Case Study 2: Evaluating CHP Systems for a Swiss Municipality

Introduction and Context

Imagine a mid-sized Swiss municipality committed to achieving energy self-sufficiency while reducing its carbon footprint. Faced with increasing energy costs and a desire to bolster local resilience, the municipality is considering the installation of Combined Heat and Power (CHP) systems. Two potential options are on the table: a gas-fired CHP system and a biomass-fired CHP system. Each option offers different advantages in terms of efficiency, fuel availability, and environmental impact.

In this case study, you will analyze these two CHP systems to determine which configuration better meets the municipality's heating and electricity demands. You will evaluate technical efficiencies, fuel requirements, and CO_2 emissions, and you will explore the potential benefits of a hybrid approach that integrates both systems.

Municipal Energy Demand:

Demand Type	**Value**	**Unit**
Heating Demand	100	GWh/year
Electricity Demand	60	GWh/year

CHP System Characteristics:

Parameter	**Gas-Fired CHP**	**Biomass-Fired CHP**
Electric Efficiency (LHV)	35%	25%
Thermal Efficiency	45%	50%
Fuel Emission Factor	200 g CO_2/kWh	30 g CO_2/kWh

Table 1: Technical Specifications for CHP Options

Additional Information:

- Conversion factor: 1 GWh = 10^6 kWh.
- The CHP system must simultaneously meet the heating and electricity demands.
- Local fuel availability, infrastructure costs, and maintenance considerations are important factors.
- Supplementary data on cost trends and efficiency improvements in CHP technology are available from recent regional studies.

Problem Description: You are tasked with evaluating the performance of both CHP options by:

1. Estimating the fuel input required to deliver 100 GWh/year of heat for each option.
2. Calculating the electricity output based on the given electrical efficiencies, and comparing these outputs to the municipality's 60 GWh/year demand.
3. Estimating the annual CO_2 emissions from each system.
4. Developing a hybrid scenario in which the heating demand is split equally between the two systems, and evaluating the resulting energy outputs and emissions.
5. Conducting a sensitivity analysis to determine the impact of a $\pm 10\%$ change in local demand.

Supplementary Data Table:

Parameter	**CCGT-CHP**	**Biomass-CHP**	**Hybrid**
Heating Demand Allocated (GWh)	100	100	50 each
Electric Efficiency (%)	35	25	—
Thermal Efficiency (%)	45	50	—
Fuel Requirement (GWh fuel)	—	—	—
Electricity Output (GWh)	—	—	—
CO_2 Emissions (kt)	—	—	—

Your final report should include:

- A clear estimation of the fuel requirements for each CHP option.
- A comparative analysis of electricity outputs relative to demand.
- An estimation of CO_2 emissions.
- A detailed evaluation of a hybrid CHP strategy.
- A discussion of the sensitivity of your findings to demand variations.

Step-by-Step Instructions

1. Fuel Input Estimation

Calculate the fuel input required for each CHP option to meet the 100 GWh/year heating demand by dividing the heat demand by the thermal efficiency (expressed as a decimal).

2. Electricity Output Calculation

Determine the electricity produced by each system by multiplying the calculated fuel input by the electric efficiency.

3. CO_2 Emissions Estimation
Estimate the CO_2 emissions for each system by applying the fuel-specific emission factors to the total fuel input.

4. Hybrid Scenario Analysis
Assume a split in the heat demand (e.g., 50 GWh each) and recalculate fuel inputs, electricity outputs, and emissions. Compare the hybrid system's performance with the individual systems.

5. Sensitivity Analysis
Examine how a ±10% variation in energy demand affects the performance metrics of both systems.

Reflection and Discussion Points

- How do the efficiencies and emissions of gas-fired and biomass-fired CHP systems compare?
- What are the benefits of a hybrid approach in balancing output and emissions?
- How sensitive is the optimal configuration to changes in local energy demand?

Multiple Choice Calculation

1. **Carnot Engine Work Output and Heat Rejection:** An ideal Carnot engine receives 1500 MJ of heat from a reservoir at 800 K and rejects heat to a reservoir at 300 K. Calculate the engine's efficiency, the net work output, and the heat rejected.

   A) Efficiency: 50.0%, Work: 750 MJ, Rejected Heat: 750 MJ B) Efficiency: 62.5%, Work: 937.5 MJ, Rejected Heat: 562.5 MJ C) Efficiency: 55.0%, Work: 825 MJ, Rejected Heat: 675 MJ D) Efficiency: 66.7%, Work: 1000 MJ, Rejected Heat: 500 MJ

2. **Brayton Cycle – Compressor and Turbine Calculations:** A gas turbine operating on a Brayton cycle compresses air isentropically from 1 bar to 10 bar. With an inlet temperature of 300 K and a specific heat ratio $\gamma = 1.4$, determine (i) the compressor outlet temperature, (ii) the turbine outlet temperature if the turbine inlet is 1400 K (expanding from 10 bar to 1 bar), and (iii) the net work per unit mass given $c_p = 1.005$ kJ/(kg·K).

   A) $T_{c,out} \approx 579$ K, $T_{t,out} \approx 725$ K, Net Work ≈ 399 kJ/kg
   B) $T_{c,out} \approx 600$ K, $T_{t,out} \approx 700$ K, Net Work ≈ 350 kJ/kg
   C) $T_{c,out} \approx 550$ K, $T_{t,out} \approx 750$ K, Net Work ≈ 400 kJ/kg
   D) $T_{c,out} \approx 580$ K, $T_{t,out} \approx 710$ K, Net Work ≈ 420 kJ/kg

3. **Rankine Cycle Performance:** In a Rankine cycle, water is pumped from 30°C to 10 MPa (assume liquid incompressibility with specific volume 0.001 m^3/kg), heated in a boiler to generate steam at 480°C, and expanded in a turbine producing 350 kJ/kg. If the pump work is 5 kJ/kg and the heat input is 1500 kJ/kg, calculate the net work output and overall thermal efficiency.

   A) Net Work: 345 kJ/kg, Efficiency: 23.0% B) Net Work: 350 kJ/kg, Efficiency: 25.0% C) Net Work: 340 kJ/kg, Efficiency: 22.7% D) Net Work: 355 kJ/kg, Efficiency: 24.0%

4. **Solar Photovoltaic Energy Yield:** A PV panel with an efficiency of 18% is exposed to an average insolation of 5 kWh/m^2/day. Compute (i) the daily electrical energy output per square meter and (ii) the annual yield in MWh/m^2.

   A) Daily: 0.9 kWh/m^2, Annual: 0.33 MWh/m^2 B) Daily: 1.0 kWh/m^2, Annual: 0.40 MWh/m^2 C) Daily: 0.8 kWh/m^2, Annual: 0.30 MWh/m^2 D) Daily: 1.2 kWh/m^2, Annual: 0.44 MWh/m^2

5. **Wind Turbine Average Power Output:** A wind turbine with a rotor diameter of 100 m operates in a wind speed of 8 m/s. Given air density 1.225 kg/m^3, calculate (i) the available wind power using $P = 0.5\rho AV^3$, and (ii) the average power output if the capacity factor is 35%.

   A) Available Power: 2.46 MW, Average Output: 861 kW

   B) Available Power: 2.00 MW, Average Output: 700 kW

   C) Available Power: 3.00 MW, Average Output: 1050 kW

   D) Available Power: 2.75 MW, Average Output: 963 kW

6. **Nuclear Reactor Fuel Requirement:** A nuclear reactor produces 4000 MW of thermal power and operates at 33% efficiency. (i) Determine its electrical output in MW, and (ii) compute the annual fuel requirement in tonnes if the fuel energy density is 80,000 MJ/kg and the reactor runs continuously (8760 hours/year).

   A) Electrical Output: 1320 MW, Fuel: 1520 tonnes/year

   B) Electrical Output: 1500 MW, Fuel: 1600 tonnes/year

   C) Electrical Output: 1200 MW, Fuel: 1480 tonnes/year

   D) Electrical Output: 1400 MW, Fuel: 1550 tonnes/year

7. **CCGT Overall Efficiency Calculation:** A Combined Cycle Gas Turbine (CCGT) plant has a Brayton cycle efficiency of 57%. It rejects 43% of the fuel energy as waste heat; 30% of this waste is recovered by a Rankine cycle operating at a Carnot efficiency of 54%. Calculate (i) the additional work output from the recovered heat and (ii) the overall efficiency of the plant.

A) Additional Work: 7.0% of fuel input; Overall Efficiency: 64.0%

B) Additional Work: 6.5% of fuel input; Overall Efficiency: 63.5%

C) Additional Work: 8.0% of fuel input; Overall Efficiency: 65.0%

D) Additional Work: 7.5% of fuel input; Overall Efficiency: 64.5%

8. **Sensitivity Analysis on Net Work Output:** In an energy model, a $\pm 10\%$ change in energy demand leads to a $\pm 15\%$ change in net work output. If the original net work output is 500 kJ/kg, determine the range of net work outputs under these variations.

   A) 425 to 575 kJ/kg B) 450 to 550 kJ/kg C) 400 to 600 kJ/kg D) 430 to 570 kJ/kg

9. **Heat Engine Irreversibility Factor:** A heat engine receives 2000 kJ of heat from a source at 900 K and rejects heat to a sink at 300 K. It produces 1100 kJ of work. (i) Calculate the actual efficiency, (ii) the Carnot efficiency, and (iii) the irreversibility factor defined as $\frac{\eta_{Carnot} - \eta_{actual}}{\eta_{Carnot}}$.

   A) $\eta_{actual} = 55\%$, $\eta_{Carnot} = 66.7\%$, Factor=17.5%

   B) $\eta_{actual} = 60\%$, $\eta_{Carnot} = 70\%$, Factor=14.3%

   C) $\eta_{actual} = 50\%$, $\eta_{Carnot} = 65\%$, Factor=23.1%

   D) $\eta_{actual} = 57\%$, $\eta_{Carnot} = 66.7\%$, Factor=14.6%

10. **PV System Degradation:** A photovoltaic system initially operates at 20% efficiency but degrades by 0.5% per year. (i) Determine its efficiency after 10 years, and (ii) if the initial annual energy yield is 200 kWh/m^2, what is the expected yield after 10 years?

    A) Efficiency: 15%, Yield: 150 kWh/m^2/year

    B) Efficiency: 16%, Yield: 160 kWh/m^2/year

    D) Efficiency: 18%, Yield: 180 kWh/m^2/year

    D) Efficiency: 19%, Yield: 190 kWh/m^2/year

Multiple Choice Knowledge

1. **Components of a CCGT Plant:** Which of the following components are essential for the operation of a Combined Cycle Gas Turbine (CCGT) power plant? (Select all that apply.)

   A) Gas turbine (Brayton cycle) B) Heat Recovery Steam Generator (HRSG) C) Steam turbine (Rankine cycle) D) Photovoltaic array

2. **Definition of Primary Energy:** In energy system analysis, primary energy is best defined as: (Select one.)

   A) Energy delivered to end-users after conversion losses.
   B) Energy extracted directly from natural resources before any conversion process.
   C) The sum of renewable and nonrenewable energy consumed in the final demand.
   D) Energy remaining after distribution losses.

3. **Heat Engine Performance Factors:** Which of the following statements about heat engine performance are true? (Select all that apply.)

   A) The Carnot efficiency represents the theoretical maximum efficiency between two temperature reservoirs.

   B) Real engines often achieve efficiencies higher than the Carnot limit.

   C) Irreversibilities in the cycle lower the actual efficiency relative to the Carnot efficiency.

   D) Increasing the temperature difference between the source and sink increases the theoretical efficiency.

4. **Advantages of Cogeneration (CHP):** Which of the following are considered advantages of employing cogeneration (CHP) systems in urban energy applications? (Select all that apply.)

   A) Higher overall energy efficiency due to simultaneous production of heat and power.
   B) Reduction of transmission and distribution losses.
   C) Lower capital costs compared to separate heat and power systems.
   D) Enhanced local energy security and resilience.

5. **Key Components in a Rankine Cycle:** Identify the primary components of a typical Rankine cycle used in power generation. (Select all that apply.)

   A) Boiler or steam generator
   B) Turbine
   C) Condenser
   D) Compressor

6. **Factors Affecting Brayton Cycle Efficiency:** Which factors critically influence the efficiency of a Brayton cycle? (Select all that apply.)

   A) Compressor pressure ratio
   B) Maximum combustion temperature
   C) Ambient inlet temperature
   D) Choice of working fluid (to a lesser extent)

7. **Understanding Coefficient of Performance (COP):** Regarding heat pumps, which of the following statements correctly describe the Coefficient of Performance (COP)? (Select all that apply.)

   A) COP is the ratio of useful heat delivered to the electrical work input.
   B) A COP greater than 1 is possible because the device transfers ambient heat.
   C) COP is independent of the temperature difference between the heat source and sink.
   D) A higher COP indicates a more efficient heat pump.

8. **Challenges of Integrating Wind Energy:** Which of the following challenges are commonly associated with integrating wind energy into the electrical grid? (Select all that apply.)

   A) Variability and intermittency of wind speeds
   B) High energy density compared to conventional fuels
   C) Fluctuating power output requiring backup generation
   D) Geographic and siting limitations

9. **Reactor Performance in Nuclear Systems:** In assessing the performance of a nuclear reactor, which factors are most critical? (Select all that apply.)

   A) Thermal efficiency of the power conversion cycle
   B) Energy density of the nuclear fuel
   C) Adherence to safety and regulatory requirements
   D) Local solar irradiance

10. **Impact of the Industrial Revolution on Energy Systems:** Which of the following outcomes can be directly attributed to the industrial revolution's influence on energy systems? (Select all that apply.)

    A) Significant increase in per capita energy consumption
    B) Transition from predominantly biomass-based energy to fossil fuels
    C) Immediate development of renewable energy technologies
    D) Substantial rise in CO_2 emissions and environmental impact