Week 7 - Exercise Set: Energy System Modeling and LCA Calculations — Detailed Solutions

Part A: Annualization and Impact Calculations

Exercise 1: Lifetime PV System Cost and Grid Reinforcement:

Solution:
(a) Year 1 production is 15,000 MWh. With a 0.5% annual degradation, the lifetime production is

$$15,000 \times \frac{1-(0.995)^{25}}{1-0.995} \approx 15,000 \times 24 \approx 360,000\,\text{MWh},$$

or about 14,400 MWh/year on average.

(b) Investment cost = $10,000\,\text{kW} \times 1,200$ CHF/kW = 12,000,000 CHF; annualized over 25 years = 480,000 CHF/year. Annual O&M = $10,000 \times 20 = 200,000$ CHF/year. Total = 680,000 CHF/year.

(c) Extra capacity = 10 MW – 8 MW = 2 MW; one-time grid reinforcement = $2 \times 50,000 = 100,000$ CHF, annualized to 4,000 CHF/year.

(d) Total annual cost = 680,000 + 4,000 = 684,000 CHF; LCOE = 684,000/14,400 $\approx$ 47.5 CHF/MWh.

Correct Answer: Option A.

Exercise 2: Wind versus Gas Turbine: Lifetime Cost and Emissions:

Solution:
(a) Wind: $5\,\text{MW} \times 8760 \times 0.30 \approx 13,140$ MWh/year; Gas: $5 \times 8760 \times 0.80 \approx 35,040$ MWh/year.

(b) Wind: Investment = $5,000\,\text{kW} \times 2,000 = 10,000,000$ CHF; annualized = 400,000 CHF/year; O&M = $5,000 \times 30 = 150,000$ CHF/year; total $\approx$ 550,000 CHF/year. Gas: Investment = $5,000\,\text{kW} \times 1,000 = 5,000,000$ CHF; annualized = 200,000 CHF/year; O&M = $5,000 \times 50 = 250,000$ CHF/year; total $\approx$ 450,000 CHF/year.

(c) Gas fuel cost = $35,040,000$ kWh $\times 0.05 = 1,752,000$ CHF/year.

(d) Gas total annual cost = 450,000 + 1,752,000 = 2,202,000 CHF; LCOE = 2,202,000/35,040 $\approx$ 62.9 CHF/MWh; CO_2 emissions = $35,040,000 \times 0.4 \approx 14,000$ tonnes/year.

Correct Answer: Option B.

Exercise 3: Urban Grid Reinforcement Requirement:

Solution:
Revised numbers: PV output = 24 MW; local load = 14 MW; net export = 24 – 14 = 10 MW. Since only 5 MW is permitted, 5 MW extra must be reinforced. Reinforcement cost = $5 \times 120,000 = 600,000$ CHF, annualized over 20 years = 30,000 CHF/year.

Correct Answer: Option C.

Exercise 4: Carbon Capture for a Coal-Fired Power Plant:

Solution:
(a) Without CCS: 500 GWh = 500×10^6 kWh; emissions = $500 \times 10^6 \times 0.9 = 450,000$ tonnes.

(b) With 60% capture, residual = 40% of 450,000 = 180,000 tonnes.

(c) Captured CO_2 = 450,000 – 180,000 = 270,000 tonnes; cost = $270,000 \times 50 = 13,500,000$ CHF/year.

Correct Answer: Option B.

Exercise 5: Lifetime Cost and Impact of a CHP System:

Solution:
(a) Fuel input = 100 GWh / 0.45 $\approx$ 222.2 GWh.

(b) Fuel cost = 222.2 GWh $\times$ 0.06 CHF/kWh $\approx$ 13,333,200 CHF/year.

(c) Capital = $20,000\,\text{kW} \times 1,200 = 24,000,000$ CHF; annualized over 20 years = 1,200,000 CHF/year; O&M = 3% of 24,000,000 = 720,000 CHF/year.

(d) Total cost $\approx$ 13,333,200 + 1,200,000 + 720,000 $\approx$ 15,253,200 CHF; electrical output = 222.2 GWh $\times$ 0.35 $\approx$ 77.8 GWh.

Correct Answer: Option A.

Exercise 6: LCOE for a Nuclear Plant (Construction, O&M, and Decommissioning):

Solution:
(a) Investment = $1,000,000\,\text{kW} \times 4,000 = 4,000,000,000$ CHF; annualized over 40 years = 100,000,000 CHF/year.

(b) Decommissioning cost = 10% of 4,000,000,000 = 400,000,000 CHF; annualized = 10,000,000 CHF/year.

(c) O&M = $1,000,000 \times 100 = 100,000,000$ CHF/year; total annual cost =

100M + 100M + 10M = 210,000,000 CHF. Annual energy = 1 GW × 8760 h × 0.90 ≈ 7,884,000 MWh.

(d) LCOE = 210,000,000 / 7,884,000 ≈ 26.7 CHF/MWh.

Correct Answer: Option C.

Exercise 7: Urban Grid Reinforcement Cost (Revisited):

Solution:
With an excess export of 5 MW, cost = $5 \times 120,000 = 600,000$ CHF; annualized over 20 years = 600,000/20 = 30,000 CHF/year.

Correct Answer: Option A.

Exercise 8: CCS Application on a Gas-Fired Plant:

Solution:
70% of 20,000 tonnes = 14,000 tonnes captured; residual emissions = 20,000 – 14,000 = 6,000 tonnes. CCS cost = 14,000×60 = 840,000 CHF/year.

Correct Answer: Option C.

Exercise 9: Lifecycle Construction Emissions of a Wind Farm:

Solution:
Total emissions = $10,000\,\text{kW} \times 50 = 500,000$ tonnes; average annual = 500,000/25 = 20,000 tonnes/year.

Correct Answer: Option B.

Exercise 10: Trade-off Ratio in Multi-Objective Optimization:

Solution:
Ratio = 12% / 8% = 1.5.

Correct Answer: Option A.

Exercise 11: Comparison of Battery Storage versus Pumped Hydro:

Solution:
Battery: To store 1 MWh net, gross = 1/0.9 ≈ 1.111 MWh = 1,111,000 Wh; mass = 1,111,000 / 200 ≈ 5,555 kg.

Pumped Hydro: $1\,\text{MWh} = 3.6 \times 10^9\,\text{J}$; energy per $\text{m}^3 = 1000 \times 9.81 \times 100 \approx 981,000\,\text{J/m}^3$; volume $\approx \frac{3.6 \times 10^9}{981,000} \approx 3,670\,\text{m}^3$.

Note: The pump efficiency (80%) is not applied separately because the requirement is specified as 1 MWh net energy, meaning the efficiency losses have already been considered.

Correct Answer: Option B.

Exercise 12: Levelized Cost of Storage (LCOS) for a Battery System:

Solution:

Annualized capital = 300/10 = 30 CHF/kWh-year; total annual cost = 30 + 5 = 35 CHF/kWh-year; LCOS = 35/200 = 0.175 CHF/kWh.

Correct Answer: Option C.

Exercise 13: Net Fossil CO_2 Emissions from a Biomass Plant:

Solution:
Only 20% of 50,000 tonnes = 10,000 tonnes over lifetime; annual net emission = 10,000/30 $\approx$ 333 tonnes/year.

Correct Answer: Option B.

Exercise 14: Technology Mix Optimization for Emissions:

Solution:
Let f be the fraction from System Y. Then: $0.35f + 0.20(1 - f) = 0.25 \Rightarrow 0.15f = 0.05 \Rightarrow f \approx 0.333$, i.e. about 33%.

Correct Answer: Option A.

Exercise 15: Grid Reinforcement Investment versus Savings:

Solution:
Annual saving = 50,000 kWh $\times$ 0.10 CHF/kWh = 5,000 CHF/year; over 30 years = 150,000 CHF. Net cost = 500,000 – 150,000 = 350,000 CHF.

Correct Answer: Option C.

Exercise 16: LCOE Including Carbon Pricing for a Gas Plant:

Solution:
Additional cost = 0.4 t/MWh $\times$ 30 CHF/t = 12 CHF/MWh; new LCOE = 65 + 12 = 77 CHF/MWh.

Correct Answer: Option B.

Exercise 17: Investment versus O&M Cost Trade-off:

Solution:
Technology A: Annualized investment = 2000/20 = 100 CHF/kW-year; plus O&M 50 gives 150 CHF/kW-year.

Technology B: Annualized investment = 1500/20 = 75 CHF/kW-year; plus O&M 100 gives 175 CHF/kW-year.

Note: Although Technology B's annual cost is 175 CHF/kW-year, it is higher than Technology A's 150 CHF/kW-year. Hence, Technology A has the lower annual cost.

Correct Answer: Option C.

Exercise 18: Annual Emission Savings from a BEV:

Solution:

Savings per km = (200 – 100) = 100 g CO_2; annual saving = 100 g/km × 20,000 km = 2,000,000 g = 2 tonnes/year.

Correct Answer: Option A.

Exercise 19: CCS Retrofit Cost for a Coal Plant:

Solution:
Extra capital = 500 CHF/kW × 500,000 kW = 250,000,000 CHF; annualized = 250,000,000/25 = 10,000,000 CHF/year.

Annual O&M = 5% of 250,000,000 = 12,500,000 CHF/year; total extra annual cost = 10,000,000 + 12,500,000 = 22,500,000 CHF/year.

Annual energy = 500 MW × 8,000 h = 4,000,000 MWh; additional cost per MWh = 22,500,000 / 4,000,000 ≈ 5.63 CHF/MWh.

Correct Answer: Option B.

Exercise 20: System-Level Optimization: Cost-to-Impact Ratio:

Solution:
Ratio = 10% / 5% = 2.

Correct Answer: Option A.

Part B: Renewable System and Climate Resilience Case Study

Exercise 21: PV Efficiency Loss Due to Temperature Increase:

Solution:
Loss = 0.5%/°C × 2°C = 1%.

Correct Answer: Option B.

Exercise 22: Wind Capacity Factor Change under SSP3:

Solution:
Baseline = 2 TWh/year; 5% increase gives 2 × 1.05 = 2.1 TWh/year.

Correct Answer: Option C.

Exercise 23: Optimized System – Lifetime Generation:

Solution:
Solar = 3.5 TWh/year × 25 = 87.5 TWh; Wind = 3 TWh/year × 25 = 75 TWh.

Correct Answer: Option A.

Exercise 24: Optimized System – LCA Emissions Calculation:

Solution:

Solar emissions $= 87.5 \times 10^9\,\text{kWh} \times 0.04\,\text{kg/kWh} = 3.5 \times 10^9\,\text{kg}$;

Wind emissions $= 75 \times 10^9\,\text{kWh} \times 0.02\,\text{kg/kWh} = 1.5 \times 10^9\,\text{kg}$;

Total $= 3.5 + 1.5 = 5.0 \times 10^9$ kg CO_2-eq.

Correct Answer: Option B.

Exercise 25: Optimized System – LCA Water Usage Calculation:

Solution:
Solar water usage $= 87.5 \times 10^9\,\text{kWh} \times 3\,\text{L/kWh} = 262.5 \times 10^9\,\text{L}$;

Wind water usage $= 75 \times 10^9\,\text{kWh} \times 1\,\text{L/kWh} = 75 \times 10^9\,\text{L}$;

Total $= 337.5 \times 10^9\,\text{L} \approx 3.4 \times 10^{11}\,\text{L}$.

Correct Answer: Option D.

Exercise 26: Hybrid System – Annual Emission Reduction:

Solution:
Percentage change $= ((5.0–4.0)/4.0) \times 100\% = 25\%$ increase.

Correct Answer: Option C.

Exercise 27: Grid Reinforcement Requirement:

Solution:
Excess generation = 4 TWh/year – 2 TWh/year = 2 TWh/year.

Correct Answer: Option B.

Exercise 28: Renewable System Investment – Cost Estimation:

Solution:
Solar cost $= 1\,\text{GW} \times 1200\,\text{CHF/kW} = 1.2 \times 10^9$ CHF;

Wind cost $= 0.5\,\text{GW} \times 1800\,\text{CHF/kW} = 0.9 \times 10^9$ CHF;

Total $= 1.2 + 0.9 = 2.1 \times 10^9$ CHF.

Correct Answer: Option C.

Exercise 29: Sensitivity Analysis – Demand Variation Impact:

Solution:
Increase = 2.5 GW $\times$ 12% = 0.30 GW; new capacity = 2.5 + 0.30 = 2.8 GW.

Correct Answer: Option A.

Exercise 30: Discussion – Climate Change Adaptation:

Solution:
The most effective strategy is to enhance system resilience by technological adaptations (e.g., advanced cooling for PV, robust wind turbine design).

Correct Answer: Option D.