PHY555 Energy & Environment
Homework - due for Friday, Nov. 7th 2025

This homework can be prepared by groups of max 3 and has to be submitted on Moodle. As much as possible, avoid scanning handwritten copies. Upload only one copy for each group, and make sure all participants names are included in the document content and title.

The use of AI is allowed (but not recommended) for the coding of scripts required to analyse the data. It is forbidden for the production of comments and analysis - the whole point is that you will have to think by yourselves. Any use of AI must be disclaimed explicitly.

1 Numerical analysis

The goal of this exercise is to estimate the storage capacities required to accommodate a share of solar power into the electrical grid.

Data are provided by the French Transmission System Operator (RTE) and are available on the Eco2Mix website, or on the ENTSOE platform. The data file is also available directly in Moodle.

- Power demand is assumed to follow the same profile as the French consumption in 2023. It will be re-scaled to 1 TWh electricity consumption over the year.
- Power supply can be provided by different sources:
  - The solar production is assumed to follow the same hourly profile as the French production in 2024. It will be re-scaled depending on the investigated scenario.
  - Dispatchable power sources (such as gas, nuclear, hydro...) are aggregated as a single source, which can be adjusted to any power up to its installed capacity.
  - Among dispatchable sources, we will consider a storage system which assumed to be perfect (ie the energy stored can be recovered entirely).

Question 1 (to start playing with the data) The load factor is the ratio between the average and installed power. Explain why this quantity can be approximated as the ration of the average and maximal power throughout the year. Estimate the load factor of the solar production.

Question 2: We will first consider an integration strategy relying entirely on the dispatchable source.

- The installed solar capacity is such that x TWh are produced over the year.
- We don't consider storage in this question.

- When the solar power exceeds demand, production is curtailed. When solar power is not sufficient to meet power demand, the difference is supplied by the dispatchable source.

1. Plot the required installed capacity of the dispatchable source (in GW) as a function of the solar production.
2. RTE has published a series of reference scenario in their "Futurs Energétiques 2050" report. Comment on these values.
3. Plot the amount of electricty produced by the dispatchable source and the total amount of electricity produced by the whole system over the year (in TWh) as a function of the solar production.
4. Comment these results.

Question 3: We will now consider a different strategy, where the integration is entirely based on a storage system. This question is thus independent from the previous one.

- The installed solar capacity is such that x TWh are produced over the year.
- The dispatchable sources are used at a constant power, so that the total energy produced by the system (solar + dispatchable) is 1 TWh over the year.
- The power balance is ensured entirely by a storage system, which charges whenever production exceeds demand, and supplies power whenever demand exceeds production.

1. Plot the required installed capacity (in GW) and the load factor of the dispatchable source as a function of the solar production.
2. Plot the total amount of energy provided by and to the storage system throughout the year as a function of the solar production.
3. Plot the required capacity of the storage system (ie the maximal amount of energy that needs to be stored at any given time, in TWh) as a function of the solar production.
4. Comment these results.

Question 4: We now consider an intermediate strategy, in which both the dispatchable source and the storage system are used to integrate the solar production. This question is thus independent from the previous ones.

- The installed solar capacity is such that 0.4 TWh are produced over the year.
- The dispatchable source has an installed capacity of y GW.
- The storage system supplies energy to meet demand when {solar + dispatchable} sources are not sufficient.
- When {solar + dispatchable} exceed demand, the excess power can be used to charge the battery. The charging power is limited to the minimal value such that the battery receives as much energy as it provides throughout the year.

1. What is the minimum dispatchable capacity y_{min} (in GW) below which the system cannot be balanced? What is the maximal dispatchable capacity y_{max} above which the storage system is not required?

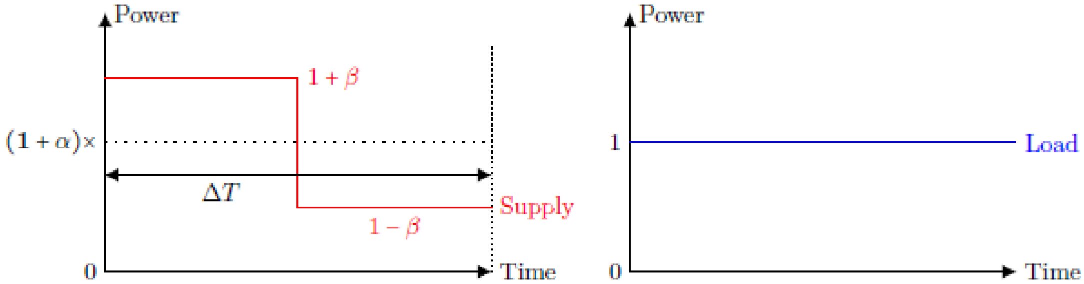
2. Plot the amount of energy produced by the dispatchable source, the required capacity of the storage system and the total amount of energy provided by the storage system over the year as a function of y.
3. Comment your results.

2 Analytical investigation

The analysis is adapted from the work of Arthur Clerjon et Fabien Perdu at CEA. It aims at showcasing that different storage technologies may be relevant for different applications.

Consider that we have a constant power demand P throughout period T (typically, 1 year).

During this period, the power source produces a varying power, with a period ΔT. We note β the amplitude of the variation and α the oversizing of production as compared to demand. These quantities are illustrated over a single cycle below.



We aim at supplying demand at all times through a storage system.

1. Estimate the amount of energy supplied to the storage system over the duration ΔT.
2. Estimate the amount of energy provided by the storage system over the duration ΔT.
3. The efficiency of the storage system is defined as the fraction η which can be recovered from the energy supplied to it. Express the required oversizing of the production α as a function of the efficiency of the storage system.
4. For simplicity, we will consider that the variation of the power source production brings it down to zero. How does this simplify the previous expression? How much energy is produced over the duration ΔT? How much is stored? How much is provided by the storage system?
5. The LCOE for electricity production is γ_e (in €/kWh produced). The cost of the battery γ is related to the amount of energy the battery is able to release in one full discharge. Estimate total cost over the period T.
6. Consider two possible storage technologies with efficiency $\eta_{i,j}$ and cost $\gamma_{i,j}$. Discuss the tradeoff and illustrate it with concrete examples.