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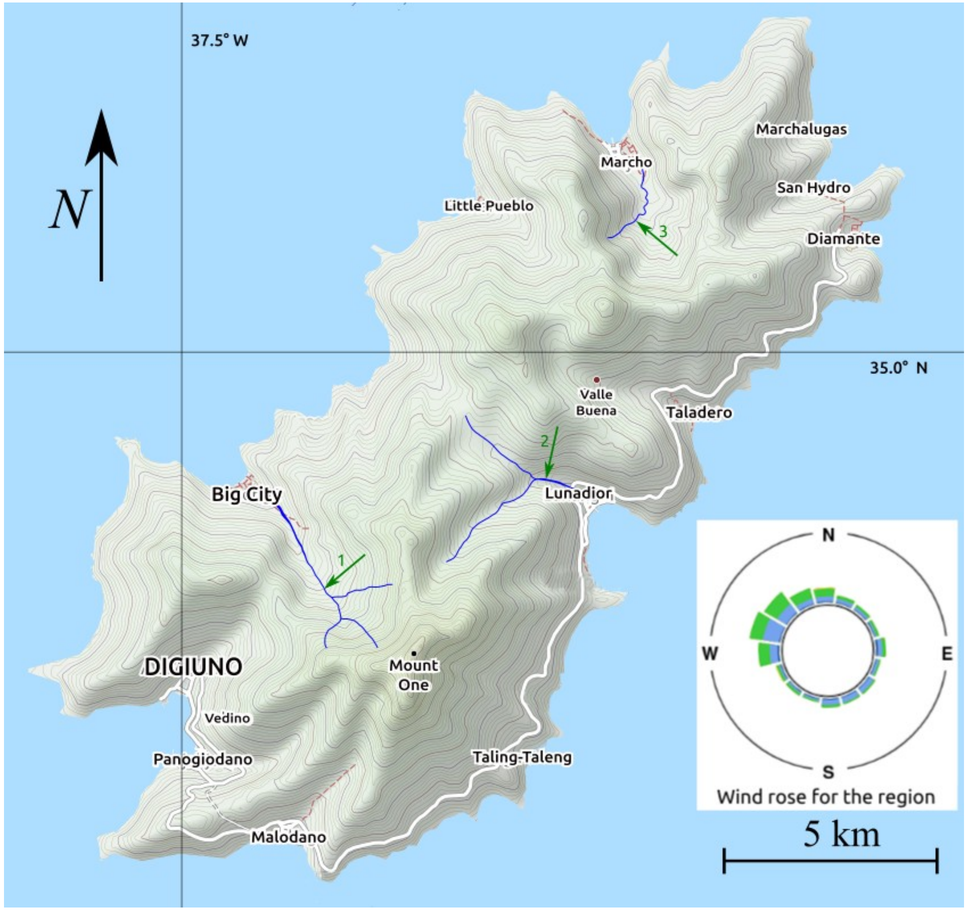
Energy Studies Project



Project

- Power up

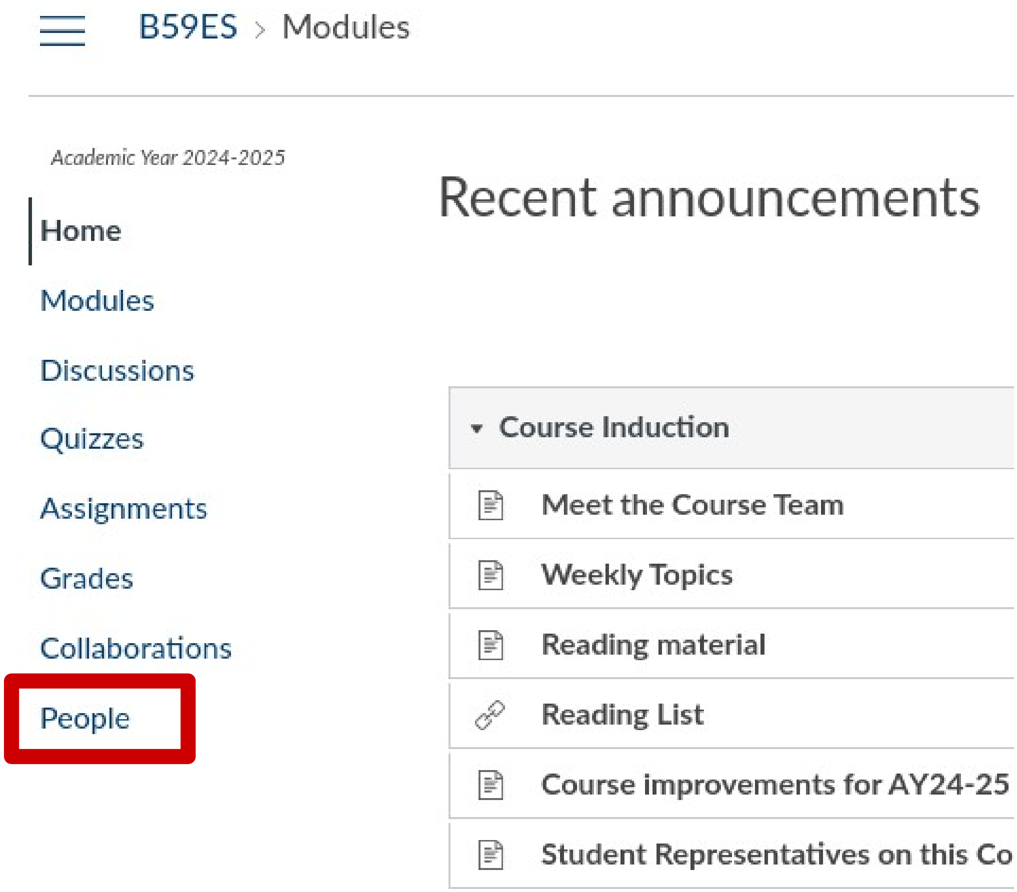
  - An isolated island far from the mainland is looking at switching to renewable-only electricity generation
  - The island is too far from the mainland and the grid to be connected, so:
    - any electricity needed MUST be generated on the island
    - all electricity generated MUST be consumed on the island

Project

- Worth 30% of the total course marks
- There will be further guidance sessions during the semester
  - check local schedule
- It's a Group project with Peer Assessment
  - details at the end of this presentation

Enrol to a group

- Visit the People page
- Add yourself to a group in your campus



Sign up for a group

- After this class, within 10 days
- Until the deadline, you can move around groups:
  - remove yourself from the old one
  - add yourself to the new one (drag&drop?)
- After deadline (Fri, 31st Jan), we'll lock the groups: you won't be able to change any more (it would disrupt group work)
  - Any "loose" student will be allocated to a group with vacancy

Intended Learning Outcomes

- Handling and Manipulation of large data sets
- Know how to calculate electricity output of different RE technologies for given resources
- Know how electricity grids work:
  - knowledge on balancing mechanisms
  - matching electricity demand and supply in small grids

Intended Learning Outcomes

- Analytical Skills and deep learning
  - Awareness of challenges associated with renewable electricity generation
  - Awareness of function of electricity grids and challenges for small electricity grids
  - Working knowledge of energy storage technologies (by selection and sizing)

Data Available

- Map of the island (location, hydrology and orography*)
- Resource datasets for
  - Load (i.e. demand to be satisfied)
  - Wind
  - Solar
  - Hydro

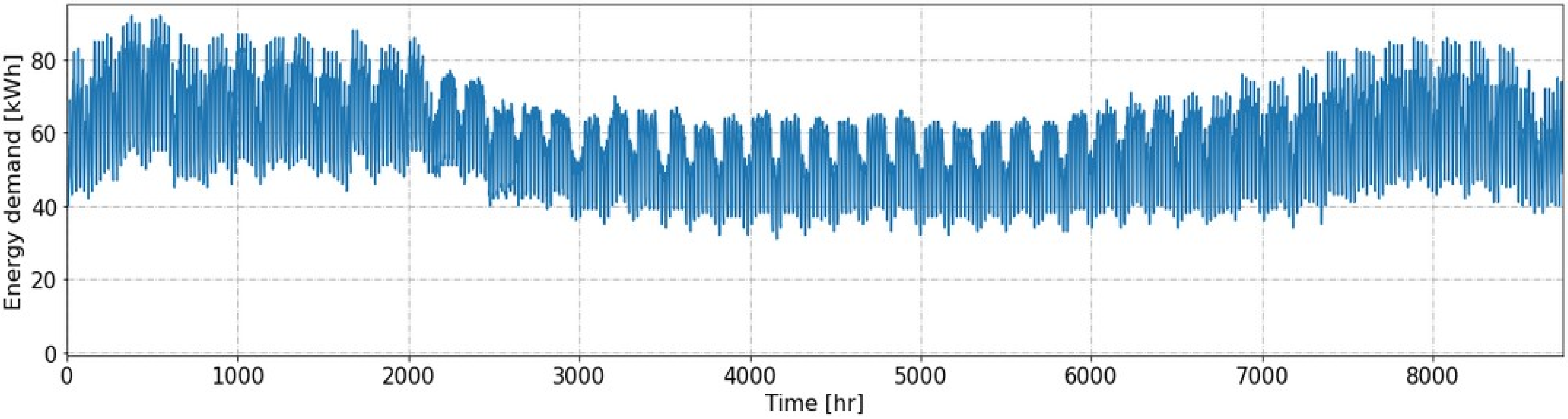
* the height of land, shown by contour lines on the map

Information on the islanders

- Islanders are environment-aware and very keen on transitioning away from 100% generation from diesel (*status quo*)
- The cost of electricity on the island is currently about 2~3 times the cost in mainland Spain
  - use this as a reference when costing your solution
- islanders are used to energy regulation:
  - they would comply with reasonable Demand Side Management requests

Electricity demand (load)

- Total load power, averaged over 1-hour intervals, looks like:
  - make a better plot
  - analyse trends and patterns



Load Data

- How do you calculate the yearly demand?
  - 87 **kW** average **power** between 9:00 and 10:00?
  - 87 **kWh** of **energy** used in that hour
  - sum them all together
- but also keep a running total: energy must be delivered when needed

$$E(h)=\int_0^h P(t)\cdot dt \quad \text{or} \quad E(h)=\sum_{i\leq h} P_i \Delta t$$

Wind

Wind turbines

- Resource pack contains
  - Power curves of 3 different wind turbines
    - you are free to find others on the web
  - Hub heights of turbines
  - Hourly wind data taken at 10 m height
- Worked example: 20 kW turbine

Worked example

20 kW wind turbine from resource file

- Rotor diameter 11.35 m => A ~ 101 m²
- Density of Air = 1.23 kg/m³
- Wind speed from file (not corrected for hub height)

Power curve

- Kinetic power in the wind:

$$P = \frac{1}{2} \times \rho \times A \times U^3$$

  - ρ = density of air (1.23 kg/m³, affected by Temp and Humidity)
  - A = swept area of the turbine in m^2
  - U = wind speed in m/s

What is the power output?

Hour	U [m/s]	Wind Power [kW]
1	9.3	51
2	8.6	40
3	7.8	30
4	7.1	22
5	5.9	12
6	4.6	6
7	3.4	2
8	3.7	3
9	4.0	4
10	5.7	12
11	6.8	19
12	11.0	82
Energy in 12 hours [**kWh**]		**283**

Ask yourself:

- Can all the wind power be extracted?
  - what would happen if we took **all** the kinetic energy from the moving air mass (i.e. wind)?
  - can anything be 100% efficient?
  - Hint: What is the rated power output of the turbine?

Let's be more realistic…

- Actual maximum power output

$$P = c_{Betz} \cdot \frac{1}{2} \cdot \rho \cdot A \cdot U^3$$

- Betz limit: 59 %

Yet more realistically …

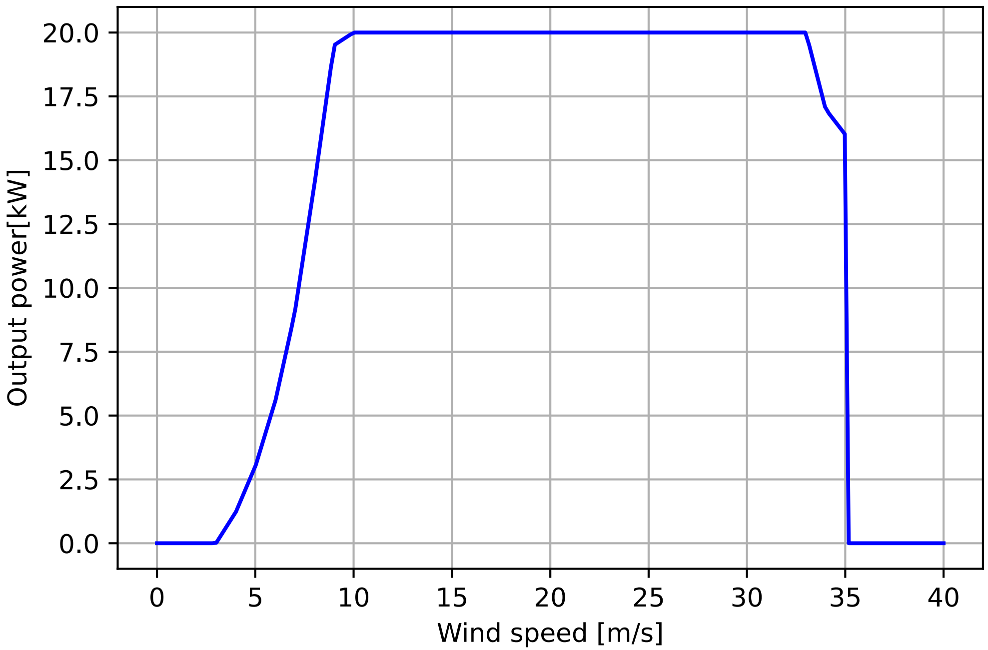
- Actual maximum power output

$$P = \eta \cdot c_{Betz} \cdot \frac{1}{2} \cdot \rho \cdot A \cdot U^3$$

$\eta < 1$

- and still, this equation says that the power will grow indefinitely as the wind speed increases. Possible??

Power curve (found in datasheet)

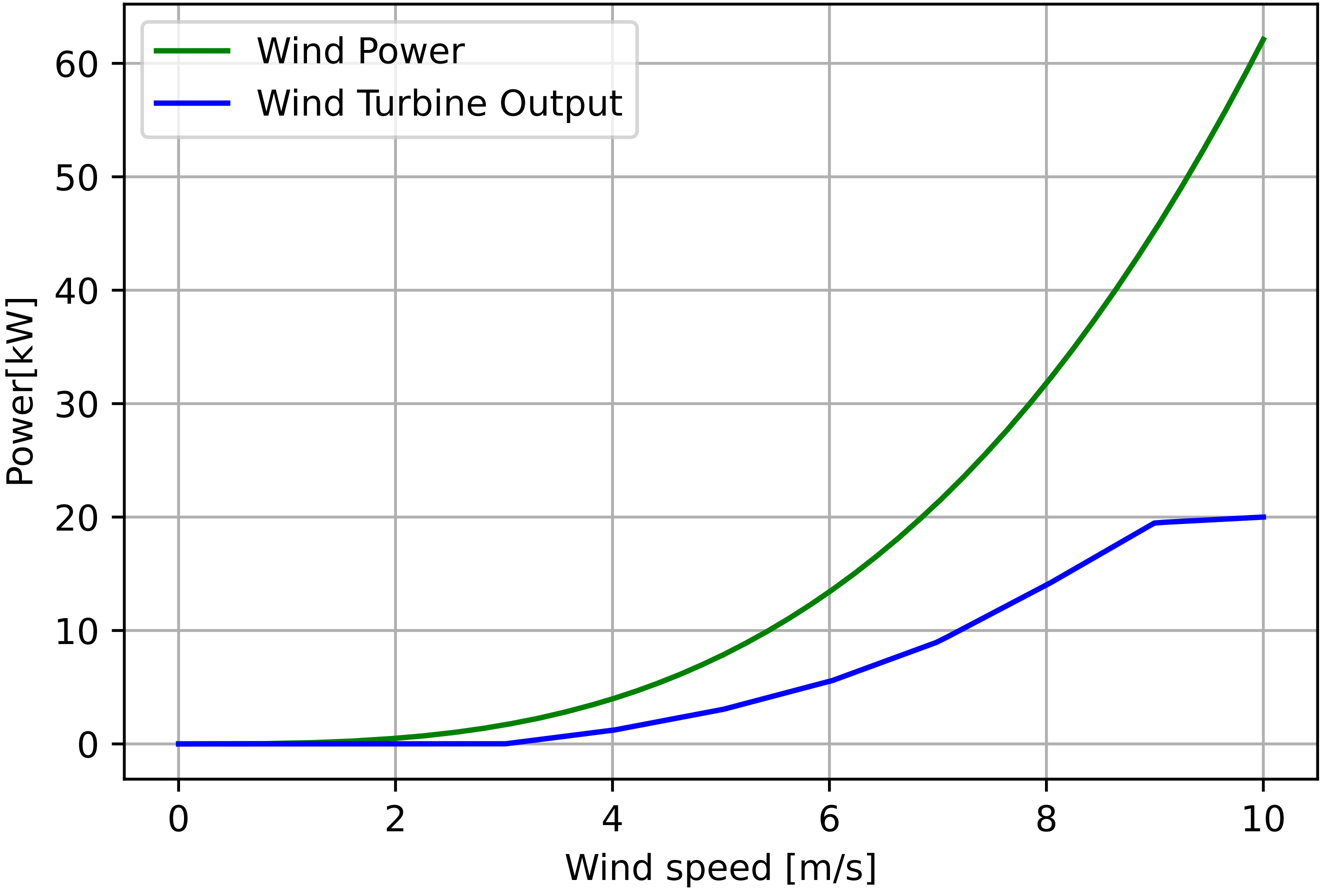


- (large) wind turbines adjust the pitch of the blades with wind-speed
- they apply brakes and stop if wind speed too high (self protection)
- you should spend some time selecting the best turbine for your location

Output using wind turbine power curve:

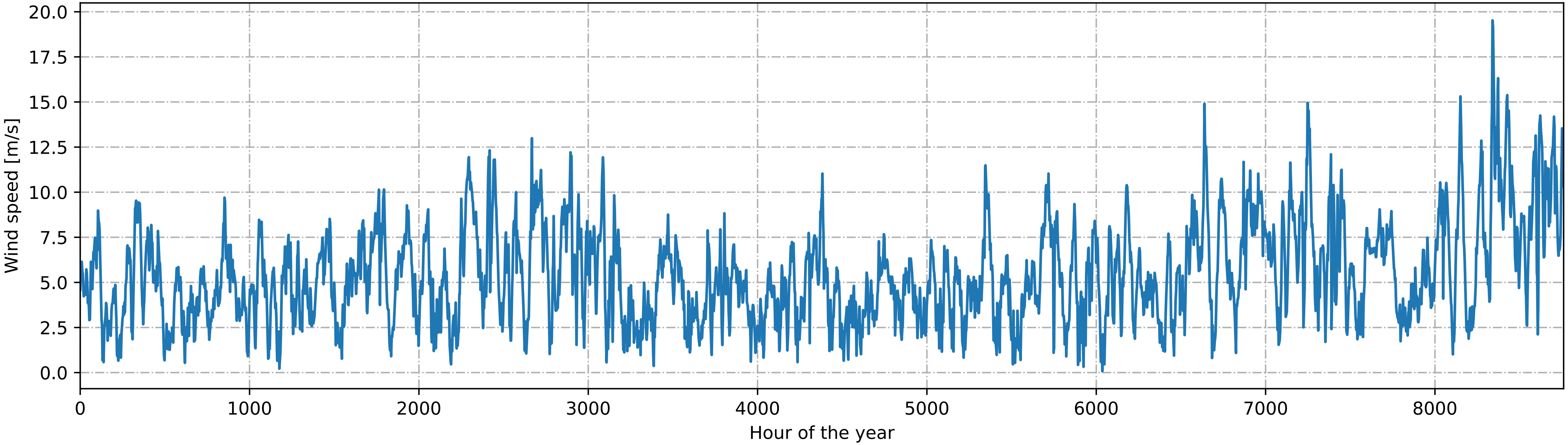
Hour	U [m/s]	Wind Power [kW]	Betz Power [kW]	Power factor	Actual Power Out [kW]
1	9.3	51	30	0.975	19.5
2	8.6	40	23	0.7	14
3	7.8	30	18	0.45	9
4	7.1	22	13	0.45	9
5	5.9	12	7	0.15	3
6	4.6	6	4	0.06	1.2
7	3.4	2	1	0	0
8	3.7	3	2	0	0
9	4.0	4	2	0.06	1.2
10	5.7	12	7	0.15	3
11	6.8	19	11	0.275	5.5
12	11.0	82	48	1	20
Energy in 12 hours [kWh]		283	167		85

Power input vs. power output



Wind dataset

- A year of wind data plotted with 1-hour resolution
  - another stochastic plot with little information…



Yearly energy generation

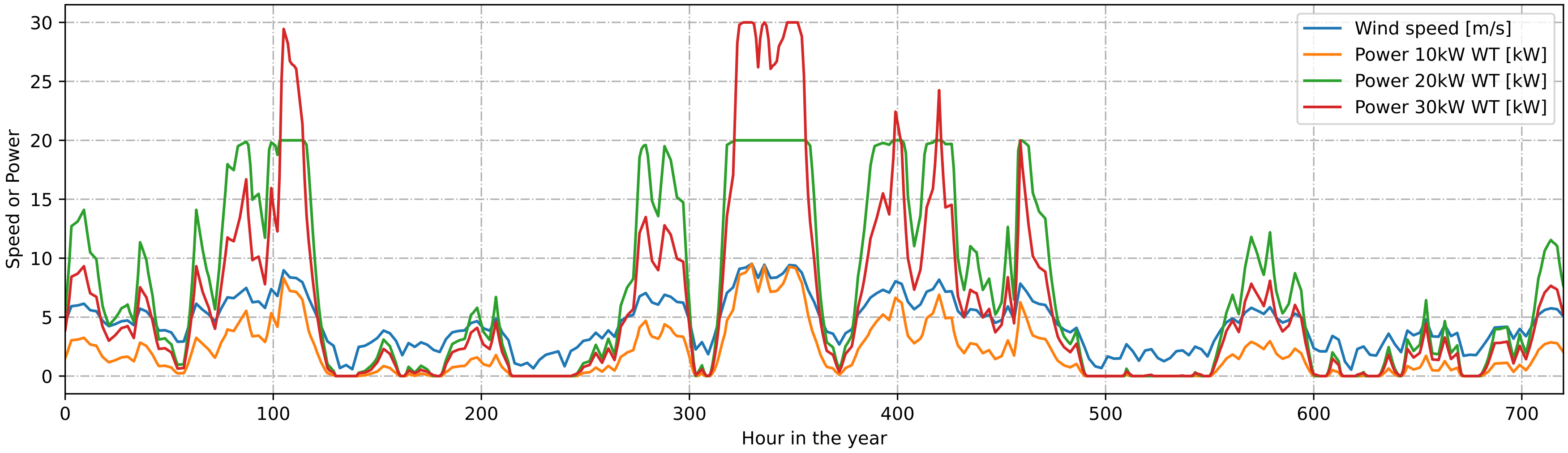
- (At least) two ways to go about it:
  - the interpolation way
  - the bins way

Interpolation Approach

- Flexible, powerful, fast to repeat/reproduce:
  - get MATLAB to interpolate (`interp1, spline,...`) the turbine performance curve
  - get, for all points in the time series, $P_i = P(v_i)$
  - numerically integrate (e.g. `trapz`): $E = \Sigma\, \Delta t \cdot P_i$
- Bonus: cumulative generation easily calculated (`cumtrapz`)
- I strongly advise to use a computational s/w like MATLAB: it'll save you a lot of time in the long run

With interpolation

- With MATLAB and similar s/w, plots like this are very quickly made
- Takes some effort to get started, but quick, powerful, flexible and … the right way to work for an engineer



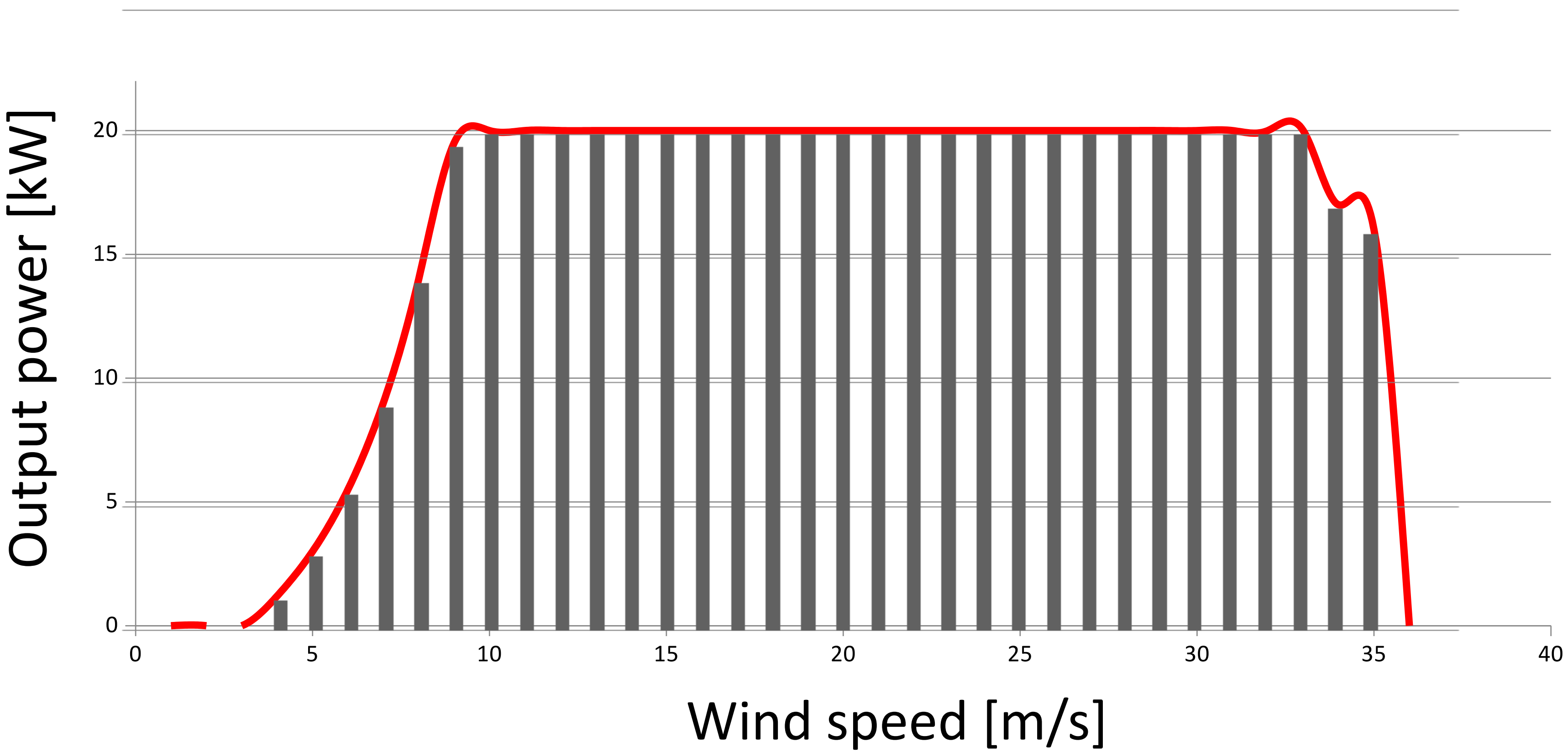
This plot made with matplotlib and python in a jupyter notebook. Ask me more …

this and other plots are not for the same data you are given

Bin Approach

- Take the timeseries: wind speed vs. hours in the year(s)
- Build a Histogram
  - Create equal bins for wind speed, e.g. [0, 0.2), [0.2, 0.4), etc.
  - For each bin, count how many hours have a speed within it
  - Should look like a Weibull
- Then work on the power curve of the wind turbine:

Bin Approach



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Wind Power Output

If P_i = power corresponding to midpoint of i^{th} wind speed bin (given by WT power curve), energy output of WT over the time interval is for *n* bins

$$E = \sum_{i=1}^{n} P_i \Phi_i$$

where Φ_i is the total time (hours) in which that speed was recorded (i.e. height of that bin in histogram)

Wind calculation - Bins

- Origin
  - Copy data to Origin
  - "Select Plot: 2D: Histogram: Histogram or click the Histogram button on the 2D Graphs menu"
- Excel (not recommended):
  - "Install Analytical tools" add-in if missing
  - Make Histogram
- MATLAB and matplotlib can also make histograms!

Wind power output

- Availability:
  - % of time when WT is actually available to produce power (typically 95-99%), i.e. not broken down or undergoing maintenance
- Capacity factor:
  - ratio of energy generated in a given time period to energy produced if WT ran at rated power over that same period (typically 25-30%)
  - e.g. DTI survey of small WTs in urban areas found that they had capacity factors of 5-7%; it's much better for wind farms (>30%)

One sure way to get it WRONG

- Take the average <U> of wind speeds in the year, or month, or week, or …
- apply formula:

$$P=\frac{1}{2}\cdot\eta\cdot c_{Betz}\cdot\rho\cdot A\cdot\langle U\rangle^{3}$$

or look up this value <U> in the power curve for the turbine

- Why will these <u>NOT</u> work?

Why that approach is WRONG

- It's wrong because the function *P(U)* is not linear. Counterexample:

$$P = k\,U^3$$

$$U_1 = 1 \quad P_1 = k$$

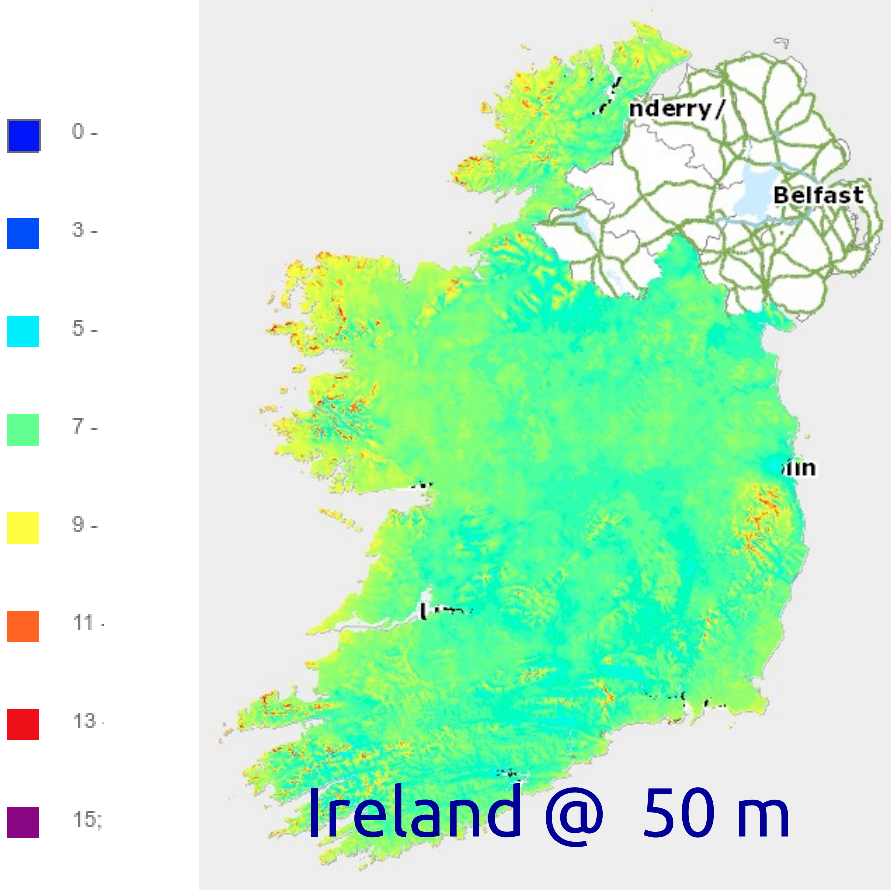
$$U_2 = 5 \quad P_2 = 125\,k$$

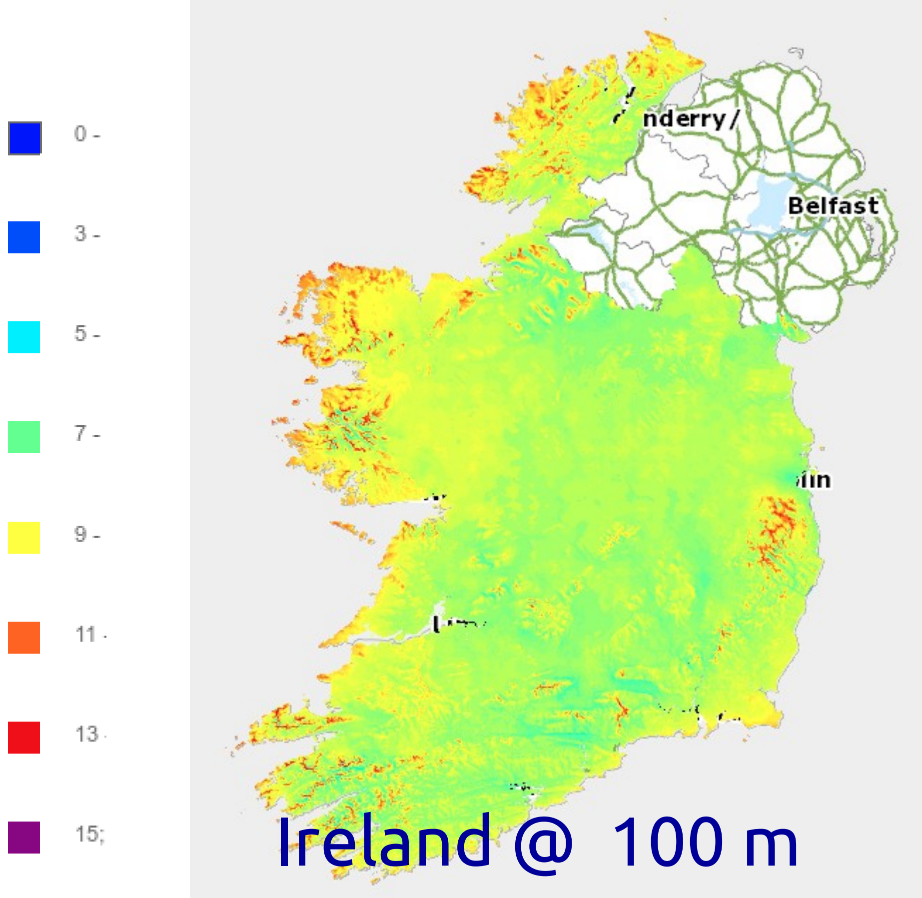
$$\langle P \rangle = \frac{P_1 + P_2}{2} = 63\,k$$

$$P_{\langle U \rangle} = k \langle U \rangle^3 = 27\,k$$

WRONG!

Remember to correct for height

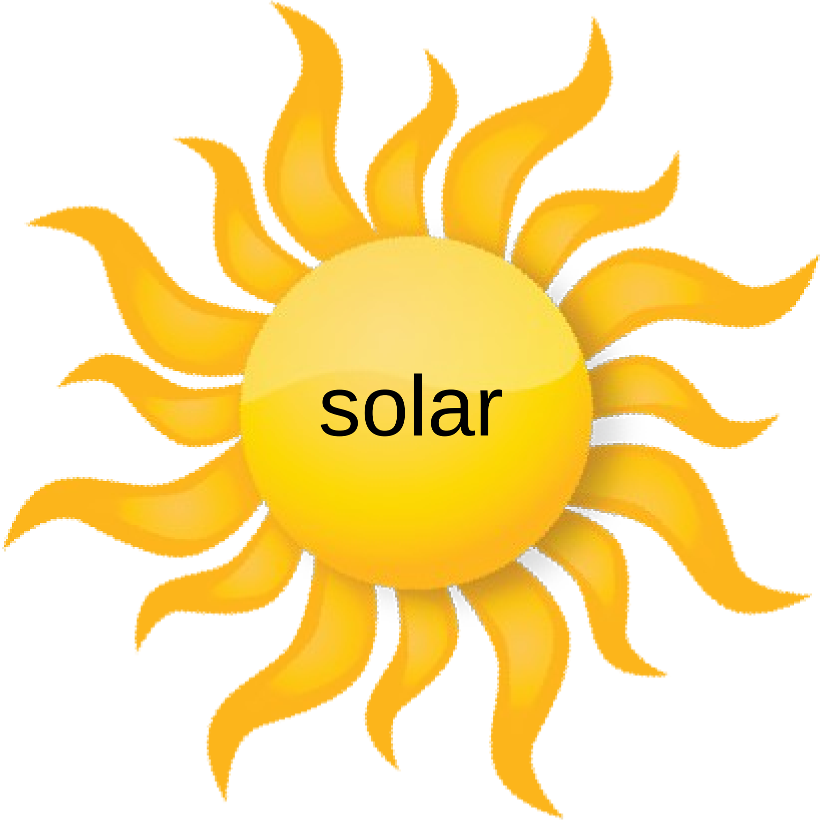




http://maps.seai.ie/wind/

General considerations

- Interpolation technique:
  - arguably more accurate
  - calculates hour-by-hour energy generation
    - useful for selecting storage
    - but for past years: each year is different
- Bin technique:
  - simple (possibly tedious) procedure
  - no information about <u>when</u> energy is generated
    - could repeat procedure in each month for more granularity


solar

Solar generation

- PV is your friend (CSP not feasible on Monkey Island)
- The main “micro” aspect of the solar resource that needs to be considered is shading:
  - path of sun across the sky – e.g. what happens early in the morning in mid-summer for PV panels facing directly south?
  - shading from other buildings, trees, etc
  - seasonal variation
- Use the topographic map of the island to decide on siting

Orienting panels

- Usually the orientation that gives the max energy over the year is
  - due South
  - tilt = latitude
- However, if more tilted you get more in winter (and less in summer)
  - may help satisfy demand in winter and balance your grid

Solar irradiance

- Three components of solar irradiance on your panels [W/m²]
  - G_b = beam (direct): the most powerful one, the one that makes the difference between sunlit areas and shadows
  - G_d = diffused irradiance: reaches the shadows as well; due to diffusion of sunlight by atmosphere (i.e. sky is blue not black)
  - G_r = reflected irradiance: light reflected by the surfaces the panel "sees"; zero if it's horizontal, but can be a few % of G_b if tilted
  - G total irradiance: the sum of all relevant components above

Calculating solar irradiance

- Dataset provides irradiance (G_b and G_d) on several planes but also the Sun height (H_{sun} or α)
  - you can calculate G_b on your panel:

$$G_b(\beta)=G_b\frac{\sin(\alpha+\beta)}{\sin\left(\alpha+\frac{\pi}{4}\right)}$$

  - then add the diffused irradiance G_d

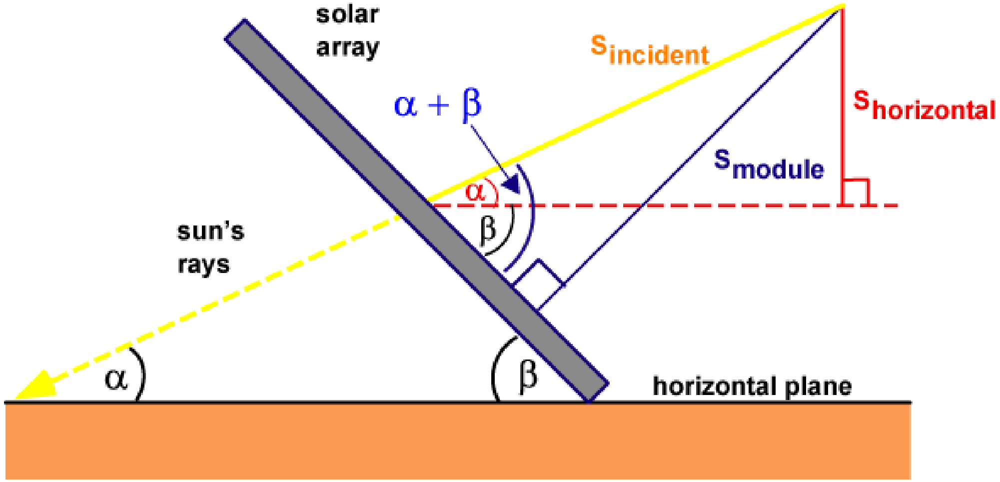


Figure from https://www.pveducation.org/

Calculating solar power

- PV panels are specified by the power they output under standard conditions (STC)
  - a 420 W_p panel generates 420 W under a total irradiance of 1 kW/m^2
- So you get the generated power simply:

$$P_{electr} = P_{STC} \cdot G(\beta)$$

- Not perfect:
  - you may overestimate generation by 10% ~ 15% over the year
  - much more when the sun is far from South (i.e. early AM & late PM)

Don't forget losses

- Many sources of losses
  - dirt on the panel (region, climate, maintenance, …)
  - losses in inverter (conversion DC→AC) and transmission
  - losses due to ageing (panel efficiency drops ~0.5 %/year)
- Good info on solar:
  - https://www.pveducation.org/
  - https://ec.europa.eu/jrc/en/PVGIS/docs/methods

Alternative approach

- An alternative way to calculate solar energy generation is to use a simulation software. Please note:
  - many are commercial: you may get a limited trial version
  - we don't know them all → limited support in their use
  - necessary for solar-tracking installations (not advised)
  - be careful not to trust whatever a model spews out!
    - advice: run the calcs on data given, and compare
- PVGIS is good but won't have data for the exact location
- Here a curated list of PV modelling software

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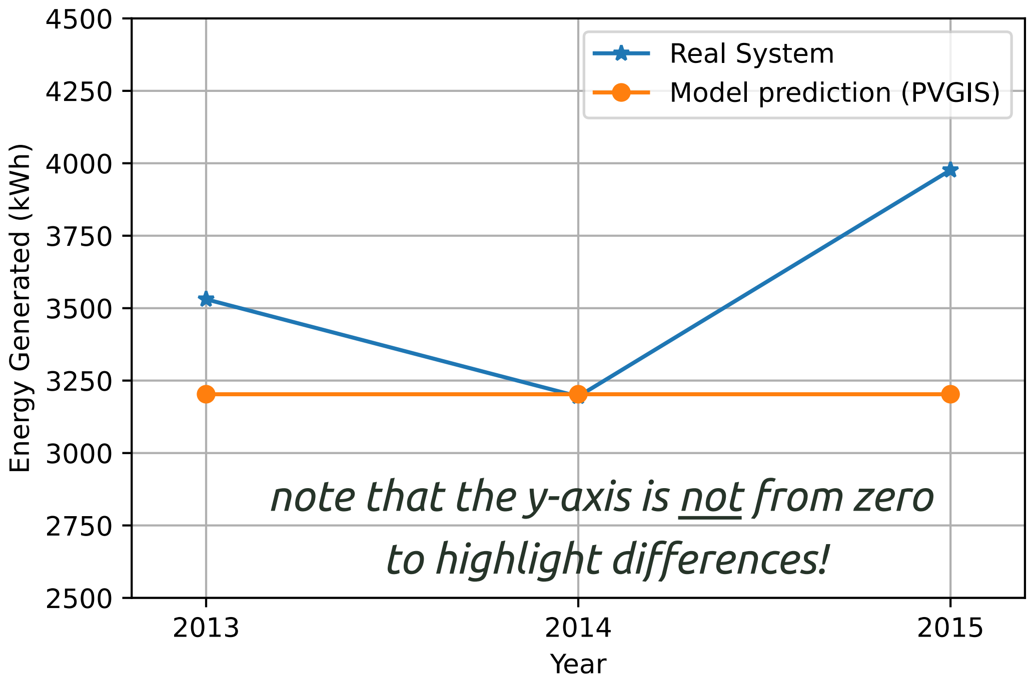
How trustworthy are simulations?

- It depends:
  - on the data you input
  - on the modeller
  - predictions are still at the whim of the climate



Plot compares data provided by a colleague in south Scotland (4 kWp on roof) with results from a modeller (14% losses, same orientation+location)


WATER

Hydrological resources

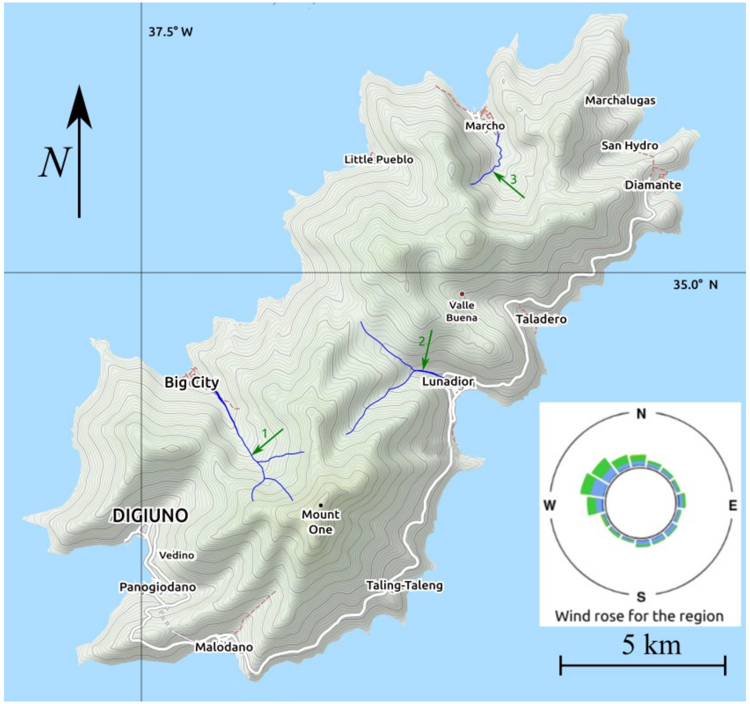
- Monkey Island has 3 rivers suitable for hydroelectric generation
- For ecological reasons, inhabitants have placed constraints on any hydro plant:
  - no more than one per river
  - no dams; weirs are ok
  - if fish-friendly (e.g. Archimedes' screw), can take 50% of river flow
  - otherwise (e.g. in ducts) max 10% of flow

Hydroelectric generation

- Hydro power is obtained via turbines (similarity with wind: kinetic energy of moving fluid)
- Power in water flowing downhill: $P = \eta \rho \dot{Q} h g$
  - η efficiency (very high for turbines in correct conditions)
  - ρ density (~1000 kg/m^3) ← this is GOOD news !
  - Q flow rate [m^3/s]
  - h head, vertical distance water flows (include head losses here!)

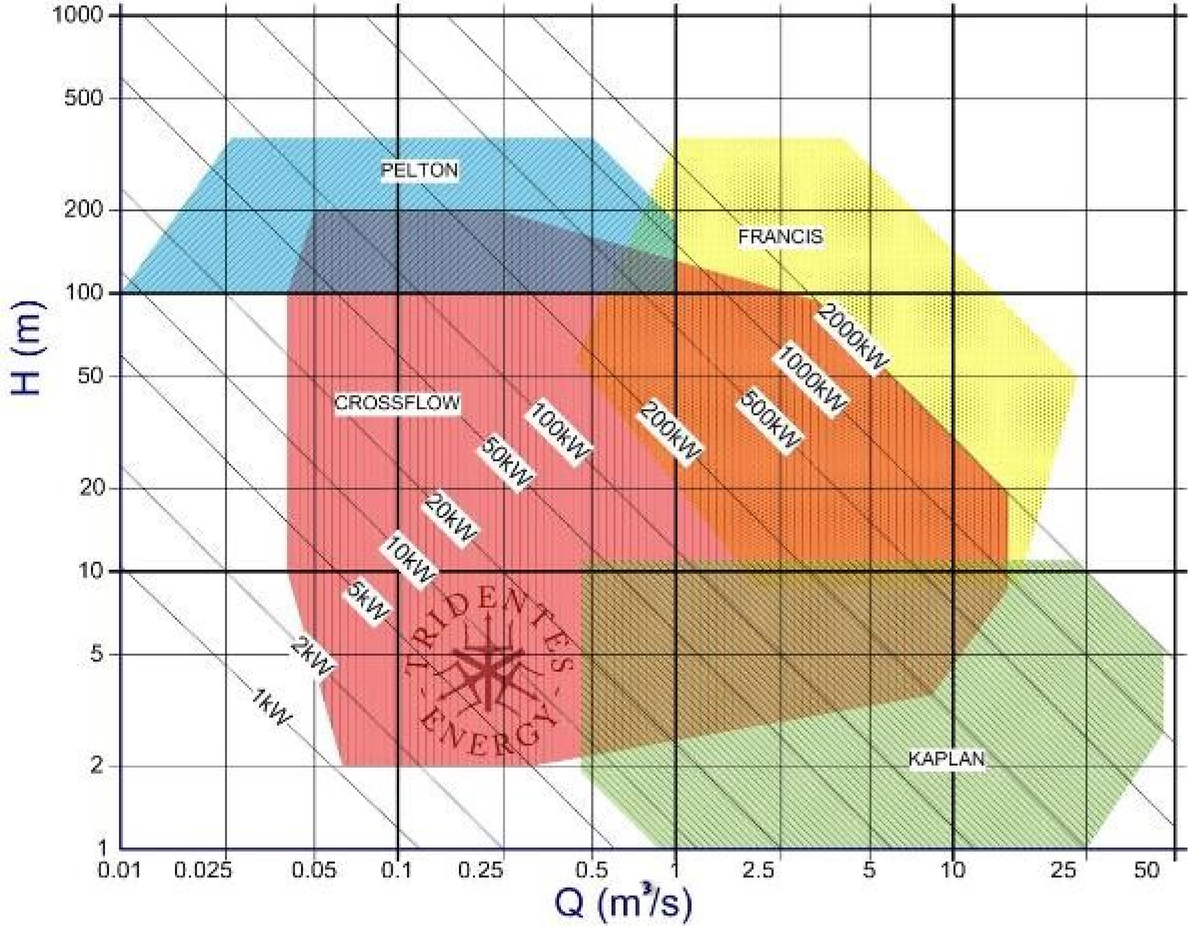
Hydrological resources

- Dataset contains water flow (m^3/s) for each day over a few years at the points indicated by green arrows on map
  - any plant should be around there, not much up/down stream
- Catchment areas are limited, hence water flow not huge
- Use the gradient lines to estimate available heads:
  - purple lines are every 100 m (grey→10m)
- Check HiRes map in DataPack



Hydroelectricity

- Modern turbines are very efficient (up to 95%)
  - Choice of turbines!
  - depends on flow-rate and head
- Data files include plots of efficiencies for some turbines types
  - opt. find others online



Balancing the grid

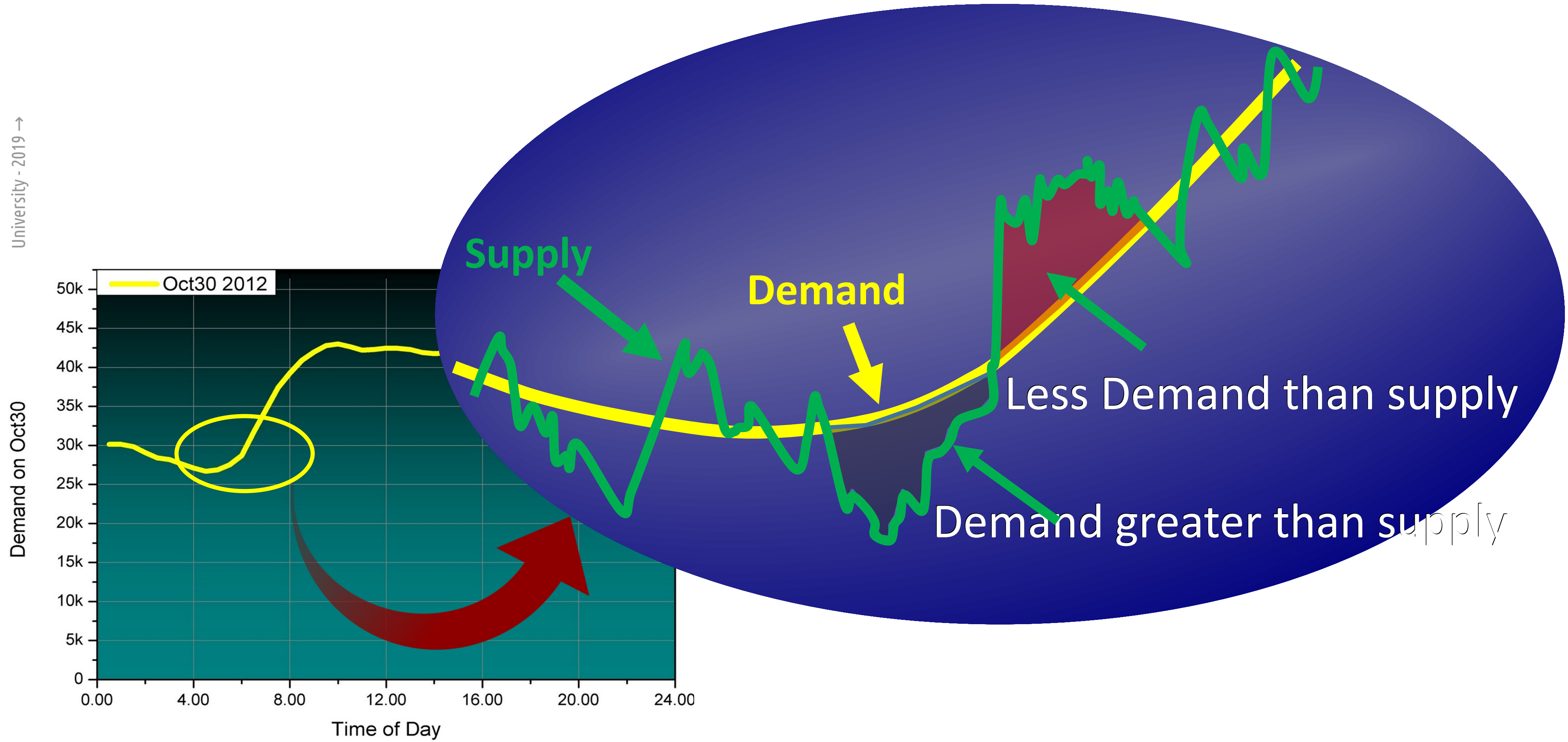
Energy generated & Energy consumed

- A solution for a stable power supply includes:
  - appropriate electricity generation
    - one resource unlikely to provide stable, 24/365 power supply
    - a mix of renewable technologies will help
  - carefully sized energy storage
    - combine hourly generation with demand to size storage
  - demand management measures
    - can help you reduce the size of storage
  - (diesel generators)
    - can be retained as back-up (max 10% of yearly energy)

Grid Security

- What is grid security?
  - What happens in periods where you generate too much electricity?
  - Are there periods when you do not generate enough electricity?
- Which measures would you suggest to cover both cases (too much production and too little)?

Why you need time evolution



Stabilizing the grid

- Curtailment:
  - renewable generators can be switched off
  - only occasionally, or economically wasteful
- DSM measures
  - explain, justify, detail and estimate their effects

Things that won't work

- Installing 30 turbines, but only running 5 to 7 most of the time is not an acceptable solution
  - Neither wise from an engineering PoV nor economically
- Generating enough electricity to cover demand for every hour of the year and suggesting "export to mainland" is not a valid solution
  - There is NO CONNECTION
- Adding Energy Storage that is equivalent to more than 30 days worth of electricity demand is not an acceptable solution (as your economic analysis should show)

Some tips

- Typical size of Electrical Energy Storage (EES)
  - 2 to 8 % of your annual demand.
- EES is usually a very cost intense part of the grid
  - Try to keep it as small as possible
- Use the web to find current costs of the technology you choose, both EES and generation (many projects have dedicated websites, with a wealth of info)

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Finance

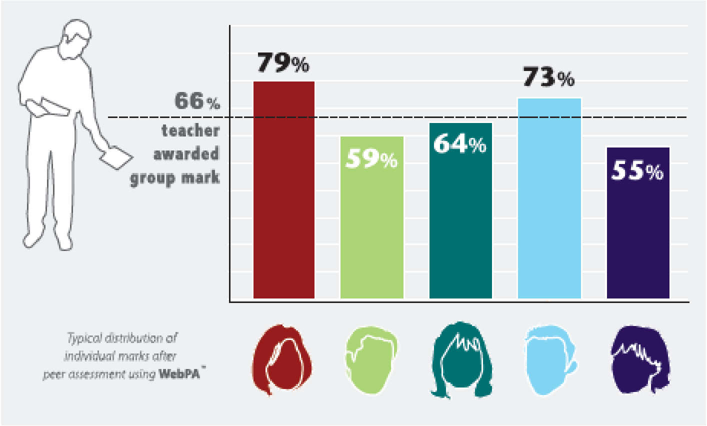
- Islanders are used to paying a lot for their energy and they are committed to do the best for their island, …
  - **but** their economy is limited: be sensible on costs
- The island is part of a larger, developed country with stable economic outlook
  - use this info for your projections of inflation and interest rate
- Before consolidation week
  - only record the cost to buy/install any parts you select
  - after consolidation week you’ll learn how to deal with the *time value* of money and other financial issues

Report marking

- A rubric will be applied:
  - Introduction [10%]
  - Resources and Generation [35%]
  - Grid, storage & DSM [30%]
  - Finance [15%]
  - References, conclusions and presentation [10%]
- Please check Canvas for details
  - rubric is attached to the assignment, published end of Jan

Peer assessment

- You will score all group members' performance in different domains
- All scores are added together and used to normalise the scores you received from your peers



- This gives a multiplicative factor (>1 if you did better than others and <1 if you did less well) that is applied to the report mark, as evaluated by the lecturers
- More details on the algorithm (but we'll use MS Forms): http://webpaproject.lboro.ac.uk/student-guidance/