Data Science for Energy System Modelling
Lecture 3: Wind and Solar Potentials

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Hybrid Format Information: Zoom and Recordings

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- The camera and microphone are directed **only at the lecturer**.
- Student contributions are **not recorded**.
  When interaction takes place, the recording will be **paused**.
- If you **voluntarily speak** while the recording is running, you **consent** to the recording and publication of your contribution.
- You may **withdraw** this consent at any time for the future; that part will then be deleted or edited.
- Participants who wish to remain anonymous may join under a **pseudonym** and/or use the **chat or Q&A** function instead of speaking.

Today's Mentimeter

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www.menti.com

Enter the code

7120 7738

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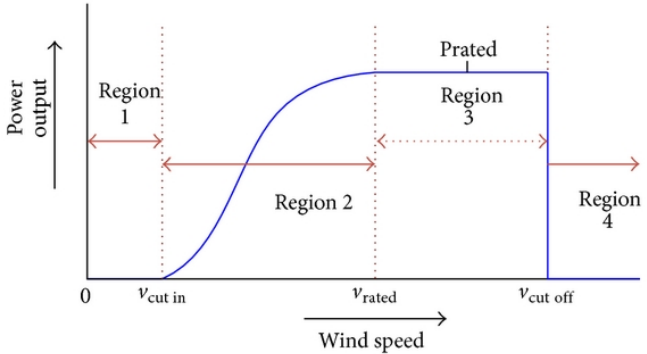
How do we derive wind time series from last time?

We take times series weather data for the wind speeds at hub height (e.g. 120m) at each location in ms^{-1}. In theory, the power in the wind grows in proportion to v^3, but in practice high wind speeds are so rare such that it is not economic to build the turbine so large.

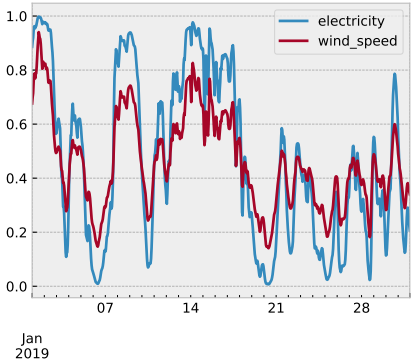


Source: https://www.hindawi.com/journals/jen/2016/8519785/

Let's revisit the wind production time series...

...and compare them with the **wind speed data** used to generate it.

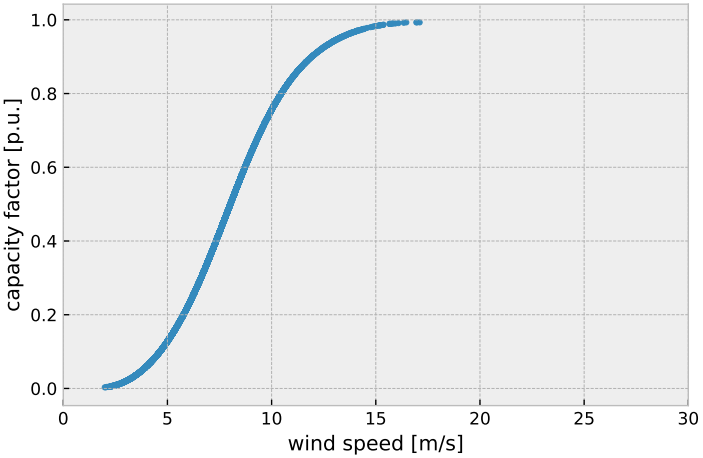
time	electricity p.u.	wind_speed m/s
2019-01-01 00:00	0.880	11.569
2019-01-01 01:00	0.901	11.958
2019-01-01 02:00	0.913	12.222
2019-01-01 03:00	0.941	12.937
2019-01-01 04:00	0.955	13.438



(here we use wind data from Warnemünde at the Baltic Sea)

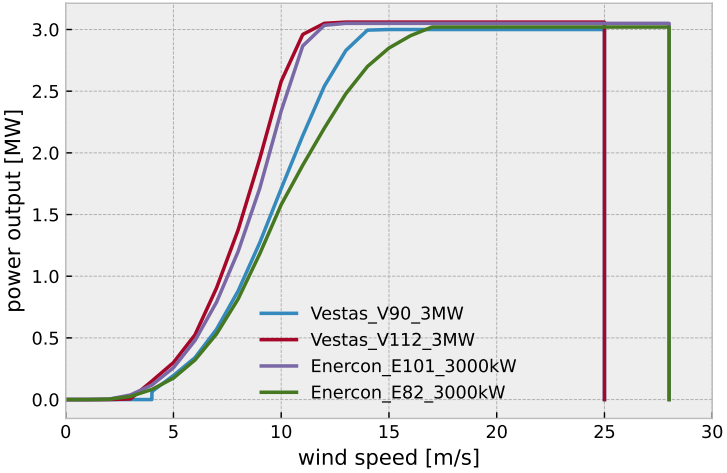
Source: https://renewables.ninja

Let's plot capacity factor against wind speeds



- it looks like we have **reverse-engineered** the power curve used for this simulation
- **cut-in speed** at 2 m/s
- **rated speed** above 16m/s

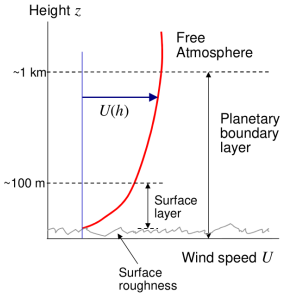
Different turbines have different power curves

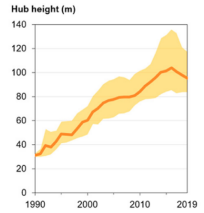


- some specialise on dominant medium-/low-wind conditions
- left: example power curves for **3 MW** wind turbines
- newest offshore wind turbines have **15 MW** rated capacity
- typical **hub height**: 80-100m

Impact of hub height on wind resource

- **decreasing wind speeds with lower height** result from impact of surface on the atmospheric wind
- **surface roughness** caused by topology (mountains) and land coverage (water, crops, trees, buildings)
- led to a **trend of increasing hub heights**
- for adequate resource assessment need to **scale meterological data** (typically given at 10m or 100m) to hub height





Source: McKenna et al. (2021), https://doi.org/10.1016/j.renene.2021.10.027

Impact of hub height on wind resource

- Two common 'laws' relate wind speeds at height z to a known reference height z_r
- **Log law**

$$\frac{U(z)}{U(z_r)} = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_r}{z_0}\right)}$$

- z_0 is terrain-dependent roughness length
- **Power law** (simpler)

$$\frac{U(z)}{U(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha}$$

- normally assumes $\alpha = 1/7$

Roughness length:

Terrain	z_0 [m]
Open sea	0.0002
Snow	0.001
Open flat grass	0.03
Low crops	0.1
Tall crops	0.25
Parkland	0.5
Forest	1.0
Cities	$\geq$2

Impact of hub height on wind resource

Exercise 1: According to log law, what is the wind speed at a hub height of 90 metres if the wind speed at 10 metres is 4 m/s and the turbine is located on low cropland?

Exercise 2: Repeat the same calculations, but use the power law instead of the log law.

Exercise 3: Would the wind speed at hub height be higher or lower if it was located at sea with the same wind conditions?

How do we derive solar PV time series?

We take times series weather data for the solar radiation (also called irradiation or insolation) at each location in W/m^2. This is often provided for a horizontal surface, so we need to convert for the angles of the solar panel to the horizontal, and account for factors that affect the energy conversion (losses, outside temperature).

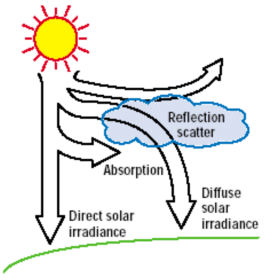


FIGURE 2. Sunlight passing through the atmosphere

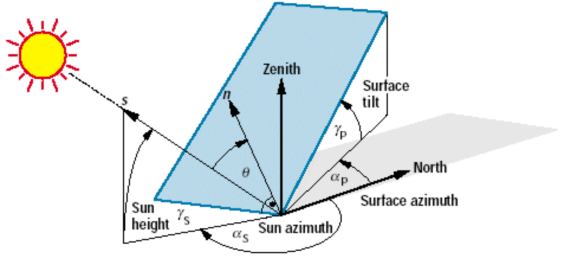


FIGURE 5. Angles to define the position of the sun and the orientation of a tilted plane

Source: Volker Quaschning

Let's also briefly revisit the solar production time series

More than one parameter needed: **irradiance (diffuse and direct)** as well as **ambient temperatures** since the efficiency of the PV module is less efficient in high temperatures.

time	electricity	irradiance_direct	irradiance_diffuse	temperature
2019-01-01 08:00:00	0.032	0.017	0.030	5.801
2019-01-01 09:00:00	0.106	0.058	0.068	5.772
2019-01-01 10:00:00	0.122	0.060	0.083	6.019

irradiance given in kW/m² – temperature given in $°C$ – location: Warnemünde

There are different ways to simulate PV module output, e.g. Huld model, an empirical model to estimate PV power output from irradiance and temperature in Europe.

Source: https://renewables.ninja

Software helps us handle the angles calculations…

Atlite: Convert weather data to energy systems data

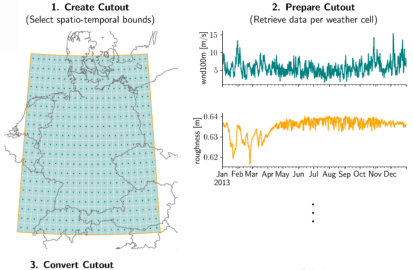
pypi v0.2.9 | conda-forge v0.2.9 | CI passing | codecov 72% | docs passing | license GPLv3 | REUSE compliant

JOSS 10.21105/joss.03294

Python library for converting **weather data** (e.g. wind, solar radiation, temperature, precipitation) into **energy systems data**:

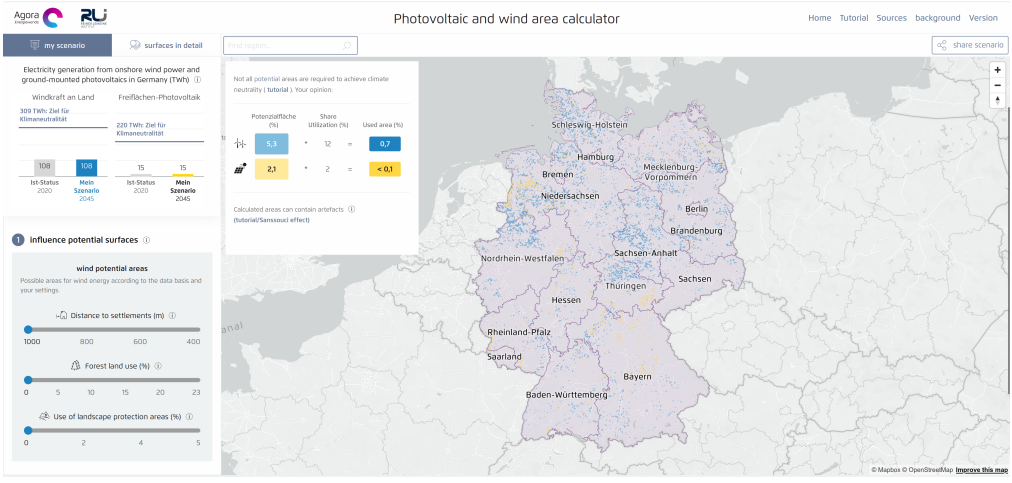
- solar photovoltaics
- solar thermal collectors
- wind turbines
- hydro run-off, reservoir, dams
- heat pump COPs
- dynamic line rating
- heat demand (HDD)

It can also perform **land eligibility analyses**.



Source: https://github.com/pypsa/atlite

Example from first lecture: Agora EW's Online Calculator



Source: https://www.agora-energiewende.de/service/pv-und-windflaechenrechner/#

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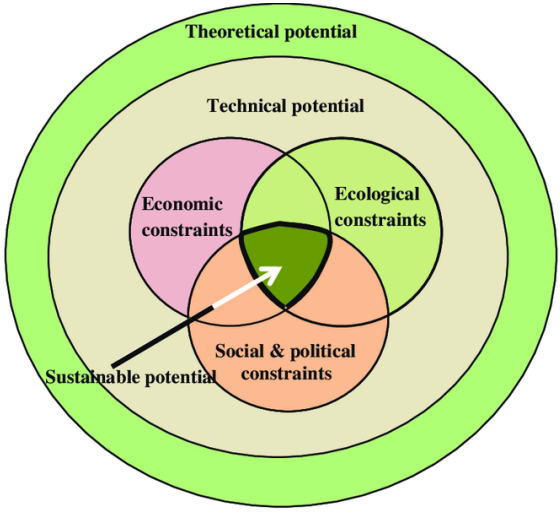
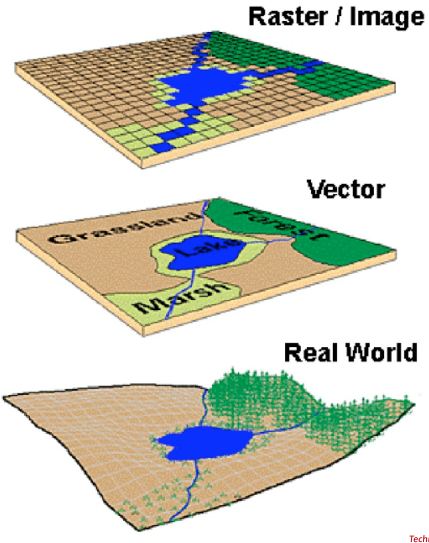
Potentials? What is meant by it?



Geospatial Data Formats

There are **two primary data structures** for geospatial information:

- Raster Data
- Vector Data



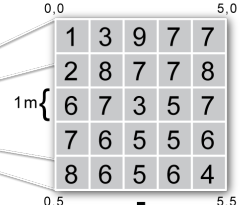
Source: https://doi.org/10.13140/2.1.3030.1767

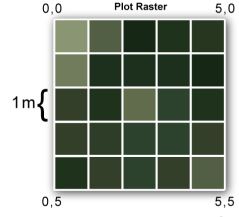
Raster Data vs Vector Data

- data is stored as a grid of values
- each pixel represents an area
- values can be **continuous** or **categorical**
- like a **photo** with spatial information: has information about extent, resolution and coordinate reference system (CRS)
- **typical formats:** GeoTIFF

Examples

- surface elevation
- weather data (e.g. wind speeds)
- land use categories (e.g. forest)





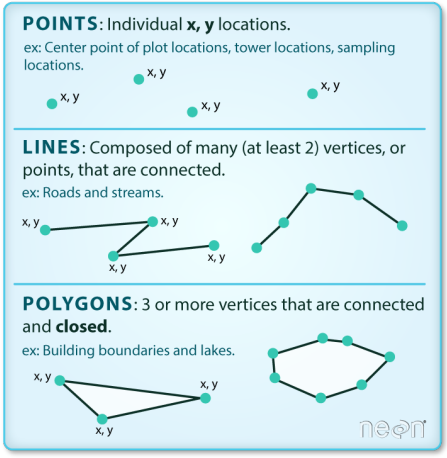
Source: https://datacarpentry.org/organization-geospatial/01-intro-raster-data/

Raster Data vs **Vector Data**

- vector data structures represent specific **features** on the Earth's surface, and assign **attributes** to those features
- vectors are composed of **geometric vertices** defining the **shape** of an object
- **typical formats:** `.shp`, `.geojson`

Examples

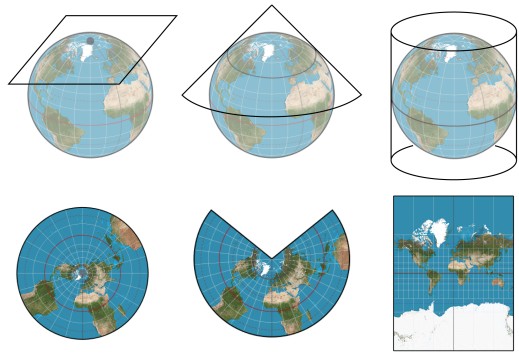
- roads and airports
- administrative regions
- natural protection areas



Source: https://datacarpentry.org/organization-geospatial/02-intro-vector-data/index.html

Projections and Coordinate Reference Systems (CRS)

- **Issue:** Earth is a globe, but we present maps on two-dimensional surfaces
- Need to **project** geographical data
- all geospatial data is stored according to a **coordinate reference system (CRS)**
- **CRS** provide a mathematical model to connect data to the Earth's surface
- it is possible to **convert between CRS**
- but some information is always **lost** compared to representation on a sphere



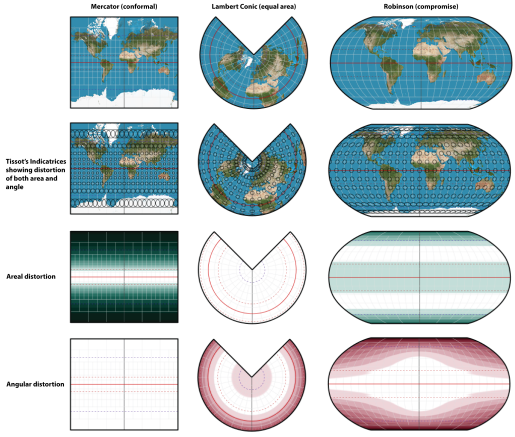
planar / conic / cylindrical

Source: https://www.youtube.com/watch?v=kIID5FDi2JQ, https://gistbok.ucgis.org/bok-topics/2018-quarter-02/map-projections

Projections and Coordinate Reference Systems (CRS)

Projections preserve different metrics

- **conformal** projections preserve angles (e.g. Mercator)
- **equal-area** projections preserve area (e.g. Mollweide)
- **equidistant** projections preserve distances (e.g. Plate carrée)
- **compromise** projections balance distortions (e.g. Robinson)



Source: https://gistbok.ucgis.org/bok-topics/2018-quarter-02/map-projections

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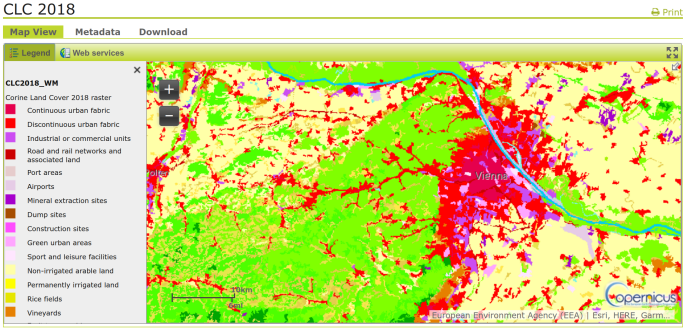
What data to find the area available for wind parks of a country?

CORINE Land Cover Inventory for Europe



- 44 land use classes
- derived from satellite data
- ≈ 100m resolution
- public open data

Example Categories

- 111 - Continuous urban fabric
- 211 - Non-irrigated arable land
- 311 - Broad-leaved forest
- 321 - Natural grasslands

Source: https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html/index.html, https://collections.sentinel-hub.com/corine-land-cover/readme.html

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Resolution matters – LUISA Land Cover Extension

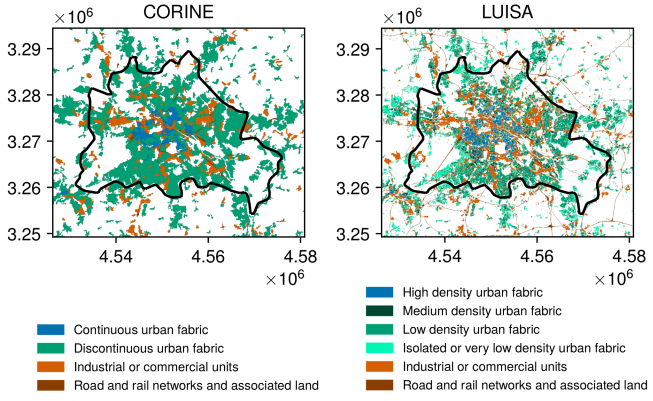
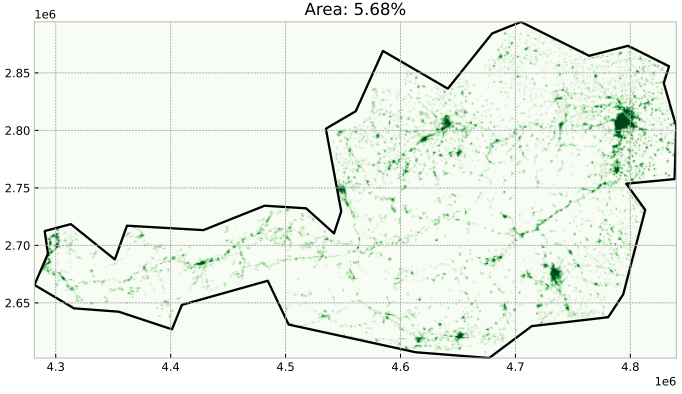


Fig. 3.2.: Comparison of Artificial surfaces for *CORINE Land Cover* and *LUISA* dataset for the vicinity of Berlin, Germany.

- extension of CORINE
- additional data sources
- ≈ 50m resolution
- public open data

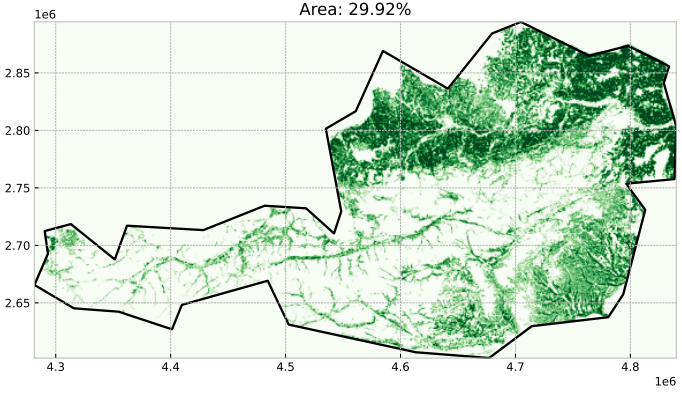
Source: https://data.jrc.ec.europa.eu/dataset/51858b51-8f27-4006-bf82-53eba35a142c, MA Calvin Triems

CORINE Land Cover – Settlements and Industrial Area



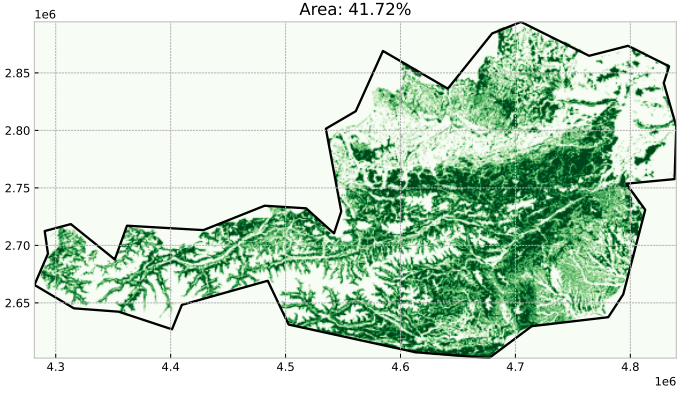
- green area shows settlements and industrial area
- see urban areas: Vienna, Linz, Salzburg, Innsbruck, Graz, Villach, Klagenfurt
- around 6% of land area classified as settlement or industrial area

CORINE Land Cover – Agricultural Land



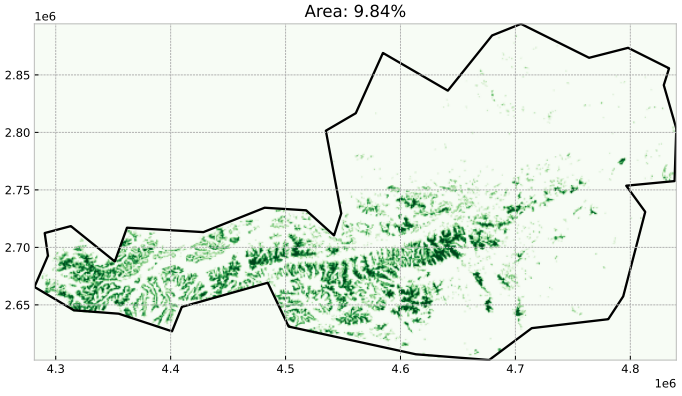
- green area shows agriculatural land
- land for agriculture centred in North-East/East Austria
- around 30% of land area classified as agricultural land

CORINE Land Cover – Forests



- green area shows forest areas
- forests make up around 40% of Austrias land mass

CORINE Land Cover – Other Vegetation

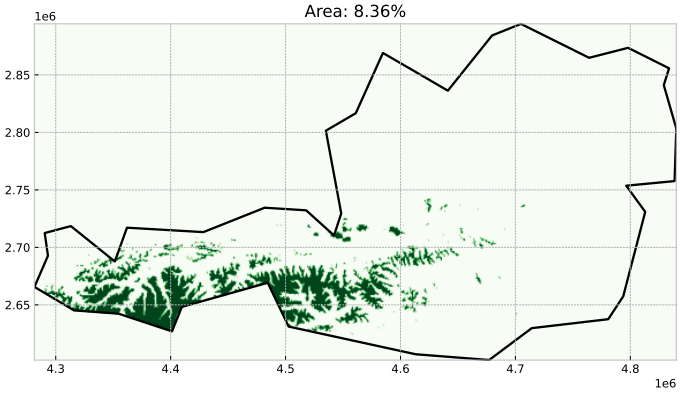


- other vegetation (e.g. sparse vegetation, grassland) make up around 10% of Austrias land mass

CORINE Land Cover – Eligible for Wind Turbines?

- 111 - Continuous urban fabric
- 112 - Discontinuous urban fabric
- 121 - Industrial or commercial units
- 122 - Road and rail networks and associated land
- 123 - Port areas
- 124 - Airports
- 131 - Mineral extraction sites
- 132 - Dump sites
- 133 - Construction sites
- 141 - Green urban areas
- 142 - Sport and leisure facilities
- 211 - Non-irrigated arable land
- 212 - Permanently irrigated land
- 213 - Rice fields
- 221 - Vineyards
- 222 - Fruit trees and berry plantations
- 223 - Olive groves
- 231 - Pastures
- 241 - Annual crops associated with permanent crops
- 242 - Complex cultivation patterns
- 243 - Land principally occupied by agriculture with significant areas of natural vegetation
- 244 - Agro-forestry areas
- 311 - Broad-leaved forest
- 312 - Coniferous forest
- 313 - Mixed forest
- 321 - Natural grasslands
- 322 - Moors and heathland
- 323 - Sclerophyllous vegetation
- 324 - Transitional woodland-shrub
- 331 - Beaches - dunes - sands
- 332 - Bare rocks
- 333 - Sparsely vegetated areas
- 334 - Burnt areas
- 335 - Glaciers and perpetual snow
- 411 - Inland marshes
- 412 - Peat bogs
- 421 - Salt marshes
- 422 - Salines
- 423 - Intertidal flats
- 511 - Water courses
- 512 - Water bodies
- 521 - Coastal lagoons
- 522 - Estuaries
- 523 - Sea and ocean

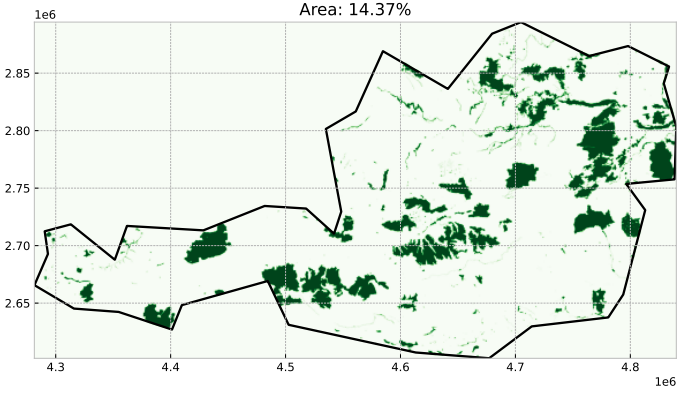
Exclusion Areas: Mountain Terrain



- areas with **high elevation or slope** excluded
  - elevation 2000-3500m
  - slope 5-30 degrees
- GEBCO: global terrain data at land and sea
- 8% of land area in Alps
- **use at sea:** water shallow enough for wind park?

Source: https://www.gebco.net, https://doi.org/10.1016/j.renene.2021.10.027

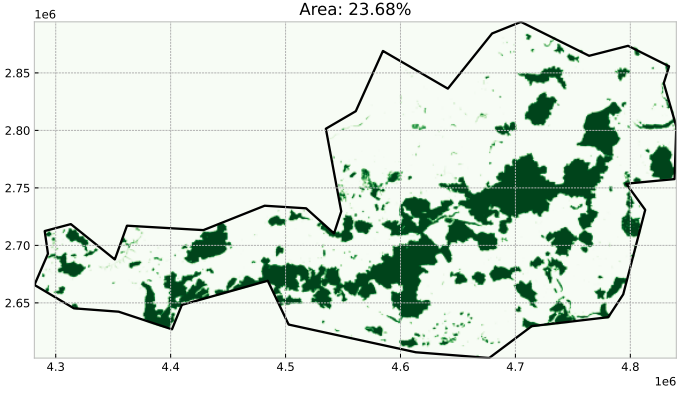
Exclusion Areas: Natural Protection Areas



- **Natura 2000** dataset for EU natural protection areas
- **around 18%** of land area in EU, 14% in Austria
- includes special areas of conservation, special protected areas, designated areas under **habitats and birds directive**

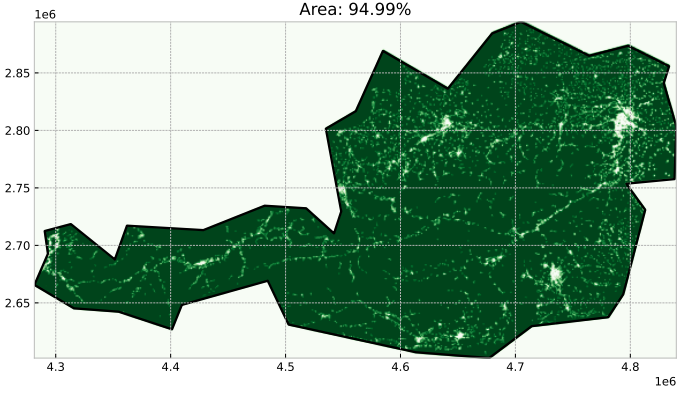
Source: https://ec.europa.eu/environment/nature/natura2000/index_en.htm, https://en.wikipedia.org/wiki/Natura_2000

Exclusion Areas: Nationally Designated Areas (CDDA)



- compared to Natura 2000, also includes **lower-tier protection areas**
- e.g. **protected landscapes** ('Landschaftsschutzgebiete')
- almost 24% of land area in Austria

Distance Criteria to Settlements – 0m



- wind turbines need to keep **distances from settled areas**
- **rules differ** between countries or even federal states

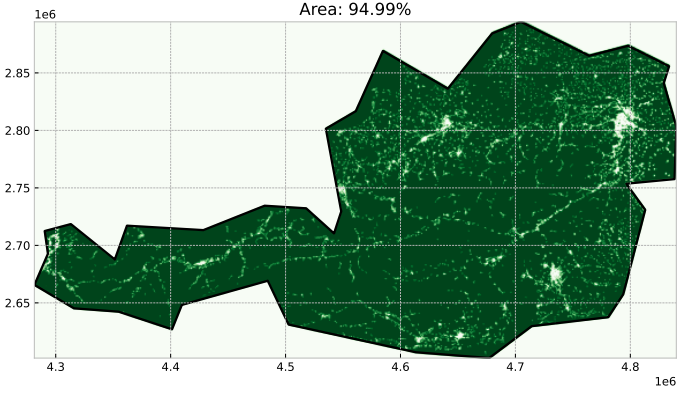
Source: https://de.wikipedia.org/wiki/10H-Regelung

Minimum setback distances to settlements in European countries

Country	Distance
Belgium	
Flanders	>3x rotor diameter
Wallonia	400 m, or 4x total height
Brussels	Not permitted
Austria	
Lower Austria	1,200 m
Upper Austria	800 m
Burgenland	1,000 m
Styria	1,000 m
Croatia	350 m, <45 dBA
Denmark	4 x total height
Estonia	1,000–2,000 m
Finland	1,000–2,000 m
France	500 m
Germany	In most states 400-1,100 m. Regional differences, up to 10x tower
Greece	500–1500 m
Ireland	500 m
Italy	200 m from single dwellings; 6x tip height from towns (~700 m)
Latvia	500 m
Lithuania	<45 dB night time noise, shadow coverage <30 h/year
Netherlands	4x hub height
Poland	10x total height
Portugal	~ 400 m (noise regulation)
Romania	500 m
Spain	500–1,000 m
Sweden	1,000 m to urban areas; 500 m to single houses
UK	
England	Local regulations, from 700 m to 10x total height; some cases 2,000 m
Wales	500 m recommended
Scotland	Local recommendation 2,000 m
Northern Ireland	10x rotor diameter to occupied property & minimum distance 500 m recommended

Source: https://doi.org/10.1016/j.renene.2021.10.027

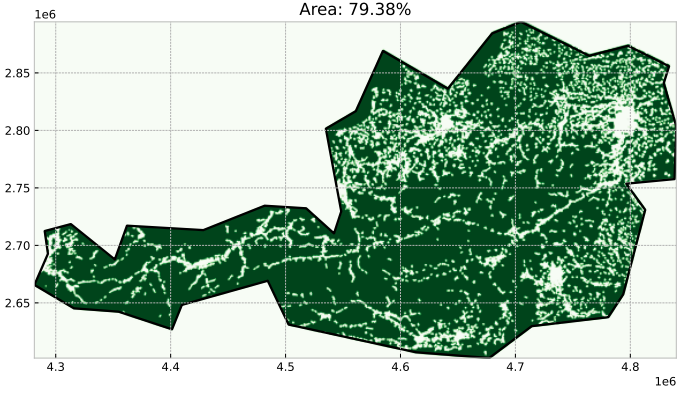
Distance Criteria to Settlements – 0m



- wind turbines need to keep **distances from settled areas**
- **rules differ** between countries or even federal states
- **example:** ‘10-H-Regelung’ in Bavaria

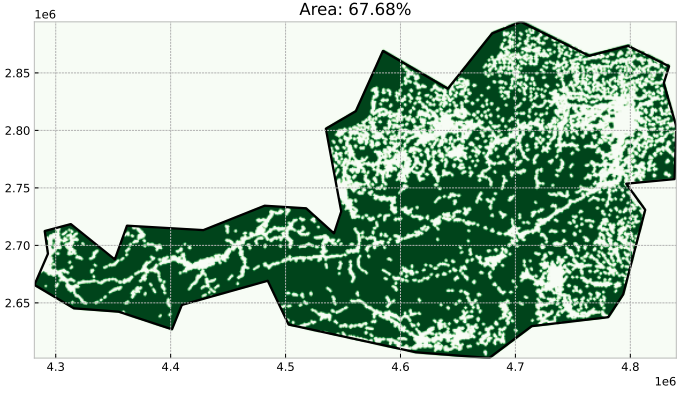
Source: https://de.wikipedia.org/wiki/10H-Regelung

Distance Criteria to Settlements – 500m



- with a buffer of 500m around settlement areas, excluded area **increases from 5% to 20%**.

Distance Criteria to Settlements – 1000m



- with a buffer of 1000m around settlement areas, excluded area **further increases from 20% to 32%**.

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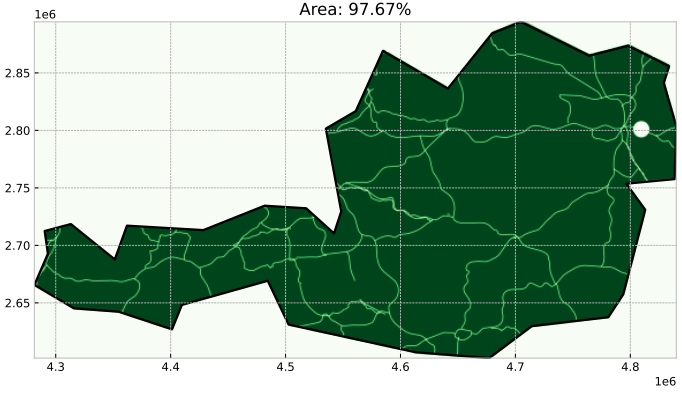
Distance Criteria to Roads and Airports



- typically a buffer of 200m is enforced around **major roads**
- a radius of 7-15km around **airports and radio beacons** is usually set

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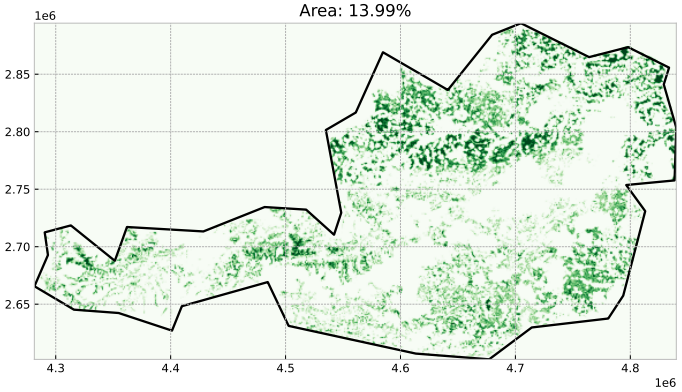
Now, we overlay all excluded areas and see what is left...



- by combining all land use restrictions, we are left with **14% of the land area**
- $83,879 \cdot 0.14 = 11,743 \text{km}^2$
- 2-10MW/km^2 power density
- **23-117GW wind potential**
- asssumptions for power density influenced by competing land use, public acceptance, wind replenishment.

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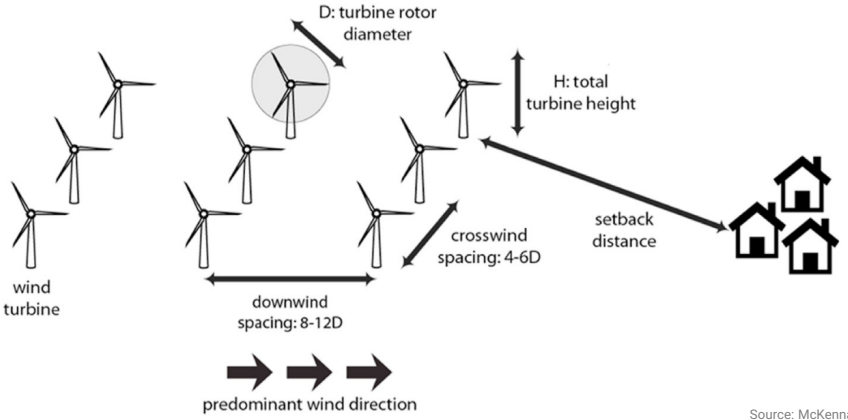
What to do after we found the eligible land area?

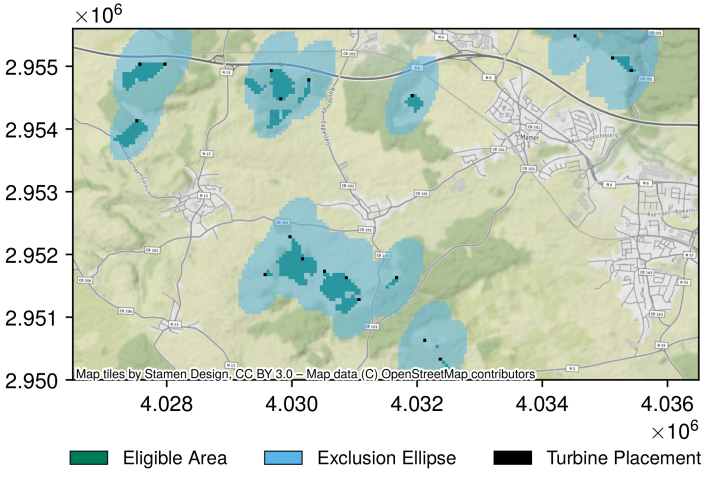
Wind farm layouts need proper **spacing between turbines**.

For instance, to minimise **wake effects** and allow for replenishment areas.



Source: McKenna et al. (2021), https://doi.org/10.1016/j.renene.2021.10.027

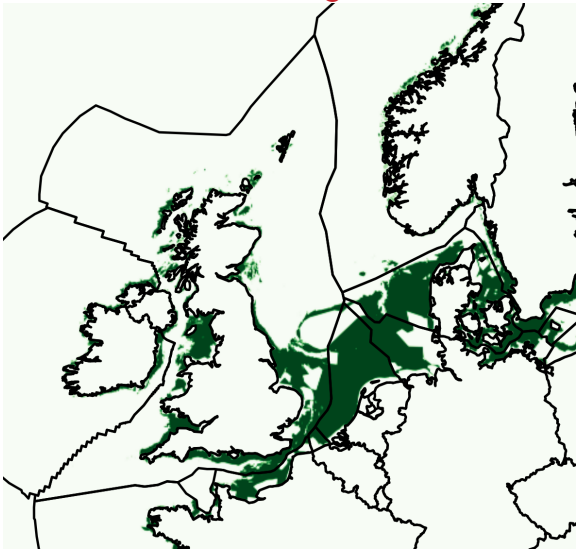
Wind turbine placement algorithms



- variety of wind turbine placement **algorithms**
- **objective:** place the most turbines given land eligibility and spacing criteria

Source: MA Triems

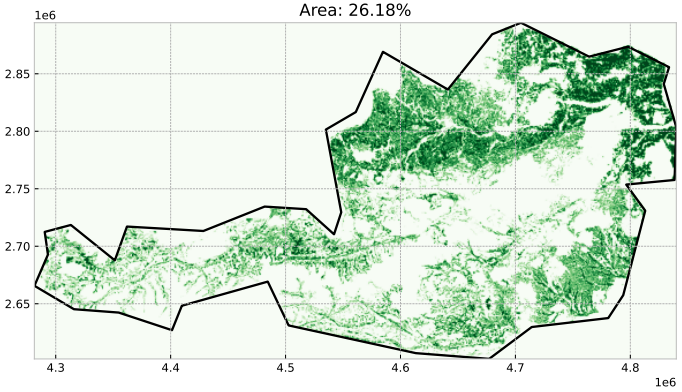
What about area eligible for offshore wind turbines?



- water depth up to 50-60 metres
- protection areas (e.g. Wadden Sea)
- busy commercial shipping lanes (not shown in Figure)
- minimum distance to shore (potentially)

Source: Neumann et al. (2023), https://doi.org/10.1016/j.joule.2023.06.016

And for utility-scale solar PV in Austria? (‘Freiflächen-PV’)



- distinction between **utility-scale / rooftop PV**; agrivoltaics
- for rooftop PV need rooftop area, orientation, inclination; approximation 1 kW per capita
- for utility-scale PV left with **26% of the land area**
- e.g. 3% of 21,808km^2 with 170 MW/km^2 density
- **111 GW utility-scale PV potential**

Up next

Today: Introduction to `geopandas` and `cartopy`.

Next Thursday (1/2): Introduction to `atlite` and `rasterio`

Next Thursday (2/2): Consultation for Assignment 1