demand of 1 800 MW]

Curtailed energy (200 MW curtailed for 200 h/yr):

$E_{\text{curtailed}} = 200 \text{ MW} \times 200 \text{ h} = 40\,000 \text{ MWh} = 40 \text{ GWh/yr}$

Economic cost: 40 000 000 kWh × €0.04/kWh = €1 600 000/yr

The €1.6 million annual cost of curtailement illustrates why grid-scale battery storage is economically attractive even at high upfront cost – it converts wasted energy into usable electricity. The battery absorption calculation shows that 2 hours is sufficient for most conventional plant to respond, validating battery storage as a 'bridge' technology for frequency regulation.

Answer – Exercise 7

Calculation

Multi-commodity grid – power-to-gas and seasonal thermal storage

POWER-TO-GAS ROUND TRIP:

Surplus electricity: 500 GWh
Hydrogen produced (70 % eff.): $500 \times 0.70 = 350$ GWh (hydrogen, HHV)
Electricity recovered (60 % FC eff.): $350 \times 0.60 = 210$ GWh
Round-trip efficiency: $210 / 500 = 42$ %
Energy lost: $500 - 210 = 290$ GWh (mainly low-grade heat)

HYDROGEN BLENDING (20 % H₂ by volume in 1 000 m³ blend):

H₂ volume: 200 m³ | NG volume: 800 m³
Heat from H₂: $200 \text{ m}^3 \times 3.0 \text{ kWh/m}^3 = 600 \text{ kWh}$
Heat from NG: $800 \text{ m}^3 \times 10.0 \text{ kWh/m}^3 = 8\,000 \text{ kWh}$
Total from blend: 8 600 kWh
Pure NG (1 000 m³): $1\,000 \times 10.0 = 10\,000 \text{ kWh}$
Blend delivers 14 % less heat energy per m³ of gas delivered

SEASONAL THERMAL STORAGE:

Summer heat stored: 800 MWh
Recovered at 85 % efficiency: $800 \times 0.85 = 680$ MWh
Neighbourhood need: $500 \text{ homes} \times 8 \text{ MWh/home} = 4\,000 \text{ MWh}$
680 MWh covers: $680 / 4\,000 = 17$ % of winter heat demand
NOT sufficient alone - additional sources needed (heat pump, biomass, etc.)

The hydrogen blending result highlights an important practical issue: blending 20 % hydrogen by volume only reduces the heating value by about 14 % because hydrogen has a much lower volumetric energy density than methane. Consumers with gas appliances calibrated for natural gas may notice slightly lower heat output. The seasonal thermal store covers 17 % of the neighbourhood's winter heat demand – a meaningful but not sufficient contribution, reinforcing the lesson's point that no single technology solves the whole problem.

Answer – Exercise 8

Calculation

Carbon emissions and lifecycle analysis

CO₂ AVOIDED FROM WIND REPLACING GAS:

Gas: $200 \text{ TWh} \times 0.50 = 100 \text{ TWh}$ replaced
Emissions avoided from gas: $100 \times 10^9 \text{ kWh} \times 450 \text{ g/kWh} = 4.5 \times 10^{11} \text{ g} = 45 \text{ Mt CO}_2$
Emissions from wind: $100 \times 10^9 \text{ kWh} \times 11 \text{ g/kWh} = 1.1 \times 10^{11} \text{ g} = 1.1 \text{ Mt CO}_2$
Net CO₂ avoided: $45 - 1.1 = 43.9 \text{ Mt CO}_2/\text{year}$

WIND TURBINE CARBON PAYBACK:

Annual generation: $3\,000 \text{ kW} \times 8\,760 \text{ h} \times 0.30 = 7\,884\,000 \text{ kWh/yr}$

Lifecycle emission factor: 11 g CO₂/kWh
 Annual lifecycle CO₂: 7 884 000 × 0.011 kg = 86 724 kg/yr
 Gas avoided per year: 7 884 000 × (0.450 - 0.011) kg = 7 884 000 × 0.439 kg
 = 3 461 076 kg CO₂/yr avoided vs gas baseline
 Carbon payback: 1 500 000 kg / 3 461 076 kg/yr ≈ 0.43 years ≈ 5 months

 SOLAR PANEL WASTE:
 Total waste mass: 10 000 000 panels × 20 kg = 200 000 000 kg = 200 000 tonnes
 Electricity generated per panel: 400 kWh/yr × 30 yr = 12 000 kWh/panel
 Total electricity: 10 000 000 × 12 000 kWh = 120 000 000 000 kWh = 120 TWh

The carbon payback of just 5 months is remarkably short, confirming the lesson's statement that renewables become 'net positive' within 1–4 years (the lesson uses this range for the manufacturing energy payback, which is slightly different from the carbon payback). The 200 000 tonnes of panel waste in a single year in Europe illustrates the urgency of developing recycling infrastructure – this is equivalent to thousands of lorry loads of specialist electronic waste containing silicon, silver, lead, and various plastics. The 120 TWh of lifetime generation shows just how much clean energy was produced – the environmental benefit vastly outweighs the disposal challenge.

Answer – Exercise 9

Calculation

Energy equity – transition levy and social tariff

LEVY PAYMENTS:
 Low-income HH: 2 000 kWh × €0.05 = €100/yr
 As % of bill: 100 / 800 = 12.5 % of annual energy bill
 High-income HH: 6 000 kWh × €0.05 = €300/yr
 As % of bill: 300 / 2 400 = 12.5 % of annual energy bill
 (Same %-of-bill in this example – a flat rate levy is proportional)
 BUT in absolute €: low-income pays €100, high-income €300
 The absolute burden is 3× higher for the high-income household,
 but since the low-income HH has 3× less income, the relative
 burden on disposable income is likely much higher for low-income.

SOCIAL TARIFF (first 1 200 kWh exempt):
 Low-income HH levied on: 2 000 - 1 200 = 800 kWh
 Levy with exemption: 800 × €0.05 = €40/yr
 Reduction: €100 - €40 = €60/yr saved (60 % reduction in levy)
 As % of bill: 40 / 800 = 5.0 % (vs 12.5 % without exemption)

GRID FUNDING:

Fund raised: €5 billion/yr
Grid upgrade cost: €200 billion
Years needed: $200 / 5 = 40$ years

Global annual need: €3 000 billion / 25 years = €120 billion/yr
Current global RE investment: €500 billion/yr
Grid/storage shortfall: €120 billion/yr additional needed
(beyond current RE investment, which mostly funds generation)

The equity calculation reveals that while a flat-rate levy is proportionally equal in percentage-of-bill terms, the social tariff meaningfully reduces the burden on low-income households (from 12.5 % to 5.0 % of their bill). The grid funding calculation shows that even with a significant levy, grid upgrade costs take 40 years to recover – highlighting why most grid investment is funded through regulated network tariffs and government borrowing rather than direct levies alone.

Answer – Exercise 10

Calculation

Island renewable energy system – whole-course integration

ELECTRICITY GENERATION:

Wind (2 MW, 35 % CF): $2\,000\text{ kW} \times 8\,760\text{ h} \times 0.35 = 6\,132\text{ MWh/yr}$
Solar PV (1 MW, 12 % CF): $1\,000\text{ kW} \times 8\,760\text{ h} \times 0.12 = 1\,051\text{ MWh/yr}$
Total generation: $6\,132 + 1\,051 = 7\,183\text{ MWh/yr}$
Electricity demand: $2\,000\text{ MWh/yr}$
Surplus: $7\,183 - 2\,000 = 5\,183\text{ MWh/yr}$ (2.6× demand!)
This surplus is available for heat pump, storage, or export.

HEAT PUMP CONTRIBUTION:

Electricity for heat pump: 500 MWh
Heat delivered (COP 3.5): $500 \times 3.5 = 1\,750\text{ MWh of heat}$
Remaining heat demand: $3\,000 - 1\,750 = 1\,250\text{ MWh}$

SOLAR THERMAL AREA NEEDED:

Irradiance: 150 W/m^2 average
Collector efficiency: 60 %
Heat output per m^2 : $150\text{ W/m}^2 \times 0.60 = 90\text{ W/m}^2$
Annual heat per m^2 : $90\text{ W/m}^2 \times 8\,760\text{ h} = 788\,400\text{ Wh} = 0.788\text{ MWh/m}^2$
Area needed for 1 250 MWh: $1\,250 / 0.788 = 1\,586\text{ m}^2 \approx 1\,600\text{ m}^2$

PESTEL reflection on the island system (one advantage + one disadvantage per dimension):

PESTEL	Advantage	Disadvantage
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Technological	Wind surplus is large enough to power heat pumps and potentially produce hydrogen for storage – multi-commodity integration is feasible.	Seasonal mismatch: wind is stronger in winter (good for heat demand) but solar PV and thermal peak in summer. Storage or backup needed.
Economic	Near-zero marginal fuel cost once installed; no fossil fuel import costs for an island.	High upfront capital cost; 1 600 m ² of solar thermal collectors is significant investment for a small community.
Environmental	Zero operational carbon emissions from all three systems.	Land use for solar thermal; visual impact of wind turbines; end-of-life panel and blade disposal.

Section C – Internet Exploration

Answer – Exercise 11

Internet Exploration

Reference: <https://www.iea.org/reports/world-energy-outlook-2023> |
<https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023>

Global renewable electricity share: as of 2023–2024, renewable energy supplies approximately 30–33 % of global electricity generation (check the latest IEA/IRENA reports for the exact current figure; it was 30 % in 2023). In 2010, the share was approximately 19–20 %. Solar PV has grown fastest: from near-zero in 2010 to approximately 5–6 % of global electricity by 2024, with annual installations now exceeding 400 GW/year.

High-renewable country example: Denmark consistently generates over 55–60 % of its electricity from wind, with some years exceeding 80 %. It achieves this through: (1) extensive offshore and onshore wind capacity relative to its size; (2) strong grid interconnections with Norway (which provides hydro-based flexibility), Sweden, and Germany; (3) district heating systems using heat pumps and thermal storage; (4) active demand response. Remaining challenges include lack of domestic long-duration storage and dependence on neighbouring grids for balancing.

Permitting barriers: in the EU, average permitting time for onshore wind is 4–9 years in many member states (compared to 1–2 years in the US). The REPowerEU plan introduced the concept of ‘Renewable Acceleration Areas’ where streamlined procedures cut permitting to 1–2 years. The EU’s revised Renewable Energy Directive (RED III, 2023) also sets maximum permitting deadlines. This directly illustrates the legal PESTEL dimension: without legal reform, even cost-competitive renewable projects cannot be built fast enough to meet climate targets.

Go deeper: <https://www.iea.org/reports/world-energy-outlook-2023> |
https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-clean-and-secure-energy-europe_en

Answer – Exercise 12

Internet Exploration

Reference: <https://www.entsoe.eu> | https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-clean-and-secure-energy-europe_en

Cross-border interconnection example: the ENTSO-E Ten-Year Network Development Plan (TYNDP) identifies dozens of planned interconnection projects. A well-known example is the 'Celtic Interconnector' between Ireland and France (700 MW, operational from 2026), enabling Ireland's large offshore wind resources to reach mainland Europe. Another example is the 'BalWin' HVDC cable connecting the North Sea offshore wind cluster to Germany. These interconnectors directly implement the multi-commodity grid concept by enabling surplus renewable electricity from one region to fill deficits in another.

International hydrogen trade: the EU's Global Gateway hydrogen programme, the H2Med pipeline (connecting Spain/Portugal to France and Germany), and agreements between Germany and Namibia, Morocco, and Canada for green hydrogen imports are prominent examples. The EU aims to import 10 million tonnes of green hydrogen per year by 2030. These projects involve green hydrogen produced from offshore wind or solar in sun-rich or wind-rich countries, shipped or piped to European industrial centres. Students may find specific current projects by checking the IEA Global Hydrogen Review or the European Hydrogen Backbone initiative.

Community energy example: Bürgerwind projects (citizen wind cooperatives) in Germany have thousands of members who co-own wind turbines and share profits. In the Netherlands, cooperatives like 'Energie Samen' and local projects like the Buurtbatterij Rijsenhout (also mentioned in Lesson 4d) demonstrate community energy in practice. In Denmark, community ownership of wind turbines has been a cornerstone of social acceptance – roughly one third of Denmark's wind capacity was historically owned by local cooperatives. These models directly address the social PESTEL dimension by distributing economic value locally and increasing acceptance.

Go deeper: <https://www.entsoe.eu/data/map> | <https://ehb.eu> (European Hydrogen Backbone) | <https://energiesamen.nu>

Section D – Home Activities

Answer – Exercise 13

Home Activity – Personal PESTEL Analysis

This is a personal reflection exercise – there is no single correct answer. The following guidance indicates what a strong response looks like for each part.

Part A – Home energy audit: a strong audit lists specific devices and estimates their power and usage hours (e.g. 'gas boiler: 15 kW, runs ~4 hours/day in winter for space heating'). It distinguishes between electricity and gas uses and correctly identifies which uses are most energy-intensive (typically space heating, hot water, and cooking). A good response

correctly notes that electrification (e.g. heat pump replacing gas boiler) increases electricity demand but typically reduces total energy input ($COP > 1$).

Part B – PESTEL examples for a typical Dutch household:

Dimension	Typical answer (Dutch context)
Political	The Dutch government's ISDE subsidy scheme (Investeringssubsidie Duurzame Energie) provides €2 000–5 000 subsidy for heat pumps. The EU's renovation wave and national insulation programmes also apply.
Economic	A heat pump costs €10 000–15 000 installed; payback time is 7–12 years depending on gas vs. electricity price differential. Home battery payback is ~15–20 years at current prices (from Lesson 4d).
Social	Renting from a housing corporation: the landlord controls heating system upgrades. Split-incentive problem: tenant pays energy bills but landlord pays for upgrades. Energy communities (VvE for apartments) require collective decision-making.
Technological	Smart meters (slimme meters) are now standard in the Netherlands. Home batteries and bidirectional EV chargers (V2H) are commercially available but still expensive. Not all homes have suitable roofs for solar PV.
Environmental	The Netherlands grid has a carbon intensity of ~0.30 kg CO ₂ /kWh (2024), falling as more renewables are added. Switching from gas (1.9 kg CO ₂ /m ³) to heat pump roughly halves household CO ₂ emissions even at current grid intensity.
Legal	Planning permission is generally not needed for rooftop solar panels in the Netherlands (under 15 m ² on a listed building is exempt). However, renters cannot install panels without landlord permission. Grid connection rules limit how much solar can be exported.

Part C – CO₂ calculation example: replacing a gas boiler ($1\,300\text{ m}^3/\text{yr} \times 1.9\text{ kg CO}_2/\text{m}^3 = 2\,470\text{ kg CO}_2/\text{yr}$) with a heat pump ($2\,800\text{ kWh}/\text{yr} \times 0.30\text{ kg CO}_2/\text{kWh} / COP\,3 \approx 280\text{ kg CO}_2/\text{yr}$) saves approximately $2\,190\text{ kg CO}_2/\text{yr}$ – roughly 2.2 tonnes, or 60–70 % of a typical Dutch household's energy-related CO₂.

Answer – Exercise 14



Home Activity – Map Local Energy Infrastructure

This is an observation and research activity – answers will vary by location. The following guidance indicates what a strong response looks like.

Part A – Infrastructure identification: strong responses correctly identify each element and link it to course content. Example annotations:

- Electricity substation – ‘This is a distribution substation that steps voltage down from 10 kV to 400/230 V for local homes, as described in Lesson 4c. It contains a transformer (introduced in the AC Transformer slide) and switches that disconnect sections of the network for maintenance.
- High-voltage tower – ‘This 150 kV transmission line carries electricity from the regional grid to the local area. According to Lesson 4c, this voltage level is in the “medium-high voltage network” range (between the 380 kV national backbone and the 10 kV local distribution level).

- Solar farm – ‘This is a ground-mounted PV installation that converts sunlight directly to DC electricity (Lesson 4c); it will have an inverter to convert to AC for grid injection. In the Netherlands, large PV farms connect to the 10 kV or 50 kV grid.

Part B – Grid challenge analysis: in areas with high rooftop solar penetration (e.g. suburbs with many owner-occupied homes), voltage rise in the low-voltage network is the primary concern. When many panels simultaneously produce at peak (midday), local voltage can exceed the maximum allowed 253 V, causing inverters to switch off or grid operators to curtail exports. The lesson’s description of ‘voltage stability’ and ‘grid congestion’ directly applies.

Part C – Reflection and future infrastructure: good responses identify which course technologies are present (typically: distribution transformers, solar PV, possibly EV charging stations) and which are likely to appear in the next 10 years (smart meters already widespread in NL; home batteries and bidirectional EV chargers growing; district heating expansion in urban areas; possible hydrogen distribution points in industrial zones). Students in Randstad (Dutch urban agglomeration) might note planned grid congestion hotspots; those near the coast might identify planned offshore wind grid connections.

References & Resources for Further Study

- IEA – World Energy Outlook 2023: <https://www.iea.org/reports/world-energy-outlook-2023>
- IRENA – World Energy Transitions Outlook 2023: <https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023>
- European Commission – REPowerEU: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-clean-and-secure-energy-europe_en
- ENTSO-E – Transmission System Map: <https://www.entsoe.eu/data/map>
- European Hydrogen Backbone: <https://ehb.eu>
- EU – Renewable Energy Directive (RED III) 2023: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en
- Netkaart (NL grid infrastructure map): <https://www.netkaart.nl>
- OpenStreetMap: <https://www.openstreetmap.org>
- IEA – Electricity Grids and Secure Energy Transitions (2023): <https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions>
- Energie Samen (NL energy cooperatives): <https://energiesamen.nu>
- IPCC AR6 – Mitigation of Climate Change: <https://www.ipcc.ch/report/ar6/wg3/>