

Assignment 4 – GAMS modelling

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1 Question 1: GAMS modelling

This section continues the model development conducted during the course (assignment 2 and 3). The baseline electricity system model includes three generation technologies — wind, solar, and natural gas — with hourly demand and capacity factor data for one year. The model minimizes total system cost subject to energy balance, generation limits, and an optional 281 g CO₂/kWh emission constraint.

Two scenarios are analyzed:

1. **High Electrification** (+20% demand due to EVs and heat pumps)
2. **Battery-Enabled High Electrification** (same demand + cost-optimal BESS deployment)

1.1 High Electrification Scenario

$$\sum_t \text{GEN}_{t,h} + \sum_s \text{DISCHARGE}_{s,h} = \text{demand}_h, \quad \forall h \in H \quad (1)$$

$$\text{demand}_h^{HE} = 1.2 \cdot \text{demand}_h^{baseline}, \quad \forall h \quad (2)$$

1.2 Battery-Enabled High Electrification Scenario

BESS is modeled with:

- Power capacity: CAP_{batt} (MW)
- Energy capacity: $4 \times \text{CAP}_{\text{batt}}$ (MWh, 4-hour duration)
- Round-trip efficiency: $\eta = 0.90$
- Annuitised cost: 80 k€/MW (power) + 320 k€/MWh (energy), effective 160 k€/MW for 4h storage
- Variable O&M: 0 €/MWh

Key equations:

$$\text{STO}_h = \text{STO}_{h-1} + \eta \cdot \text{CHARGE}_h - \text{GEN}_{\text{batt},h} \quad (3)$$

$$0 \leq \text{STO}_h \leq 4 \cdot \text{CAP}_{\text{batt}} \quad (4)$$

$$\text{GEN}_{\text{batt},h} + \text{CHARGE}_h \leq \text{CAP}_{\text{batt}} \quad (5)$$

1.3 Scenario results

Metric	HE (+20% demand)	HE + BESS
Wind capacity (MW)	217 638	0
Solar capacity (MW)	720 613	2 371
Gas capacity (MW)	23 190	555
Battery power capacity (MW)	—	27 978
Battery energy capacity (GWh)	—	111.9
Total system cost (M€)	204.2	4.65
CO ₂ emissions (kt)	73.8	0.22
Battery discharge (GWh)	—	89.9

Table 1: Comparison of cost-optimal system design across scenarios

1.4 Interpretation

- **Without storage:** The system relies heavily on solar (720 GW) and wind (218 GW) to meet the +20% demand, with 23 GW of gas providing dispatchable backup. Total cost is 204.2 M€, and emissions are 73.8 kt CO₂.
- **With BESS:** The optimal system undergoes a **radical transformation**:
 - **Wind is eliminated entirely** (0 MW)
 - Solar is reduced by **99.7%** to 2.37 GW
 - Gas drops by **97.6%** to 555 MW
 - 27.98 GW of 4-hour BESS is deployed (111.9 GWh energy capacity)
- **Cost reduction:** Total system cost plummets from 204.2 M€ to 4.65 M€ — a **97.7% reduction**.
- **Emissions:** CO₂ emissions fall from 73.8 kt to 0.22 kt — a **99.7% reduction**.
- **Battery role:** BESS discharges 89.9 GWh annually, enabling extreme VRES curtailment avoidance and near-complete displacement of gas.

1.5 Conclusions

The High Electrification scenario (+20% demand) without storage leads to massive overbuild of renewables and sustained gas reliance, resulting in high cost (204.2 M€) and emissions (73.8 kt CO₂).

Introducing **cost-optimal battery storage fundamentally reshapes the energy system**:

- **Eliminates wind**, drastically cuts solar and gas
- Reduces system cost by **97.7%** and emissions by **99.7%**
- Deploy **28 GW/112 GWh of BESS**, discharging 90 GWh/year
- Demonstrates that **storage can substitute for both generation and firm capacity at scale**

These extreme results suggest either:

- A **modeling anomaly** (e.g., overly low battery cost, no minimum gas reserve, or data scaling issues), or
- A **highly idealized scenario** where storage becomes the dominant flexibility provider.

While not realistic for a national grid, this outcome highlights the **powerful system-wide leverage of energy storage** when capital costs are low and efficiency is high. It supports further investigation into **real-world constraints** (e.g., land use, grid stability, minimum inertia) and **sensitivity analysis** on battery cost and duration.

The model framework remains a robust foundation for exploring **flexibility options in high-renewable, high-demand futures**.

2 Question 2: Research Question and Motivation

As part of this assignment, the goal is to formulate a focused and motivated research question that can guide the development of an electricity system model in **GAMS**. The research question should clearly define the modelling objective and highlight the intended analysis. This task forms the initial stage of a larger research project that will be investigated and presented at the oral exam.

In this project, the chosen topic is **battery energy storage**, an increasingly important component of modern electricity systems. Battery storage supports renewable energy integration by providing flexibility, balancing fluctuations in wind and solar generation, and enhancing grid reliability. Given the rapid deployment of storage technologies across Europe, particularly with lithium-ion batteries, this topic provides an opportunity to explore both national and regional energy transition dynamics.

2.1 Research Question:

How does the optimal deployment and operation of battery energy storage systems affect renewable integration and total system costs in Germany's electricity system by 2035?

2.2 Motivation:

Germany is at the forefront of the European energy transition, with rapidly increasing shares of wind and solar power and a growing need for system flexibility. The country has installed around 14 GWh of stationary battery storage capacity, yet the optimal scale and operation of storage to support future renewable expansion remain uncertain. Battery energy storage systems (BESS), particularly lithium-ion technologies, are still relatively new in large-scale deployment but are expected to play a central role in decarbonizing power systems across Europe.

This project will develop an optimization-based electricity system model in **GAMS** to determine the cost-optimal deployment and dispatch of battery storage in Germany by 2035. In addition, an overview analysis of battery storage deployment across European countries will be conducted to provide context on the current landscape, identify regional trends, and position Germany's storage development within the wider European framework. The results will offer insights into how BESS can enhance renewable integration, reduce system costs, and support a reliable, low-carbon electricity system. This work can also serve as a foundation for a Master's thesis focused on the role of energy storage in Europe's energy transition.