Liberalised Power Markets
Bonus Assignment

Introduction

In this project, you will develop and analyse a linear optimisation model inspired by real-world power system applications. The case study builds on models commonly used to assess the impact of increasing renewable generation and to estimate electricity production costs. You are expected to complete the modelling tasks using the methods and concepts covered in the course so far.

The assignment consists of three tasks. In Task 1, you will implement a deterministic baseline model. Task 2 requires you to extend this model with additional constraints and features. In Task 3, you will transform the framework into a stochastic model that captures uncertainty in demand and wind generation profiles. Your goal is to evaluate the results and provide insights based on your model-based analysis. Keep in mind to have your `Data` folder and jupyter file in the same directory.

General Requirements

1. Students can work individually, in pairs, or in groups of up to four people to complete this project. Groups of five or more people will not be accepted. All students must register by entering their student ID in **this Excel file** . Registration is required to participate in the assignment.

2. Students are expected to submit a report (see details in the *Report format* section) **and** the notebook skeleton filled with your code used for the project. The code will be tested for correctness and, therefore, is part of the assessment. The notebook skeleton can be downloaded from the exercise page.

3. **Rename your files according to your student ID before submission.** For example, if your student ID is *abcde*, rename the jupyter notebook and report as *BA-abcde.ipynb* and *BA-abcde.pdf*. If you're working in groups, name them accordingly to *BA-abcde-fghij.ipynb* and *BA-abcde-fghij.pdf*. Follow the same logic in case of three or four-student groups.

4. The deadline for this assignment is **16 February 2026, 11:59 PM** and should be submitted in the Submission folder in the ILIAS course. Work retourned via e-mail or after the deadline will not be accepted.

Project Description

Background

Consider a power system comprising five nodes and five generation technologies: wind, nuclear, coal, combined-cycle gas turbines (CCGT), and open-cycle gas turbines (OCGT). These technologies differ in capacity, generation cost, and fuel source. Wind represents the only renewable technology and is weather-dependent. Nuclear generation emits no greenhouse gases but is treated as non-renewable, while coal and gas-fired units rely on fossil fuels and therefore produce emissions. In this assignment, at least 25% of total electricity generation must come from renewable sources (i.e., wind).

The electricity generated at a given node i can be transferred from/to neighbouring nodes j by means of transmission lines. Electricity can flow in either direction of the line (i.e. from i to j or from j to i) but not in both directions at a given time period (in our case, hour). To model this, we normally use variables that are unconstrained in sign to represent the flow, and an auxiliary set of constraints and variable to capture the absolute value of the flow for taking into account operational costs. For example, let $f_{\ell,h}$ be the flow on line ℓ and period h, $f_\ell^{\max} \geq 0$ the line transmission capacity and $f_{\ell,h}^{\text{abs}} \geq 0$ be an auxiliary variable capturing the value of $|f_{\ell,h}|$. We can constrain the flow considering the line transmission capacity and obtain the value of $|f_{\ell,h}|$ to calculate the correct transmission operational cost by considering the following constraints:

$$-f_\ell^{\max} \leq f_{\ell,h} \leq f_\ell^{\max}, \tag{1}$$

$$f_{\ell,h}^{\text{abs}} \geq f_{\ell,h}, \tag{2}$$

$$f_{\ell,h}^{\text{abs}} \geq -f_{\ell,h}. \tag{3}$$

In theory, (2)–(3) only imply $f_{\ell,h}^{\text{abs}} \geq |f_{\ell,h}|$. However, the variable $f_{\ell,h}^{\text{abs}}$ is only used in the objective function of a minimization problem, with a positive coefficient. It follows that while $f_{\ell,h}^{\text{abs}} > |f_{\ell,h}|$ is feasible, it is not optimal. In an optimal solution $f_{\ell,h}^{\text{abs}} = |f_{\ell,h}|$. The process of introducing such auxiliary variables and constraints is known as *linearization* of the problem (remember that a linear formulation cannot have absolute values)[1].

To model electricity demand, we use multiple demand profiles, each representing a 24-hour representative day. The choice of representative days depends on modelling objectives. Since we aim to evaluate system-wide performance across the year, we select one representative day per season to reflect seasonal variation in demand. This reduces the planning horizon from 8,760 hours (full year) to 96 hours (4×24), significantly improving tractability while retaining seasonal dynamics. Winter is assumed to start on January 1 and last 92 days; the remaining seasons each span 91 days.

Wind availability varies by node and season. The corresponding data is provided in the `Data` folder. All additional model parameters are included in the skeleton code. Plots of seasonal demand and wind availability are also available for reference.

The model simultaneously determines investment decisions (power plant and transmission expansion) and operational decisions (generation and power flows in each hour). Generators may supply local demand or export power to other nodes through the network. Ten transmission line candidates are available to connect the nodes, illustrated in Figure 1. Investment choices influence hourly dispatch, and dispatch outcomes in turn drive capacity investment decisions.

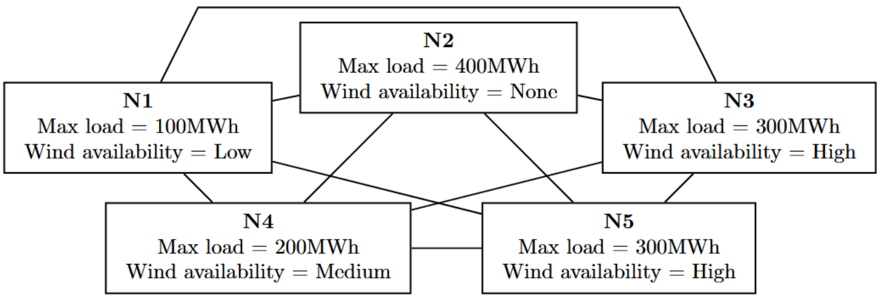

Figure 1: Power network (schematic).

The objective is to obtain the minimal cost for one year of operation given the demand and wind availability for each node. The costs are either due to investments or operating the system.

[1] Similar linearization approaches exist for products of two decision variables where at least one of them is a binary variable.

Investments should be annualised to account for how much is paid per year, given an interest rate and the generation plant/transmission line lifetime.

Task 1: Deterministic model

You are requested to complete the implementation of the deterministic version of the GTEP model. As you will see in the skeleton provided, the required decision variables have already been defined. Your task is to write the objective function and constraints of the model, using the parameters and variables provided in the skeleton code. Pay attention to the comments presented in the skeleton code, as they will serve as guidelines for correctly implementing the model.

The data concerning wind profiles and demand accounts for three different wind/demand profiles for each node and each season. Those three series represent, respectively, the minimum, the maximum, and the mean wind/demand in the node/season. For the deterministic model, the mean values are used to plan the system. Thus, the deterministic GTEP needs to consider only four different demand and wind profiles per node (one for each season).

Once you have implemented the model, provide answers to the following questions:

a) What was the generation capacity per technology per node installed? What was the transmission capacity installed?

b) What is the average fair price for electricity (€/MWh)?

c) Provide any additional analysis you may find insightful to understand the system's behaviour. This can include: capacity utilisation (the energy generated, i.e. dispatch, divided by available capacity), energy profile for the system or per node (i.e. percentage of the energy generated by each technology), trade profile (amount of energy sent to and from each node) and so forth.

Task 2: Modelling extensions

In this task, you are required to implement the following changes to the model implemented in Task 1. Once these changes are implemented, please provide an analysis on how the system changes in terms of the analysis you have made in the previous task.

a) How would the model have to be adapted to consider node-specific minimum renewable energy shares, specifically 45% for nodes 1 and 2, 60% for node 3 and 70% for nodes 4 and 5?

b) In practice, most power plants have technical limitations in how much their output can vary per hour as the generators follow different types of inertia depending on the technology. In other words, the difference between the generation levels of two consecutive hours cannot surpass a given percentage of the installed capacity. This limit is called ramping up or down depending on the variation (upward or downward, respectively).

   Consider that the total output from any technology *except wind* cannot ramp more than 20% (up or down) of the installed capacity each hour. Wind power is much more flexible in terms of production variability and it has no limit for ramping. What is the additional constraint needed in this case? Notice that no additional sets or parameters other than those already defined are necessary.

Task 3: Stochastic model

In this task, you are required to implement the following changes to the model implemented in Task 1, i.e. without the extra constraints from Task 2.

Now, consider that the decision maker wants to use the extra information about the demand and wind availability, considering the min and the max data. For that, you must consider a set of scenarios: a pessimistic, an optimistic, and a mean. The first scenario occurs when the wind availability is the lowest possible, i.e. $W^{\min}$, and the demand is the highest, i.e. $D^{\max}$; the second scenario considers the occurrence of a low demand with a high wind availability. The last one considers that both demand and wind availability follow the mean, i.e. the same scenario considered in the deterministic approach (Task 1).

The probabilities (specialist-defined likelihoods of each scenario) are considered as 25%, 25% and 50%. Once you have implemented this version of the model, provide answers to the following questions:

a) Were there any significant changes in the generation capacity installed per technology per node? What was the transmission capacity installed?

b) Provide an analysis on how the system behaves in terms of the analysis you have made in the previous tasks.

c) How do the investment decisions change if the probability distribution is modified to 60%, 10% and 30% for pessimistic, optimistic and mean scenarios, respectively, i.e. the forecast becomes much more pessimistic about the future availability of wind and demand levels?

Report format

The report must be **10 pages at maximum**, including figures. References are not necessary, but if used, they are not included in the page limit.

The report must consist of the following sections:

1. **Introduction** — Describe the project setting, such as its main tasks and objectives and the computational platform used (operating system, processor specifications). All details that allow for replicating the experiments must be described in this section.

2. **Formulations and discussion** — Create a subsection for each of the Tasks (1)–(3). You are expected to clearly describe the proposed formulation (i.e. objective function and constraints) in each of the tasks. Provide reasoning behind the proposed constraints and use equation references to refer to the expression in your models, if needed. Include your answers to the questions posed in each task in their respective subsections, including any additional analyses you may find pertinent. For example, consider aspects related to how the proposed modifications influence the optimal objective function value and the optimal system configuration. Consider supporting your discussion by making use of plots and tables.

3. **Conclusions** — Provide an overall assessment of the results from each task, comparing the effects of the modifications, and providing an overall reflection on the employment of linear optimisation models to obtain analytical insight about real-world problems. For example, you could provide a reflection on the value and the limitations of the model and your ideas on how it could be further improved to better represent reality.