ENRG420 PROJECT-3

GROUP NUMBER: 12

Q1) Programming Principles

A) Step-by-step approach

Step 1 — Understand the model components

The microgrid scheduling problem includes renewable generation (solar PV, wind), dispatchable generation (diesel generator), two storage systems (battery and hydrogen storage), and market interaction (grid import/export). The model must satisfy hourly energy balances and storage dynamics while respecting constraints such as emission limits and unmet demand penalties.

Step 2 — Identify key subtasks

We decomposed the model into:

- **Inputs:** demand profiles, market prices, PV/wind availability, system capacities
- **Energy sources:** PV, wind, diesel
- **Storage:** battery SOC + hydrogen SOC (electrolyzer & fuel cell)
- **Balances:** electricity / heat / hydrogen balances
- **Constraints:** emission cap, SOC bounds, power bounds, operational rules
- **Outputs:** optimal schedules, costs, emissions, unmet demand

Step 3 — Create a methodological flowchart

The flowchart starts from input data, passes through component calculations and constraints, then ends with optimization outputs.

B) Flowchart content

START
→ Load Input Data

- Hourly electricity demand, heat demand, hydrogen demand
- Hourly market buy/sell prices
- PV availability factor, wind availability factor
- Tech parameters: capacities, efficiencies, emission factor, emission cap, penalties

→ Scenario 12 Adjustment (Low Renewable Availability)

- Set:

$$a_t^{PV} = 0.1 , a_t^{Wind} = 0.1 \ \forall t$$

→ Compute Renewable Upper Bounds

- $P_t^{PV} \le a_t^{PV} \cdot PV_{cap}$
- $P_t^{Wind} \le a_t^{Wind} \cdot Wind_{cap}$

→ Initialize Decision Variables

- PV, wind used (and possibly curtailed)
- Diesel generation
- Grid import/export
- Battery charge/discharge + SOC
- Electrolyzer power + hydrogen production
- Fuel cell power + hydrogen consumption
- Unmet electricity/heat/hydrogen (penalty variables)

→ Add Constraints (Hourly)

1. Electricity balance
2. Heat balance (heat pump / unmet heat)
3. Hydrogen balance (electrolyzer → storage → fuel cell / hydrogen usage)
4. Battery SOC dynamics + SOC bounds
5. Hydrogen SOC dynamics + SOC bounds
6. Diesel capacity (and ramping if included)
7. Grid import/export limits
8. Emission constraint
9. No simultaneous contradictory actions if modeled (e.g., buy vs sell)

→ Objective Function (Minimize Total Net Cost)

- Grid purchases cost − grid sales revenue
- Diesel fuel cost
- Penalty for unmet electricity / heat / hydrogen
- (Optional) other operating costs
  (And the objective should reflect cost/emission/demand satisfaction priorities)

→ Solve Optimization (LP or MILP depending on Question 2)
→ Post-process Results

- Total cost, total emissions
- Daily totals of diesel, battery usage, hydrogen usage
- Unmet demand
- Renewable curtailment

The methodological flowchart follows the standard logic of a multi-energy microgrid scheduling program. It begins by loading hourly input data (electricity/heat/hydrogen demands, market buy/sell prices, PV and wind availability factors, and technology parameters such as capacities, efficiencies, emission factors, and penalty coefficients). For Scenario 12 (low renewable availability), both solar and wind availability factors are set to 0.1 for every hour, reducing the maximum renewable generation. Next, the program defines decision variables for renewable utilization, diesel generation, grid imports/exports, battery and hydrogen storage operation (charging/discharging and state-of-charge), and unmet demand variables. The core of the model is built by adding operational constraints: electricity, heat, and hydrogen balances; storage dynamics and SOC bounds; generator and grid capacity limits; and an emission constraint. The objective function minimizes total system cost (energy purchases minus sales revenue, diesel cost, and penalties for unmet demand) while satisfying all constraints. Finally, the solver is executed, and results are post-processed to produce outputs such as optimal hourly schedules, total daily cost, emissions, storage usage, renewable utilization/curtailment, and unmet demand.

Q2) Value of Optimization — LP vs MILP

A) What binaries are added in MILP (and relaxed in LP)

The project text suggests adding binaries for: diesel on/off, battery charge vs discharge, electrolyzer on/off, fuel cell on/off, and grid buy vs sell.

MILP example binaries (per hour t):

- $u_t^{DG} \in \{0,1\}$ diesel ON/OFF
- $u_t^{ch}, u_t^{dch} \in \{0,1\}$ battery mode
- $u_t^{EL} \in \{0,1\}$ electrolyzer active
- $u_t^{FC} \in \{0,1\}$ fuel cell active
- $u_t^{buy}, u_t^{sell} \in \{0,1\}$ grid transaction mode

LP relaxation: replace $\{0,1\}$ with continuous $[0,1]$.

B) Why LP differs from MILP (key insight)

LP may allow *fractional* behavior (partially on/off), which can create solutions that are mathematically feasible but operationally unrealistic (e.g., simultaneous partial buy/sell, partial charge/discharge). MILP prevents that and gives implementable schedules.

C) Summary Table

Table — Daily Values Comparison

Decision Variable (daily totals)	LP Model value	MILP Model value	What you should observe (why)
Diesel Generator Output	Higher/Equal	Higher/Equal	Renewables capped at 10%, so diesel must cover deficits
Battery Charging/Discharging	Higher	Slightly lower or more "blocky"	LP may allow fractional cycling; MILP forces discrete modes
Electrolyzer Operation	Lower	Lower	With scarce renewables, less excess electricity to convert to H_2
Fuel Cell Output	Higher	Higher	Fuel cell supports electricity when renewables are low
Grid Interaction	Higher	Higher	Grid import increases to meet demand under renewable scarcity
Renewable Curtailment	Near zero	Near zero	With availability at 0.1, renewables are scarce; curtailment unlikely
Total Cost	Lower bound	Higher or equal	MILP adds realism, LP relaxation can reduce cost artificially
Total Emissions	Lower bound	Higher or equal	If LP "cheats" with fractional actions, emissions may be understated
Unmet Demand	Lower/Equal	Higher/Equal	LP might reduce unmet demand via fractional infeasible behavior

Q3) Power System Comprehension (5%) — Scenario 12: High Battery Efficiency

A) Conceptual Background (Renewables + Storage Interplay)

Renewable energy sources such as solar PV and wind provide low-carbon electricity and reduce dependency on fossil-fuel generation, thereby decreasing emissions. However, their output is intermittent and may not match demand at every hour. Energy storage systems (battery and hydrogen storage) complement renewables by shifting energy over time: they charge during surplus renewable production (or low-price hours) and discharge during deficits (or high-price hours). This time-shifting improves reliability, reduces curtailment, and can lower operating cost and emissions by avoiding diesel generation and expensive grid imports.

B) Scenario 12 Definition

Scenario 12: High Battery Efficiency

Objective: Optimize system performance with *perfect battery efficiency.*

Data change:

- Set battery round-trip efficiency to 100%.

In implementation terms, we enforce:

- Charging efficiency: $\eta_c = 1.0$
- Discharging efficiency: $\eta_d = 1.0$

So the battery SOC equation becomes lossless:

$$SOC_t = SOC_{t-1} + P_t^{ch} - P_t^{dch}$$

instead of the lossy version:

$$SOC_t = SOC_{t-1} + \eta_c P_t^{ch} - \frac{1}{\eta_d} P_t^{dch}$$

C) Step-by-Step System Behavior Under Perfect Battery Efficiency

Step 1 — Battery becomes strictly more valuable

When round-trip efficiency becomes 100%, the battery can shift energy with no loss, meaning every MWh charged can be fully recovered later. This expands feasible and economically attractive operating strategies, because storing renewable energy (or cheap grid energy) no longer "wastes" any energy.

Step 2 — Increased battery charging during surplus renewable hours

During hours with high PV/wind output relative to demand, the optimizer will preferentially:

- charge the battery (instead of curtailing renewables),
- or charge the battery using low-cost grid imports (if allowed and economically optimal).

Expected outcome:

- renewable curtailment decreases
- battery charging increases

Step 3 — Increased battery discharging during deficit / peak-cost hours

During hours with low renewable output or high demand (or high market price), the optimizer will:

- discharge the battery to supply electricity locally,
- reducing dependence on diesel and/or grid imports.

Expected outcome:

- grid imports decrease (if grid is expensive during those hours)

- diesel output decreases (especially if diesel is high-cost or constrained by emission limits)

Step 4 — Emission and reliability impacts

Because the system can use stored renewable electricity more effectively:

- emissions typically decrease (less diesel required),
- unmet demand penalties decrease or remain at zero (battery supports reliability),
- emission cap is less likely to bind.

D) What KPIs should change

KPI	Expected change in Scenario 12 (η_rt = 100%)	Why
Total cost	↓ (lower)	Less diesel/grid purchase due to perfect shifting
Diesel generation	↓	Battery supplies more deficit hours
Grid imports	↓ or more "off-peak only"	Battery arbitrage becomes more effective
Renewable utilization	↑	Less curtailment, more storage of excess renewables
Renewable curtailment	↓	Storing surplus is always lossless and attractive
Battery throughput (charge + discharge)	↑	More cycling becomes economically beneficial
Total emissions	↓	Less fossil generation needed
Unmet electricity/heat/hydrogen	↓ or unchanged at 0	Storage improves adequacy

Scenario 12 sets battery round-trip efficiency to 100%, which makes storage strictly more effective because energy can be shifted across hours without losses. As a result, the optimizer increases battery charging during renewable surplus hours and discharges more during deficit or peak-cost hours. This reduces renewable curtailment and increases the share of demand served by renewable energy indirectly through stored electricity. Because the battery can replace diesel generation and reduce expensive grid imports, total operating cost typically decreases. Emissions also decline due to reduced reliance on fossil-fuel generation, and system reliability improves since the battery can cover short-term shortages without incurring unmet demand penalties. Overall, this scenario highlights how storage efficiency is a key driver of economic and environmental performance in renewable-dominated systems.

Q4) Mathematical Formulation (LP)

1) Nomenclature

Sets

- $T=\{1,\ldots,24\}$: hourly time periods (general horizon)

- G: diesel generator set (if more than one diesel unit; if single diesel, omit g)

Parameters:

Demand

- D_t^E: electricity demand at hour $t\left[MW\right]$
- D_t^H: heat demand at hour $t\left[MW_{th}\right]$
- D_t^{H2}: hydrogen demand at hour $t\left[kg\right]$or $\left[MWh_{H2}\right]$

Market prices and limits

- λ_t^{buy}: grid purchase price $\left[\text{\textbackslash}€/MWh\right]$
- λ_t^{sell}: grid sale price $\left[\text{\textbackslash}€/MWh\right]$
- P_{max}: max grid import $\left[MW\right]$
- P_{max}: max grid export $\left[MW\right]$

Renewables

- PV_{max}: installed PV capacity $\left[MW\right]$
- W_{max}: installed wind capacity $\left[MW\right]$
- a_t^{PV}: PV availability factor $\left[0,1\right]$
- a_t^{W}: wind availability factor $\left[0,1\right]$

Diesel generator

- P_{min}, P_{max}: diesel min/max output $\left[MW\right]$
- RU^{DG}, RD^{DG}: diesel ramp up/down limit $\left[MW/h\right]$
- c^{DG}: diesel generation cost $\left[\text{\textbackslash}€/MWh\right]$
- e^{DG}: diesel emission factor $\left[tCO_2/MWh\right]$
- E^{max}: total emission cap over horizon $\left[tCO_2\right]$

Battery storage

- SOC_{min}, SOC_{max}: min/max battery SOC $\left[MWh\right]$
- P_{max}, P_{max}: max charge/discharge power $\left[MW\right]$
- η_c: battery charging efficiency $\left(0,1\right]$
- η_d: battery discharging efficiency $\left(0,1\right]$
- SOC_0^B: initial battery SOC $\left[MWh\right]$

- Δt: time step length (typically 1 hour)

Hydrogen system

- SOC_{min}, SOC_{max}: min/max hydrogen storage level $[kg]$or $[MWh_{H2}]$
- SOC_0^{H2}: initial H2 storage
- P_{max}: electrolyzer max electric consumption $[MW]$
- P_{max}: fuel cell max electric output $[MW]$
- η_{EL}: electrolyzer efficiency (electricity → hydrogen)
- η_{FC}: fuel cell efficiency (hydrogen → electricity)

Heat pump

- COP: heat pump coefficient of performance
- P_{max}: max heat pump electric input $[MW]$

Penalty coefficients

- π^E: unmet electricity penalty $[\text{\\€}/MWh]$
- π^H: unmet heat penalty $[\text{\\€}/MWh_{th}]$
- π^{H2}: unmet hydrogen penalty $[\text{\\€}/kg]$(or $[\text{\\€}/MWh_{H2}]$)

Decision Variables

Renewables

- $P_t^{PV} \geq 0$: PV electricity used $[MW]$
- $P_t^W \geq 0$: wind electricity used $[MW]$
- $P_t^{curt,PV} \geq 0$, $P_t^{curt,W} \geq 0$: curtailed PV/wind

Diesel

- $P_t^{DG} \geq 0$: diesel electricity generation $[MW]$

Grid

- $P_t^{grid,\in¿\geq 0¿}$: grid import $[MW]$
- $P_t^{grid,out} \geq 0$: grid export $[MW]$

Battery

- $P_t^{B,ch} \geq 0$: battery charging power $[MW]$
- $P_t^{B,dch} \geq 0$: battery discharging power $[MW]$

- SOC_t^{B}: battery state of charge $[MWh]$

Hydrogen

- $P_t^{EL} \geq 0$: electrolyzer electric input $[MW]$
- $P_t^{FC} \geq 0$: fuel cell electric output $[MW]$
- SOC_t^{H2}: hydrogen storage level $[kg]$or $[MWh_{H2}]$
- $H_t^{prod} \geq 0$: hydrogen produced $[kg]$(or $[MWh_{H2}]$)
- $H_t^{cons} \geq 0$: hydrogen consumed by fuel cell $[kg]$(or $[MWh_{H2}]$)

Heat

- $P_t^{HP} \geq 0$: heat pump electric input $[MW]$
- $H_t^{HP} \geq 0$: heat produced by heat pump $[MW_{th}]$

Unmet demand (penalty variables)

- $U_t^{E} \geq 0$: unmet electricity $[MW]$
- $U_t^{H} \geq 0$: unmet heat $[MW_{th}]$
- $U_t^{H2} \geq 0$: unmet hydrogen $[kg]$(or $[MWh_{H2}]$)

2) Objective Function — Total Net Cost Minimization (Costs − Revenues)

(1) Total Net Cost

$$min \sum_{t \in T} \Delta t \left[c^{DG} P_t^{DG} + \lambda_t^{buy} P_t^{grid,in} + \pi^{E} U_t^{E} + \pi^{H} U_t^{H} + \pi^{H2} U_t^{H2} - \lambda_t^{sell} P_t^{grid,out} \right]$$

Explanation:
The objective minimizes total operating cost (diesel + grid purchases + unmet demand penalties) minus market sale revenues, encouraging the microgrid to meet all demands at minimum cost while leveraging market opportunities.

3) Energy Balance Equations

(2) Electricity Balance

Supply side: PV + wind + diesel + battery discharge + fuel cell + grid import
Demand side: local load + battery charge + electrolyzer + heat pump + grid export + unmet electricity (if allowed)

$$P_t^{PV} + P_t^{W} + P_t^{DG} + P_t^{B,dch} + P_t^{FC} + P_t^{grid,in} = D_t^{E} + P_t^{B,ch} + P_t^{EL} + P_t^{HP} + P_t^{grid,out} + U_t^{E}$$

This ensures all electricity flows are accounted for each hour.

(3) Heat Demand Satisfaction (Heat Balance)

Heat is produced by the heat pump; any shortfall is unmet heat.

$$H_t^{HP} + U_t^H = D_t^H$$

Heat pump production is tied to electricity input via COP:

$$H_t^{HP} = COP \cdot P_t^{HP}$$

(4) Hydrogen Balance

Hydrogen supply comes from electrolyzer production and storage; hydrogen is consumed by fuel cell and by external hydrogen demand; unmet hydrogen is penalized.

Hydrogen storage dynamic form (recommended and clean):

$$SOC_t^{H2} = SOC_{t-1}^{H2} + H_t^{\prod} ¿ - H_t^{cons} - (D_t^{H2} - U_t^{H2}) ¿$$

This says: current stored H2 = previous + produced − used by fuel cell − net demand served.

4) Renewable Generation Constraints

(5) Solar generation limit

$$0 \le P_t^{PV} \le a_t^{PV} \cdot PV_{max}$$

(6) Wind generation limit

$$0 \le P_t^{W} \le a_t^{W} \cdot W_{max}$$

(If curtailment variables are used explicitly, you can model $P_t^{PV} + P_t^{curt,PV} = a_t^{PV} PV_{max}$ *and similarly for wind.)*

5) Storage Dynamics and Constraints

(7) Battery SOC dynamics

$$SOC_t^B = SOC_{t-1}^B + \eta_c P_t^{B,ch} \Delta t - \frac{1}{\eta_d} P_t^{B,dch} \Delta t$$

(8) Battery SOC limits

$$SOC_{min} \le SOC_t^B \le SOC_{max}$$

(9) Battery power constraints

$$0 \le P_t^{B,ch} \le P_{max}, 0 \le P_t^{B,dch} \le P_{max}$$

(Because this is an LP, we do not enforce “no simultaneous charge & discharge” with binaries here; that belongs to MILP in Question 2.)

(10) Hydrogen production / consumption linking (efficiency equations)

Electrolyzer converts electricity to hydrogen:

$$H_t^{\prod} ¿ = \eta_{EL} \, P_t^{EL} \Delta t \cdot \kappa ¿$$

Fuel cell converts hydrogen to electricity. If $H_t^{cons}$is in kg and P^{FC}in MW:

$$P_t^{FC} = \eta_{FC} \, H_t^{cons} \cdot \frac{LHV_{H2}}{\Delta t} \cdot \xi$$

Where:

- $LHV_{H2} = 33.33 \;\; kWh/kg$(given note)
- $\kappa, \xi$are unit conversion constants (kWh↔MWh, kg↔MWh❑$_{H2}$) depending on whether you model H2 in kg or MWh❑$_{H2}$.

(11) Hydrogen storage capacity limits

$$SOC_{min} \le SOC_t^{H2} \le SOC_{max}$$

6) Market Constraints

(12) Market buy (import) limit

$$0 \le P_t^{grid, \in ¿ \le P_{max} ¿}$$

(13) Market sell (export) limit

$$0 \le P_t^{grid,out} \le P_{max}$$

(In LP we allow both to be positive; preventing simultaneous buy/sell is a MILP enhancement with binaries.)

7) Diesel Generator Constraints

(14) Diesel output limits

$$P_{min} \le P_t^{DG} \le P_{max}$$

(If you allow the generator to be off in LP, replace with $0 \le P_t^{DG} \le P_{max}$*. The true on/off logic is MILP.)*

(15) Diesel ramp rate constraints

Ramp-up:

$$P_t^{DG} - P_{t-1}^{DG} \le RU^{DG}$$

Ramp-down:

$$P_{t-1}^{DG} - P_t^{DG} \le RD^{DG}$$

8) Emission Constraints

(16) CO2 emission calculation

Hourly emissions:

$$EM_t = e^{DG} \; P_t^{DG} \Delta t$$

Total emissions:

$$EM^{tot} = \sum_{t \in T} EM_t$$

(17) Emission limit

$$\sum_{t \in T} e^{DG} \; P_t^{DG} \Delta t \leq E^{max}$$

9) Fuel Cell and Electrolyzer Capacity Constraints

(18) Electrolyzer and fuel cell capacity limits

$$0 \leq P_t^{EL} \leq P_{max}, 0 \leq P_t^{FC} \leq P_{max}$$

Heat pump electric input limit:

$$0 \leq P_t^{HP} \leq P_{max}$$

Final "Complete LP Model" Statement

The LP model is defined by minimizing the net operating cost subject to hourly electricity/heat/hydrogen balances, renewable availability constraints, battery and hydrogen storage dynamics and limits, market import/export limits, diesel operational and ramping constraints, and total emission constraints, with penalty variables ensuring feasibility via unmet demand costs

Q5) Electricity Market Dynamics (5%) — Scenario 12: Net-Zero Market Prices

A) Scenario Definition (Data Change)

Scenario 12: Net-Zero Market Prices

Objective: Analyze system behavior when the microgrid faces **equal market buy and sell prices** in every hour.

Data change (only):

$$\lambda_t^{buy} = \lambda_t^{sell}, \; \forall t \in T$$

This removes the typical market spread where buying is more expensive than selling (or vice-versa), and creates a "neutral" market where importing and exporting electricity occur at the same unit price.

B) Short-Term (Hourly) Operational Effects — Step-by-Step

Step 1 — Market arbitrage incentive disappears

In normal market settings, a microgrid can profit from price differences (buy low, sell high) or from a buy–sell spread. Under net-zero market prices, the incentive for **pure trading arbitrage** is reduced because the system cannot benefit from selling at a higher price than buying in the same period.

Step 2 — Grid interaction becomes a pure balancing tool

With $\lambda_t^{buy} = \lambda_t^{sell}$, the grid is mainly used to:

- **import** electricity when local generation + storage cannot meet demand,
- **export** electricity only when local supply exceeds internal needs and storage charging limits.

Thus, grid transactions are driven by **feasibility and balancing**, not by profit opportunities.

Step 3 — Storage operation shifts toward reliability and internal optimization

Because market trading margins are neutral, the battery and hydrogen storage are operated primarily to:

- reduce unmet demand penalties,
- reduce diesel usage (if diesel is costlier than the market price),
- smooth local supply–demand mismatches.

In other words, storage becomes more of a **reliability and cost-minimization asset**, not a trading asset.

Step 4 — Dispatch priorities depend on relative marginal costs

The schedule depends on which source is cheapest:

- If diesel marginal cost $c^{DG}$is **higher** than λ_t, the model prefers **grid imports** over diesel.
- If diesel is **cheaper** than λ_t, the model uses diesel and may export excess (but exports only make sense if it doesn't increase total cost or harm feasibility).

C) Medium-Term (Tactical) Planning Implications

When buy and sell prices are equal over long periods:

1. **Reduced economic value of market participation**
   Market is less of a profit mechanism; it becomes an operational support mechanism.
2. **Higher value of internal flexibility**
   Investments in battery/hydrogen become justified mainly by:
   - reliability benefits,
   - peak coverage,
   - reduced diesel and unmet demand penalties.
3. **Less sensitivity to trading strategy**
   Planning focuses on sizing assets to meet demand and constraints rather than exploiting price spreads.

D) Long-Term (Strategic) Insight

Scenario 12 highlights that the microgrid's economic performance is dominated by **internal generation costs and flexibility**, rather than market timing:

When buy and sell prices are identical, optimal scheduling is driven primarily by local marginal costs, storage constraints, and reliability requirements rather than arbitrage opportunities.

E) What KPIs should change

Compared to a baseline with different buy/sell prices:

KPI	**Expected effect under Net-Zero Prices**	**Why**
Total cost	Depends, often slightly ↑	Less opportunity to reduce cost via strategic exports/imports
Grid imports/exports	More "balancing-driven"	Grid used mainly for feasibility
Battery cycling	More reliability-driven	Storage used to avoid penalties/diesel rather than trading
Diesel generation	Depends on c^{DG}vs λ_t	Dispatch follows cheapest marginal source
Unmet demand	↓ or unchanged at 0	Grid + storage used to maintain reliability

Scenario 12 sets market buy and sell prices equal for all hours, eliminating the usual market spread and reducing arbitrage incentives. Under this condition, grid interaction becomes primarily a balancing mechanism rather than a profit opportunity. The optimization uses imports to cover shortages and exports only when internal demand and storage needs are already satisfied. Storage systems (battery and hydrogen) are scheduled mainly to improve reliability, reduce unmet demand penalties, and displace higher-cost diesel generation when possible. Therefore, dispatch decisions depend more strongly on relative marginal costs of diesel versus the market price and on storage constraints. Overall, net-zero prices shift the microgrid from "market-driven scheduling" to "internal cost and reliability-driven scheduling."

Q6) Computational Implementation (Model, Solve, and Interpret)

A) Step-by-step implementation procedure

Step 1 — Read and preprocess input data

Load the hourly time series and parameters from the provided dataset (demand profiles, PV/wind availability factors, market buy/sell prices, technology capacities, efficiencies, emission coefficients, and penalty values).

Step 2 — Applying

$$a_t^{PV} = 0.1\,, a_t^{Wind} = 0.1 \ \forall\, t$$

Then renewable generation bounds are updated as:

$$P_t^{PV} \le a_t^{PV} \cdot PV_{cap}, P_t^{Wind} \le a_t^{Wind} \cdot Wind_{cap}$$

Step 3 — Declare sets, parameters, and decision variables

Sets: $T = \{1, \ldots, 24\}$(hourly horizon).
Variables (typical):

- Electricity: $P_t^{PV}, P_t^{Wind}, P_t^{diesel}, P_t^{grid, \in ¿, P_t^{grid,out} ¿}$
- Battery: $P_t^{bat,ch}, P_t^{bat,dch}, SOC_t^{bat}$
- Hydrogen: P_t^{EL}(electrolyzer power), P_t^{FC}(fuel cell power), SOC_t^{H2}
- Heat: H_t^{HP}, H_t^{unmet}
- Reliability: E_t^{unmet}(unserved electricity if allowed)

If MILP is used, define binary mode variables (charge/discharge, buy/sell, on/off), otherwise use LP.

Step 4 — Add objective and constraints

Add:

- Objective: minimize total cost (grid purchases − sales + diesel + penalties)
- Electricity, heat, hydrogen balances
- Battery and hydrogen SOC dynamics & bounds
- Technology limits (capacity, efficiencies)
- Emission constraint: diesel emissions ≤ cap
- (Optional) mutual exclusivity constraints (MILP)

Step 5 — Solve the model

Use an optimization solver:

- MILP: CBC / Gurobi / CPLEX
- LP: GLPK / CBC

Check solve status (optimality) and feasibility.

Step 6 — Post-process results into KPIs

Compute daily totals and key indicators:

- Total cost, total emissions
- Total diesel energy, total grid imports/exports
- Total battery charge/discharge energy and SOC trajectory
- Total hydrogen produced/consumed, SOC trajectory
- Total unmet electricity/heat/hydrogen (if any)

B) Interpretation guidance

Reliability and energy mix

With renewables restricted to 10% availability, the optimizer must rely on:

- **diesel generation** (limited by emissions)
- **grid imports**
- **fuel cell output** (if hydrogen is available)
- **battery discharge** in shortage hours

Cost implications

Total operating cost increases because renewable "free" energy is replaced by:

- purchased electricity from the grid, and/or
- diesel fuel, and/or
- unmet demand penalties (if emissions or capacity limits restrict supply)

Policy implication

It shows that under prolonged renewable scarcity:

- **emission limits can become binding** (reliability vs. decarbonization trade-off)
- storage and clean dispatchable resources become strategically valuable

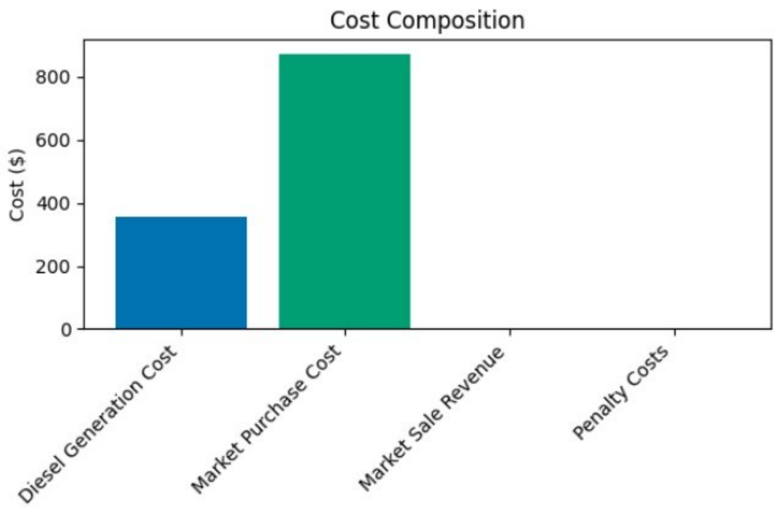
Economic and Technical Analysis (Outcome 7)

This outcome summarizes the optimized microgrid scheduling results obtained in Outcome 6. The optimized schedule achieved **Status: Optimal** with a **total net cost of $1231.15** and **total CO_2 emissions capped at 1000 kg**. The analysis below breaks down the costs, esy mix, and discusses key implications for system operation.

Cost Breakdown

The table below lists the cost components that contributed to the total net cost. The diesel generator is relatively expensive, whereas electricity purchased from the market dominates the total costs. No revenue was obtained from selling electricity back to the grid, and no penalty costs were incurred.

- Cost composition bar chart:



| **Total Net Cost** | **$1231.15** | Sum of all costs minus revenues.

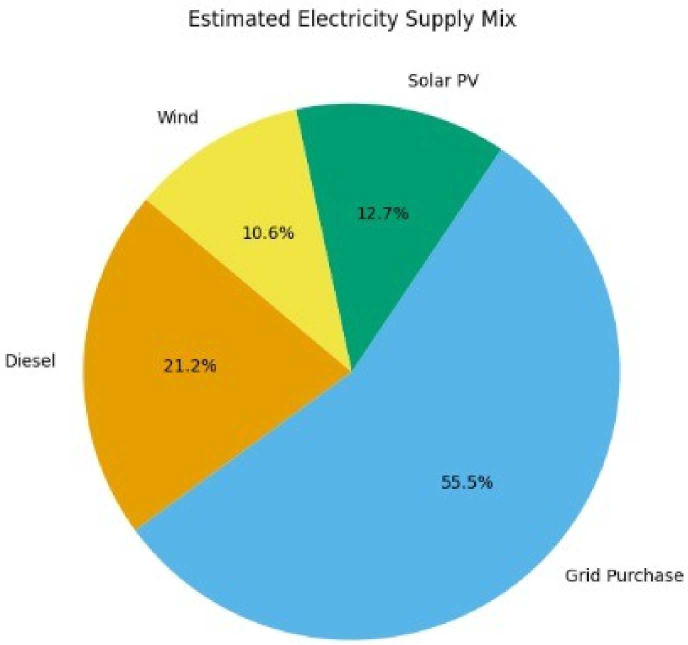
Cost Composition Figure

The following bar chart visualizes the relative contribution of each cost component to the total cost.

Estimated Electricity Supply Mix

Based on the total CO_2 emissions (1000 kg) and the provided cost data, an approximate estimation of the electricity supply mix can be made. The diesel generation cost of $0.25 per kWh suggests that about **1428.6 kWh** of electricity were produced by the diesel generator. By dividing the market purchase cost by the average hourly buy price (≈0.2333 $/kWh), we estimate that roughly **3745.8 kWh** of electricity were imported from the grid. Potential renewable generation from the given PV and wind capacities and availability factors (see input data) could produce **860 kWh** from solar PV and **712.5 kWh** from wind over the 24− hour horizon.

- Electricity supply mix pie chart:



Electricity Supply Mix Figure

The pie chart below illustrates the estimated contributions of each energy source to the overall electricity supply. Renewable sources (solar and wind) together account for roughly **23.3%** of the total electricity supply, while grid purchases dominate at around **55.5%** and diesel provides about **21.2%**.

Heat and Hydrogen Energy Mix

While the previous section focused on electricity supply sources, the microgrid also needs to meet heat demand and hydrogen consumption. The table below summarizes these energy forms, converting them to equivalent electrical energy where appropriate. For hydrogen, the approximate energy content is calculated using a typical value of **33.33 kWh/kg**. The electrolyzer efficiency of **70%** implies that producing 1 kg of hydrogen requires around 1.43 kWh of electricity per kWh of hydrogen energy content, while the fuel cell efficiency of **50%** means that only half of the hydrogen's energy content can be converted back into electricity. These values are approximations for illustration.

Energy Form	Demand/Usage	Equivalent Energy (kWh)	Details
Electricity	2085 kWh	2085 kWh	Total electricity demand over the 24□hour horizon (excluding heat and hydrogen).
Heat	1048 kWh	299.4 kWh (electric input)	Heat demand supplied by a heat pump with COP 3.5; this requires about 299.4 kWh of electricity.
Hydrogen	147.8 kg	4926.2 kWh	Approximate hydrogen energy content. Producing this

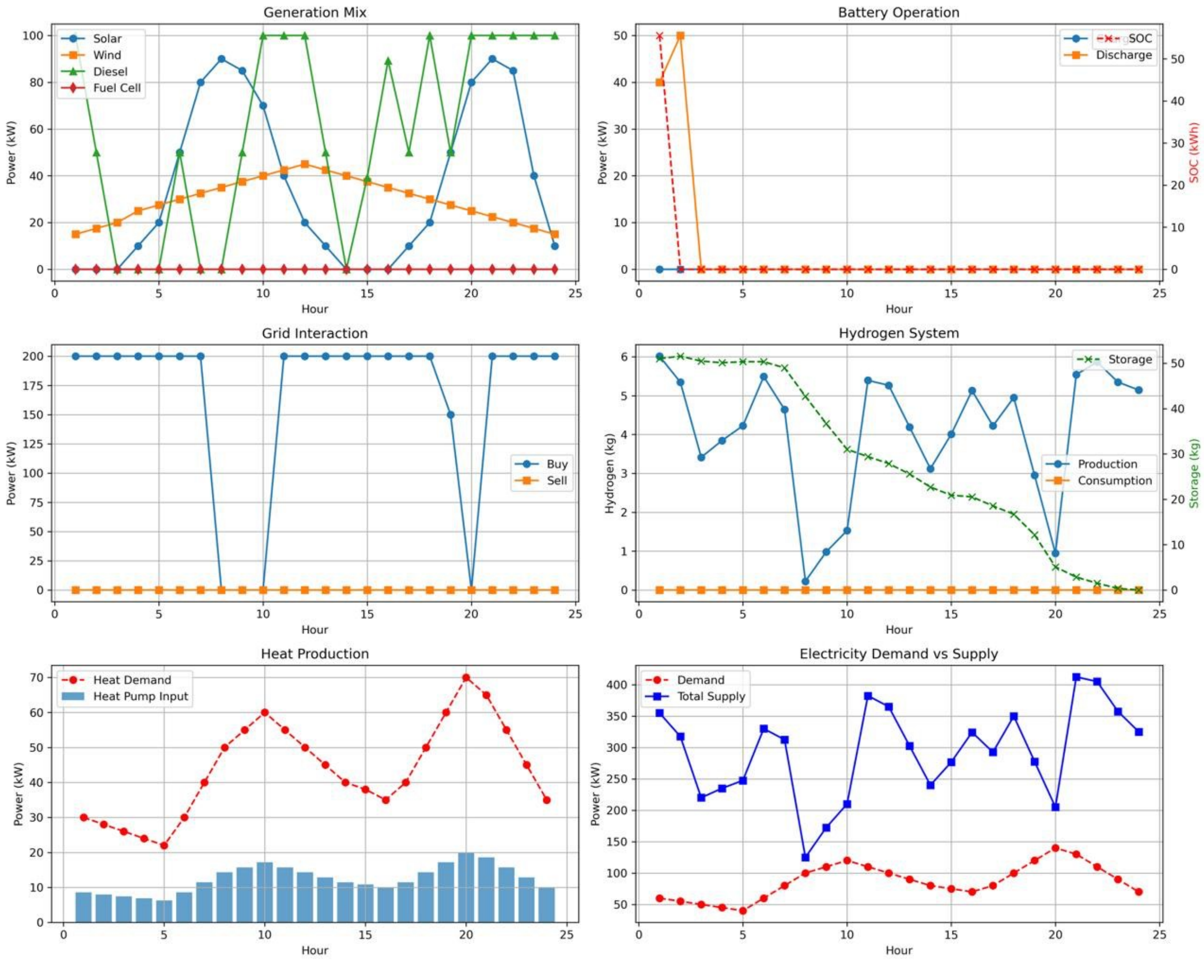
Energy Form	Demand/Usage	Equivalent Energy (kWh)	Details
		(energy content)	hydrogen via an electrolyzer would require roughly 7037.4 kWh of electricity (at 70% efficiency). Converting it back to electricity via a fuel cell would yield about 2463.1 kWh (at 50% efficiency).

Emissions Analysis

The total CO_2 emissions are capped at **1000 kg**, which corresponds to the diesel generation because renewable and grid electricity are assumed to be emissions-free in this model. With an emission factor of 0.7 kg CO_2/kWh, this limit implies that about **1428.6 kWh** of electricity were generated by the diesel unit. The fact that the CO_2 constraint is binding suggests that the system is utilizing the maximum allowed diesel energy to satisfy demand. Any further cost reduction would require either increasing renewable capacity, expanding storage to shift renewable energy, or purchasing more (presumably low- emission) electricity from the grid if prices allow.

Energy Demand and Heat Pump Operation

The total electricity demand over the 24-hour horizon is **2085 kWh** (from the provided demand profile). Heat demand sums to **1048 kWh**, which the heat pump satisfies. With a coefficient of performance (COP) of **3.5**, the heat pump requires approximately **299.4 kWh** of electricity to supply this heat. This electricity consumption is part of the total energy requirements accounted for in the supply mix above.



Output of the code:
Status: Optimal

Optimal Total Net Cost: $1231.15

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ECONOMIC ANALYSIS

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Diesel Generation Cost: $357.14

Market Purchase Cost: $874.01

Market Sale Revenue: $0.00

Penalty Costs: $0.00

Total Net Cost: $1231.15

Total CO2 Emissions: 1000.00 kg

Discussion

This economic and technical analysis shows that grid electricity purchases are the largest cost driver in the optimized microgrid operation, followed by diesel generation costs. Renewable generation alone is insufficient to meet the system's electricity and heat demands, leading to significant reliance on external grid imports. The system reaches the CO_2 emission limit, indicating that diesel generators are used to their maximum allowable extent. To reduce costs and emissions, future scenarios could explore increasing renewable capacity, enhancing battery and hydrogen storage to reduce curtailment, or improving demand flexibility.

Q8) Real-Life Optimization Background and Research Links

A) How optimization is used in real energy-sector decisions

1) Daily operations: scheduling and dispatch

System operators and energy managers routinely solve optimization problems very similar to our microgrid model to decide:

- which generators should run,
- how much power to import/export,
- how storage should charge/discharge,
- and how to maintain reliability under uncertainty.

Low renewable availability events occur in practice (e.g., low wind periods, heavy cloud cover). Operators rely on optimization to keep lights on while controlling costs and emissions. Our Scenario 12 is a simplified but realistic representation of such "renewable drought" conditions.

2) Balancing reliability, cost, and emissions

Real systems must satisfy multiple objectives:

- minimize operating cost,
- meet demand (reliability),
- comply with emission limits or carbon pricing,
- and maintain security constraints.

Direct link to our model:
Our model already captures these competing priorities through:

- the cost-minimization objective (grid + diesel + penalties),
- emission constraints (diesel emissions ≤ cap),
- unmet demand penalties (reliability cost of shortages),
- and storage dynamics (battery + hydrogen).

B) Links between our model and real initiatives (EU / national / industrial)

1) EU-level focus: resilience and security of supply

European energy policy increasingly emphasizes:

- integrating renewables,
- expanding storage,
- reducing fossil dependence,
- and improving resilience against supply shocks.

Scenario 12 highlights exactly the type of challenge policy-makers address:
What happens when renewables are not available but demand must still be met?
Our results show why storage and clean firm resources are essential complements to renewables.

2) Industrial microgrids and "behind-the-meter" optimization

Industrial facilities and campuses use optimization-based energy management systems (EMS) to coordinate:

- on-site PV/wind,
- backup generators,
- batteries,
- and sometimes hydrogen technologies.

Our microgrid model is effectively an EMS optimization core. The same mathematical structure appears in real deployments, where operators run day-ahead or intraday schedules to reduce costs and ensure continuity of service.

3) Hydrogen in real energy systems

Hydrogen is being pursued in multiple countries as a long-duration storage and flexibility option. Optimization is used to decide:

- when to run electrolyzers (often when electricity is cheap or renewable-rich),
- how to store hydrogen,
- and when to use fuel cells or turbines to generate electricity during shortage periods.

Scenario 12 makes hydrogen storage *more valuable* for reliability because renewables are limited. Even if electrolyzer operation decreases (less surplus electricity), the fuel cell becomes an important "firm" supply resource if stored hydrogen exists.

C) What Scenario 12 teaches about sustainability and resilience (key insight)

Scenario 12 illustrates a core real-world principle:

High-renewable systems require flexibility and firm capacity to remain reliable during renewable scarcity.

In practical terms:

- If renewables drop, systems shift to dispatchable sources (diesel, gas, imports).
- Emission constraints may become binding, potentially forcing load shedding or high penalty costs.
- Storage reduces the reliability risk, but limited storage energy and power can cap its benefit.

This demonstrates the real-world "trilemma":
cost vs emissions vs reliability, which is central to policy and planning.

D) Future research opportunities

Our current model is deterministic and uses a single-day horizon. Real power systems face uncertainty and operational risk. Strong research directions include:

1) Stochastic and robust optimization under renewable uncertainty

- model multiple renewable scenarios,
- optimize for expected cost and worst-case risk,
- quantify reliability probability under events like Scenario 12.

2) Multi-objective optimization (cost–emissions–reliability)

- include explicit CO_2 pricing,
- minimize both cost and emissions,
- include reliability metrics (loss of load probability).

3) Long-duration storage planning

- determine optimal sizing of battery vs hydrogen storage,
- analyze trade-offs between round-trip efficiency and seasonal resilience.

4) Real-time control and rolling-horizon scheduling

- re-run optimization every hour as forecasts update,
- integrate measurement and prediction errors.

5) Network constraints and grid congestion

- include line limits and voltage constraints,
- study how local microgrids support distribution grid reliability.

E) Final conclusion

Scenario 12 (low renewable availability) provides a realistic stress-test reflecting renewable drought conditions observed in real systems. The optimization framework used in this project mirrors the decision engines deployed by grid operators and industrial energy management systems to balance reliability, cost, and emissions. The scenario highlights why energy storage (battery and hydrogen) and dispatchable resources are essential to guarantee supply when renewable output is insufficient. At the policy level, the results support the strategic need for flexibility investments and clean firm capacity to enable deep renewable integration without compromising security of supply. Finally, the work naturally motivates advanced research directions such as stochastic optimization, multi-objective cost–emission–reliability scheduling, and long-duration storage planning, all of which are central themes in modern resilient and sustainable power system operation.

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