LINMA 2415 Project
Capacity Expansion Problem

Assignment date: March 28
Due date: May 19

Introduction

In this project, you will solve a capacity expansion problem. Throughout the project, you will consider different variations of the problem by including : renewable energy sources, storage, a CO_2 tax, etc.

The project should be done by group of 2 students. Each group will work on a different country. You can choose the country you work on (on a first come first served basis) by choosing your group in Moodle (if you really want to work on a country which is not in the list on Moodle, send me an email). You are free to propose any other country by adding it in the *Country* column. The results should be presented in a report (either as a classic written report or as a set of slides). Your submission in Moodle should include both your report and your code (including julia and xlsx files used). The deadline for submission is the **19th of May 2023 at 23h59**. The project will count for **5/20** points of the final grade of the course.

Part I — Capacity expansion with thermal power plants

Consider the optimal investment problem for a system facing a demand $\bar{D}_t$ for each hour $t \in T$ where $T = \{1, \ldots, 8760\}$ (one year, hourly data resolution). The data necessary for the problem can be found in Table 1, while the demand data ($\bar{D}_t$) is to be searched for online. The data for most European countries can be found here : `https://open-power-system-data.org` (pick one recent complete historical year, for instance, the year 2019). This demand is price inelastic up to a threshold price of $\bar{\lambda} = 5000$ €/MWh.

Assume that the cost of debt is 3%, the cost of equity 6%, the corporate tax represents 30% and the economic life is 20 years. Take natural gas price at 25€/MWh and coal price at 5 €/MWh. Assume that the variable O&M costs are zero and that capacity factors are 1 for all thermal technologies.

Table 1 – Technologies available to serve the demand.

Ressource	Capex [€/kW]	Fixed O&M [€/kW]	Debt ratio (%)	Heat rate [MWh_i/MWh]
Coal	2000	3% CAPEX/yr	62	2.4
CCGT	950	3% CAPEX/yr	56	1.62
OCGT	700	3% CAPEX/yr	60	2.5

1. From Table 1, compute the equivalent annuity of investment charges.
2. Write the investment problem as an optimization program (use variable k_g to represent investment in technology g and $p_{g,t}$ to represent production of technology g in hour t). Solve the long-term competitive equilibrium as an optimization problem using JuMP.
3. Report, and briefly comment, the optimal results. In particular, you should report : (i) the optimal installed capacity mix, (ii) the share of each technology in the effective production,

(iii) the total production and investment cost of your system, (iv) the total CO_2 emitted by your system (see the CO_2 emission rates of Table 4) and (v) the amount of load curtailment.

4. What can you say about the *dual values of the balance constraints* throughout the year in terms of their economic interpretation ?
5. Pick a technology and compute its Levelized Cost of Electricity (LCOE). Comment on the profitability of this technology.
6. Draw the graph of the production of the different technologies for the different hour of the year. Present this graph as a monotone (**sorted** from highest to lowest).

Part II — Capacity expansion with renewables

Consider renewable energies as wind farms and solar panel which profiles can be found in `https://www.renewables.ninja/`. These profiles (capacity factor) indicate for every hour of the year how much energy (in MWh) you will get if you install 1MW of capacity.

7. It has been shown in the course that if a technology has a higher investment cost and a higher fuel cost than an other one, this technology can be excluded a priori. Can you use this statement in this problem? Justify.
8. Write the new version of investment problem as an optimization model. Solve the new competitive equilibrium (with thermal production and renewables) with JuMP using the data of Table 1 and Table 2 (*Bonus*: *in case the new capacity mix for your country does not include renewable investment with the given data, determine what subsidies would be necessary from public authority in order to have meaningful investment in renewable and obtain the equilibrium in this case*).
9. As in the previous section (use the same indicators to ease the comparison), report and analyse the results. How did it modify the technological mix compare to the first case ? What is the average received price of each renewable assets, how does that compare to the average baseload price ?

Table 2 – Technologies available to serve the demand.

Ressource	Capex [€/kW]	Fixed O&M [€/kW]	Debt ratio (%)	Heat rate [MWh_i/MWh]
Onshore Wind	700	3% CAPEX/yr	70	0
Offshore Wind	1300	3% CAPEX/yr	70	0
PV	400	3% CAPEX/yr	80	0

Part III — Capacity expansion with storage and renewables

Consider that you can invest in the thermal and renewable units considered in the previous questions and also in a **storage technology** with the parameters described in Table 3.

Table 3 – Storage technology available.

	Capex [€/kW]	Fixed O&M [€/kW]	Debt ratio (%)	Efficiency (%)	E/P ratio
Battery	25	6	50	90	4

10. Write the new version of investment problem as an optimization model. Solve this new investment problem with JuMP.
11. As in the previous section (use the same indicators to ease the comparison), report and analyse the results.

Part IV — Effect of a CO_2 tax

In order to reduce CO_2 emissions, the public authority decides to introduce a carbon tax of 30€ per ton of CO_2 emitted [1], representing the negative externality (the "social cost") of carbon emission.

12. How does the CO_2 tax affects your objective function ?
13. As in the previous section (use the same indicators to ease the comparison), report and analyse the results.

The data about the CO_2 emissions of each technology is shown in Table 4.

TABLE 4 – CO_2 emission of the different technologies.

Technology	Tons of CO_2 per MWh
Coal	1.4
CCGT	0.5
OCGT	0.6
Wind	0
Solar	0

Part V — The EU gas crisis

In the context of the Gaz crisis, European countries have experienced a significant increase of gas prices (for example, TTF prices—the Dutch gas hub—reached levels above 300€/MWh in August [2]). Given the installed mix of capacities, those prices led to high *windfall profits* for some infra-marginal technologies [3].

14. Let's assume the gas price is now 100€/MWh instead of 25€/MWh. Keeping the same capacity mix as the one you had in the previous section, compute the profits of each technology and compare them with what they used to be. Compute the consumer surplus as well as the social welfare and compare it to what it used to be.
15. Compute and report the new optimal mix of capacities given this gas price of 100€/MWh. In your opinion, what could be a measure to alleviate those windfall profits ? Briefly discuss it.

Part VI — Capacity expansion with indivisibilities

Starting from the model of Part IV (with renewables, batteries and a CO_2 tax), we add one more subtlety. The different technologies now come in *lumps* of capacity instead of being continuous (see Table 5). Concretely, the investment decision is now discrete instead of being continuous. This reflects the fact that, when investing into power plants, you can choose to invest into one CCGT, two CCGT, etc. but you cannot invest into half a CCGT plant.

16. Adapt your model.
17. Solve it and report the results. Report in particular : (i) the optimal capacity mix and (ii) the final profit of each technology [4]. What do you observe ? What does it mean in terms of the incentives the private investors are facing ? Discuss it.

1. This is the *social cost of carbon* reported by Nordhaus, W. (2014). A question of balance : Weighing the options on global warming policies. Yale University Press.
2. `https://www.theice.com/products/27996665/Dutch-TTF-Gas-Futures/data?marketId=5519350&span=2`
3. In economical terms, "windfall profits" refer to an increase in profits due to some outside event, as opposed to an increase in profits due to production decision.
4. Since the problem is non-convex, computing the prices is less obvious than in the previous questions. You can here assume the following pricing rule : first solve the optimization problem to determine the capacities. Then, fix the (integer) capacity variables to their optimal value and re-solve the (convex) problem to retrieve the prices.

Table 5 – Lumps of capacity (size of the power plant) for the different technologies.

Technology	Size of one plant [MW]
Coal	600
CCGT	500
OCGT	300
Wind	*continuous*
Solar	*continuous*