Course Project: building an electricity generation mix

Objective

The objective of this exercise is to build a mix of generation of electricity for an imaginary country. Each group will have a particular set of data regarding the size of the imaginary country, the population, latitude and longitude and other constrains. According to these constrains you will have to build the generation mix and see the evolution during 1 year. There will be an investment that you will need to distribute wisely among solar wind and nuclear technologies.

The final goal is to calculate the evolution of the power provided by each technology for every hour during one year and also to calculate the share in energy for the total time studied.

Global warming is a major concern in the definition of new electricity mixes; one of the objectives is to minimize CO2 emissions. In addition, we will consider that the country does not possess any resources of natural gas and thus we want to minimize the use of this technology as much as possible. Therefore, your goal will be to find the best distribution of investment that will minimize the use of natural gas as an electricity source.

Data

The following data will be different for each group:

- Surface of the country.
- Population.
- Longitude and latitude (just a single location).

The following data will be the same for all groups (details are provided in Table 1):

- Demand per capita during a time period of 1 year.
- Nuclear power per capita.
- Hydroelectric power (run-of-the-river) per square km.
- Hydroelectric storage dam per square km.
- Each storage dam will have the same conditions as in the exercise in class.
- Investment for wind, solar or nuclear power per capita [€/person].
- See the attachment for the characteristics of the solar panel.
- See the attachment for the characteristics of the wind mills.
- The volume of water available for storage is a function of the surface of the country.
- The initial storage available is 50%.

Constrains and assumption:

- The mix will be composed of:
    - Nuclear power
    - Hydro power (storage plus run-of-the-river)
    - Solar PV
    - Wind power
    - Thermal combined cycle power
- Nuclear and Hydro (Run-of-the-river) will work as they typically do.

- Solar and wind power will depend on irradiation and wind data (downloaded from NASA).
- When possible, electricity will be used to pump water to the hydro storage dam
- If need be, water from the storage will be used to cover electricity needs
- If need be, you will need to install a thermal combined cycle power plant.
- We will assume that the Thermal combined cycle plant will be fictitious and that it can be started and stopped at any time and with any power rate. This assumption is included to simplify the exercise; however, you can decide to eliminate this or part of this assumption (for instance set a minimum power).
- We live in a global world where exports and imports of electricity are very common and important. However, in order to simplify, we will consider an isolated system where imports and exports are not allowed.

- **Table 1 Details of the parameters common for all groups. Some of the values have been estimated from ref. [1]**

Parameter	value
Nuclear power per capita	0.15 kW
Hydro power (run-of-the-river) per km2	20 kW
Investment per capita	2000 €
Cost per mill (max power 5MW)	6.5 million €
Cost per solar panel (550W)	600€
Cost of nuclear SMR (100 MW)	500 million €
Volume storage (number of dams)	1 each 10000 km2

Guide and recommendations

In order to solve all the constraints and the data for each hour you will have to program the solution. I believe you can do that using Microsoft Excel, but it could be wiser to use a programming language (python, matlab, C++, Fortran, etc). In preparing my solution, I used Python (this means I can validate your solutions).

This is a team exercise and therefore each of you need to participate in all levels of the exercise, however it is also true that some tasks must be distributed. When setting up the team, you will need a person with programming skills, a person who can understand the implementation of the constrains, a person that can define how is the power calculated for each technology and a person that can describe and understand the results.

Assignment:

Delivery of a report which describes the work. The report needs to contain answers for the following points but not necessarily in this order or directly answering the questions:

1) Description of your team: organization and tasks.
2) Plot of the generation of electricity as a function of time as a stackpile plot for different periods of the year. (a 1 week example is shown in Figure 1)
3) Plot of the final generation mix as a pie chart. (an example is shown in Figure 2)
4) Plot of the evolution of the volume of water in hydro storage dams.
5) Additional plots you might find interesting.
6) What are the load factor and the installed capacity of Combined cycle power plants?

7) What is the share of wind, solar PV, and solar thermal investment (in percentage)? Try to minimize Gas imports and thus CO_2 emissions)
8) What are the emissions of CO_2 per kwh generated? (assign general values for each technology, check out https://app.electricitymaps.com/map
9) Were the wind mills or solar panels disconnected (production above demand)? If yes, how much electricity was spared?
10) Evaluation of the resulting generation mix including a description of the strong and weak points.
11) Finally, you can calculate sensitivities with variation of some of the parameters or constraints that will allow you to add some conclusions to the report. For instance, you can check what happens **if you increase the investment per capita or use different solar panels..**. Be creative.

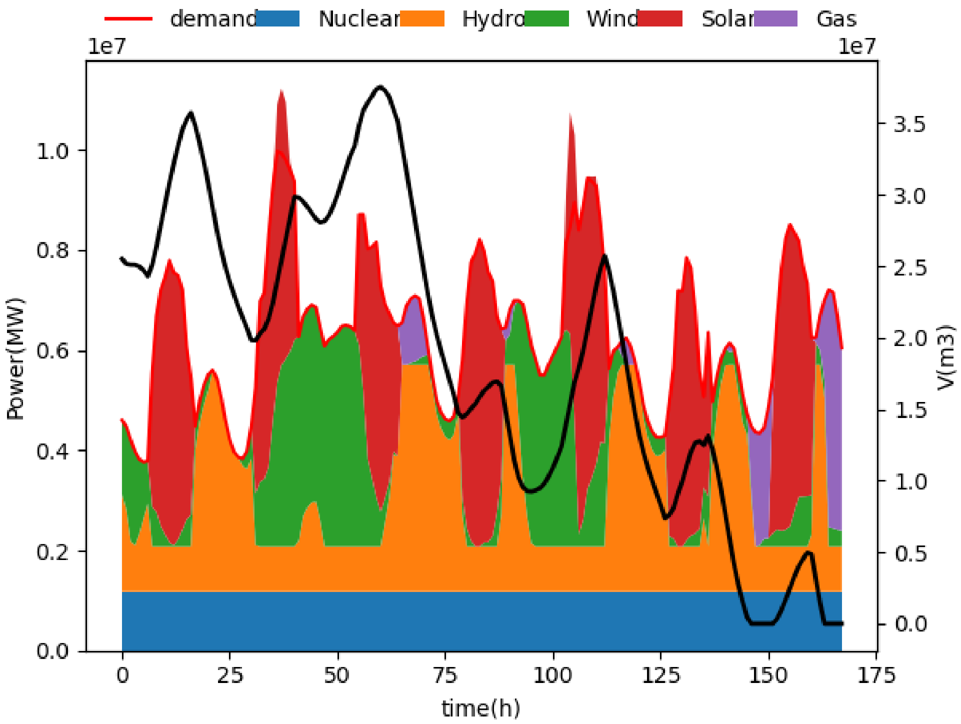

Figure 1 Evolution of the electricity generation divided by sources. The red line represents the demand. The Black line represents the volume of the hydro storage dams.

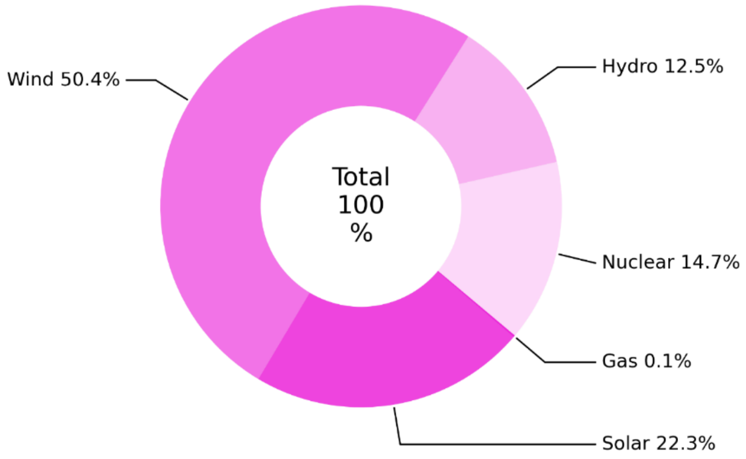

Figure 2 Electricity generation mix

Annex I: Group specific data

Group	city	latitude	longitude	Population (in milions)	Area (km^2)
1	Alexandria	031d14N	029d89E	14.456	43379
2	Athens	037d79N	023d88E	12.314	25246
3	Austin	030d44N	097d72W	7.229	14601
4	Barcelona	041d38N	002d18E	10.191	30102
5	Brighton	050d81N	000d13W	14.691	19161
6	Cancun	021d10N	086d75W	5.016	32530
7	Kyoto	034d99N	135d84E	7.848	44889
8	Malaga	036d75N	004d40W	12.561	29908
9	MardelPlata	038d03S	057d55W	5.007	78195
10	Milano	045d46N	009d18E	11.769	61936
11	Munich	048d13N	011d57E	9.845	32598
12	Nantes	047d21N	001d55W	8.501	43089
13	Oporto	041d14N	008d59W	13.125	52001
14	Orlando	028d56N	081d29W	11.369	56234
15	Santander	043d45N	003d83W	8.265	33589
16	Tenerife	028d45N	016d38W	7.154	18265
17	Washington	038d81N	076d91W	13.258	95568
18	Lima	012d08S	077d02W	9.689	13958

Annex II: Downloading data

- Go to https://power.larc.nasa.gov/data-access-viewer/ and select:
    1. renewable energy
    2. hourly
    3. location
    4. from 1/01/2020 to 31/12/2020
    5. csv (or other format)
    6. All sky shortwave surface downward, Integrated solar zenith angle and wind speed at 50 meters.
    7. Submit and get csv file

Annex III: Wind power details

The wind mill design that you are going to install has the following design features:

G132-5.0 MW https://en.wind-turbine-models.com/turbines/768-gamesa-g132-5.0mw

- We will consider a hub height of 140 m.
- From the link above extract the data of the power curve in order to calculate the power as a function of the wind speed.

The wind data is not very realistic because it was taken in a location almost randomly close to a city (in general they are near the sea that makes it a bit better). In addition, the data is taken at 50 m and the hub is at 140 m. We can roughly estimate the wind speed at 140 m by using the roughness profile and considering **a roughness class of 4**:

$$v_2 = v_1 \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)}$$

Where v_1 is the speed at elevation h_1 (50 meters in your case) and v_2 speed at h_2. Finally, z_0 is the roughness length that depends on the roughness class. For a roughness class of 4, $z_0$is 1.6 m. You can find more details in the following link:

https://wind-data.ch/tools/profile.php?h=50&v=10&z0=1.6&abfrage=Refresh

- You don't need to use the tool but just estimate the single multiplier that will increase all your wind speeds
- For the location of **Lima**, use an increase value of 1.7, otherwise wind is not competitive

Annex IV: Solar panel details

- Panels will follow the sun orientation with 2 axis rotation.
- Efficiency of the inverter: 96%
- Complete Landscape shadow at 10 degrees.
- PV panels, see attachment for specifications

You can calculate the efficiency of the panel when working at the nominal operating Cell temperature (NOCT).

Annex V: Hydro storage power plant

This is a pumped-storage plant, with one upper and one lower reservoir. Water is supplied to the hydraulic machine (used as a turbine) during peak-hours (high electric demand) and is pumped during off-peak hours (minimum demand).

Important characteristics of the reservoirs:

- Upper reservoir capacity: 13 Hm^3
- Lower reservoir capacity: 22.8 Hm^3 (not really needed)
- Average head: H=762.5 m

- Power plant equipped with 3 groups of turbopumps: Each group works as a turbine/generator when generating electricity and as an electricity consumer motor/pump for pumping water into the upper reservoir.
  - Turbine: 201.9 MW (67.3 MW per group)
  - Pump: 226.95 MW (75.65 MW per group)
  - Turbine: 30 m^3/s (10 m^3/s per group)
  - Pump: 26 m^3/s (8.67 m^3/s per group)

Annex V: Optimization

This annex will be useful for those who want to apply an algorithm to find the best solution. We have a minimization problem. We want to find the best combination of:

- Number of new SMR (nuclear reactors)
- Number of Wind turbines
- Number of solar panels

That will provide the minimum use of natural gas through the year. You need to build a function f that provides you the simulation of the whole year hour by hour and the final result is the sum of the production with natural gas for each hour, so:

$$f(N_{SMR}, N_{wind}, N_{panels}) = \sum Gas(h)$$

Notice that each input parameter has bounds, the minimum is 0 and the maximum can be calculated from the total investment.

In addition, we need to make sure that:

$$N_{SMR} \cdot Cost_{SMR} + N_{wind} \cdot cost_{wind} + N_{panel} \cdot cost_{panel} = Total\ investment$$

This means that we have 3 variables and an equality constraint to fulfil. This can be converted to a problem with two variables and an inequality constraint as:

$$N_{SMR} \cdot Cost_{SMR} + N_{wind} \cdot cost_{wind} < Total\ investment$$

All of this is important because only some optimization algorithms allow the use of constraints. In addition, the input variables are integers which in general are not accepted in many solvers. And, what more, the type of function has nonlinear variations with the input parameters. There are work arounds for each of these problems but after playing with different tools and optimizers I concluded that the best solution is to use a Bayesian Gaussian process approach. This approach explores the variable space and works on the Bayesian probability theorem to find the best solution. The package I used was (in Python) Scikit-optimize

https://scikit-optimize.github.io/stable/index.html

This was actually easier to use than the other approaches I tried (many solvers in Scipy and PuLP). So I recommend to use this solver or other Bayesian Gaussian process for this particular problem.

Below I show you a snippet of the code I used that can be a good guide to write your own method. The hard work is to put everything in a function that returns the total electricity produced from Gas sources (in my case it is called calc3).

```
from skopt import gp_minimize
from skopt.plots import plot_convergence

best = gp_minimize(calc3,                          # function to minimize
                  [(0, max_smr),(0, max_mills)],# bounds on each dimension of x
                  acq_func="EI",                # acquisition function
                  n_calls=110,                  # number of evaluations of f
                  n_random_starts=100,          # number of random
initialization points
                  x0=x0,                        # initial values
                  random_state=1234)            # the random seed
plot_convergence(best)
plt.savefig('convergence.png', bbox_inches="tight", pad_inches=0)
```

References

1. I. E. AGENCY, “Projected Costs of Generating Electricity” (2020).