Electricity System Modelling

Analyzing CO2 Emissions, Storage and Transmission

Project Assignment

Miljö och Matematisk Modellering - MVE347

LP4 2022

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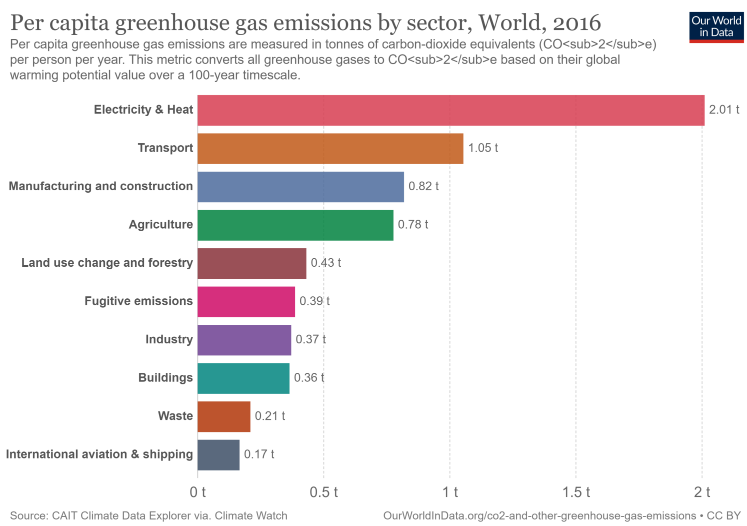
1 Introduction

To limit global warming, we need to limit the carbon dioxide (CO_2) emitted to the atmosphere by human activity. A significant portion of the global CO_2-emissions comes from electricity production (see figure below). Traditionally, electricity has been supplied with fossil-fueled technologies (such as coal and natural gas), nuclear power, and hydropower. So, if we are to meet a CO_2 target, what could replace fossil-fueled technologies? Wind power and solar photovoltaics (PV) are two fast-growing renewable technologies that could be a considerable part of the future electricity system.

An important difference between wind and solar power, on the one hand, and traditional fossil-fueled technologies, on the other, is the possibility of controlling when electricity is produced. This difference is important since, if we turn on our microwave at home, the electricity to run it needs to be produced precisely at the same time as we push the on-button. Alternatively, it has to be available in some kind of electricity storage unit, such as batteries. This is referred to as ***load balance***, i.e., we must produce simultaneously as the electricity is demanded. Coal power plants and gas turbines can be operated flexibly to uphold the load balance, while wind power and solar PV only can produce when the weather allows for it, i.e., when it is windy and when the sun is shining. Therefore wind and solar power are referred to as ***variable*** generation technologies. That said, there are several strategies we can use together with variable renewables to uphold load balance. These strategies could be, for example, batteries (so that we can store electricity from sunny periods to non-sunny periods), transmission lines (so that we can take advantage of when it may be windy somewhere else), flexible generation such as hydro power or gas or biogas turbines, or demand side management (to adapt when we use electricity to when it is produced).

Using investment models is one way to analyze the cost and CO_2 emissions for future electricity systems. In short, an investment model costs minimize the configuration of an energy system (e.g., what technologies to invest in and how to operate them every hour) given some constraints (e.g., maintaining load balance at every hour). In this project assignment, you will build your own investment model using linear programming. You will then use your model to analyze a future electricity system.



1.1 Learning Objectives

After completing this project, you should:

- Know how to apply linear optimization in a simple electricity system model.
- Be able to use an investment model to analyze an electricity system with respect to:
  - The interplay between different generation technologies
  - What happens in the system, and why, when a CO_2 cap is to be met
  - How transmission and storage affects the system with regards to cost and energy mix
- Know what variable renewable energy means, and be able to mention a few options to handle this variability

The energy system project is mandatory in MVE347 and is graded with 0-1 points. 0p corresponds to have passed the project, and bonus points (0.5 or 1) can be obtained for a well-executed project. To be able to get bonus points, the project needs to be submitted on time. No bonus points on re-submissions.

Betygskriterier:

- Godkänt (0 bonuspoäng): Modellen fungerar, och studenterna har genererat rätt figurer och i huvudsak svarat rätt på frågorna för varje uppgift och förstår koden (dvs att de skrivit koden själva). Mindre slarvfel accepteras.
- (+0.5 bonuspoäng): Studenterna förstår i stort hur variationshanteringsstrategier samspelar med olika produktionsteknologier.
- (+0.5 bonuspoäng): Studenterna kan resonera kring vilka begränsningar och parametrar som påverkar kostnaden för systemet.

1.2 Practicalities

You will work in groups of 2 and you choose who you work with. Make sure to sign up to a group number in Canvas. If you have trouble finding someone to work with, send an email to hanna.ek.falth@chalmers.se, and we will group you together. Each group will have 3 supervision occasions (15 min each, see schedule in Canvas). Switch with another group with the same supervisor if the time does not fit and **send us an email if you will not attend**. The examination of the project will be in form of a 15-20 minute seminar with the supervisor, one group at the time. 5-10 minutes of presentation of your results and discussion followed by 5-10 minutes when the supervisor will ask questions and discuss the results with you.

Note that we do not supervise groups (by email or similar) that do not attend the supervision occasions.

Recommended plan for the supervision occasions:

- Do exercise 1 before occasion 1
- Do exercise 2 before occasion 2
- Do exercise 3 and 4 before occasion 3

The purpose with the supervision occasions is for you to ask questions if you are stuck on the exercise, and/or show results to make sure you are on the right track.

2 Assignment

Your task is to model a future electricity system in Sweden, Denmark and Germany using linear programming. The objective function is to minimize the total cost of the system. We assume that nothing from today's system is still in place in 2050, except for hydro power in Sweden. So, the system is built from scratch, i.e. there is no pre-existing capacity in place (except for hydro power in Sweden), but the cost of investment is distributed over the economic life-time of the investments. The cost is constituted of two parts: the annualized investment cost for the chosen technologies (€/MW), and the variable cost when the technologies supply electricity (€/MWh). One whole year will be modelled, and during that year the electricity demand must be met by the supply at each single hour.

You are free to choose programming language for yourself, but note that we will only provide supervision regarding programming/code if you choose **Julia** (see more in Section 3). We will still provide general supervision if you choose another language.

2.1 Model Setup and Data

Some input data is needed in order to be able to depict the system. You find the hourly electricity demand (in MWh) for each region in a file called TimeSeries.csv in Canvas. A number of generation options are available in each country to fulfill the demand. Namely wind power, solar PV and gas turbines (and in some scenarios also batteries, transmission lines and nuclear power). In addition, we assume that the hydro power in place in Sweden today (14 GW) is still in place in 2050. The cost- and technology assumptions for all technologies are displayed in the table below.

	Investment cost [€/kW]	Running cost [€/MWh_elec]	Fuel cost [€/MWh_fuel]	Lifetime [yrs]	Efficiency [-]	Emission factor [ton CO_2/MWh_fuel]	Maximum capacity to invest in [GW]
Wind	1100	0.1	0	25	-	0	SE: 280, DK: 90, DE: 180
PV	600	0.1	0	25	-	0	SE: 75, DK: 60, DE: 460
Gas	550	2	22	30	0.4**	0.202	Inf
Hydro	0	0.1	0	80	-	0	SE:14, DK:0, DE: 0
Batteries	150*	0.1	0	10	0.9***	0	Inf
Transmission	2500	0	0	50	0.98****	0	Inf
Nuclear	7700	4	3.2	50	0.4**	0	Inf

Table 1: * when you invest in 1 kW of batteries, you get a battery with the capacity of 1 kW and the storage size of 1 kWh. Meaning that you can empty the storage in one hour. ** a fuel efficiency in [MWh_elec/MWh_fuel], note that you can still make use of all installed capacity. *** This is the round trip efficiency, meaning that we loose 10% of the stored energy from what we put in to what we get out. Note that you can still make use of all installed capacity. **** This efficiency corresponds to a 2% loss of energy when you transmit electricity from region A to region B.

The installable renewable power capacity is limited in each country. For hydro power there is a limit of suitable rivers, and for solar and wind the suitable land area for installment is limited, with different estimates available. The limits to be used in this exercise can be found in table 1.
The output from solar PV and wind power generators depends on weather patterns. Thus, only a fraction of the installed capacity is producing electricity at a given point in time. For example, during a windy hour you might be able to produce 100% of the installed capacity, whereas the

solar output during night is 0% of installed capacity. The fraction of the installed wind and solar capacity that can be produced (the capacity factor) at every hour in every country is given in the file TimeSeries.csv in Canvas. These time series are based on local weather conditions in each country.

Regarding hydro power in Sweden, we will assume that we can represent all hydro power plants by aggregating them into one big plant with one reservoir and one turbine. The aggregated installed capacity is 14 GW and the aggregated hydro reservoir has a storage size of 33 TWh. The water inflow to the reservoir is spread over the year. You find the inflow profile in the file TimeSeries.csv in Canvas. The inflow profile is given in MWh of inflow for each hour. You need to constrain the reservoir so that you avoid using all the water in the reservoir during the modeled year and a saving nothing for the coming year.

Assume a discount rate (r) of 5%, and the lifetimes (lt) and investment costs (IC) for each technology as in table 1 for the calculation of the annualized investment costs. The annualized cost (AC) can be calculated as:

$$AC = IC * \frac{r}{1 - \frac{1}{(1+r)^{lt}}} \tag{1}$$

2.2 Model Formulation

The objective function of the model should be to minimize the total costs, i.e. the sum of all annualised investment costs, plus the variable costs. Start by formulating:

- The decision variables
- The input parameters
- The constraints

When you have formulated your model, implement it in code (see section 3). Then go through the exercises in Section 2.3, analyze and discuss your results, and answer the questions posted.

2.3 Analysis

You will use the model you build to run a few different scenarios and analyze the results. We recommend you to start with Exercise 1, and disregard batteries and transmission to begin with. Make sure that you have worked with Exercise 1 before the first supervision occasion, so that you can use that occasion to ask questions if you are stuck, or to make sure that you are on the right track. Most of the work lies in getting the first step to work. When you have that working, the next steps will be easier. Do not add nuclear power until Exercise 4.

Calculate the average capacity factors for PV and Wind, for the three different regions. Use this information when you answer and discuss the questions in the exercises.

It is important to note that this model is very simplified, and the assignment is built as a stylized case for you to learn about different mechanisms in a renewable based electricity system. Therefore the takeaway messages lies in general insights about mechanisms and not in exact numbers from model runs.

Exercise 1

To begin with, you should find the cost-optimal electricity system in Germany, Sweden and Denmark without any limit on CO_2 emissions, without any battery storage options and without the possibility to trade between the regions (no transmission). Hint for the hydro power reservoirs: constrain the reservoir content the first hour to be equal to the last hour.

Analyse the system cost and CO_2-emissions for all three countries in total, i.e. make sure to perform the optimisation for all countries simultaneously (this will help for the next exercises). Which technologies emerge? What explains the differences between countries?

Plot the installed capacities and the total annual production per plant in each region, preferably as stacked bars. Also plot the production of the domestic generators together with the load in Germany between hour 147 and 651 (three weeks in January) per plant. Also present the total system cost and the CO_2-emissions.

Exercise 2

(a) Add a CO_2 cap (a limit on how much CO_2 that can be emitted from the three countries jointly) and set it to reduce the total CO_2-emissions by 90% compared to Exercise 1. What happens and why?

(b) After this, add batteries and analyze the results compared to Exercise 1. What is the effect on the total system cost and on the capacity and production mix? Can you explain the differences compared to Exercise 1?

Batteries can store electric energy over time. Assume that the batteries can discharge the full installed capacity, or up to as much as is contained in the storage at each hour. The amount of energy that can be stored in the batteries is limited by the installed capacity, such that 1 MW of batteries can store 1 MWh of energy (this is a simplification, in reality the effect (W) and the energy storage (Wh) are separated). You need to add a constraint (equation) which represents the storage level at each hour. Hint: constrain the first hour to be equal to the last hour (as for the hydro reservoir). Do not forget to add the storage to the supply and demand balance constraint.

Plot the installed capacities (including the batteries) and the total annual production per plant in each region, preferably as stacked bars. Also plot the production of the domestic generators together with the load in Germany between hour 147 and 651 (three weeks in January) per plant. Also present the total system cost and the CO_2-emissions. Compare the total system cost and the CO_2-emissions between Exercise 1 and 2.

Exercise 3

Add the possibility to invest in transmission between the regions, and examine the changes in the electricity system.

Transmission is used to transmit electricity in space, so you need to connect the regions with a transmission grid. There are several ways to model transmission. Here we suggest a simple approach. A connection between two regions can work in both directions, but we suggest to set one line in each direction. Let the model build a double line between each region but set a constraint for both lines to have equal capacity. The costs for the transmission grid therefore need to be halved when you sum up the costs. This way you do not need to handle "negative" transmission values. Do not forget to add the transmission to the supply and demand balance constraint.

Plot the installed capacities and the total annual production per plant in each region, preferably as stacked bars. Also plot the production of the domestic generators together with the load in Germany between hour 147 and 651 (three weeks in January) per plant. Also plot the installed transmission capacities and the transmitted energy between the regions. Compare total system costs with the previous exercises and explain the differences. What is the effect of the transmission on the generation capacities and on the overall cost?

Exercise 4

Add nuclear power as technology as a last step, to see in what way that changes the configuration of your electricity system and the system cost. Present the same plots as in the previous exercises. Answer also the questions below.

- Compare total system costs with the previous exercises and explain the differences.
- Does nuclear power emerge? Which capacities are especially reduced?
- What parameters is this sensitive to?
- What country differences are there and what do they depend on?

2.4 Summary and presentation

Prepare a final 5-10 minute presentation of the project based on the exercises, main results **and your answers to the questions posted under each exercise**. The presentation will be followed by 5-10 minutes of discussion, when the supervisor will ask some questions and discuss with you. Also, before the presentation, read again the learning objectives stated in Section 1.1 and reflect about what you have learned from this project.

3 Programming

You are free to choose programming language for yourself, but note that we will only provide supervision regarding programming/code if you choose **Julia**. We will still provide general supervision if you choose another language. To solve the linear program you build, you will need to use a linear programming solver. There are several different options, both commercial and open source solvers. We recommend you to use Gurobi, which has a free license available for students. You download the software here: Gurobi Download. You need to register first. Note that you should click the box *Academic* when you register. You download the license here: Gurobi licence. After downloading, you will need to add the paths to the software and the licence to your environment variables on you computer.

3.1 Julia + JuMP

If you choose to work in Julia, there is an embedded domain-specific modeling language for mathematical optimization called JuMP. You find the documentation of JuMP here: JuMP, with some helpful resources and examples to get started.

If you do not feel like starting completely from scratch, feel free to use the prepared Julia+JuMP model structure, where you can also find some minor helpful code snippets.

3.2 Python + Pyomo

For Python, there is an optimization modelling language called Pyomo, with documentation and helpful resources and examples to get started.

Feel free to use the prepared Python+Pyomo model structure, where you can also find some minor helpful code snippets.