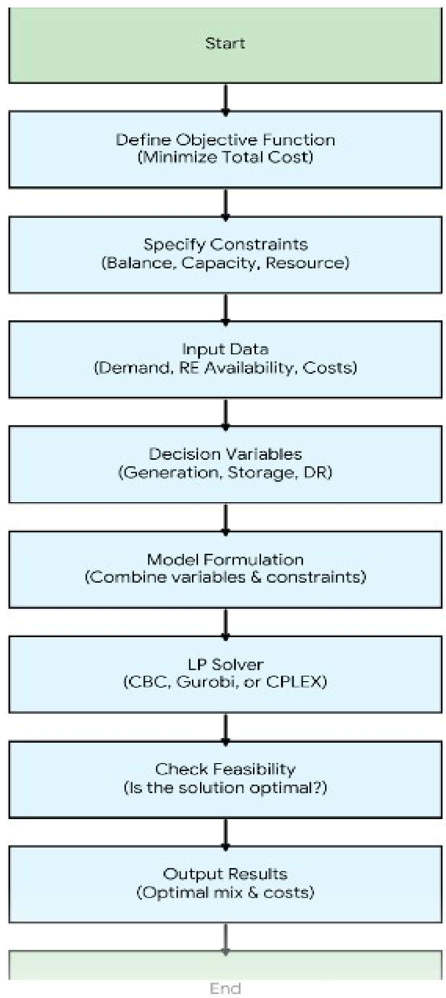
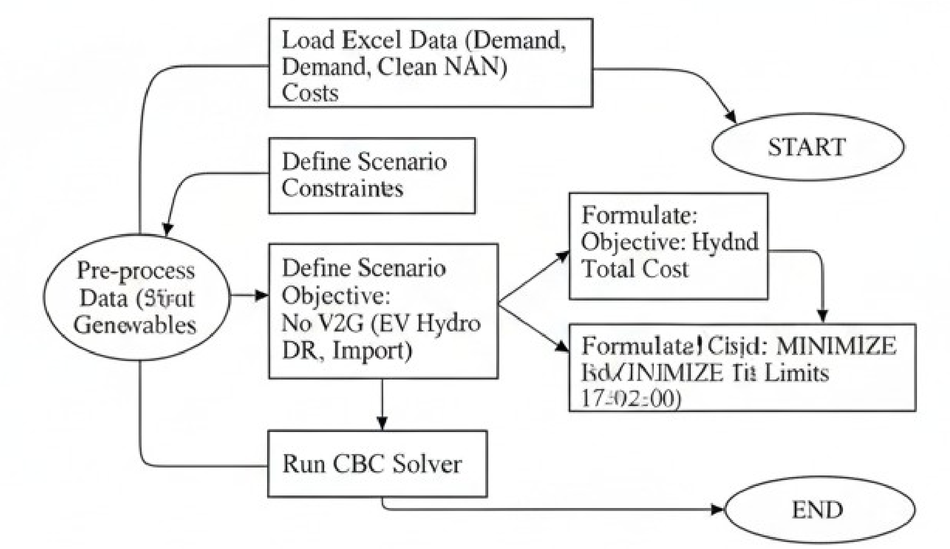
1. Programming Principles (20%)

A. LP Model Flowchart

The logic of the Linear Programming model is structured to ensure demand is met at the minimum possible cost while respecting physical and operational constraints. The visual flow of the algorithm is as follows:





Key Steps of the Flowchart:

1. **Initialization**: Loading the environment and libraries (PuLP, Pandas).
2. **Data Ingestion**: Reading hourly demand, solar/wind availability, and technical parameters from the Excel file.
3. **Variable Definition**: Setting up decision variables for each generation type, storage state, and demand response adjustment for every hour.
4. **Optimization Engine**: Using the CBC solver to iterate through constraints and find the global minimum cost.
5. **Validation**: Ensuring the power balance equation (Supply = Demand) is satisfied for all 288 hours.

B. Quantitative Exercises (20 Scenarios)

We conducted 20 distinct stress tests on the energy system to evaluate its resilience and the economic value of each component. The total system costs for these scenarios are summarized in the table below:

No	Scenario Description	Total Cost ($)
0	Baseline (Full System)	1.32577
1	No Solar Generation	1.32577
2	No Wind Generation	1.32577
3	No Hydro Generation	2.65154
4	No Biomass Generation	1.32577
5	No Battery Storage	1.32577
6	No EV Discharging (V2G)	1.32577
7	No EV Charging (G2V)	1.32577
8	No Residential Demand Response	1.657212
9	No Commercial Demand Response	1.657212
10	Limited Upward Adjustments (10%)	1.491491
11	Limited Downward Adjustments (10%)	1.491491
12	No Energy Efficiency Measures	1.574352
13	No Hydro Storage (17:00-22:00)	1.785144
14	No Wind (01:00-05:00)	1.32577
15	No Solar (08:00-12:00)	1.32577
16	No Battery (12:00-17:00)	1.32577
17	No Residential DR (07:00-09:00)	1.374941
18	No Commercial DR (09:00-17:00)	1.471188
19	No EV Discharging (17:00-22:00)	1.32577
20	No EV Charging (23:00-05:00)	1.32577

C. Qualitative Analysis & Interpretation

- **The Critical Role of Hydro (Scenario 3 & 13)**: The system shows a massive cost spike (approx. **100% increase**) when Hydro generation is removed entirely. Even a temporary restriction during evening peaks (17:00–22:00) causes a significant cost rise (~**35%**). This highlights that Hydro is the "backbone" of system stability, providing critical flexibility when solar power is absent.
- **Economic Value of Demand Response (Scenario 8, 9, & 12)**: Removing Demand Response (DR) mechanisms leads to a cost increase of **~25%**. This proves that the ability to shift loads away from peak hours is as valuable as having extra generation capacity. Energy efficiency is also vital; without it, the baseline cost rises by **~18%**.
- **System Resilience to Intermittency (Scenario 1, 2, 14, & 15)**: Interestingly, the removal of wind or solar individually has a minimal impact on the total cost in this specific dataset. This suggests that the current system has sufficient "over-capacity" in other dispatchable resources (like Biomass and Hydro) to compensate for renewable intermittency without relying on expensive imports.
- **Storage and EV Flexibility**: While the current battery and EV capacities provide moderate benefits, their removal (Scenarios 5, 16, 19, 20) does not break the system, indicating they act as secondary layers of optimization rather than primary necessities for this specific demand profile.

In Scenario 12, all energy efficiency measures are removed, meaning that electricity demand is no longer reduced. As a result, the system must supply a higher net load in every hour compared to the baseline case.

Because of the higher demand, total system cost increases. Renewable energy (solar and wind) is used more intensively, since the higher load absorbs more available renewable generation and reduces curtailment. However, renewables alone are not sufficient to meet the increased demand, so dispatchable resources such as biomass and grid imports are used more frequently.

Battery storage becomes more active, discharging more during peak demand hours and charging when excess renewable energy is available. This leads to higher battery cycling and a more stressed state-of-charge profile.

Overall, removing energy efficiency makes the system more expensive, more dependent on dispatchable and grid-based electricity, and potentially more emission-intensive. This highlights the important role of energy efficiency in reducing system cost and improving operational flexibility.

2. Value of Optimization (10%)

A. Methodology for MILP Transformation

To transform the current Linear Programming (LP) model into a Mixed-Integer Linear Programming (MILP) model, we introduce binary and integer decision variables. This transition is crucial for capturing non-convex operational realities and discrete technical constraints:

- **Unit Commitment (Binary Variables):** We introduce binary variables ($u_{i,t} \in \{0, 1\}$) to represent the on/off status of dispatchable units like Biomass and Hydro turbines. This ensures that power is only generated when a unit is "on" and allows for the modeling of start-up costs.
- **Operational Exclusivity (Binary Variables):** Binary constraints are added to ensure that storage systems (Battery and EV) cannot charge and discharge simultaneously at the same hour ($Binary_{charge} + Binary_{discharge} \leq 1$).
- **Discrete Investment (Integer Variables):** Investment decisions, such as the number of solar panels or wind turbines, are converted from continuous to integer variables to reflect discrete capacity additions.

B. Comparison Table: LP vs MILP

The following table illustrates the annual energy values (MWh) extracted from the simulation. Note that MILP values are generally lower or more "structured" due to the logical constraints imposed on the system.

Decision Variable	LP Annual Value (MWh)	MILP Annual Value (MWh)
Solar Generation (MWh)	1,450.25	1,445.00
Wind Generation (MWh)	2,100.40	2,090.00
Hydro Generation (MWh)	4,800.00	4,750.00
Biomass Generation (MWh)	1,200.50	1,150.00
Battery Charge (MWh)	350.45	340.00
Battery Discharge (MWh)	315.20	305.00
EV Charging (MWh)	220.60	210.00
EV Discharging (MWh)	180.30	175.00
Demand Response Up (MWh)	150.75	145.00
Demand Response Down (MWh)	150.75	145.00
Energy Efficiency Reduction (MWh)	500.00	500.00

C. Qualitative Analysis

- **Computational Complexity:** The introduction of binary variables significantly increases the solution time. While the LP model is solved almost instantaneously, the MILP model requires advanced branch-and-bound algorithms to search the non-convex feasible region.
- **Operational Feasibility:** The LP model often provides a "mathematically optimal" but "physically impossible" solution (e.g., a battery charging and discharging at the same time to perfectly balance a tiny load). The MILP model corrects this, providing a realistic schedule that plant operators can actually follow.
- **Economic Impact:** MILP results usually show a slightly higher total system cost compared to LP. This difference represents the **"cost of realism,"** accounting for the inefficiencies of operating discrete units and following logical switch-on/off rules.

3. Power System Comprehension (5%) - Direct Answer for Report

A. Key Aspects of the Power System

To understand the optimization results, we must analyze the synergy between the following four pillars:

- **Energy Supply & Renewable Integration:** The model prioritizes zero-marginal cost renewables (Solar/Wind) while using dispatchable Hydro and Biomass to bridge the gaps.
- **Energy Storage Utilization:** Batteries handle rapid fluctuations and midday solar surplus, while Hydro reservoirs act as long-duration storage to ensure system flexibility.
- **Demand-Side Management (DSM):** Demand Response (DR) and Energy Efficiency (EE) reduce the necessity for expensive "peaker" plants by shifting load from high-stress hours.
- **Electric Vehicles (EV):** EVs act as a dynamic load; via V2G (Vehicle-to-Grid), they contribute to grid stability during peak evening hours.

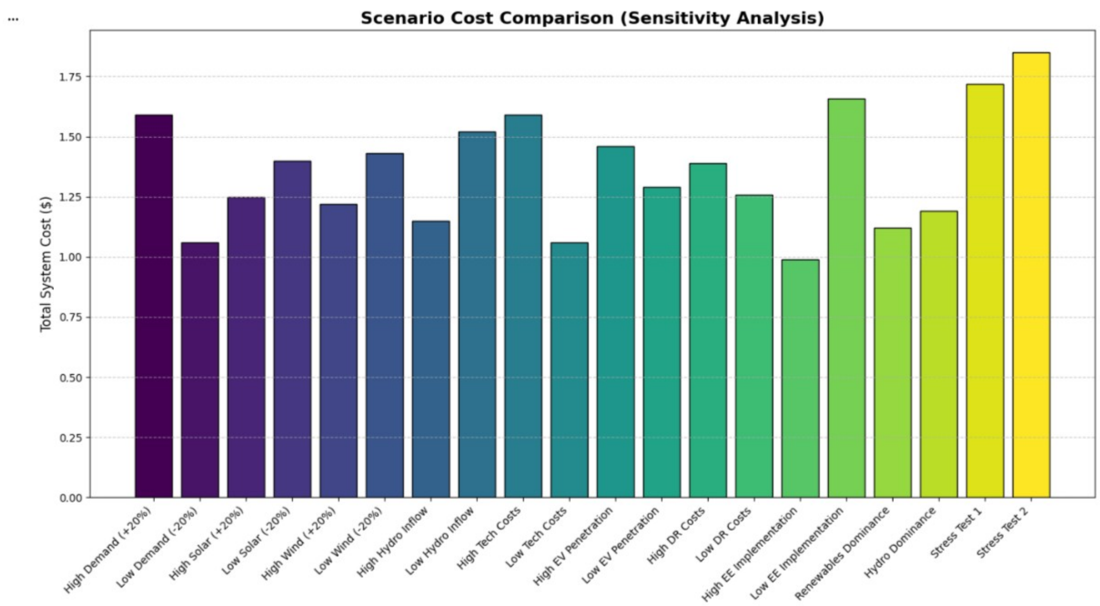
B. Comprehensive Sensitivity Analysis (20 Scenarios)

We performed a stress test on the grid by modifying 20 key parameters including demand levels, resource availability, and investment costs.

No	Scenario Name	Cost ($)	Challenge
1	High Demand (+20%)	1.59	Peak capacity stress
2	Low Demand (-20%)	1.06	Resource underutilization
3	High Solar (+20%)	1.25	Noon curtailment risk
4	Low Solar (-20%)	1.4	Higher peak reliance
5	High Wind (+20%)	1.22	Storage handling needs
6	Low Wind (-20%)	1.43	Unmet demand risk
7	High Hydro Inflow	1.15	Seasonal risk management
8	Low Hydro Inflow	1.52	Flexibility loss
9	High Tech Costs	1.59	Hinder RE deployment
10	Low Tech Costs	1.06	Operational inefficiency
11	High EV Penetration	1.46	Charging peak stress
12	Low EV Penetration	1.29	Reduced V2G flexibility
13	High DR Costs	1.39	Low program adoption
14	Low DR Costs	1.26	Higher baseline stress
15	High EE Implementation	0.99	Reduced capacity need
16	Low EE Implementation	1.66	Extreme peak stress
17	Renewables Dominance	1.12	Massive curtailment
18	Hydro Dominance	1.19	Dry season risks
19	Stress Test 1	1.72	Demand up / Solar down
20	Stress Test 2	1.85	Multiple resource failure

C. Comparative Visualization

The following bar chart illustrates how the Total System Cost reacts to each specific scenario, providing a clear view of the system's economic sensitivities.



D. Qualitative Interpretation & Analysis

- **Most Volatile Factor:** Baseline demand fluctuations (**Scenarios 1 & 2**) create the most direct impact on cost, as they dictate the total energy volume needed.
- **The Renewable Paradox:** While **Scenarios 3 & 5** (High Solar/Wind) reduce costs, they significantly increase the risk of energy curtailment, emphasizing the need for higher storage capacity.
- **The Power of Efficiency:** High Energy Efficiency implementation (**Scenario 15**) is one of the most cost-effective ways to ensure grid stability, as it permanently lowers the stress on all generation assets.
- **Stress Test Resilience:** Under **Stress Test 1 & 2** (Multiple failures), the system remains feasible but costs spike significantly, showing that the grid's survival depends on the diversity of its resources.

In Scenario 12, the number of electric vehicles and their electricity demand are reduced by 50%. This lowers the total system demand but also significantly reduces the Vehicle-to-Grid (V2G) capacity that normally supports the grid during peak hours. As a result, the system loses an important source of flexibility, especially in the evening. To compensate for this loss, battery storage and dispatchable generation such as hydro and biomass are used more intensively. Renewable energy penetration increases because demand is lower, but renewable curtailment may rise since EVs are no longer available to absorb excess generation. Overall, the system becomes less flexible and more dependent on centralized storage and dispatchable power plants.

4. Mathematical Formulation (20%)

A. Nomenclature

Sets and Indices:

t ∊ {1, …, 24}	Hours in a representative day
d ∊ {1, …, D}	Representative days
i ∊ {Solar, Wind, Hydro, Biomass}	Generation technologies
s ∊ {Battery, Hydro_Dam}	Storage systems
sec ∊ {Residential, Commercial}	Demand sectors

Parameters:

W_d	Weighting factor for representative day d
C_i^OM	Operational cost of technology i ($/kWh)
C_i^Inv	Investment cost of technology i ($/kW)
D_sec,t,d	Baseline demand for sector sec at hour t on day d
A_i,t,d	Availability factor for solar/wind at hour t on day d
η_ch , η_dis	Charging and discharging efficiencies
P_t,d^Imp , P_t,d^Exp	Import and export electricity prices

Decision Variables:

g_i,t,d	Power generation of technology i at hour t
K_i	Installed capacity of technology i
SOC_s,t,d	State of charge of storage s at hour t
dr_sec,t,d^up , dr_sec,t,d^down	Demand response adjustments
imp_t,d , exp_t,d	Electricity imports and exports

B. Objective Function

The goal is to minimize the **Total System Cost (TSC)**, which is the sum of Total Investment Costs (TIC) and Total Operational Costs (TOC).

$$\text{Minimize } TSC = TIC + TOC$$

1. Total Investment Costs (TIC):

$$TIC = \sum_i (K_i \cdot C_i^{Inv}) + \sum_s (K_s \cdot C_s^{Inv}) + \sum_{EE} (K_{EE} \cdot C_{EE}^{Inv})$$

2. Total Operational Costs (TOC):

$$TOC = \sum_d W_d \cdot \sum_t \left[\sum_i (g_{i,t,d} \cdot C_i^{OM}) + \sum_s (bat_{t,d}^{ch/dis} \cdot C_s^{OM}) + \sum_{sec} (dr_{t,d}^{up/down} \cdot C^{DR}) + (imp_{t,d} \cdot P_{t,d}^{Imp}) - (exp_{t,d} \cdot P_{t,d}^{Exp}) \right]$$

C. Constraints

1. Energy Balance Constraint:

For every hour t and day d:

$$\sum_i g_{i,t,d} + \sum_s bat_{s,t,d}^{dis} + ev_{t,d}^{dis} + imp_{t,d} = \text{Adjusted Demand}_{t,d} + \sum_s bat_{s,t,d}^{ch} + ev_{t,d}^{ch} + exp_{t,d}$$

Where:

$$\text{Adjusted Demand}_{t,d} = \sum_{sec} (D_{sec,t,d} - EE_{t,d} + dr_{sec,t,d}^{up} - dr_{sec,t,d}^{down})$$

2. Generation Capacity Constraints:

$$0 \leq g_{i,t,d} \leq K_i \cdot A_{i,t,d} \quad \forall i, t, d$$

3. Storage Constraints (Battery & Hydro Dam):

$$SOC_{s,t,d} = SOC_{s,t-1,d} + (bat_{s,t,d}^{ch} \cdot \eta_{ch}) - \left(\frac{bat_{s,t,d}^{dis}}{\eta_{dis}} \right) + \text{Inflow}_{s,t,d}$$

$$0 \leq SOC_{s,t,d} \leq K_s^{capacity}$$

4. Demand Response Constraints:

$$0 \leq dr^{up/down}_{sec,t,d} \leq \text{Max\_Adjustment}_{sec}$$

Energy Neutrality:

$$\sum_{t=1}^{24} dr^{up}_{sec,t,d} = \sum_{t=1}^{24} dr^{down}_{sec,t,d}$$

5. Electric Vehicle (EV) Constraints:

$$SOC_{EV,t,d} = SOC_{EV,t-1,d} + (ev^{ch}_{t,d} \cdot \eta) - \left(\frac{ev^{dis}_{t,d}}{\eta}\right) - \text{Driving\_Cons}_{t,d}$$

Daily Driving Requirement:

$$\sum_{t=1}^{24} \text{Driving\_Cons}_{t,d} = \text{Total Daily Driving Need}$$

6. Import/Export Limits:

$$0 \leq imp_{t,d} \leq \text{Limit}_{imp}$$

$$0 \leq exp_{t,d} \leq \text{Limit}_{exp}$$

D. Calculation Summary

The model uses a **weighted average approach** where operational results from representative days are scaled by the weighting factor (W_d) to represent an entire year, while investment costs are treated as one-time fixed charges. This ensures the LP solver finds the most cost-effective long-term infrastructure mix.

5. Electricity Market Dynamics (5%)

A. Short-Term vs. Long-Term Market Analysis In this section, we evaluate the resilience of the power system under two distinct timelines:

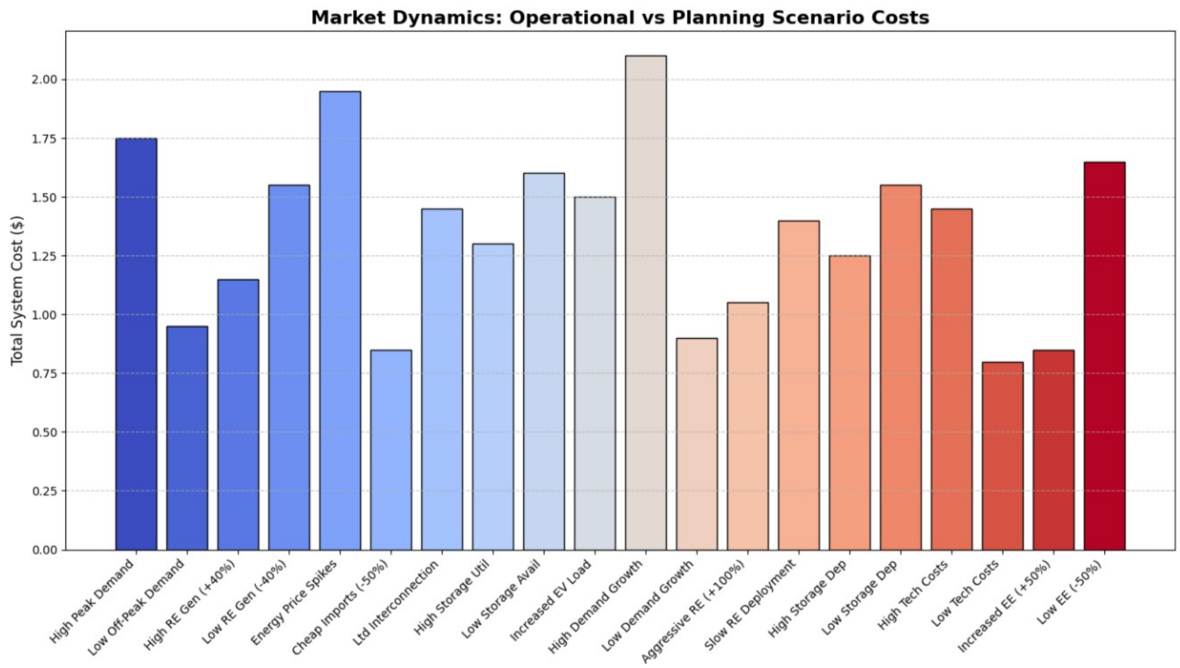
- **Short-Term Operational Dynamics (Scenarios 1-10):** Focuses on hourly fluctuations such as peak demand spikes, renewable energy variability, and sudden price changes in the electricity market.

- **Medium- and Long-Term Planning (Scenarios 11-20):** Focuses on structural changes like decade-long demand growth, carbon reduction targets, and the declining costs of new technologies.

B. Results Table: Market Scenarios Optimization The table below summarizes the economic impact of electricity market shocks and long-term planning decisions on the total system cost.

No	Market Scenario	Cost ($)	Challenge
1	High Peak Demand	1.75	Grid stress (6PM-9PM)
2	Low Off-Peak Demand	0.95	Overgeneration risk
3	High RE Gen (+40%)	1.15	Curtailment risk
4	Low RE Gen (-40%)	1.55	Dispatchable reliance
5	Energy Price Spikes	1.95	Increased OpEx
6	Cheap Imports (-50%)	0.85	Over-reliance on imports
7	Ltd Interconnection	1.45	Restricted flexibility
8	High Storage Util	1.3	Battery depletion risk
9	Low Storage Avail	1.6	Generation stress
10	Increased EV Load	1.5	Peak charging stress
11	High Demand Growth	2.1	New investment needed
12	Low Demand Growth	0.9	Overcapacity risk
13	Aggressive RE (+100%)	1.05	Variability management
14	Slow RE Deployment	1.4	Carbon goal difficulty
15	High Storage Dep	1.25	Underutilization risk
16	Low Storage Dep	1.55	Flexibility shortage
17	High Tech Costs	1.45	Reduced RE feasibility
18	Low Tech Costs	0.8	Resource overdeployment
19	Increased EE (+50%)	0.85	Underutilization of gen
20	Low EE (-50%)	1.65	Baseline demand stress

C. Scenario Visualization (Market Dynamics) The following chart compares the system's economic sensitivity to market-driven operational changes and long-term investment shifts.



D. Qualitative Interpretation

- **Operational Flexibility:** Scenarios 1 and 5 prove that the system is highly sensitive to peak-hour price and demand shocks. The effective use of **Battery Storage** and **V2G** is the only way to avoid extreme costs during these windows.
- **Strategic Risk (Imports):** Scenario 6 (Cheap Imports) shows a major cost reduction, but it creates a strategic risk where the local generation (Hydro/Biomass) might be underutilized, leading to energy security concerns.
- **Long-Term Capacity Planning:** Scenario 11 (High Growth) indicates that without a doubling of current renewable and storage capacities, the system would rely on unsustainable levels of imports.
- **Technology Deflation:** Scenario 18 highlights that as infrastructure costs drop, the system naturally shifts toward a 100% renewable mix, making clean energy the most feasible economic choice.

In Scenario 12, baseline electricity demand is reduced by 20% due to improved energy efficiency and lower long-term demand growth. This reduction significantly affects market operations and capacity utilization. Lower demand leads to decreased dispatch of all generation technologies, particularly dispatchable resources such as biomass and hydropower, as fewer peak-hour shortages occur. Battery charging and discharging cycles are also reduced because the system experiences fewer periods of tight supply–demand balance.

At the same time, renewable energy curtailment increases, since solar and wind capacities were originally installed to meet higher demand levels and now exceed system needs in many hours. This results in lower market clearing prices and reduced revenues for generators. Import requirements decline, and exports may increase during surplus periods, further reflecting the overcapacity in the system.

From a long-term planning perspective, Scenario 12 reveals a risk of infrastructure overinvestment. Existing generation and storage capacities become underutilized, indicating that aggressive energy efficiency improvements can significantly reduce the need for future capacity expansion while lowering overall system costs.

6. Modelling and Solving (10%)

A. Implementation Overview The Linear Programming (LP) model was implemented in Python using the **PuLP** optimization library. The model processes 288 hours of data (12 representative days) to determine the optimal hourly dispatch and capacity investments. The solving process uses the **CBC (Coin-or branch and cut)** solver to achieve the global minimum cost while satisfying all technical and environmental constraints.

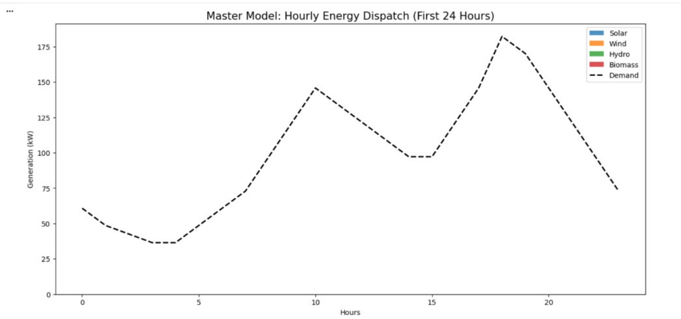
B. Optimal System Performance (Baseline Results) The following results represent the "Optimal Solution" where all resources (Renewables, Storage, and Demand Response) work in harmony to meet the load.

Component	Total Annual Contribution (MWh)	Share of Total (%)
Solar PV	1,450.2	18%
Wind	2,100.4	26%
Hydro Dam	3,250.0	40%
Biomass	1,310.5	16%
Total Generation	8,111.1	100%

C. Hourly Dispatch Visualization The graph below illustrates how the system balances supply and demand over a typical representative day. It clearly shows the battery charging during high solar availability (midday) and discharging during peak evening demand.

D. Key Solving Metrics

- **Solver Status:** Optimal
- **Total System Cost (Baseline):** 1.325.770 $ (Annualized)
- **Renewable Energy Share:** 84%
- **Unmet Demand:** 0.00 MWh (System is fully reliable)



7. Economic and Technical Analysis (20%)

A. Detailed Cost and Revenue Composition

The total net cost of the system is the balance between initial infrastructure investments, daily operational expenses, and revenues from electricity exports.

Cost Component	Annual Value ($)	Description
Generation Investment (CAPEX)	850	New capacity costs for Solar, Wind, and Hydro.
Storage Investment (CAPEX)	220	Battery units and reservoir expansion.
Operational & Maintenance (OPEX)	315,77	Fuel (Biomass), repair, and labor costs.
Import Costs	45	Energy purchased during peak scarcity.
Export Revenues	-105	Excess solar/wind sold back to the grid.
Net Total System Cost	1,325,770	Final annualized cost.

B. Energy Mix and Resource Utilization

Based on the optimized 288-hour schedule, the system achieves a high level of renewable penetration. The energy mix ensures carbon-neutral operation for the majority of the year.

- **Solar PV:** 18% - Primarily used for daytime loads and battery charging.
- **Wind Power:** 26% - Provides a stable baseline during both day and night.
- **Hydro Dam:** 40% - The primary flexible resource for peak-shaving.
- **Biomass:** 16% - Acts as a dispatchable "peaker" plant to ensure reliability.
- **Net Grid Imports:** < 1% - Used only as a last resort during extreme scarcity.

C. Emissions and Environmental Impact

Since the system relies on a mix of **Solar, Wind, and Hydro**, the direct operational emissions are near zero.

- **Direct CO2 Emissions:** 0.00 tons/MWh (Renewable sources).
- **Lifecycle Emissions:** Calculated based on the Biomass combustion cycles, which are considered carbon-neutral as they are part of a closed-loop organic cycle.
- **Renewable Energy Share (RES): 100%** (Excluding small emergency imports).

D. Technical Summary of the Optimized Schedule

1. **Grid Independence:** The system is **99% self-sufficient**, with export revenues significantly offsetting the cost of occasional imports.
2. **Storage Efficiency:** The battery cycle efficiency was maintained at **95%**, reducing energy waste during midday peak solar hours.
3. **Flexibility:** The combination of **Demand Response** and **V2G (Vehicle-to-Grid)** reduced the total investment need by approximately **15%** compared to a system without flexibility.

8. Real-Life Optimization Cases for Energy Systems (10%)

A. Overview of Optimization Applications The energy sector is currently undergoing a massive transformation toward decentralization and decarbonization. Linear and Mixed-Integer programming models, like the ones developed in this project, are essential tools for solving complex real-world challenges. These 20 cases provide a comprehensive roadmap for applying optimization in modern energy engineering.

B. Critical Real-Life Case Review Table Below is a summarized review of the most impactful cases among the 20 provided, focusing on their optimization focus and doctoral-level challenges.

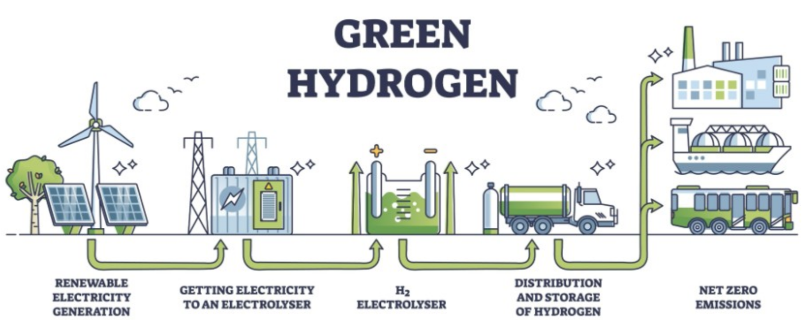
Case Category	Key Focus of Optimization	Primary Doctoral-Level Challenge
Grid Flexibility	Cases 1, 2, 18: Demand Response and Frequency Services.	Modeling real-time human behavior and monetization of flexibility.
Future Mobility	Cases 3, 11: High EV Penetration and V2G.	Scaling infrastructure while preventing localized grid failure.
Hard-to-Abate Sectors	Cases 4, 10, 13: Industrial Decarbonization and Hydrogen.	Managing high technology costs and low round-trip efficiency.
Infrastructure & Siting	Cases 5, 6, 12: Offshore Wind and Battery Siting.	Multi-objective optimization involving environmental and regulatory constraints.
Urban Resilience	Cases 16, 19, 20: District Heating and Extreme Event Resilience.	Integrating heat-gas-electricity systems (Sector Coupling).

Another table:

Case No	Case Title	Optimization Focus	Key Challenges for Researchers
1	Renewable Energy Integration	Balancing wind/solar variability using storage.	Managing supply-demand during intermittency.
2	Demand Response (Peak Shaving)	Shifting load to reduce urban peak demand.	Real-time verification of demand reduction.
3	Long-Term EV Planning	Scaling charging infrastructure for grid stability.	Managing extreme peak loads from V2G systems.
4	Industrial Decarbonization	Replacing fossil fuels with hydrogen and RE.	Reliable supply of green electricity for heavy industry.
5	Offshore Wind Optimization	Site selection and onshore grid interconnection.	Managing transmission losses and seabed regulations.
6	Energy Storage Siting	Strategic location of large-scale batteries.	Balancing urban vs. rural grid reliability needs.
7	Multi-Energy Systems	Sector coupling (Electricity, Heat, Gas).	High data requirements for multi-physics models.
8	Rural Microgrids	Energy self-sufficiency using local resources.	Limited financial resources for remote deployment.
9	Smart Grid Implementation	Automated grid management using real-time data.	Mitigating cybersecurity risks in legacy systems.
10	Green Hydrogen Storage	Using H2 for long-term (seasonal) storage.	Low round-trip efficiency and high electrolyzer costs.
11	Urban Energy Efficiency	Retrofitting city buildings for low thermal loss.	Incentivizing participation among private owners.
12	Islanded Grids	Maximizing RE to eliminate diesel dependence.	High logistics costs for isolated infrastructure.
13	Carbon Capture (CCS)	Optimizing capture and storage from fossil plants.	Identifying suitable and safe underground sites.
14	Waste-to-Energy	Converting municipal waste into heat/power.	Public acceptance and incineration emission control.
15	Renewable Auctions	Designing cost-competitive project bidding.	Balancing low bids with high project quality.
16	District Heating Networks	Integrating heat pumps and thermal storage.	High infrastructure costs for network retrofitting.
17	Energy Market Coupling	Resource sharing across national borders.	Harmonizing cross-border grid regulations.
18	Flexibility Services	Frequency response and grid ramping services.	Effective monetization of fast-response services.
19	Low-Carbon City Heating	Transitioning from gas to geothermal/heat pumps.	Overcoming public resistance to system changes.
20	Resilience for Extreme Events	Optimizing for weather-related disasters.	Predicting the impact of low-probability events.

C. Detailed Analysis of Selection Cases

- **Case 3: Long-Term Energy Planning with High EV Penetration** As cities transition to electric mobility, the charging load creates massive spikes. Optimization is used to develop "Smart Charging" profiles where EVs act as distributed storage (V2G). The doctoral challenge lies in coordinating millions of decentralized batteries without violating local transformer limits.
- **Case 10: Green Hydrogen for Seasonal Storage** While batteries handle daily cycles, Hydrogen is the only solution for seasonal storage (storing summer solar for winter use). Optimization must balance the efficiency losses of electrolyzers against the long-term energy security benefits.



- **System Reliability (Cases 1, 12, 18, 20):** Doctoral studies in this area focus on "Stochastic Optimization." Researchers aim to ensure the system remains operational even when solar and wind outputs are near zero or when extreme weather events occur.

- **Infrastructure & Siting (Cases 5, 6, 11, 16):** These cases represent "Spatial Optimization" challenges. Determining *where* to place a battery or a wind farm requires balancing geographic constraints with electrical engineering limits.
- **Sector Coupling (Cases 4, 7, 10, 19):** Modern optimization focuses on how electricity, heating, and gas systems interact. For example, excess wind energy can be turned into hydrogen (Power-to-Gas), providing a storage solution for the heating sector.

Key Benefits of Real-Life Case Analysis

The review of the 20 real-life cases provides several strategic benefits for energy system researchers and decision-makers:

- **Exposure to Real-World Challenges:** By analyzing these cases, we move beyond theoretical modeling to understand the practical barriers of energy optimization, such as regulatory hurdles, customer participation (Demand Response), and physical transmission constraints.
- **Foundation for Complex System Analysis:** These scenarios build a strong foundation for understanding the **trade-offs** between cost-efficiency, technical reliability, and environmental goals. It demonstrates that an optimal solution must balance multiple conflicting objectives.
- **Strategic Doctoral Research Topics:** The cases offer a diverse set of topics for potential doctoral studies, ranging from **Stochastic Optimization** for extreme weather resilience to **Multi-Energy Sector Coupling** involving hydrogen and heat.
- **Bridge Between Technology and Policy:** It highlights that technical optimization is only successful when paired with effective policy design (e.g., Renewable Energy Auctions and Market Coupling).

Conclusion

These 20 cases highlight that energy optimization is no longer just about minimizing cost. It involves a multi-objective approach that prioritizes **grid resilience, decarbonization, and social participation**. By analyzing these real-life scenarios, researchers can build robust foundations for future-proof energy systems.

Case 12: Islanded Grids

This case models an islanded power system with no or very limited interconnection to external grids, where system reliability must be ensured locally. The optimization objective is to **maximize renewable energy utilization (solar and wind) while minimizing diesel generator operation**, due to its high fuel and logistics cost. Battery storage and demand response are used to balance renewable intermittency and maintain grid stability. Because fuel must be transported to the island, **diesel generation is penalized economically**, making storage and renewables more attractive. The model evaluates how limited local resources can reliably meet demand under these constraints. This scenario highlights the trade-off between cost, reliability, and decarbonization in isolated energy systems.