Assignment 2 – Land Eligibility, Storage & Run-of-River

Due Wednesday, 12 June 2024, 23:59 [100 points]

Instructions and Rules

- Submission on ISIS requires two-factor authentication. Justified exceptions can be granted.
- Submissions must include both written answers and code that shows how answers were obtained.
- Always clearly mark which task and subtask you are working on.
- Always provide units for quantities (e.g. energy, power, emissions) for your results.
- All plots must have appropriate axis labels with units if applicable.
- The quality of the presentation of your results will be factored into the grading.
- Partial points will be deducted for any missing labels or units.
- Submissions must be own work, plagiarism from the web or peers will be checked and sanctioned!
- Please upload a single `.ipynb` file and the corresponding `.html` export of the notebook.
- Do not upload data!
- 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: Land Eligibility for Wind Turbines [28 points]

Required Tools: `atlite`, `geopandas`, `matplotlib`, `rasterio`

Perform an eligibility analysis for the land area available for the development of wind parks in the Grand Duchy of Luxembourg.

The following areas are to be excluded or included:

1. exclusion of natural protection areas
(Natura2000 dataset: `https://tubcloud.tu-berlin.de/s/zPMqJFPD8tKq2Ss/download/Natura2000_end2021-LU.gpkg`)
2. exclusion of a radius of 5 km around airports
(NaturalEarth dataset: `https://tubcloud.tu-berlin.de/s/TbEJ9Lsy9EpTcQS/download/ne_10m_airports.gpkg`)
3. exclusion of a buffer of 500m next to major roads
(NaturalEarth dataset: `https://tubcloud.tu-berlin.de/s/zcKQ95TgpyMJb8E/download/ne_10m_roads.gpkg`)
4. exclusion of a distance of 1200m around the following CORINE land cover classes: 111, 112, 121, 133, 141, 142
(CORINE CLC 2018 dataset: `https://tubcloud.tu-berlin.de/s/z7aY8HNCdETQMT7/download/U2018_CLC2018_V2020_20u1-LU.tif`)
5. inclusion only of the following CORINE land cover classes, which are deemed suitable for constructing wind turbines: 211, 212, 231, 241, 243, 321, 323, 324, 333
(CORINE CLC 2018: `https://tubcloud.tu-berlin.de/s/z7aY8HNCdETQMT7/download/U2018_CLC2018_V2020_20u1-LU.tif`)

The geometric shapes of countries can be found under the following link:

`https://tubcloud.tu-berlin.de/s/7bpHrAkjMT3ADSr/download/country_shapes.geojson`

The CORINE land cover dataset is given in coordinate reference system EPSG:3035 and stores classes as numbers as listed on the following website:

`https://collections.sentinel-hub.com/corine-land-cover/readme.html`

[2 points] (a) Import the relevant packages needed to perform this analysis.

[2 points] (b) Translate the CORINE land classes listed above to code values as stored in the dataset using the table above. Also state the descriptive names of the classes. Distinguish between (a) classes to which a distance should be kept and (b) classes deemed eligible for wind development. The format of the answer is up to you.

[2 points] (c) Load the country shapes as GeoDataFrame, reduce it to a single entry for Luxembourg, and reproject it to the coordinate reference system EPSG:3035.

[6 points] (d) Plot and calculate (in %) the area excluded by each of the exclusion constraints (1.-5.) individually using the `atlite.gis.ExclusionContainer` and `atlite.gis.shape_availability`. Refer to the `atlite` tutorial for information on how to plot the output of the latter function with `rasterio` and `matplotlib`.

[3 points] (e) Plot and calculate (in %) the area available for the development of wind parks considering all exclusion and inclusion criteria together?

[8 points] (f) Perform a sensitivity analysis on the distance criterion to CORINE land classes by repeating the land eligibility calculation with distance requirements of 0m, 200m, 400m, 600m, 800m, 1000m and 1200m, together with all other eligibility constraints. Plot the available area (in %) as a function of the distance requirements and describe the curve. Make sure to label your figure appropriately.

[5 points] (g) Assume that for the expansion of wind power in Luxembourg, a capacity density of 5 MW/km^2 of available land can be achieved and that the wind conditions result in an average capacity factor of 32%. What is the total energy in units of TWh that could be produced from wind power in Luxembourg each year if the distance criterion were 800m?

Task 2: Dimensioning Lossless Storage [38 points]

Required Tools: `pandas`, `matplotlib`, `numpy`

Reconsider the time series on wind and solar capacity factors and electricity demand in Germany in 2015 from the first assignment:

File: https://tubcloud.tu-berlin.de/s/ppRkB2mwsKkJrRm/download/time-series-lecture-2.csv

Load the provided dataset as a `pandas.DataFrame` such that its index contains the time stamps. The goal of this task is to dimension a lossless storage for different generation mixes of onshore wind and solar to supply demand. This means that you should assume, for simplicity, that the storing electricity does not incur any losses.

[3 points] (a) Rescale the onshore wind and solar capacity factor time series such that in total across the year as much energy is produced as is consumed according to the column "load [GW]". Ignore offshore wind. Store the two resulting new time series under the column names "onwind [GW]" and "solar [GW]" respectively.

[2 points] (b) Write code that checks that the sum of each of these two columns matches the column "load [GW]".

[3 points] (c) Determine two residual load time series: one for the case where all power is supplied by solar, another for the case where all power is supplied by wind generation.

[3 points] (d) Plot the two residual load time series for June in a single figure. Label the graph appropriately.

[5 points] (e) For each of the two residual load time series, calculate the state of charge profiles (i.e. time series) of the smallest possible storage that could align supply and demand at all times.

[3 points] (f) What are the required energy [GWh], charge [GW], discharge [GW] capacities for a purely wind-based and a purely solar-based system? To receive partial points, it can help to briefly describe how you identify these capacities.

Until now, we only looked at two extreme cases (100% wind or 100% solar). In the following, we are going to look at technology mixes with both wind and solar generation.

[2 points] (g) Write a *Python function* that computes the residual load as a function of the wind generation share α with a corresponding solar generation share of $1 - \alpha$.

[2 points] (h) Apply this function for steps of 5% between 0% and 100% for α and store the residual load time series in a `pandas.DataFrame` where each column denotes a particular value for α. Show the first 5 rows and columns of this DataFrame.

[3 points] (i) Plot the required storage charge and discharge capacities as a function of the wind generation share α. Choose appropriate labels!

[3 points] (j) Plot the required energy capacity of a storage as a function of the wind generation share α. Choose appropriate labels!

[1 point] (k) Which of the α computed results in the lowest energy capacity required for the storage?

[3 points] (l) Plot the state of charge profile for this α and compare it to the cases with 100% wind or solar. Write a short explanation of the differences and impact of mixing wind and solar power generation on the storage requirements.

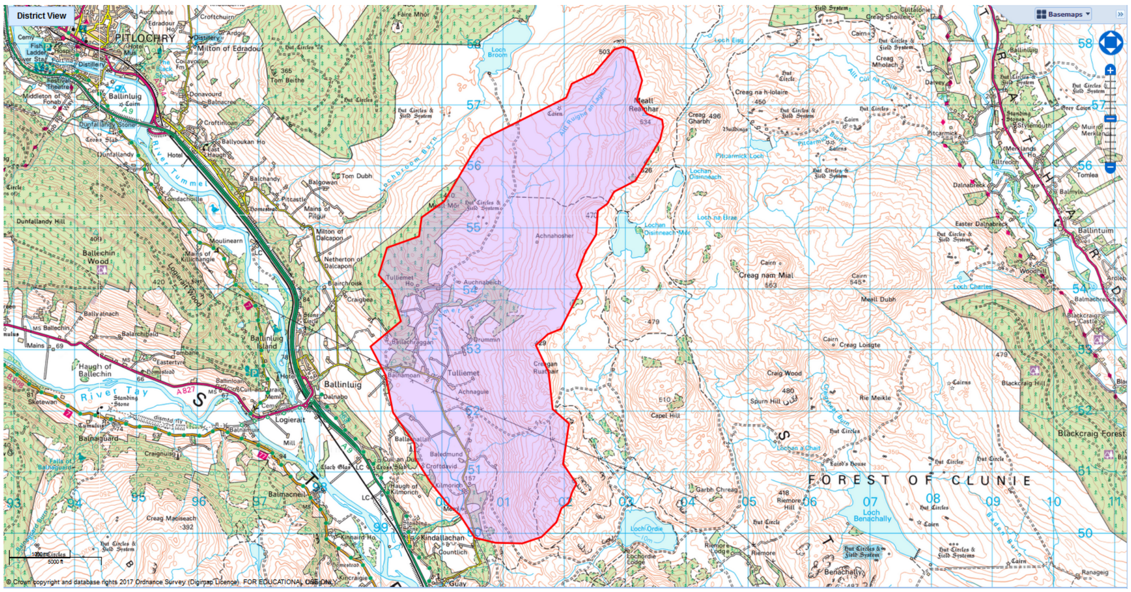
[5 points] (m) Now assume that there is an additional electricity load for electric heating with heat pumps with a strong seasonal component. The additional load profile should have a mean and amplitude

corresponding to half of the mean of the original load profile (such that the additional load profile reaches peaks on January 1 and touches zero mid-year). Does that change the α that minimizes the required storage energy capacity? If yes, how? If not, why not?
Hint: This load profile can be generated with the following code: `pd.Series(mean + amplitude * np.cos(2 * np.pi * df.index.dayofyear / 365), index=df.index)`

Task 3: Designing a Run-of-River Power Plant [34 points]

Required Tools: `pandas`, `matplotlib`, `numpy`

You have been tasked with designing a small run-of-river power plant near Pitlochry in Scotland at the Tulliemet river with a catchment area of 25 km^2.



Catchment area of the desired run-of-river plant.

For the evaluation of the site, you have been given a daily time series of daily water flow rates (in m^3/s) from 1983 to 2014:

File: https://tubcloud.tu-berlin.de/s/af5G99i35dwNPCz/download/water-flows.csv

The project lead has also already identified a suitable location for the weir, which would result in a net head of 48 metres. For the following calculations, assume a generator efficiency of 92% and that the weir cannot store significant amounts of water inflow across days.

[2 points] (a) Read the provided dataset as a `pandas.Series` with parsed dates. Demonstrate that the index is a `pandas.DatetimeIndex`.

[2 points] (b) Plot the monthly resampled mean flow rate across the whole time span. Use a figure size of 20 by 4 inches and apply appropriate labels.

Not all of the water the river carries can be used to produce power. A compensation flow (or reserve flow) must remain in the river at all times. For the compensation flow assume the 7% quantile of flows (i.e. flow rate exceeded 93% of the time). Economically, it often does not make sense to dimension the penstock and generator for the peak flow rate. Initially, assume a design flow (i.e. the maximum flow the penstock and generator can handle) corresponding to the 80% quantile (i.e. flow rate exceeded 20% of the time).

[2 points] (c) What is the value for the compensation flow?

[2 points] (d) What is the value for the design flow?

[4 points] (e) Calculate a time series for the available flow for power production (i.e. deducted reserve flow and capped at design flow, no negative flows).

[2 points] (f) In one figure, plot a duration curve for the total flow and the available flow. Label the lines. The x-axis should indicate the percentage of time across the whole 30-year time span. Limit the y-axis to 3 m^3/s.

[2 points] (g) Determine the rated power of the run-of-river scheme using the design flow.

[2 points] (h) Compute a time series for the daily electricity production in kWh of the scheme based on the available flows. Consider that daily time series for the flows are given.

[2 points] (i) What is the long-term average capacity factor of the run-of-river power plant?

[2 points] (j) Compute and plot the annual energy yields of the plant for the years 1983 to 2014.

[2 points] (k) Compute and plot the relative deviation of the annual energy yields from the long-term average annual energy yield. (I.e. negative values in % if energy yield is below long-term average.)

[6 points] (l) Plot the relationship between power rating and average annual energy yield based on design flows ranging between the 0% and 100% quantiles of flow in increments of 5%. Based on this plot, explain why it might make sense to limit the design flow. What does the slope of the curve indicate?

[4 points] (m) How is the average annual energy yield affected by reserve flow requirements? If the necessary compensation flow is decreased from the 7% to the 3% quantile of the flow, how much does the average annual energy yield decrease in absolute and relative terms?