Optimal power mix

Practicals

Each student will write a report including the description of the computation done and the analysis of the results obtained. Scripts (or excel sheets) that allowed obtaining the results will be joined as well as the log of their output. The report will be in PDF and will include the graphics. The whole package will be zipped into a file named '*LAST_NAME_first_name.zip*' and sent by email to nicolas.omont at m4x.org within three weeks after the last session, end of week. Warning: do not include any executable file (.exe) in your archive as the entire email will be dropped by email servers. One different report per person is expected.

A. Installation

- It is assumed that you already have a working AMPL and Knitro installation, including a directory in which you can run successfully "ampl testproblem.mod".
- ~~Extract the archive PSL_master_power_exchanges_practicals.zip in this directory~~
- Open a command box (a terminal), go to the directory and run the following command:

  `ampl technology_mix.run`

  Some results will print out. To log them into the file `log.txt`, you can type "`ampl technology_mix.run > log.txt`". Some .txt files will be produced. You can then import them into Excel.

- Install a good text editor, like notepad++ in order to edit `.mod`, `.dat` and `.run` files.
- Do not forget that:
  - Knitro is a numerical optimizer. Its usual relative precision is around 1E-6.
  - Knitro is a mathematical solver. It is meaningless to apply moral judgments on its results; however you are encouraged to understand the link between the hypothesis and the results.

B. Finding the optimal power mix

a. Introduction

Let's imagine an isolated country sharing some characteristics with France in 2015 and 2016: same consumption, same run-of-the-river, wind and PV generation profiles, similar hydro reservoir potential, and some differences: no possibility to build interconnections to other countries, long-term marginal costs equal to those of the "IEA 2015 median case". What would have been the optimal power mix for these 2 years, i.e. the one leading to the lowest costs / the maximum social welfare? These practicals aim at answering this question in order to illustrate pedagogically the theory, not to give real hints about what should be done in this virtual country. Indeed many factors are not taken into account (uncertainties, for example).

b. Data

The file `French_power_system_2015-2016.xlsx` contains time series of the French power system for 2015-2016, especially the half-hourly consumption (MW) and the hourly wind, PV, and run-of-the-river generation (MW). An hourly extraction has been done and converted to AMPL format. It can be found in `technology_mix_chronicles.dat`.

The file `technology_mix.dat` contains a basic set of structural data like the long-term marginal costs.

The file `lcoe-ltmc.xlsx` contains the long term margin costs extracted from the "IEA 2015 median set", i.e. for each technology:

- Its capacity cost ("fixed cost") in €/MW.year, equal to the amount of money saved by not installing and keep able to run the technology.
- Its energy cost ("variable cost") in €/MWh, equal to the amount of money saved by not producing one MWh of energy with the technology.

c. Model

Assuming that the demand is fully served, the objective is to minimize the generation cost. In mathematical term, the problem to be solved is therefore:

Minimize { sum over all [technologies t] of [
#years * fixed_cost(t) * *capacity(t)*
+ sum over all [periods p] of [variable_cost(t,p) * *generation(t,p)*]
]

On the variables *capacity(t)* and *generation(t,p)* (i.e. adjust the value of these variables in order to minimize the cost objective)

With the following constraints:
- Capacity constraints for all technologies t (generation is bounded by capacity):
generation(t,p) < capacity(t)

- Balancing constraint for all periods p (The consumption should always be equal to the generation)
sum over all [technologies t] of [generation(t,p)] = demand(t,p)

Where:
- *capacity(t)* is the capacity in MW of technology t
- *generation(t,p)* is the generation in MWh of technology t at period p
- fixed_cost(t) is the fixed cost of technology t in €/MW.year
- variable_cost(t) is the variable cost of technology t in €/MWh
- demand(t,p) is the demand at period p in €/MWh

Look at the file `technology_mix.mod`. It describes this optimization model: the objective, found on the line starting with `minimize` is to satisfy the demand at the lowest cost. In addition, the model takes into account the possibility to model several countries with exchange capacities between them, the possibility to model hydro reservoir generation and the ability to take into account non-constant generation profiles.

<u>Focus on dual variables</u>

In mathematical optimization, the general form of the problem is:

Minimize f(x) under the constraints $g_i(x) \leq a$ and $h_j(x)=b$ (*i* and *j* are the constraint indices)

The dual variable of the constraint *i* is the derivative of the optimal value of the objective with respect to the value of the right hand side *a*. For an inequality, it can only be positive. For an equality, it can be positive or negative.

For example, for the balancing constraint of period *p*, the dual variable corresponds to the decrease of the costs that would occur if it was possible to "loosen" the constraint of 1 MWh (to produce 1 MWh less than what is needed). Therefore, it is also equal to the marginal cost of the most expensive running technology and can be used as a price, more precisely, <u>the</u> price according to the neoclassical theory.

a. Script

Look at the file `technology_mix.run`. It describes the following process:

- Load the model
- Load the data files
- Solve the problem
- Display some results

b. Questions

Coal only

1- *Run it with the command* `ampl technology_mix.run` *and try to understand the output: describe the mix in few lines.*

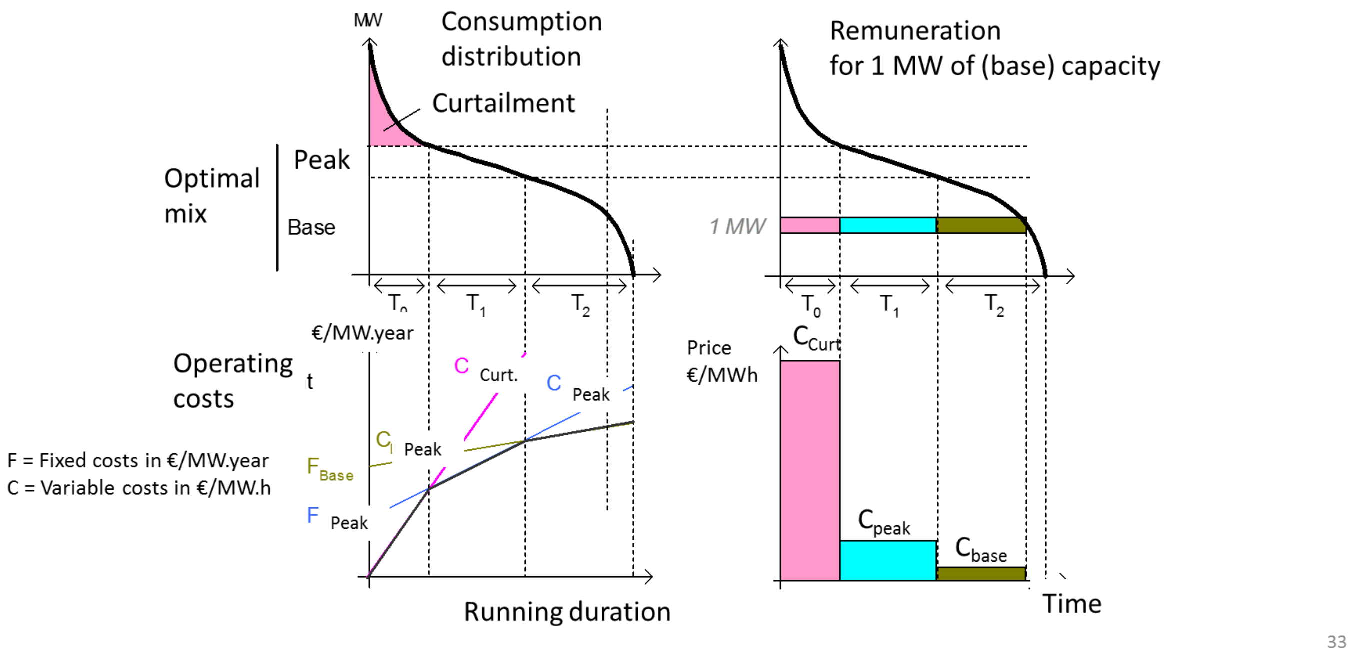
Now, you are ready to modify the data (`technology_mix.dat`), the model (`technology_mix.mod`) and the script (`technology_mix.run`):

Nuclear, Coal, CCGT, OCGT

Uncomment the 'CCGT', 'OCGT' and 'Nucl' lines in technology_mix.dat. They are filled with the costs from the "IEA 2015 median case" and run again the program.

<u>Mix</u>

2- *Check that the total cost has decreased. What happened to coal? Why? (Answer by computing the number of running hours for which coal and gas and other interesting couples of technologies have equivalent average costs. The computation can be illustrated graphically by plotting the cost of installing 1 MW of each technology and using it H hours during the year, i.e. "Cost per MW = function of the number of hour of use", as depicted on the plot shown below in the lower left quarter. To plot this graphics, you need only the data of* `lcoe-ltmc.xlsx` *and no data from the simulations).*



3- *How much capacity of nuclear power is developed? Which proportion of the total capacity does it represent? How much energy is produced by nuclear power? Which proportion of the total energy does it represent? (Answer by plotting and commenting pies of the generation mix in TWh/year and in %, called "capacity mix pies" in the following questions).*

<u>Price</u>

Remember that the dual variable of the balancing constraint (`energyCtr` in the .mod) is equal to the marginal cost of the most expensive running unit and can therefore be used as a price.

4- *Compute consumption as the sum of generation from the data in* `output_generation_schedule.txt`*. Open* `output_price.txt` *and copy/paste the prices in another column. Sort consumption in decreasing order and plot on the same graph the consumption and the price (with a different scale for prices and consumption, in Excel). What do you observe, in particular for the first hour (Be careful because excel may import badly this peculiar line)? Can you explain the relationship (except for the first hour)?*

5- *Let us assume that each generation units sells its power at the price. Find in 'output_technology_results.txt' the revenues, costs and benefits (Their computation is already implemented in the .run). What do you observe? Why? Does it help you to explain the price of the first hour?*

6- *Compare the average cost of energy per MWh and the average price paid by a consumer with a demand profile proportional to the total demand (Their computation is already implemented in the .run).*

7- *How does the LCOE of each technology compare with the average price paid by a consumer with a demand profile proportional to the total demand? Compute the average price paid by a customer with a flat profile. (What does that mean if the LCOE for a technology is higher than the average price paid by an average consumer? How to understand the difference between the average price paid by an average consumer and the average price paid by a consumer with a flat demand?)*

8- *Compare the LCOE of each technology with the ones from the "IEA 2015 median case" found in the excel sheet. Why are they different?*

CO2 price variant

9- *Set the CO2 price to 0 USD/tonne in "lcoe-ltmc.xslx", input the new costs in the .dat and execute the .run script. Plot the capacity pies. What do you observe? Why?*

Do not forget to revert to the original costs before continuing.

Nuclear, Coal, CCGT, OCGT and curtailment.

Customers are not ready to pay whatever price for energy: above a given price level, they are curtailed because they do not want to pay more. Therefore the first hour price is unrealistic. As it is not easy to determine the curtailment price ("the value of lost load"), the French law sets the expected level of curtailment at 3 hours per year. To model this, let use a trick: to model the curtailment as a new "technology" to "satisfy" the demand. It has no fixed cost and only a variable cost equal to the value of lost load. It will be called "`Curtailment`". You can add it by uncommenting the corresponding line in the .dat file.

10- *By trial and error, set this variable cost so that the number of curtailed hours per year is 3.*
11- *The current technical roof at the French power exchange is 3000 €/MWh (i.e. if the price it set at the roof, some consumers are not served and all served consumers pay 3000 €/MWh). How many hours of curtailment will there be with such a value of lost load?*
12- *Assuming that enough capacity is installed so that the 3 hours of curtailment criterion is satisfied, what is the consequence on the benefit of each technology if a price cap is put at only 3000 €/MWh? (i.e. if the prices are set according to the value of the dual variable except if its value is higher than 3000 €/MWh in which case it is 3000 €/MWh. This computation has to be done in excel from the results obtained with the value of lost load resulting in curtailments during 3 hours per year).*

Nuclear, Coal, CCGT, OCGT, curtailment, run-of-the-river hydro

Practically, one important element of a mix is missing: hydro power. It can be modeled in two parts: run-of-the-river hydro and hydro reservoir generation. Let us first introduce run-of-the-river hydro.

- Uncomment the 'HydroRiver' line in technology_mix.dat. It contains costs from the IRENA study as indicated in lcoe-ltmc.xlsx.
- Run-of-the-water output is not dispatchable to full capacity: the capacity factor is dictated by the seasonal river flow. Therefore, an extension to the model is done: the capacity constraint (generation is bounded by capacity) is modified:

  *generation(t,p) < capacity(t) * availabilityFactor(t,p)*

  The availability factor is between 0 and 1. The load factor is set up accordingly to the historical values observed in 2015 and 2016 in France. This is done by uncommenting the line containing "`availabilityFactor["FR",t,"HydroRiver"]`" in technology_mix.run.

13- *Run the script. The mix is not modified: no run-of-the-river is introduced. Why? Under which run-of-the-river fixed cost would this technology appear in this context (Compute it in an excel sheet)?*

14- *Change the fixed cost in the .dat file and check that your hypothesis is correct. Plot the new capacity mix pies.*

It is not realistic that run-of-the-river hydro takes a large share of a country's mix because it is usually limited by the possibilities to install dams. Therefore, one has to limit its capacity. It is set up to the maximum observed value in French data by uncommenting the line containing `maxCapacity["FR","HydroRiver"]` in technology_mix.run.

15- *Run the script and plot the new capacity mix pies.*
16- *What has substituted and why?*
17- *Compare the hourly prices with the one obtained with the (Nuclear, Coal, CCGT, OCGT, curtailment) mix. Can you explain what you observe? Instead of sorting the hours by decreasing consumption, try to sort them by decreasing (consumption - HydroRiver generation).*

Nuclear, Coal, CCGT, OCGT, curtailment, run-of-the-river hydro, hydro reservoirs

Let us now consider hydro reservoir generation. It will be modelled very crudely as a fixed amount of energy which is available at the beginning and can be used at any time to satisfy the demand (In practice, only a fraction of the reservoirs are managed on a yearly basis and the water inflow and the demand is not known in advance).

- First, its fixed costs are set to 0 and, as for run-of-the-river hydro, the maximum available capacity will be set. Indeed, we are not interested in whether to build new reservoirs or to close some of them. Then, the amount of energy is chosen according the produced energy in 2015-2016 in France.
- This is done by uncommenting the 3 'HydroReservoir' in the .dat file. As for run-of-the-river, the capacity is set up according to the maximum observed value in 2015-2016 data.

18- *Run the script and plot the new capacity mix pies.*
19- *What has substituted and why?*
20- *Compare the hourly prices with the one obtained with the (Nuclear, Coal, CCGT, OCGT, curtailment, run of the river) mix. The dual variable of the hydro energy storage constraint (`storageCtr`) can be interpreted as the "value of water", that is how much would be saved with one more MWh of hydro energy. Is the observed substitution between technologies consistent with the value of water (Check that the hydro reservoir generation is used if and only if the price is above the "value of water")?*
21- *Compare the average cost of energy per MWh and the average price paid by a consumer with a demand profile proportional to the total demand. What has changed with the introduction of hydro technologies? Why?*

Nuclear, Coal, CCGT, OCGT, curtailment, run-of-the-river hydro, hydro reservoirs, PV and wind

As run-of-the-river hydro technology, PV and wind are not dispatchable. Therefore, they will be modelled with a load factor profile, however no maximum capacity will be set. In order to allow to study investments in these technologies:

- Uncomment the '`WindOnshore`' and the '`PVlarge`' lines in the .dat file to set the costs according to the IEA study.
- Uncomment the "`availabilityFactor["FR",t,"WindOnshore"]`" and "`availabilityFactor["FR",t,"PVLarge"]`" lines in the .run to set the generation profile according the French historical data for 2015-2016.

22- *Execute the .run script. Plot the capacity pies. What do you observe?*

23- *How much subsides (in €/MW.year) is needed to see wind generation introduced in the mix (i.e. to obtain between 1 and 10 GW of wind generation installed)?*

24- *Display and comment this final mix (with wind):*

   a. *Capacity pie*
   b. *Prices and (demand-HydroRiver generation-Wind generation-PV generation) sorted in decreasing order*
   c. *Generation schedule for a low demand week (nuclear should be marginal part of the time)*
   d. *Generation schedule for a high demand week (with some curtailment).*