The potential of PV power production in Europe

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Questions

- Could we satisfy Europe’s energy consumption by PV energy production?
- If yes, then:
  - How much area would we have to cover?
  - Where would the panels have to be?
  - How much energy would we have to buffer to compensate fluctuations in production and consumption?

Method and Datasets

- Meteorological datasets: ERA5-Data from the copernicus data store
- Processing algorithm: using dask
  - $$T_{\text{cell}} = c_1 + c_2 \cdot (T - 273.15) + c_3 \cdot \frac{SSRD}{s} + c_4 \cdot v_{wind}$$
  - $$\beta = -0.005 \quad PR = 1 + \beta \cdot (T_{\text{cell}} - 25)$$
  - $$PV_{pot} = PR \cdot \frac{\text{SSRD}}{\text{s}} \cdot \frac{1}{1000}$$
  - $$\alpha \cdot A_{cell} \int PV_{pot}(t) \cdot \frac{P_{STC}}{m^2} dt$$

  where α is the projection correction factor dependant on longitude and latitude
- Comparison data (2010): [Eurostat]
  -

European Union - 27 countries (from 2020)	2 609 901.560

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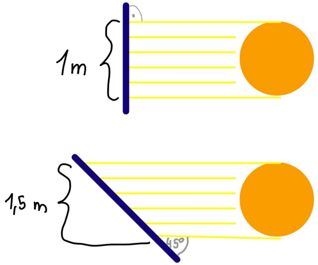
Ideal placement of panels: additional factors

- Sunlight Exposure
  - Southern European countries such as Spain, Italy, Portugal, and Greece are the best locations for installing solar panels due to direct sunlight exposure and more sunny days
- Tilt Angle Selection:
  - 0° (Flat Roofs): Rarely used; reduced efficiency due to sharp sunlight angles.
  - 10°–20° (Warm Climates): Ideal for hot regions (e.g., Southern Spain); better cooling and wind resistance.
  - 30°–40° (Moderate Climates): Optimal for regions like Poland; balanced year-round efficiency.
  - 50°–60° (Cold Climates): Best for Scandinavian areas; effective in low sunlight and heavy snow regions.
  - 90° (Vertical Installations): Rare; used on building facades.
- Panel orientation
- Local Climate
  - Temperature: high temperatures can reduced energy efficiency of the PV installation.
  - Precipitation, panels may need to be cleaned more frequently, vegetation growth
  - Wind
  - Humidity



Could we satisfy Europe’s energy need with PV?

- Europe’s annual consumption 2010: 2.609 PWh
- Assumptions to facilitate calculation:
  - Accumulation over periods of time is possible - powering over night
  - Using European union consumption data 2010
  - Using PV potential calculation from 2010
  - Using a solar panel with a max theoretical output of 237 W/m^2
  - Solar panels can be placed side by side without loss of space

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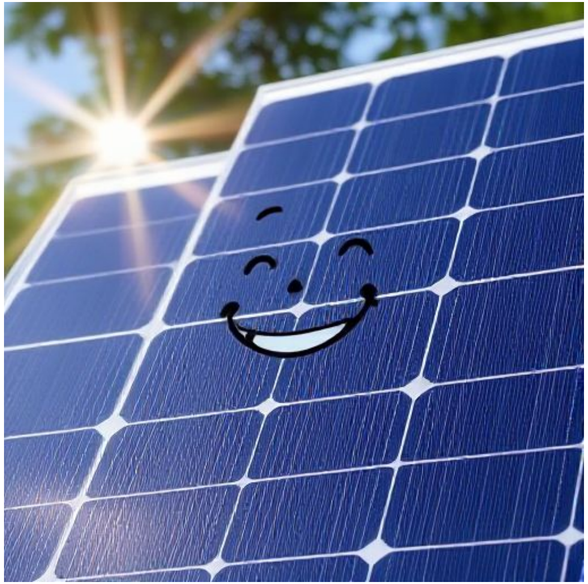
Could we satisfy Europe’s energy need with PV?

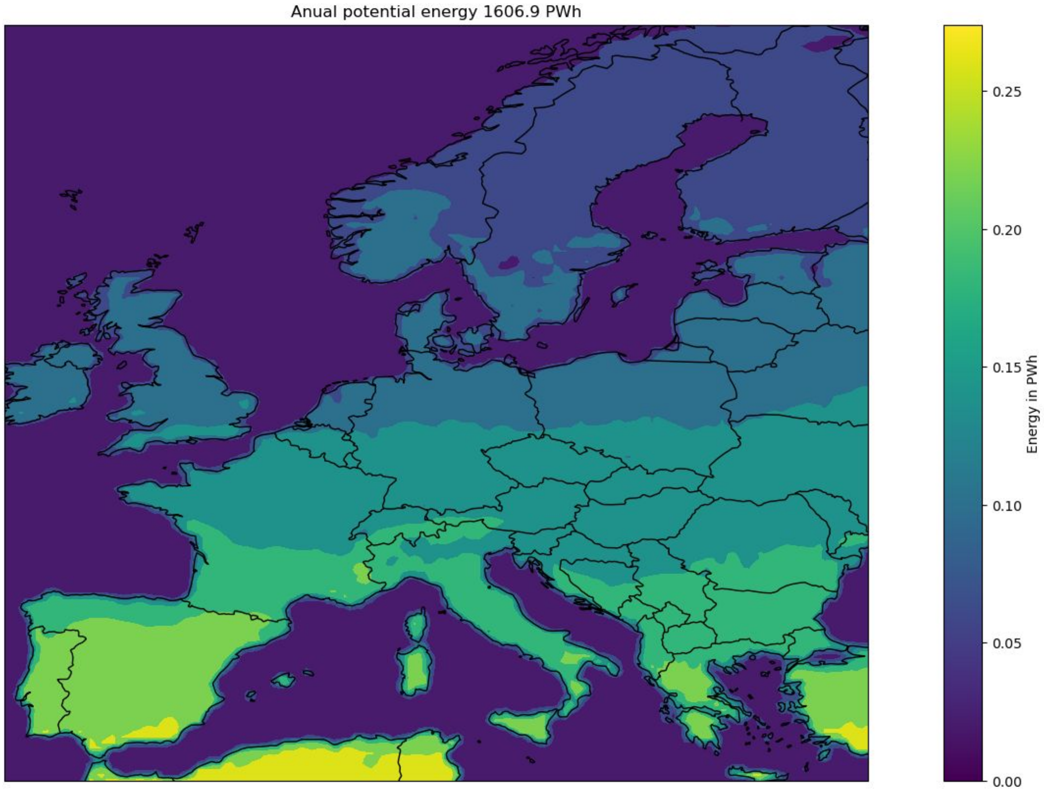
- Europe’s annual consumption 2010: 2.609 PWh
- PV production potential 2010: 1 606.876 PWh
- YES!*



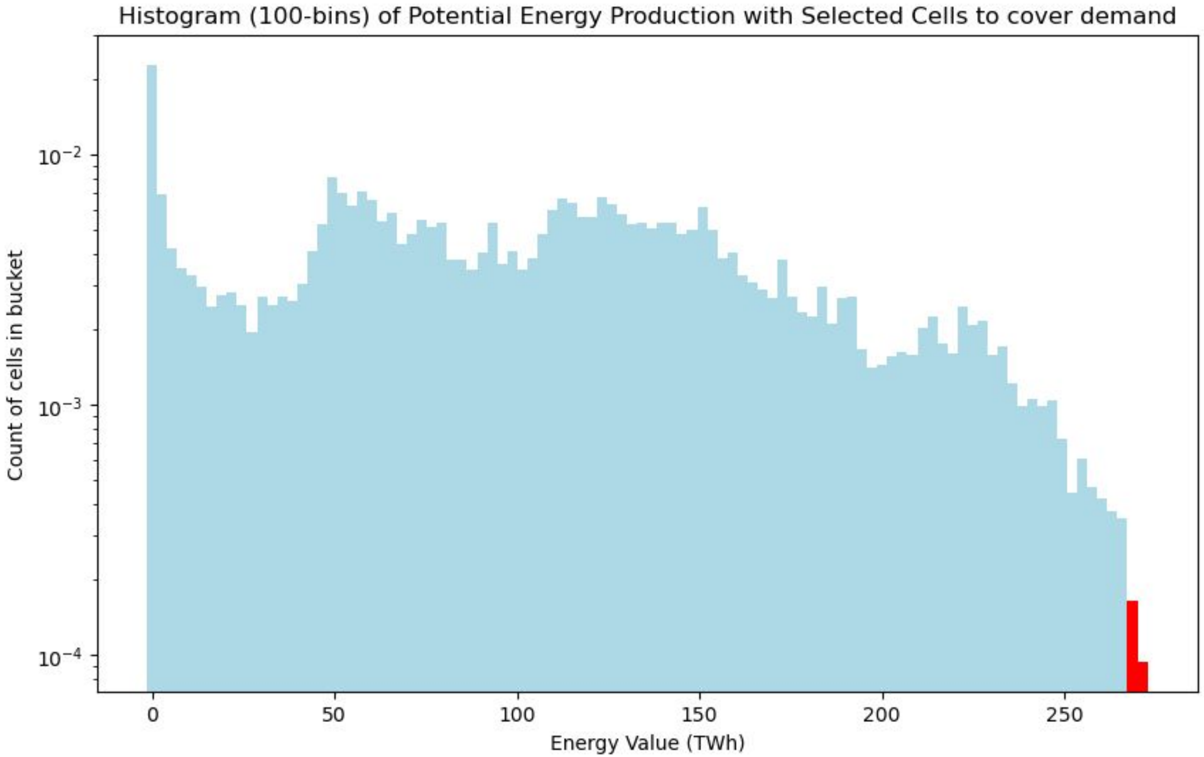
Could we satisfy Europe’s energy need with PV?

- Europe’s annual consumption 2010: 2.609 PWh
- PV production potential 2010: 1 606.876 PWh
- YES!*
- Theoretically, 0,16% of Europe’s area covered in Panels would be enough
- *BUT:
  - Huge grid losses if power production is centralized
    - additionally ~1% additional loss per 100 km
  - No energy production during the nights
  - Generally unstable energy source, leading to grid instability
  - Major monthly fluctuations

Annual PV potential



Ideal placement of panels



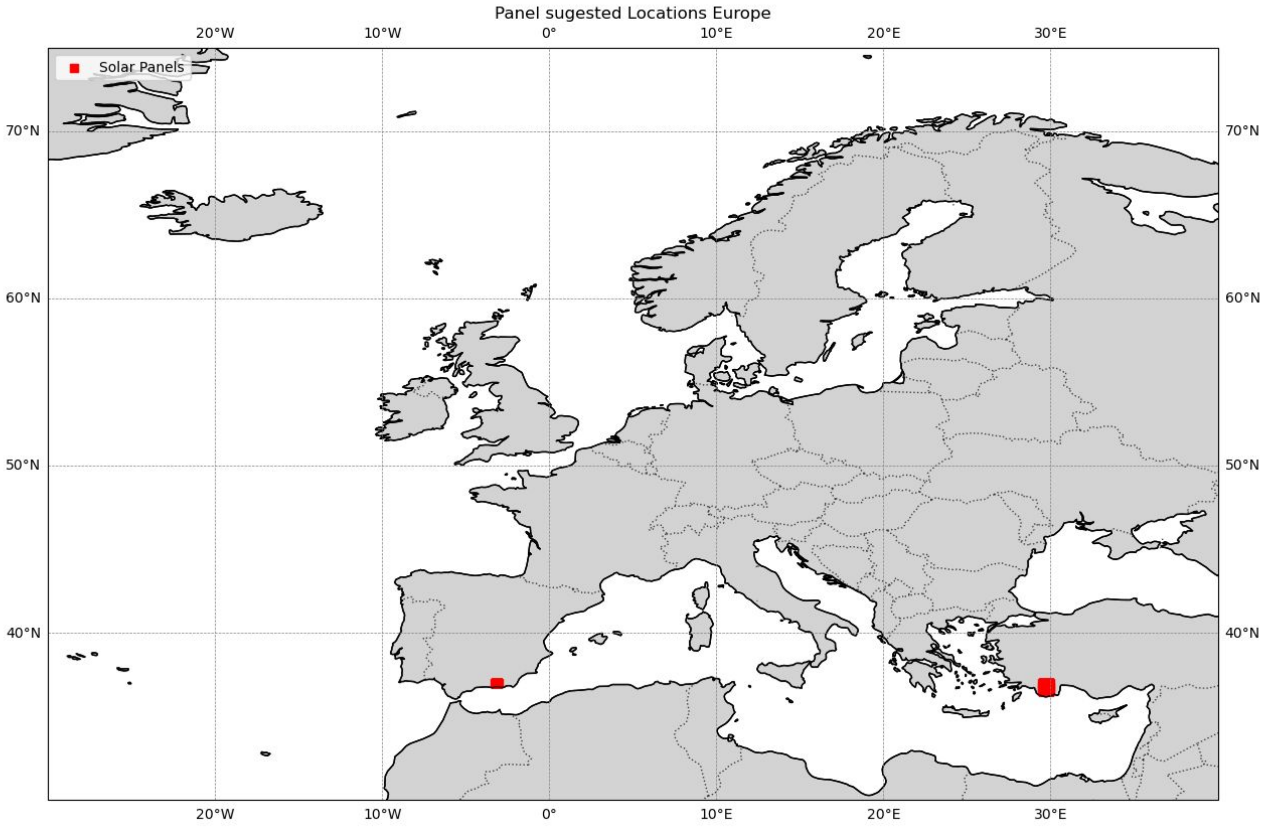
Selected cells necessary to cover 2010 energy needs

Monthly Requirements

Month	Consumption (PWh)	Percentage required
January	0.26	0.53%
February	0.23	0.30%
March	0.24	0.18%
April	0.21	0.11%
May	0.2	0.10%
June	0.2	0.09%
July	0.21	0.09%
August	0.2	0.11%
September	0.2	0.15%
October	0.22	0.24%
November	0.23	0.44%
December	0.27	0.63%

Ideal placement of panels - Mean year 2010

Adding this image as asked in class.
Some considerations: we don't count the sea, and made a mask over africa.



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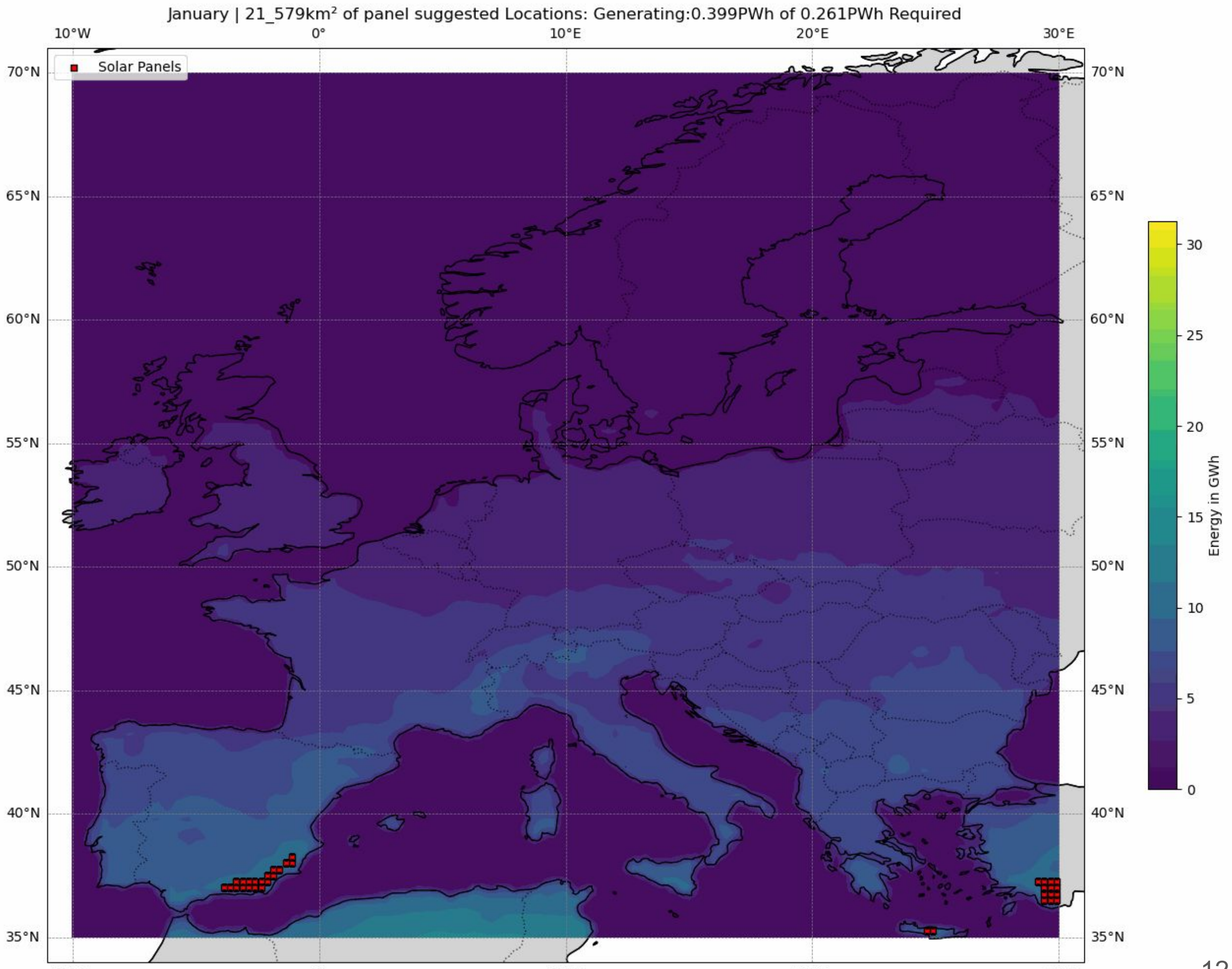
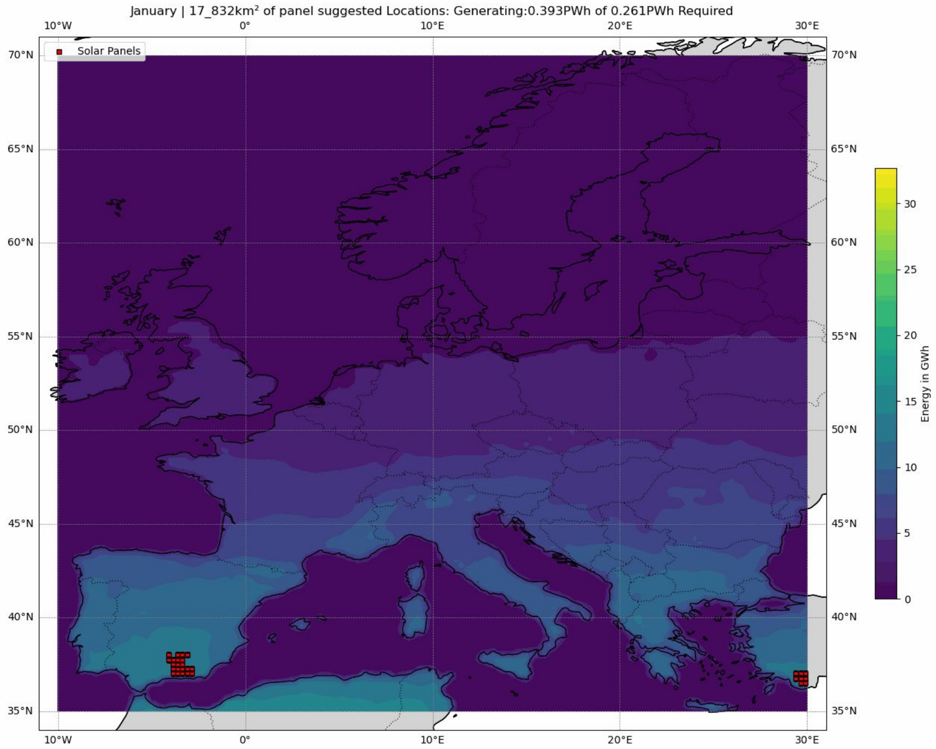
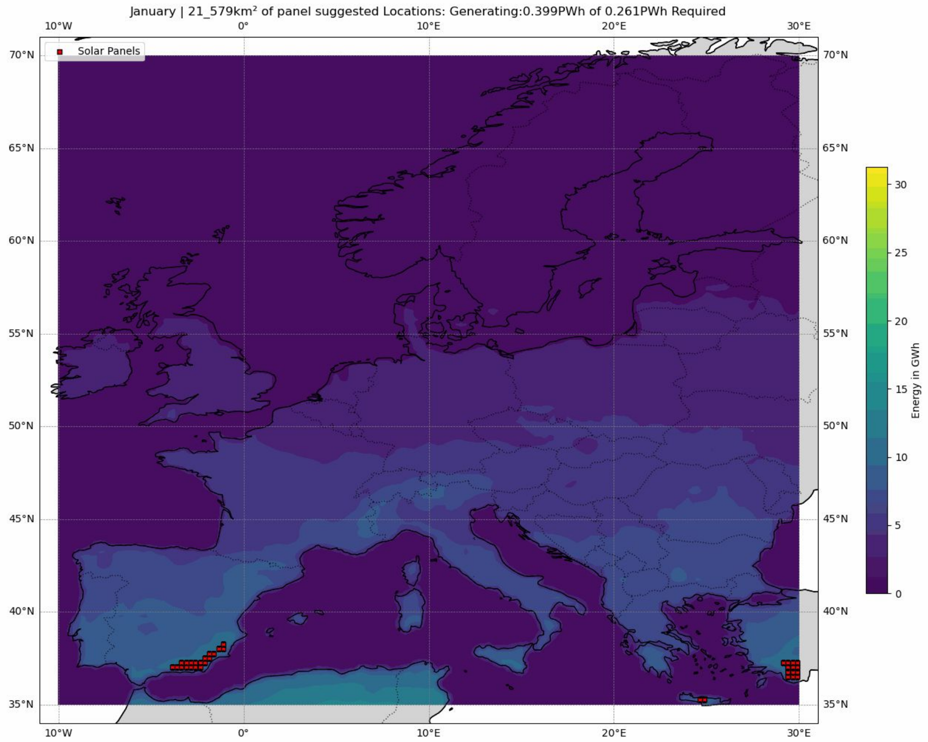
Ideal Monthly placement of panels - 1.5x energy supplied



2000



2010



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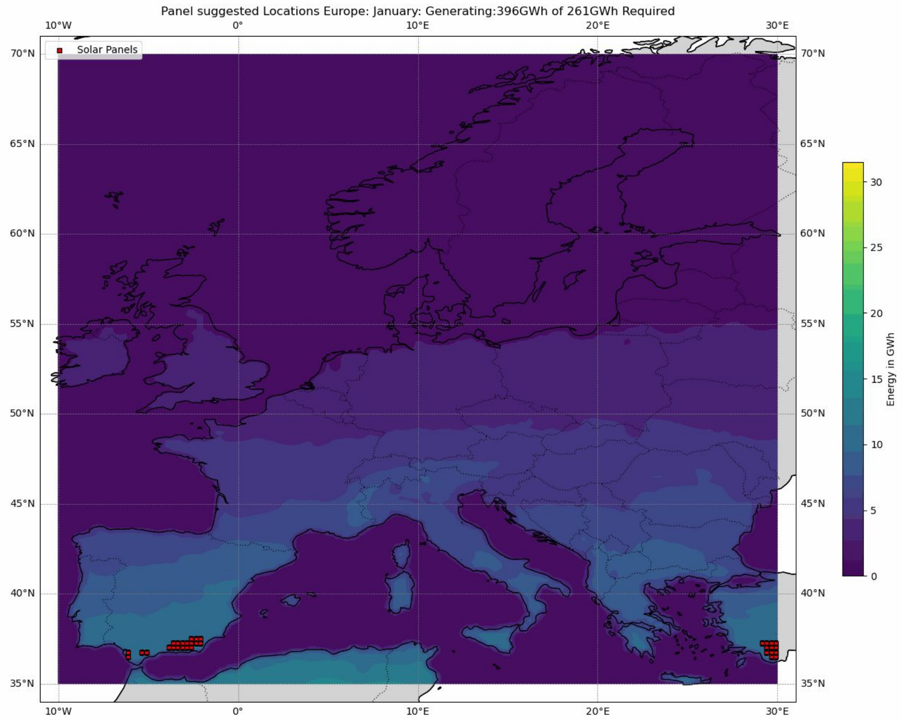
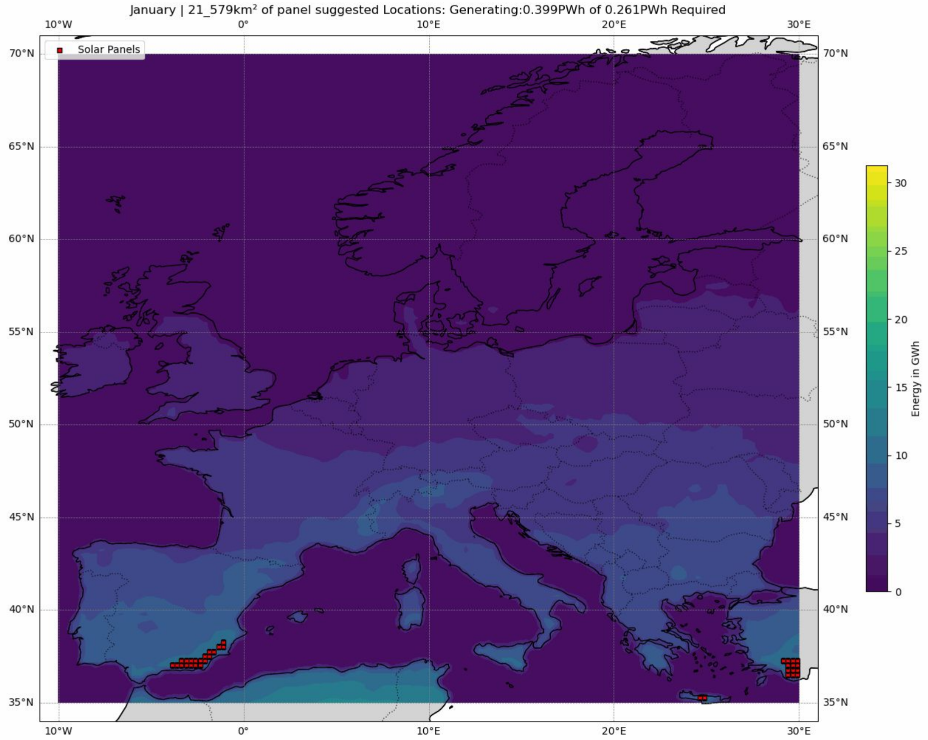
Mean 2000 - 2010

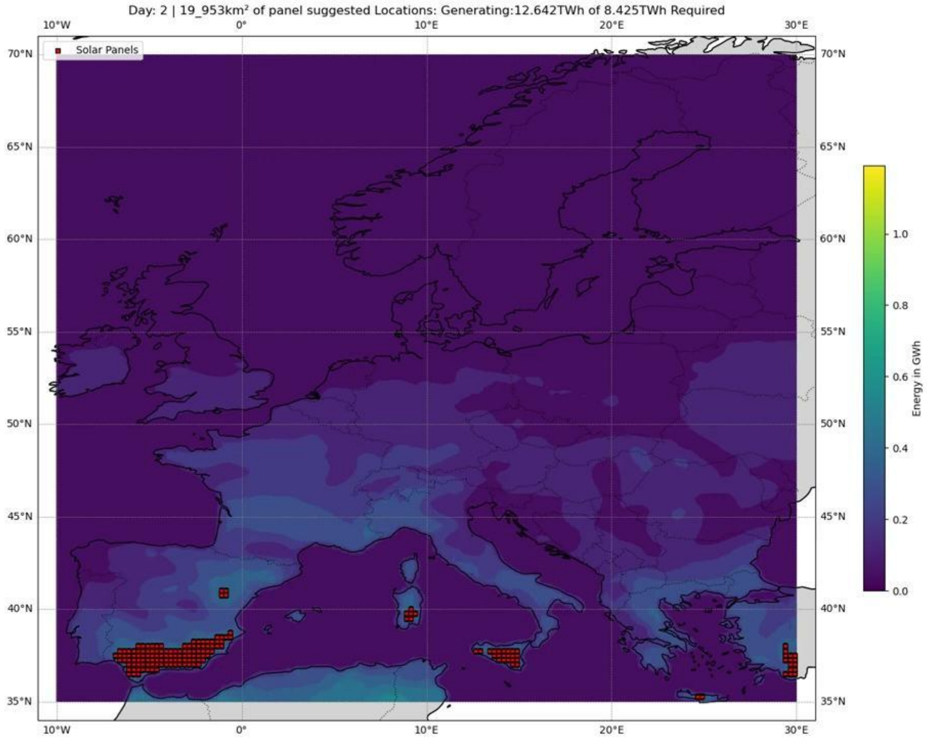


2010



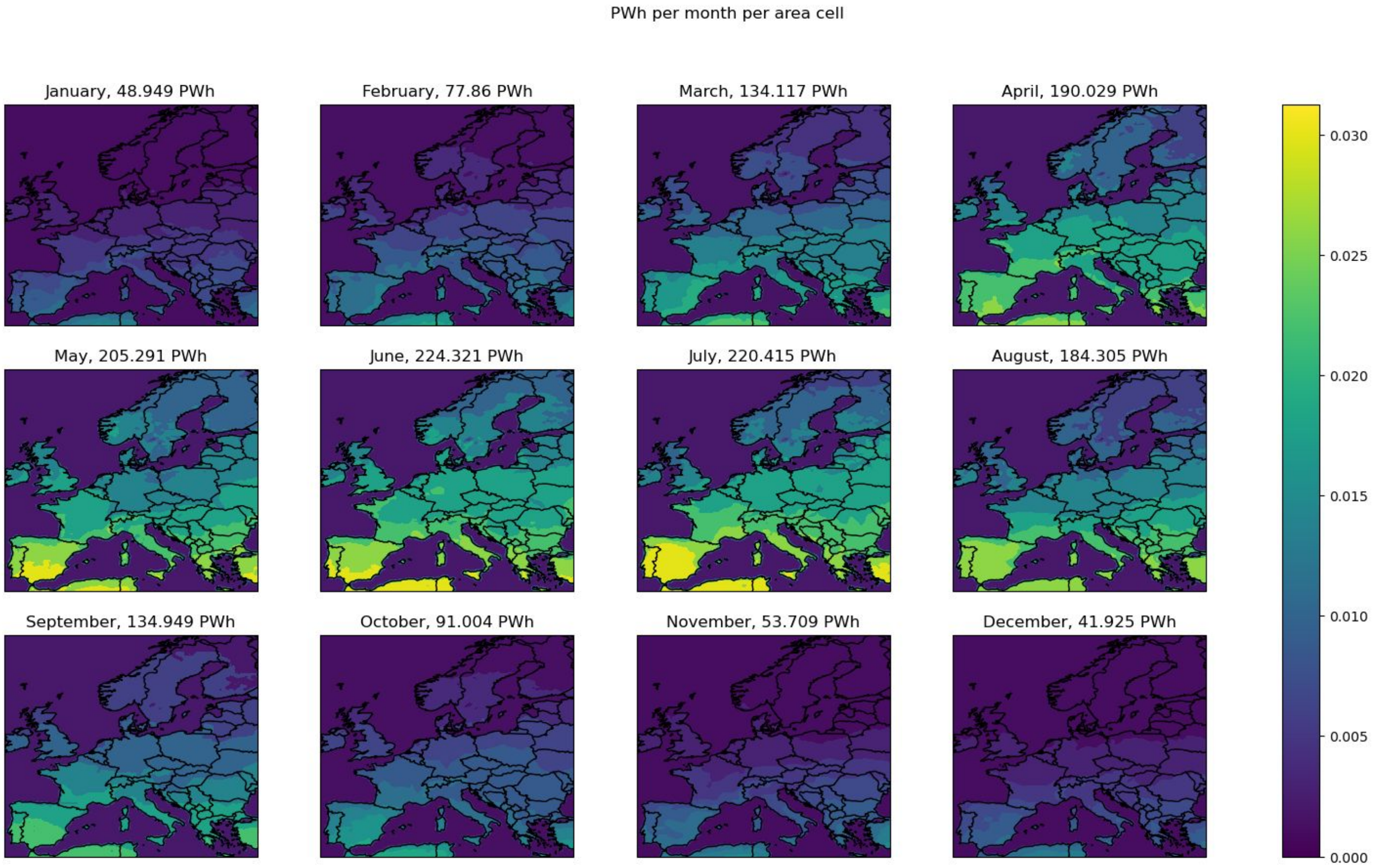
Daily, using only 20% of each cells area

Max Solar Panel Area required: 24 323 km²



Challenges

Monthly fluctuations (2010)



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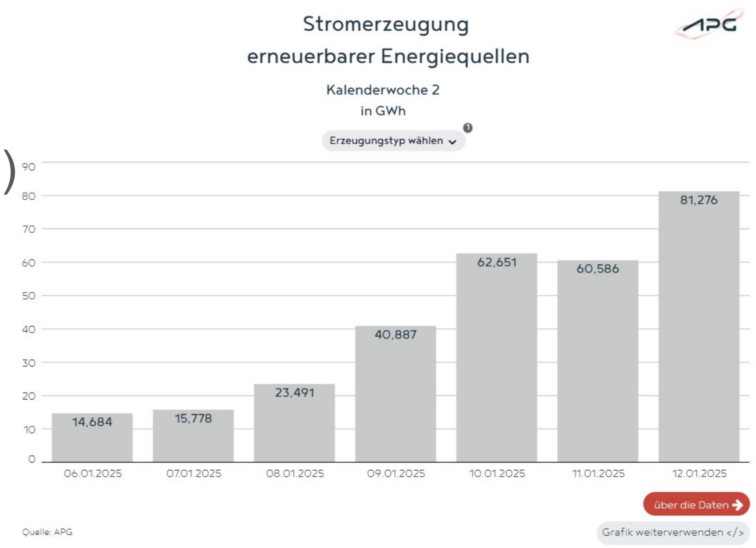
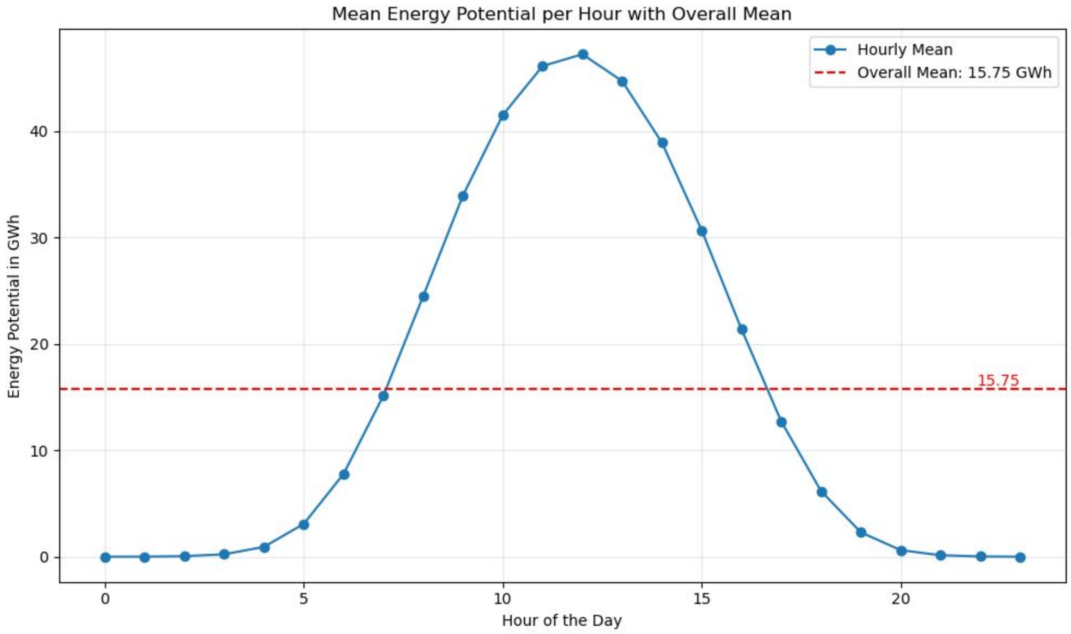
What happens if the grid is unbalanced?

- Balance of P_{out} and P_{in} essential
  - otherwise: frequency changes
- Fluctuation of renewables
- Fluctuation of consumption (Peak load times)
- Current measures to compensate
  - Pumped-storage hydroelectricity
  - Battery storages
  - Adaptive load and production - e.g. Gas, industry
- Solution: Energy storage

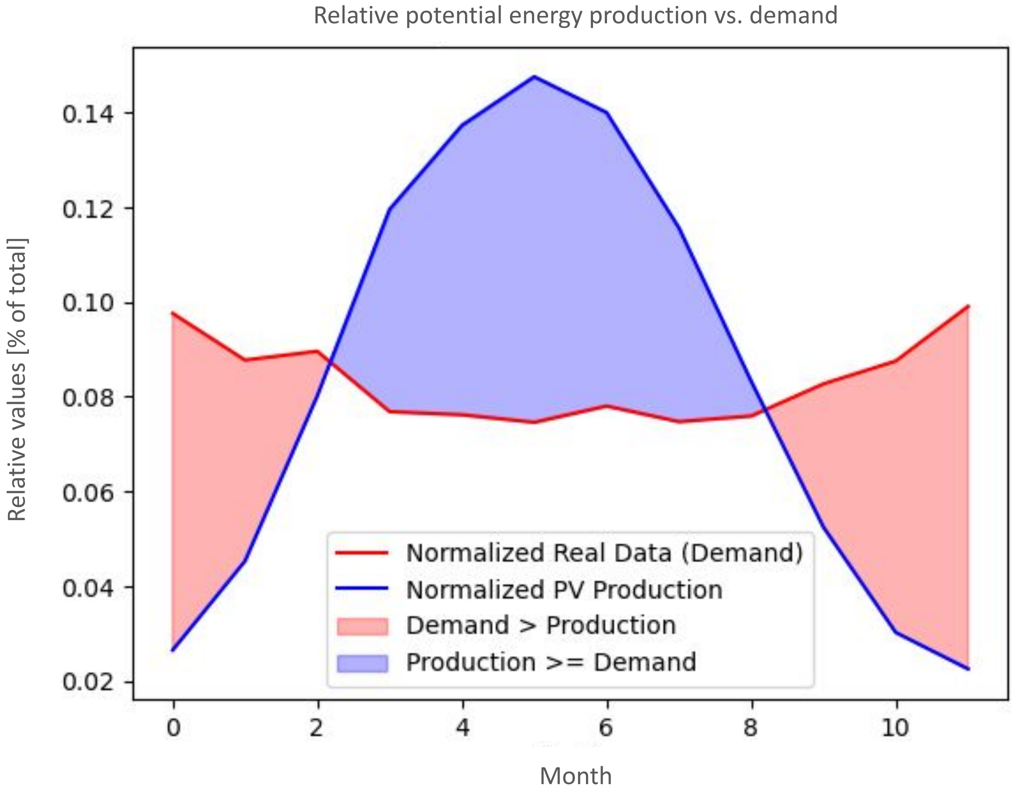


Daily fluctuations

- no production at night
- peak production around noon



Monthly fluctuations



Conclusions

- Theoretically, covering the energy need with PV is easy
- Only little area would have to be covered
  - Larger losses over larger distances
  - Larger losses if a lot of energy has to be stored
- Possible Future Work
  - Evaluation per country or subregion to account for transmission losses.
  - Account for grid losses (i.E. inverter losses, transformation losses)
  - Improve accuracy on PV generator area assumptions
    - string spacing, panel frames
    - Include generator orientation and efficiency factors
  - Account for geography
    - Exclude mountain ranges, densely populated areas, areas covered by shade
    - Include other areas of the world

Sources

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[7] Danilo Iglesias Brandão Math H. Bollen and Fernando Pinhabel. Signal Processing Of Power Quality Disturbances. Wiley-Interscience, 2006.
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[9] Peak Power Watts-PMAX. Electrical characteristics with diierent power bin (reference to 5% & 10% backside power gain) Temperature Coeecient of PMAX Temperature Coeecient of VOC Temperature Coefficient of ISC TEMPERATURE RATINGS CURVES OF PV MODULE Maximum System Voltage Max Series Fuse Rating MAXIMUM RATINGS. 2024.
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Questions?