Industrial Biorefinery Capacity Expansion & Decarbonization

A Techno-Economic Optimization Benchmark & Modeling Tutorial

Open-Source Energy Systems Modeling Series

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Abstract

This tutorial problem investigates the techno-economic optimization and multi-period capacity planning of biochemical refining infrastructure. Planners face fundamental trade-offs between capital economies of scale and operational carbon liabilities. We define a multi-site system with non-linear power-law capital scaling, plant availability restrictions, discrete sizing options, and regional emission intensities under escalating carbon tax regimes. This benchmark serves as a complete case study for evaluating capital annualization, analytical break-even pricing, and mixed-integer capacity build-up.

1 System Architecture & Baseline Technical Data

We consider the deployment of biorefinery production capacity across three candidate regional sites: **Site A**, **Site B**, and **Site C**. All candidate facilities utilize an identical conversion technology yielding the same standard biochemical product. The regional sites differ in three attributes:

1. The maximum plant size class permitted due to local resource or spatial constraints;
2. The unit variable production cost (reflecting local feedstock logistics and energy inputs);
3. The direct greenhouse gas emission intensity per unit of output.

1.1 Technology & Financing Parameters

Capital expenditure (OCC) scales non-linearly with nominal nameplate capacity S according to the classic power-law relationship:

$$\mathrm{OCC}(S) = \mathrm{OCC}_{\mathrm{ref}} \left(\frac{S}{S_{\mathrm{ref}}} \right)^{b} \tag{1}$$

where $S_{\mathrm{ref}} = 60$ kt/yr, $\mathrm{OCC}_{\mathrm{ref}} = 30$ MEUR, and $b = 0.70$ is the scale exponent. Key technological and financing parameters are summarized in Table 1.

Table 1: Baseline Technological and Financing Parameters

Parameter	Symbol	Value	Unit
Reference Facility Capacity	S_{ref}	60	kt product / year
Overnight Capital Cost (OCC) at Reference	$\mathrm{OCC}_{\mathrm{ref}}$	30	MEUR
Scale Exponent	b	0.70	–
Discount Rate / WACC	r	8.0	%
Economic Operating Lifetime	L	20	years
Plant Annual Availability	a	85.0	%
Annual Fixed Operating & Maintenance	$\mathrm{FOM}_{\%}$	4.0	% of Overnight Capital

1.2 Discrete Admissible Size Classes

Facilities cannot be deployed at arbitrary continuous sizes. Due to standardized industrial equipment modules, facilities must conform strictly to one of three discrete nameplate capacity classes (Table 2). Intermediate capacities are unavailable.

Table 2: Admissible Standardized Plant Size Classes

Size Class	**Nameplate Capacity (S)** [kt/yr]	**Effective Capacity at 85% Availability** [kt/yr]
Small	30.0	25.5
Medium	60.0	51.0
Large	120.0	102.0

1.3 Regional Site Characteristics

Local biomass procurement costs, spatial boundaries, and feedstock transport distances lead to distinct site limits and cost profiles (Table 3).

Table 3: Regional Site Data and Permitted Capacity Limits

Site	**Maximum Permitted Size Class**	**Variable Cost** [EUR/t product]	**Emission Intensity** [t CO_2/t product]
A	Large (120 kt/yr)	90.0	0.70
B	Medium (60 kt/yr)	105.0	0.45
C	Small (30 kt/yr)	128.0	0.20

Operational Rules on Siting & Expansion:

- The maximum size class in Table 3 is a permanent site ceiling. Site A may host Small, Medium, or Large; Site B may host Small or Medium; Site C may host Small only.
- Variable production costs cover feedstock, chemicals, and variable utilities. They are intrinsic site properties and do not change with the size of the plant deployed.

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2 Benchmark Problem Modules

2.1 Module 1: Static Levelized Production Cost at Maximum Permitted Sizing

Assuming each site builds a facility at its maximum permitted size class operating at full availability (85%):

1. Formulate the combined annual fixed charge factor $f = \mathrm{CRF}(r, L) + \mathrm{FOM}_{\%}$.
2. Compute the overnight capital cost (OCC), annualized fixed capital charge, and unit fixed cost in MEUR/Mt ($\equiv$ EUR/t) for all sites.
3. Add variable operating cost to compute the total levelized unit production cost (EUR/t).
4. **Discussion Requirement:** Explain the role of annualization in techno-economic assessment and interpret the economic trade-off between capital scale efficiency ($b = 0.70$) and site variable cost.

2.2 Module 2: Cost Competitiveness Under Carbon Pricing (0 to 300 EUR/t CO_2)

Introduce a carbon penalty $P_{\mathrm{CO_2}} \in [0, 300]$ EUR/t CO_2:

$$\text{Total Unit Cost}_i(P_{\mathrm{CO_2}}) = \text{Base Cost}_i + P_{\mathrm{CO_2}} \cdot I_{\mathrm{CO_2},i} \tag{2}$$

1. Derive the analytical break-even carbon price $P^*_{i,j}$ for each pairwise combination of sites ($A-B$, $B-C$, and $A-C$).

2. Plot the total levelized production cost as a function of carbon price across $0-300$ EUR/t CO_2.
3. **Discussion Requirement:** Identify the least-cost dominance regimes and explain what the crossover thresholds imply regarding technology selection under climate policy.

2.3 Module 3: Multi-Period Dynamic Capacity Expansion & Dispatch (2020–2030)

A centralized regional planner must satisfy aggregate chemical demand over two planning horizons under zero carbon tax (Table 4).

Table 4: Annual Total Product Demand

Planning Horizon Year	**Regional Chemical Demand** [kt product / year]
2020	45.0
2030	110.0

Expansion and Operational Rules:

- **Asset Longevity:** A plant built in 2020 carries forward into 2030 without requiring reconstruction.
- **Mutual Exclusivity:** Each geographic site may host at most one plant at any time.
- **Brownfield Upgrades:** A site may be upgraded to a larger permitted size class in 2030. The expansion pays the incremental overnight capital cost: $\Delta\text{OCC} = \text{OCC}(S_{\text{new}}) - \text{OCC}(S_{\text{old}})$, treated as a separate 2030 capital charge.
- **Economic Dispatch:** Production is allocated freely across all standing plants in each year to minimize variable operational cost, subject to the plant availability capacity limit ($q_i \leq 0.85 \cdot S_i$).

Optimization Deliverables:

1. Formulate and solve the optimization model to identify the least-cost investment schedule.
2. Tabulate all individual investments, incremental capital charges, and active operational years.
3. Report the merit-order production dispatch, annual system capital and variable expenditures, and the average unit production cost (EUR/t) for 2020 and 2030.
4. **Discussion Requirement:** In no more than five lines, explain why a single facility cannot meet 2030 demand, and explain why the average production cost per tonne changes between 2020 and 2030.