

Tutorial VIII - Stochastic Energy System Design Problem

Energy System Optimization with Julia

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Stochastic System Design

System Design Problem

The system design problem combines investment planning (sizing) and operational optimization to determine the optimal configuration of an energy system. This integrated approach allows us to:

1. Make optimal investment decisions
2. Account for operational flexibility
3. Balance investment and operational costs
4. Consider system-wide interactions

Note

The system design problem is a two-stage optimization problem:

1. First stage: Investment decisions (sizing)
2. Second stage: Operational decisions (dispatch)

Key Components

Investment Planning (Sizing)

- Component selection
- Capacity sizing
- Technology mix
- Investment costs

Operational Optimization (Dispatch)

- Power generation
- Storage operation
- Grid interaction
- Operational costs

Mathematical Structure

Two-Stage Problem

1. **First Stage (Here-and-Now):**
 - Investment decisions
 - Component sizing
 - Fixed costs
2. **Second Stage (Wait-and-See):**

- Operational decisions
- Power dispatch
- Variable costs

Objective Function

Minimize Investment Costs + Expected Operational Costs

Note

The objective function combines:

1. One-time investment costs (annualized)
2. Expected operational costs over the system lifetime

Solution Approaches

Deterministic Approach

- Single scenario
- Perfect foresight
- Simplified uncertainty handling

Stochastic Approach

- Multiple scenarios
- Probability-weighted costs
- Robust investment decisions

Applications

Energy System Planning

- Microgrid design
- Industrial energy systems
- Residential energy systems

Grid Integration

- Renewable energy integration
- Storage deployment
- Grid capacity planning

Market Participation

- Multi-market optimization
- Price arbitrage
- Ancillary services

Note

The system design problem provides a comprehensive framework for:

1. Optimal investment decisions
2. Efficient system operation

3. Cost-effective energy supply
4. Sustainable energy systems

Stochastic Formulation

The stochastic system design problem extends the deterministic model by considering multiple scenarios. This allows us to:

1. Account for uncertainty in renewable generation
2. Consider different demand patterns
3. Handle price variations
4. Make robust investment decisions

Sets

- \mathcal{T} - Set of time periods indexed by $t \in \{1, 2, \dots, |\mathcal{T}|\}$
- \mathcal{S} - Set of storage systems indexed by $s \in \{1, 2, \dots, |\mathcal{S}|\}$
- \mathcal{W} - Set of wind parks indexed by $w \in \{1, 2, \dots, |\mathcal{W}|\}$
- \mathcal{V} - Set of PV parks indexed by $v \in \{1, 2, \dots, |\mathcal{V}|\}$
- Ω - Set of scenarios indexed by $\omega \in \{1, 2, \dots, |\Omega|\}$

Decision Variables

Investment Variables (First Stage)

- e_s^{nom} - Nominal energy capacity of storage s [MWh]
- $p_s^{ch,nom}$ - Nominal charging power of storage s [MW]
- $p_s^{dis,nom}$ - Nominal discharging power of storage s [MW]
- p_w^{nom} - Nominal power of wind park w [MW]
- p_v^{nom} - Nominal power of PV park v [MW]

Operational Variables (Second Stage)

- $p_{w,t,\omega}$ - Power output of wind park w at time t in scenario ω [MW]
- $p_{v,t,\omega}$ - Power output of PV park v at time t in scenario ω [MW]
- $p_{t,\omega}^{in}$ - Power inflow through market at time t in scenario ω [MW]
- $p_{t,\omega}^{out}$ - Power outflow through market at time t in scenario ω [MW]
- $p_{s,t,\omega}^{ch}$ - Charging power of storage s at time t in scenario ω [MW]
- $p_{s,t,\omega}^{dis}$ - Discharging power of storage s at time t in scenario ω [MW]
- $e_{s,t,\omega}$ - Energy level of storage s at time t in scenario ω [MWh]

Annual Cost Variables

- AC_s^{inv} - Annual investment cost for storage s [EUR/year]
- AC_w^{inv} - Annual investment cost for wind park w [EUR/year]
- AC_v^{inv} - Annual investment cost for PV park v [EUR/year]
- $AC_\omega^{grid,imp}$ - Annual grid electricity import cost in scenario ω [EUR/year]
- $AP_\omega^{grid,exp}$ - Annual grid electricity export revenue in scenario ω [EUR/year]

Parameters

Investment Costs (First Stage)

- C_s^E - Cost per MWh of energy capacity for storage s [EUR/MWh]
- $C_s^{P,ch}$ - Cost per MW of charging power capacity for storage s [EUR/MW]
- $C_s^{P,dis}$ - Cost per MW of discharging power capacity for storage s [EUR/MW]
- C_w^W - Cost per MW of wind park w [EUR/MW]
- C_v^{PV} - Cost per MW of PV park v [EUR/MW]
- F^{PVAF} - Present value annuity factor for investment costs
- B^{max} - Maximum investment budget [EUR]

Operational Parameters (Second Stage)

- η_s^{ch} - Charging efficiency of storage s
- η_s^{dis} - Discharging efficiency of storage s
- sdr_s - Self-discharge rate of storage s per time step
- DoD_s - Depth of discharge limit for storage s [%]
- $f_{w,t,\omega}$ - Wind capacity factor at time t in scenario ω for wind park w
- $f_{v,t,\omega}$ - Solar capacity factor at time t in scenario ω for PV park v
- $d_{t,\omega}$ - Electric demand at time t in scenario ω [MW]
- $c_{t,\omega}^{MP}$ - Grid electricity market price at time t in scenario ω [EUR/MWh]
- $c_{t,\omega}^{TaL}$ - Grid electricity taxes and levies (including Netzentgelt) [EUR/MWh]
- π_ω - Probability of scenario ω

Objective Function

$$\text{Minimize } \sum_{s \in \mathcal{S}} AC_s^{inv} + \sum_{w \in \mathcal{W}} AC_w^{inv} + \sum_{v \in \mathcal{V}} AC_v^{inv} + \sum_{\omega \in \Omega} \pi_\omega (AC_\omega^{grid,imp} - AR_\omega^{grid,exp})$$

Note

The objective function minimizes: 1. First-stage costs (deterministic): - Investment costs for all components 2. Second-stage costs (stochastic): - Expected grid electricity costs/revenues - Weighted by scenario probabilities

Annual Cost Constraints

Investment Costs (First Stage)

$$AC_s^{inv} = \frac{C_s^E}{F^{PVAF}} e_s^{nom} + C_s^{P,ch} p_s^{ch,nom} + C_s^{P,dis} p_s^{dis,nom} \quad \forall s \in \mathcal{S} \quad AC_w^{inv} = \frac{C_w^W}{F^{PVAF}} p_w^{nom} \quad \forall w \in \mathcal{W} \quad AC_v^{inv} = \frac{C_v^{PV}}{F^{PVAF}} p_v^{nom} \quad \forall v \in \mathcal{V}$$

Investment Budget

$$\sum_{s \in \mathcal{S}} (C_s^E e_s^{nom} + C_s^{P,ch} p_s^{ch,nom} + C_s^{P,dis} p_s^{dis,nom}) + \sum_{w \in \mathcal{W}} C_w^W p_w^{nom} + \sum_{v \in \mathcal{V}} C_v^{PV} p_v^{nom} \leq B^{max}$$

Note

The investment budget constraint ensures that: 1. Total investment costs do not exceed the maximum budget 2. Includes all component investments: - Storage systems (energy and power capacity) - Wind parks - PV parks 3. Applies to first-stage decisions only

Grid Electricity Costs (Second Stage)

$$AC_{\omega}^{grid,imp} = \sum_{t \in \mathcal{T}} (c_{t,\omega}^{MP} + c^{TaL}) p_{t,\omega}^{in} \quad \forall \omega \in \Omega \quad AR_{\omega}^{grid,exp} = \sum_{t \in \mathcal{T}} c_{t,\omega}^{MP} p_{t,\omega}^{out} \quad \forall \omega \in \Omega$$

Constraints

Power Balance

$$\sum_{w \in \mathcal{W}} p_{w,t,\omega} + \sum_{v \in \mathcal{V}} p_{v,t,\omega} + (p_{t,\omega}^{in} - p_{t,\omega}^{out}) + \sum_{s \in \mathcal{S}} (p_{s,t,\omega}^{dis} - p_{s,t,\omega}^{ch}) = d_{t,\omega} \quad \forall t \in \mathcal{T}, \omega \in \Omega$$

Component Limits

Wind Parks

$$0 \leq p_{w,t,\omega} \leq f_{w,t,\omega} p_w^{nom} \quad \forall w \in \mathcal{W}, t \in \mathcal{T}, \omega \in \Omega$$

PV Parks

$$0 \leq p_{v,t,\omega} \leq f_{v,t,\omega} p_v^{nom} \quad \forall v \in \mathcal{V}, t \in \mathcal{T}, \omega \in \Omega$$

Storage Systems

$$0 \leq p_{s,t,\omega}^{ch} \leq p_s^{ch,nom} \quad \forall s \in \mathcal{S}, t \in \mathcal{T}, \omega \in \Omega \quad 0 \leq p_{s,t,\omega}^{dis} \leq p_s^{dis,nom} \quad \forall s \in \mathcal{S}, t \in \mathcal{T}, \omega \in \Omega \quad DoD_s e_s^{nom} \leq e_{s,t,\omega} \leq e_s^{nom} \quad \forall s \in \mathcal{S}, t \in \mathcal{T}, \omega \in \Omega$$

Storage Energy Balance

$$e_{s,t,\omega} = (1 - sdr_s) e_{s,t-1,\omega} + \eta_s^{ch} p_{s,t,\omega}^{ch} - \frac{p_{s,t,\omega}^{dis}}{\eta_s^{dis}} \quad \forall s \in \mathcal{S}, t \in \mathcal{T}, \omega \in \Omega$$

Note

The stochastic formulation: 1. First-stage decisions (here-and-now): - Component sizing - Investment costs 2. Second-stage decisions (wait-and-see): - Operational decisions - Scenario-dependent costs 3. Key differences from deterministic model: - Time-dependent parameters become scenario-dependent - Operational variables become scenario-dependent - Objective includes expected costs

Implementation of the Stochastic System Design Problem

1. Load Packages

2. Data Generation

3. Load and Process Data

4. Model Implementation

Now, let's implement the Stochastic System Design model using the dictionary format:

5. Solve and Analyze Results

Let's solve the model with a maximum budget of 50 million EUR:

6. Create Figures

7. Sensitivity Analysis Example

Let's analyze how the optimal solution changes with different maximum budgets:

8. Sensitivity Analysis of the Electricity Price

TASK: Watch for `##YOUR CODE HERE` and implement the missing code.

- Implement a sensitivity analysis of the electricity price.
- Plot the results in a figure.
- Interpret the results and make a recommendation in section 9.

9. Recommendations for Hamburg ChemPark GmbH

TASK: Place your recommendations here: X, Y, Z, W, A, B, C, D, E, F, G.

Based on our analysis, we can provide the following recommendations for Hamburg ChemPark GmbH for the expected case of a price scaled by 200%:

1. **Optimal System Configuration:**
2. **Economic Performance:**
3. **Findings:**

In a comprehensive sensitivity analysis, the following aspects should be considered:

- The solution is most sensitive to [parameter]
- Key uncertainties include [uncertainty]
- Robustness can be improved by [action]

i Note

The model provides a foundation for decision-making, but additional factors should be considered:

1. Site-specific constraints
2. Grid connection capacity
3. Environmental ambitions
4. Maintenance requirements and costs
5. Future expansion possibilities

Solutions

You will likely find solutions to most exercises online. However, I strongly encourage you to work on these exercises independently without searching explicitly for the exact answers to the exercises. Understanding someone else's solution is very different from developing your own. Use the lecture notes and try to solve the exercises on your own. This approach will significantly enhance your learning and problem-solving skills.

Remember, the goal is not just to complete the exercises, but to understand the concepts and improve your programming abilities. If you encounter difficulties, review the lecture materials, experiment with different approaches, and don't hesitate to ask for clarification during class discussions.

Later, you will find the solutions to these exercises online in the associated GitHub repository, but we will also quickly go over them in next week's tutorial. To access the solutions, click on the Github button on the lower right and search for the folder with today's lecture and tutorial. Alternatively, you can ask ChatGPT or Claude to explain them to you. But please remember, the goal is not just to complete the exercises, but to understand the concepts and improve your programming abilities.