Assignment 5 – Domestic Production and Imports of Hydrogen

Due Friday, 17 March 2022, 23:00 [100 points]

Instructions and Rules

- Submission on ISIS requires two-factor authentication.
- Justified exceptions may be granted. Contact f.neumann@tu-berlin.de.
- Submission must include both written answers and code that shows how answers were obtained. All submitted material will be factored in for the grading.
  - **Option A**: combined answers and code in `.ipynb` file + `.html` export of notebook
  - **Option B**: `.pdf` with written answers (incl. figures) + `.py`/`.ipynb` with code and comments
- Submissions must be your own work, plagiarism from the web or your peers will be sanctioned!
- Always clearly mark which task and subtask you are working on.
- Always provide units for quantities (e.g. energy, power, emissions).
- All plots must have axis labels with units if applicable.
- It must be possible to run submitted code without manually setting variables or executing code cells multiple times to retrieve all results (exception: local file paths)!
- You may use additional Python packages as long as they are available via `pip` or `conda`.

Task 1: Domestic Hydrogen Production [70 points]

Required Tools: `pypsa`, `pandas`

The European Commission's REPowerEU plan "[set] a target of 10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of imports by 2030, to replace natural gas, coal and oil in hard-to-decarbonise industries and transport sectors." 10 Mt of hydrogen correspond to 333 TWh. In this task, you will investigate the cost of hydrogen production within Europe and later in Task 2 in three candidate countries for energy exports: Argentina, Namibia and Algeria.

For the domestic hydrogen production, you will build on a German single-node and hourly-resolved electricity system as a simplified example with fully renewable supply based on wind and solar generation combined with battery and hydrogen storage. You will explore how system design and operation change when in addition to the country's electricity demand, all of the 333 TWh of domestic hydrogen would have to be produced in Germany.

[4 points] (a) Import the necessary packages and load the pre-built PyPSA network from
`https://tubcloud.tu-berlin.de/s/m73a6SGXEYAsiyY/download/network-assignment-5.nc`
This network is identical to the tutorial on capacity expansion planning with the only difference that the time series are now hourly resolved and the bus "Germany" is now called "electricity".

[3 points] (b) This network has some components we no longer want to consider in this task. Therefore, remove the following components:
- The Generator named "OCGT".
- The Storage Unit names "hydrogen storage underground"

- The Global Constraint named “CO2Limit”

[8 points] (c) Add a hydrogen storage system to the PyPSA network where storage, electrolysis and re-electification can be individually sized by the model. You can follow the tutorial for this: the steps consist of adding a hydrogen bus, a link for the electrolysis, a link for the hydrogen fuel cell, and a store for the hydrogen store.

Use the following techno-economic parameters:

technology	parameter	value	unit
electrolysis	efficiency	70	%
electrolysis	capital cost	50	€/kW/a
fuel cell	efficiency	50	%
fuel cell	capital cost	120	€/kW/a
hydrogen storage	capital cost	140	€/MWh/a

Note that the capital costs are already annualised. Pay attention to the units when adding the costs. At the end of the year, the hydrogen storage should have the same state of charge as at the beginning of the year.

[4 points] (d) Attach a constant hydrogen demand to the hydrogen bus, such that the total annual demand sums up to 333 TWh. How does it relate to the average electricity demand?

[6 points] (e) Solve the model and list the optimised capacities of each system component in GW and the total annual system costs in G€/a.

Hint: *To save time, you may want to use the Gurobi solver. See installation instructions here.*

[6 points] (f) As you know from various previous assignments, there are constraints to how much wind capacity can be built. Therefore, now limit installable potentials for wind to 200 GW for onshore wind and 70 GW for offshore wind and rerun the model. Describe what changed:

- Are the capacity limits reached for onshore and offshore wind?
- How much more expensive is the system with these constrained wind potentials (in %)?
- Visualise and describe the differences in capacities built.

[4 points] (g) Plot the state of charge of the hydrogen store for the full year in units of TWh and of the battery storage for the month of July in units of GWh.

[4 points] (h) Plot the hydrogen production of the electrolysis and the hydrogen consumption of the fuel cells over time. Choose a figure size of 20 by 3 inches.

[9 points] (i) Determine the average utilisation rate (in % of installed capacity) of the electrolysis and the fuel cell. Also determine the monthly average utilisation rates. Describe when electrolysers and fuel cells are running and formulate a hypothesis what might be causing this behaviour.

[5 points] (j) Plot the price duration curves for electricity and hydrogen. Label all axes appropriately. For each carrier, determine the month with the lowest and highest prices reached?

[5 points] (k) Determine the demand-weighted average price of electricity and the demand-weighted average price of hydrogen. Which price is lower? Try to explain why.

[6 points] (l) Plot the power consumption of the electrolysis and the power injection of the fuel cell against the electricity price in a scatter plot. Limit the extent of the axis with the electricity prices to 500 €/MWh. At what prices do fuel cell and electrolysis tend to run?

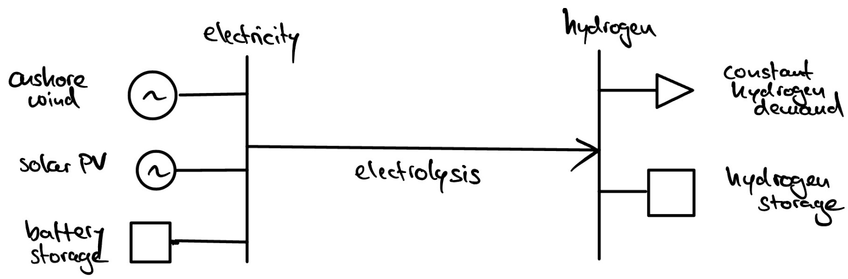
[6 points] (m) Name and describe three of the major limitations of the modelling above.

Task 2: Hydrogen Imports **[30 points]**

Required Tools: `pypsa`, `pandas`

Until now, you only looked at the domestic production cost of 333 TWh of hydrogen, but the REPowerEU plan also assumes imports of hydrogen in equal amounts into Europe. In this task, you will evaluate the import costs of hydrogen from three candidate countries: Argentina, Namibia and Algeria.

[8 points] (a) Build and solve a new PyPSA model for each of the potential exporting country according to the following scheme:



Use the same cost and technology assumptions as for the PyPSA network in Task 1, but take onshore wind and solar capacity factor time series from model.energy for the year 2011:

- Algeria:
  `https://model.energy/data/time-series-7302b235f1cf37e19e408c863c038290.csv`
- Argentina:
  `https://model.energy/data/time-series-91c3af7cc2178900eb8c7248d0aa12c5.csv`
- Namibia:
  `https://model.energy/data/time-series-57f7bbcb5c4821506de052e52d022b48.csv`

Hint: *The easiest approach to build the model for exporting countries is to make a deep copy of the PyPSA network from Task 1 with `n.copy()`, remove the parts that are not required, and update the capacity factor time series. Beware that if you choose this approach you have to align the datetime indices of time series data by overriding the year of the capacity factor time series.*

[12 points] (b) Compare (i) the average hydrogen production cost (in €/MWh), (ii) the optimal capacities built of all system components (in GW), and (iii) the average utilisation rate of the electrolysis (in %) for each of the three candidate countries. Use a table to present your comparison and also explain the key differences in written text.

So far, this analysis neglects the varying distances over which the hydrogen would need to be transported.In the following, let us assume for simplicity that hydrogen can only be transported over large distances as liquified hydrogen in ships. An approximative function for the transport costs (€/MWh of hydrogen delivered) that includes costs of liquefaction at the export terminal and regasification at the import terminal is given by the function

$$T(d) = 30 + 0.001d$$

where d is the shipping distance in km.

The sea route distances from the exporting countries to Wilhelmshaven in Germany are given in the table below:

country	sea route distance
Algeria	3500 km
Argentina	13000 km
Namibia	10000 km

[6 points] (c) Which of the three candidate countries offers the lowest import costs to Germany when transport costs are taken into account? At what price? By what margin?

[4 points] (d) Name and describe two limitations of the modelling above you can think of.