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

Part A: Annualization and Impact Calculations

Exercise 1: Lifetime PV System Cost and Grid Reinforcement:

A photovoltaic (PV) plant is installed at 10 MW (DC) with an investment cost of 1,200 CHF/kW and an annual operations & maintenance (O&M) cost of 20 CHF/kW-year. Its lifetime is 25 years and it experiences a uniform degradation of 0.5% per year. Under standard test conditions, the system initially produces 15,000 MWh in year 1. In addition, the local grid can integrate up to 8 MW of PV capacity without reinforcement; any excess capacity requires grid reinforcement at 50,000 CHF per MW (assume the reinforcement cost is annualized by simple division over the plant lifetime). Calculate:

(a) The total lifetime production (in MWh) accounting for degradation.

(b) The annualized cost of investment plus O&M (ignoring discounting).

(c) The extra annual cost due to grid reinforcement.

(d) The final levelized cost of electricity (LCOE) in CHF/MWh.

Options:

A) $\sim$ 47 CHF/MWh **B)** $\sim$ 60 CHF/MWh **C)** $\sim$ 54 CHF/MWh **D)** $\sim$ 50 CHF/MWh

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

A wind turbine plant (5 MW) has a capacity factor of 5 MW $\times$ 8760 h $\times$ 0.30 and an investment cost of 2,000 CHF/kW with annual O&M of 30 CHF/kW-year. A gas turbine plant (5 MW) operates at an 80% capacity factor, with an investment cost of 1,000 CHF/kW, annual O&M of 50 CHF/kW-year, and a fuel cost of 0.05 CHF/kWh (thermal basis). The gas turbine's CO_2 emission factor is 0.4 kg/kWh. Both systems have a 25-year lifetime. Determine:

(a) Annual energy production for each system.

(b) Annualized capital and O&M costs (ignore discounting).

(c) Annual fuel cost for the gas turbine.

(d) LCOE (in CHF/MWh) and annual CO_2 emissions for the gas turbine.

Options:

A) Wind: $\sim$ 41 CHF/MWh; Gas: $\sim$ 60 CHF/MWh and $\sim$ 12 000 tonnes CO_2/year **B)** Wind: $\sim$ 42 CHF/MWh; Gas: $\sim$ 63 CHF/MWh and $\sim$ 14 000 tonnes CO_2/year **C)** Wind: $\sim$ 38 CHF/MWh; Gas: $\sim$ 65 CHF/MWh and $\sim$ 13 000 tonnes CO_2/year **D)** Wind: $\sim$ 50 CHF/MWh; Gas: $\sim$ 70 CHF/MWh and $\sim$ 15 000 tonnes CO_2/year

Exercise 3: Urban Grid Reinforcement Requirement:

An urban area has a peak load of 50 MW. At noon, the installed PV capacity produces 80% of its 30 MW rating (i.e., 24 MW), while the local load is only 28% of the peak load (i.e., 14 MW). Determine:

(a) The net power flow (export or import).

(b) The additional capacity (in MW) that must be reinforced if the grid permits a maximum net export of 5 MW.

(c) The annual reinforcement cost, given a cost of 120,000 CHF per MW and a reinforcement lifetime of 20 years.

Options:

A) 35,000 CHF/year **B)** 25,000 CHF/year **C)** 30,000 CHF/year **D)** 40,000 CHF/year

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

A coal-fired plant produces 500 GWh/year with an emission factor of 0.9 kg CO_2/kWh. A carbon capture system (CCS) captures 60% of the CO_2 at a cost of 50 CHF per tonne captured. Calculate:

(a) Annual CO_2 emissions without CCS.

(b) Annual CO_2 emissions with CCS.

(c) The annual operating cost of the CCS system.

Options:

A) 400,000 tonnes; 160,000 tonnes; 12.0 million CHF/year **B)** 450,000 tonnes; 180,000 tonnes; 13.5 million CHF/year **C)** 500,000 tonnes; 200,000 tonnes; 15.0 million CHF/year **D)** 450,000 tonnes; 200,000 tonnes; 13.5 million CHF/year

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

A gas-fired combined heat and power (CHP) system must supply 100 GWh of heat annually. Its thermal efficiency is 45% and electrical efficiency is 35%. The fuel cost is 0.06 CHF/kWh (thermal basis). The required thermal capacity is 20 MW, with an investment cost of 1,200 CHF/kW, a lifetime of 20 years, and annual O&M of 3% of the capital cost. Calculate:

(a) The fuel input (in GWh) required for heat production.
(b) The annual fuel cost.
(c) The annualized capital cost and O&M cost.
(d) The total annual cost and the electrical output (in GWh) produced by the system.

Options:

A) Fuel cost ≈ 13.33 million CHF, total cost ≈ 15.25 million CHF, electrical output ≈ 77.8 GWh **B)** Fuel cost ≈ 12.00 million CHF, total cost ≈ 14.00 million CHF, electrical output ≈ 80 GWh **C)** Fuel cost ≈ 14.00 million CHF, total cost ≈ 16.00 million CHF, electrical output ≈ 75 GWh **D)** Fuel cost ≈ 13.33 million CHF, total cost ≈ 15.25 million CHF, electrical output ≈ 80 GWh

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

A nuclear power plant of 1 GW capacity has an investment cost of 4,000 CHF/kW, an annual O&M cost of 100 CHF/kW-year, and a decommissioning cost equal to 10% of the initial investment, incurred at the end of a 40-year lifetime. Its capacity factor is 90%. Determine:

(a) The annualized investment cost (using straight-line depreciation).
(b) The annualized decommissioning cost.
(c) Total annual cost and annual energy production (in MWh).
(d) The LCOE in CHF/MWh.

Options:

A) ∼ 28 CHF/MWh **B)** ∼ 30 CHF/MWh **C)** ∼ 26.7 CHF/MWh **D)** ∼ 25 CHF/MWh

Exercise 7: Urban Grid Reinforcement Cost (Revisited):

In an urban grid, at noon the local load is 80 MW while a PV plant produces 90 MW. If the grid's design allows a maximum net export of 5 MW, the excess export must be managed via reinforcement. Assuming the excess export is 5 MW and a reinforcement cost of 120,000 CHF per MW with a reinforcement lifetime of 20 years, compute the annualized reinforcement cost. **Options:**

A) 30,000 CHF/year **B)** 40,000 CHF/year **C)** 35,000 CHF/year **D)** 25,000 CHF/year

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

A gas-fired power plant emits 20,000 tonnes CO_2/year. A CCS system is installed that captures 70% of the emissions at an operating cost of 60 CHF per tonne captured. Determine:

(a) The residual annual CO_2 emissions.

(b) The annual operating cost of the CCS system.

Options:

A) 7,000 tonnes; 900,000 CHF **B)** 6,500 tonnes; 850,000 CHF **C)** 6,000 tonnes; 840,000 CHF **D)** 5,000 tonnes; 800,000 CHF

Exercise 9: Lifecycle Construction Emissions of a Wind Farm:

A 10 MW wind farm has a construction-related emission factor of 50 tonnes CO_2 per kW installed. With a 25-year lifetime, calculate:

(a) The total construction emissions (in tonnes).

(b) The average annual construction-related emission.

Options:

A) 600,000 tonnes total; 24,000 tonnes/year **B)** 500,000 tonnes total; 20,000 tonnes/year **C)** 500,000 tonnes total; 25,000 tonnes/year **D)** 400,000 tonnes total; 16,000 tonnes/year

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

In an optimization study, increasing renewable penetration by 15% reduces CO_2 emissions by 12% while increasing overall system cost by 8%. What is the ratio of emission reduction to cost increase? **Options:**

A) 1.5 **B)** 2.0 **C)** 1.8 **D)** 1.2

Exercise 11: Comparison of Battery Storage versus Pumped Hydro:

A battery system has an energy density of 200 Wh/kg and must store 1 MWh net energy (round-trip efficiency = 90%). A pumped hydro system stores 1 MWh net energy by raising water 100 m (water density = 1000 kg/m^3, efficiency = 80%). Calculate:

(a) The required battery mass (in kg).

(b) The required water volume (in m^3) for pumped hydro.

Options:

A) Battery: $\sim 5\,000$ kg; Pumped hydro: $\sim 4,000\,\mathrm{m}^3$ **B)** Battery: $\sim 5,555$ kg; Pumped hydro: $\sim 3,670\,\mathrm{m}^3$ **C)** Battery: $\sim 6,000$ kg; Pumped hydro: $\sim 3,500\,\mathrm{m}^3$ **D)** Battery: $\sim 5,555$ kg; Pumped hydro: $\sim 4,000\,\mathrm{m}^3$

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

A battery storage system is installed at a cost of 300 CHF/kWh. It has a round-trip efficiency of 90% and a lifetime of 10 years with an annual O&M cost of 5 CHF/kWh-year. If each kWh of storage sees an annual throughput of 200 kWh, compute the LCOS in CHF/kWh. **Options:**

A) 0.20 CHF/kWh **B)** 0.15 CHF/kWh **C)** 0.175 CHF/kWh **D)** 0.18 CHF/kWh

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

A biomass power plant emits 50,000 tonnes CO_2 over its lifetime. However, 80% of these emissions are biogenic (and considered carbon neutral). Calculate the net fossil CO_2 emissions per year if the plant has a lifetime of 30 years. **Options:**

A) $\sim$ 400 tonnes/year **B)** $\sim$ 333 tonnes/year **C)** $\sim$ 500 tonnes/year **D)** $\sim$ 200 tonnes/year

Exercise 14: Technology Mix Optimization for Emissions:

A planner compares two systems: System X costs 0.05 CHF/kWh and emits 0.20 kg CO_2/kWh, while System Y costs 0.04 CHF/kWh and emits 0.35 kg CO_2/kWh. To achieve a combined average emission of 0.25 kg CO_2/kWh, what fraction of the energy should come from System Y? **Options:**

A) $\sim$ 33% **B)** $\sim$ 50% **C)** $\sim$ 25% **D)** $\sim$ 40%

Exercise 15: Grid Reinforcement Investment versus Savings:

A grid reinforcement project costs 500,000 CHF and is expected to save 50,000 kWh of transmission losses annually, valued at 0.10 CHF/kWh. Over a 30-year lifetime, determine the net (total) cost or saving. **Options:**

A) 0 CHF net cost **B)** 500,000 CHF net cost **C)** 350,000 CHF net cost **D)** 150,000 CHF net cost

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

A natural gas power plant has an LCOE of 65 CHF/MWh and emits 0.4 tonnes CO_2 per MWh. With a carbon price of 30 CHF/tonne imposed, determine the new LCOE. **Options:**

A) 75 CHF/MWh **B)** 77 CHF/MWh **C)** 80 CHF/MWh **D)** 72 CHF/MWh

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

Two technologies are compared: Technology A has an investment of 2,000 CHF/kW and O&M of 50 CHF/kW-year, while Technology B has an investment of 1,500 CHF/kW and O&M of 100 CHF/kW-year. Both have a lifetime of 20 years. Which technology has the lower annual cost per kW (using simple straight-line depreciation)? **Options:**

A) Technology B is lower **B)** Both equal **C)** Technology A: 150 CHF/kW-year **D)** Technology B: 175 CHF/kW-year

Exercise 18: Annual Emission Savings from a BEV:

A battery electric vehicle (BEV) has a life-cycle emission of 100 g CO_2/km, compared to 200 g CO_2/km for a fossil-fuel car. If annual travel is 20,000 km, calculate the annual emission savings when switching to a BEV. **Options:**

A) 2 tonnes CO_2/year **B)** 4 tonnes CO_2/year **C)** 1 tonne CO_2/year **D)** 3 tonnes CO_2/year

Exercise 19: CCS Retrofit Cost for a Coal Plant:

A coal plant of 500 MW retrofits CCS at an extra capital cost of 500 CHF/kW. Its annual O&M for CCS is 5% of the extra capital cost. The plant operates 8,000 h/year at full capacity. Calculate:

(a) The extra capital cost and its annualized value (assume a 25-year lifetime).

(b) The annual O&M cost for the retrofit.

(c) The additional cost per MWh of energy produced due to the retrofit.

Options:

A) $\sim$ 7.00 CHF/MWh **B)** $\sim$ 5.63 CHF/MWh **C)** $\sim$ 4.50 CHF/MWh **D)** $\sim$ 6.00 CHF/MWh

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

An energy system planner can reduce overall system cost by 10% by increasing renewable penetration; however, this increases the life-cycle environmental impact by 5% (e.g., due to higher storage requirements). What is the ratio of cost reduction to environmental impact increase? **Options:**

A) 2.0 **B)** 1.5 **C)** 1.8 **D)** 2.5

Part B: Renewable System and Climate Resilience Case Study

Exercise 21: PV Efficiency Loss Due to Temperature Increase:

A PV panel loses 0.5% efficiency per 1°C above 25°C. Under an SSP2 scenario, if the average temperature increases by 2°C, by what percent is the PV output reduced?

A. 5%
B. 1%
C. 2%
D. 0.5%

Exercise 22: Wind Capacity Factor Change under SSP3:

Under SSP3, if the wind capacity increases by 5% relative to a baseline of 2 TWh/year, what is the new annual generation?

A. 2.05 TWh/year
B. 1.9 TWh/year
C. 2.1 TWh/year
D. 2.2 TWh/year

Exercise 23: Optimized System – Lifetime Generation:

An optimized configuration targets 3.5 TWh/year from solar and 3 TWh/year from wind. Over 25 years, what are the lifetime generation totals?

A. Solar: 87.5 TWh, Wind: 75 TWh
B. Solar: 85 TWh, Wind: 75 TWh
C. Solar: 90 TWh, Wind: 80 TWh
D. Solar: 80 TWh, Wind: 70 TWh

Exercise 24: Optimized System – LCA Emissions Calculation:

For the optimized configuration in Exercise 23, calculate the lifetime CO_2-eq emissions using:

- Solar: 87.5 TWh, emission factor = 40 g CO_2-eq/kWh.
- Wind: 75 TWh, emission factor = 20 g CO_2-eq/kWh.

A. 6.0×10^9 kg CO_2-eq
B. 5.0×10^9 kg CO_2-eq
C. 4.5×10^9 kg CO_2-eq

D. 3.5×10^9 kg CO_2-eq

Exercise 25: Optimized System – LCA Water Usage Calculation:

For the optimized configuration (Solar: 87.5 TWh, Wind: 75 TWh) with water usage of 3 L/kWh for solar and 1 L/kWh for wind, compute the lifetime water usage.

A. 2.0×10^{11} L
B. 2.5×10^{11} L
C. 2.8×10^{11} L
D. 3.4×10^{11} L

Exercise 26: Hybrid System – Annual Emission Reduction:

If the baseline hybrid system (Solar: 3 TWh/year, Wind: 2 TWh/year) has lifetime emissions of 4.0×10^9 kg CO_2-eq and the optimized system has lifetime emissions of 5.0×10^9 kg CO_2-eq, what is the percentage change?

A. Increase of 10%
B. Increase of 20%
C. Increase of 25%
D. Decrease of 20%

Exercise 27: Grid Reinforcement Requirement:

A region's grid can accommodate an additional 10 TWh/year. If a new PV installation is expected to generate 4 TWh/year during peak hours and the local load is 2 TWh/year during those periods, what is the net excess generation that must be accommodated?

A. 6 TWh/year
B. 2 TWh/year
C. 4 TWh/year
D. 8 TWh/year

Exercise 28: Renewable System Investment – Cost Estimation:

Assume the cost for solar PV is 1200 CHF/kW and for wind is 1800 CHF/kW. If the optimized system from Exercise 23 requires 1 GW of solar capacity and 0.5 GW of wind capacity, what is the total investment cost?

A. 1.2×10^9 CHF + 1.0×10^9 CHF = 2.2×10^9 CHF
B. 1.0×10^9 CHF + 0.9×10^9 CHF = 1.9×10^9 CHF
C. 1.2×10^9 CHF + 0.9×10^9 CHF = 2.1×10^9 CHF
D. 1.2×10^9 CHF + 0.8×10^9 CHF = 2.0×10^9 CHF

Exercise 29: Sensitivity Analysis – Demand Variation Impact:

Assume a 10% increase in local electricity demand leads to a 12% increase in required renewable capacity. If the original system was sized at 2.5 GW, what is the new required capacity?

A. 2.8 GW

B. 3.1 GW

C. 2.9 GW

D. 3.0 GW

Exercise 30: Discussion – Climate Change Adaptation:

Which statement best describes an adaptation strategy for renewable systems in light of climate change?

A. Focus solely on grid reinforcement.

B. Shift entirely from wind to solar PV.

C. Reduce renewable capacity to lower costs.

D. Install advanced cooling systems for PV panels and design wind turbines for variable wind conditions.