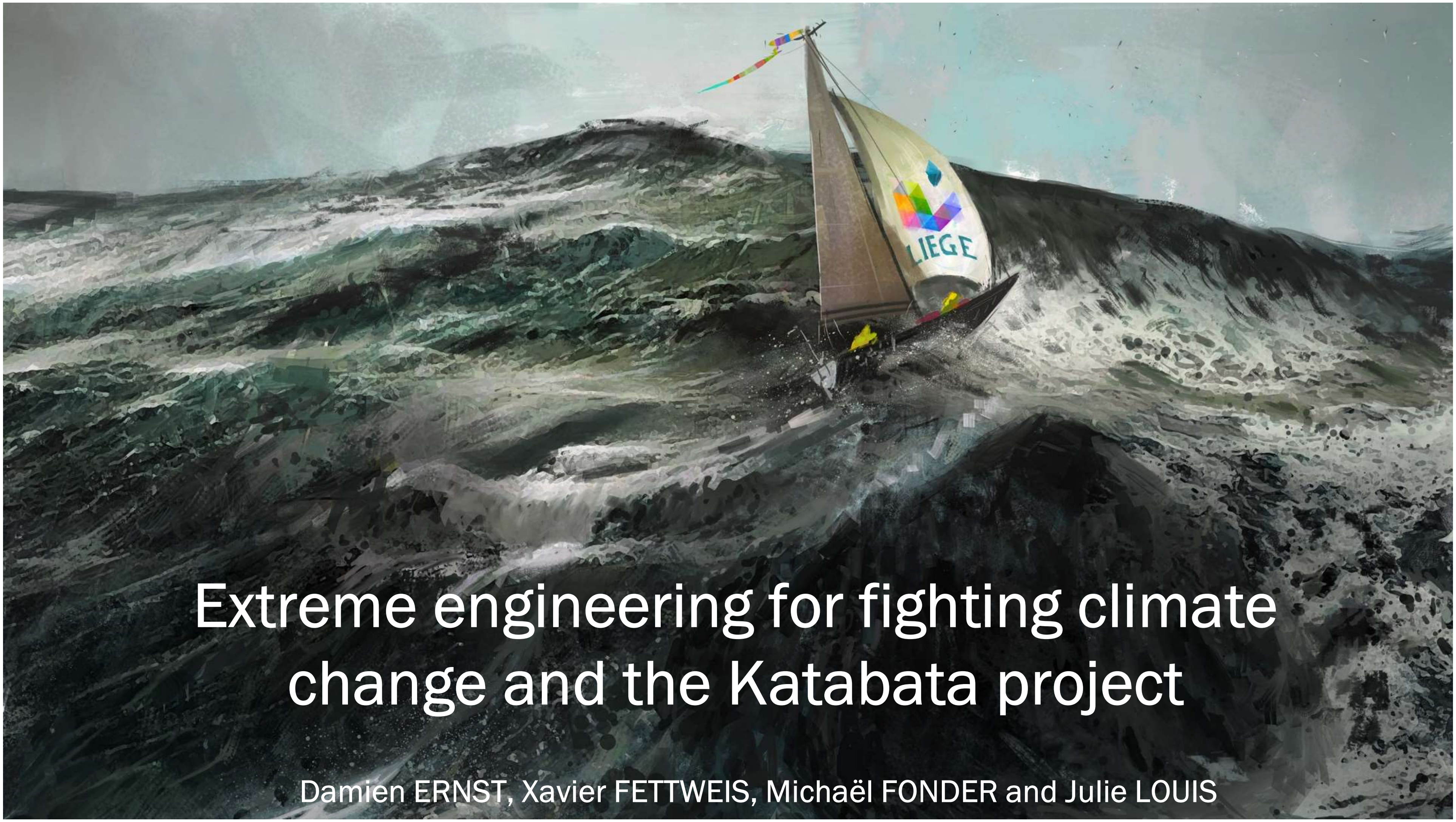


# Extreme engineering for fighting climate change and the Katabata project

Damien ERNST, Xavier FETTWEIS, Michaël FONDER and Julie LOUIS

80% of our primary energy comes from fossil fuels.

This percentage has hardly changed in the past decade.

$CO_2$ concentrations are climbing at a record pace.

And now ? Extreme engineering solutions are needed.

# Global grid:
# The extreme electrical network

Fact 1: Natural smoothing of renewable energy sources and loads variability in a global grid setting. Very little investment in storage needed.

Fact 2: Renewable electricity – in €/MWh – is very cheap in high-density renewable energy fields (e.g., Atacama desert for solar energy, Greenland coast for wind energy).

Fact 3: Transporting electricity over long-distances is becoming cheap.

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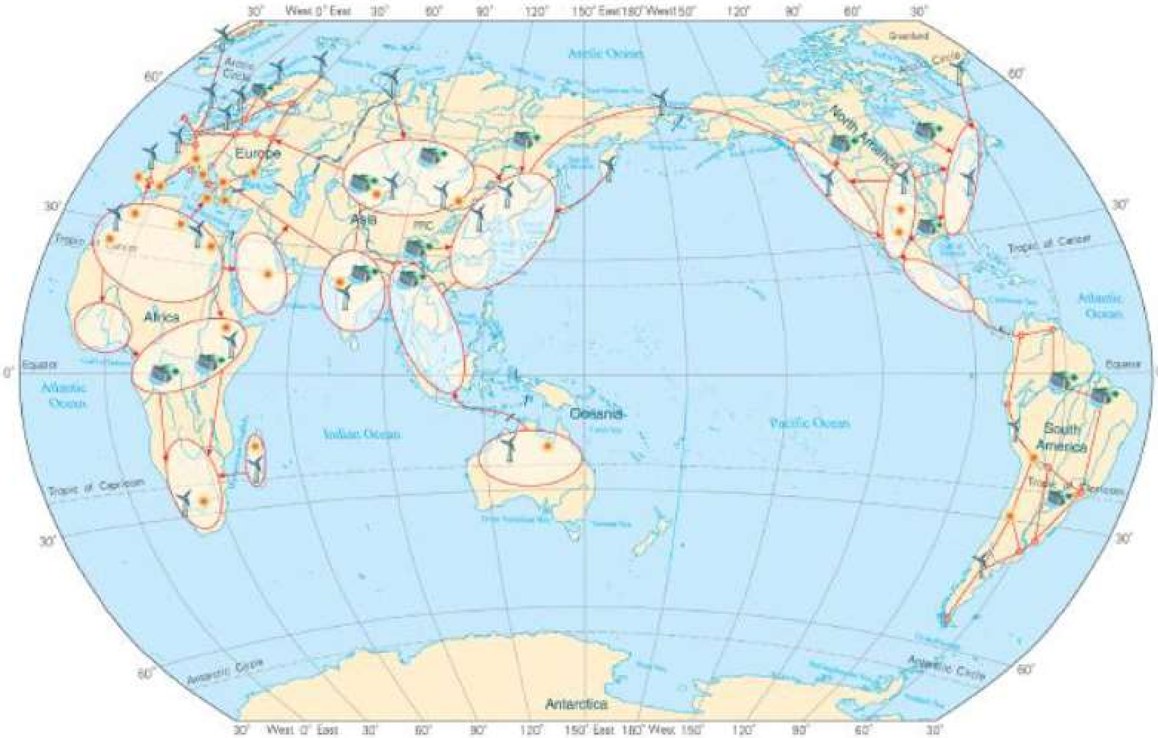
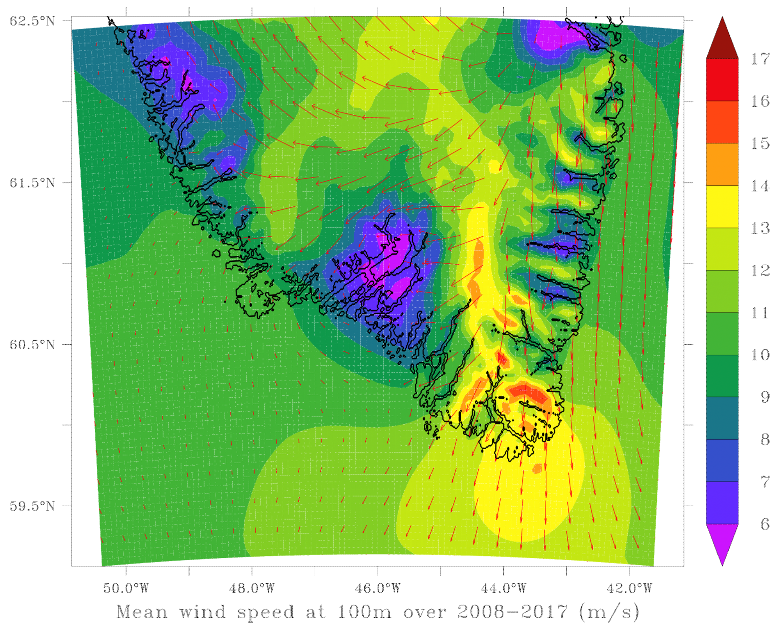
Fact 1 + Fact 2 + Fact 3 offer a true possibility for putting fossil fuels out of business for electricity generation (even without a $CO_2$ tax) by building a global grid.




*Schematic representation of the backbone electricty interconnection.*

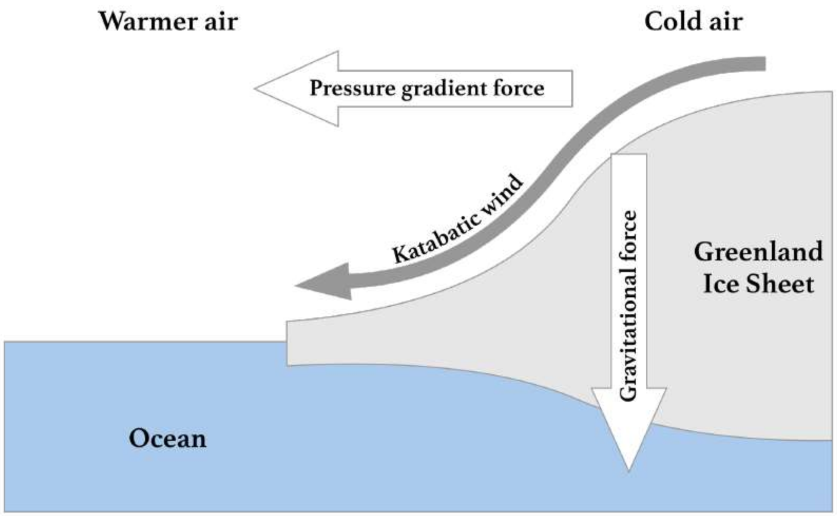
# Why should Europe harvest wind energy in Southeastern Greenland?




1. High wind speeds.
2. Decorrelation with European wind temporal variability.
3. Huge areas. No NIMBY issues.
4. Half-way between Europe and the US.
5. Nice flagship project for accelerating the building of the global grid.

# Winds in Southeastern Greenland

In the southeastern part of Greenland, general circulation (synoptic) winds (driven by the Sun's energy) add up to Katabatic winds.




Katabatic winds are the result of heat transfer processes between the cold ice cap and the warmer air mass above it.

When the air mass temperature is higher than that of the ice sheet, the former is cooled down by radiation, thus the air density increases forcing it down the sloping terrain.

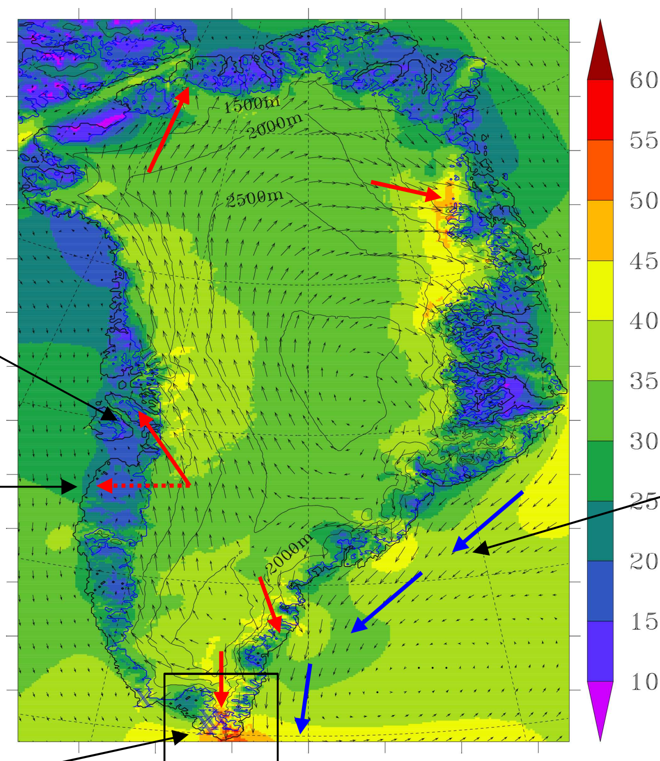
The flow of katabatic winds is driven by gravity, temperature gradient and inclination of the slope of the ice sheet.

# Winds in Southeastern Greenland

Real katabatic wind (deviated on its right due to the Coriolis force)

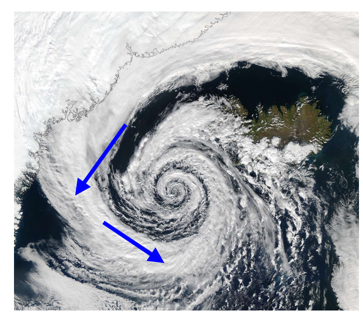
Pure katabatic wind

In this area, combination of both katabatic and synoptic winds




Mean Wind speed at 100m (km/h)

Synoptic wind due to the inland low pressure.



# Data acquisition for our analysis

We relied on data reanalysis and simulations to reconstruct wind signals from past in-situ and satellite observations.

The regional MAR (Modèle Atmosphérique Regional) model was used to simulate the weather over Greenland. This model can accurately represent physical processes in polar regions, including Katabatic winds, and has high spatial and temporal resolutions. Boundary conditions determined by the ERA5 reanalysis model.

Hourly values of wind speed at 100 meters above ground level are generated using the reanalysis models for the period 2008-2017.

# Regions selection for our analysis

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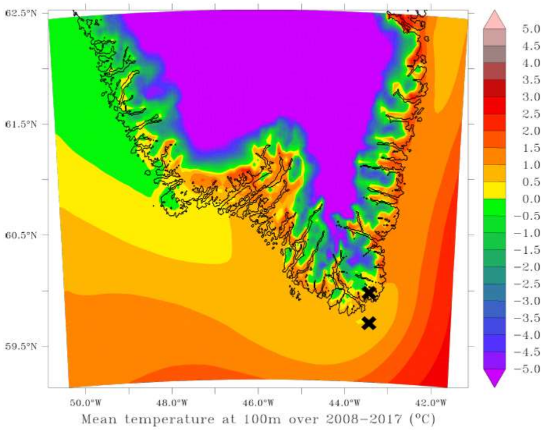
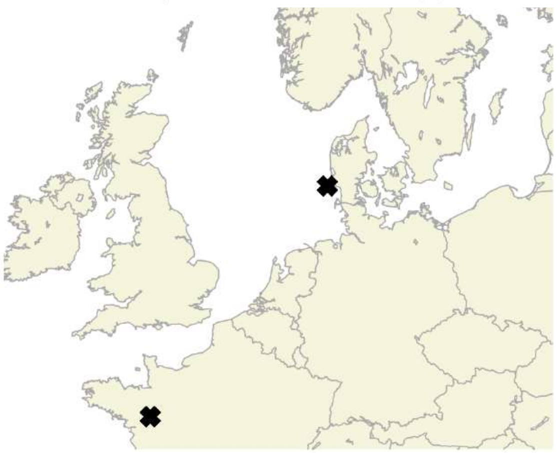


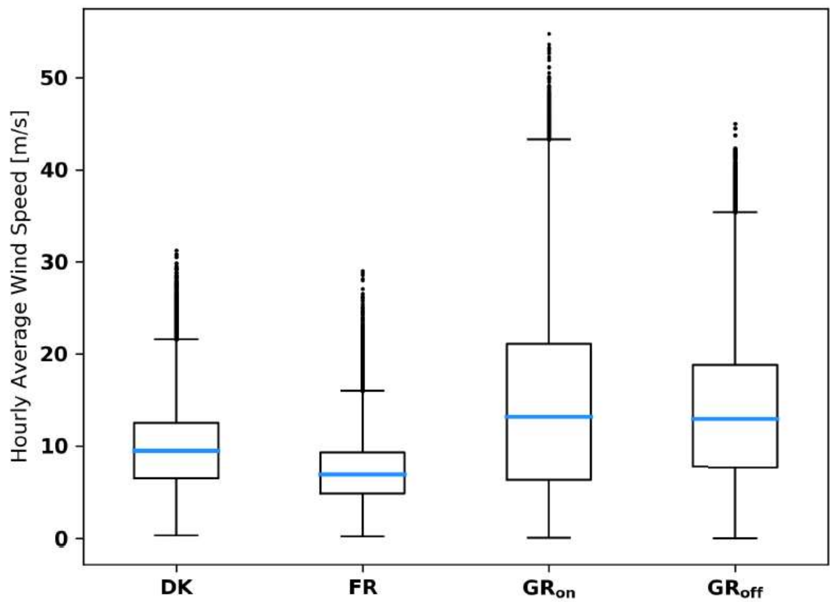

Two areas in Greenland: one offshore ($GR_{OFF}$) and one onshore ($GR_{ON}$).

Temperatures too mild to have a frozen sea or permanent ice on-shore.



Two areas in Europe: one offshore wind farm in Denmark (DK) and one on-shore wind farm in France (FR).

# Wind ressource assessment

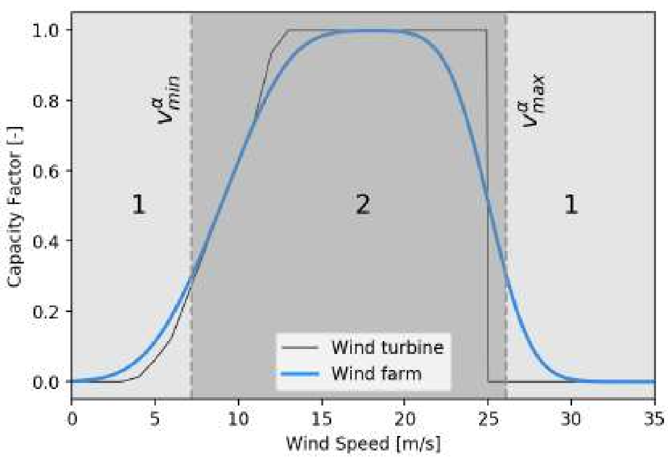



Higher mean wind speeds in Greenland than in the two European locations.

Distribution of wind speeds more asymmetric for $GR_{off}$ and $GR_{on}$ than for DK and FR.

The high standard deviations of the wind speeds in Greenland do not correspond to a high turbulence intensity, but to the strong influence of seasonality of the local natural resource.

# Load factors of the wind farms




Single turbine and wind farm transfer functions. Example of wind farm power curve aggregation based on multiple aerodyn SCD 8.0/168 units.

| DK | FR | $GR_{on}$ | $GR_{off}$ |
|---|---|---|---|
| 0.55 | 0.32 | 0.50 | 0.59 |

Capacity factors for the different locations

| $v_{cut}^{out}$ (m/s) | **DK** | **FR** | $\mathbf{GR_{on}}$ | $\mathbf{GR_{off}}$ |
|---|---|---|---|---|
| 25 | 0.55 | 0.32 | 0.50 | 0.59 |
| Highest wind speed observed | 0.56 | 0.33 | 0.66 | 0.69 |

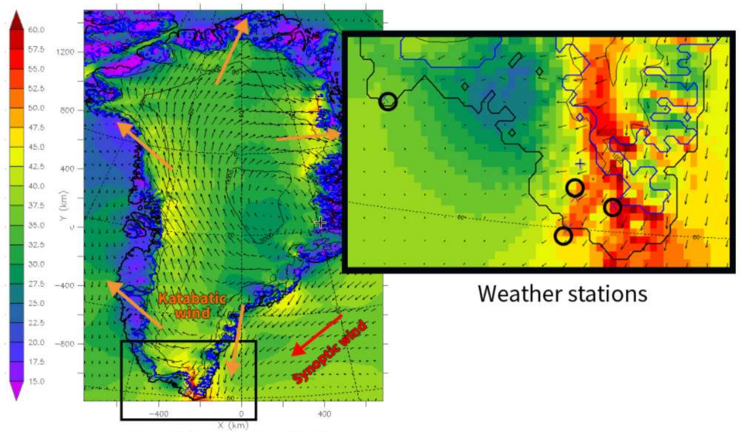
Capacity factors versus cut-out wind speed for the wind turbines.

Important remarks for manufacturers of wind turbines willing to tap into the Greenland wind energy market:

1. Wind turbines capable of operating with higher cut-out speed lead to significantly higher capacity factors in Greenland.

2. May also be interesting to design wind turbines which saturate in terms of power output for higher wind speeds (i.e., turbines having a higher rated output speed).

# Katabata project



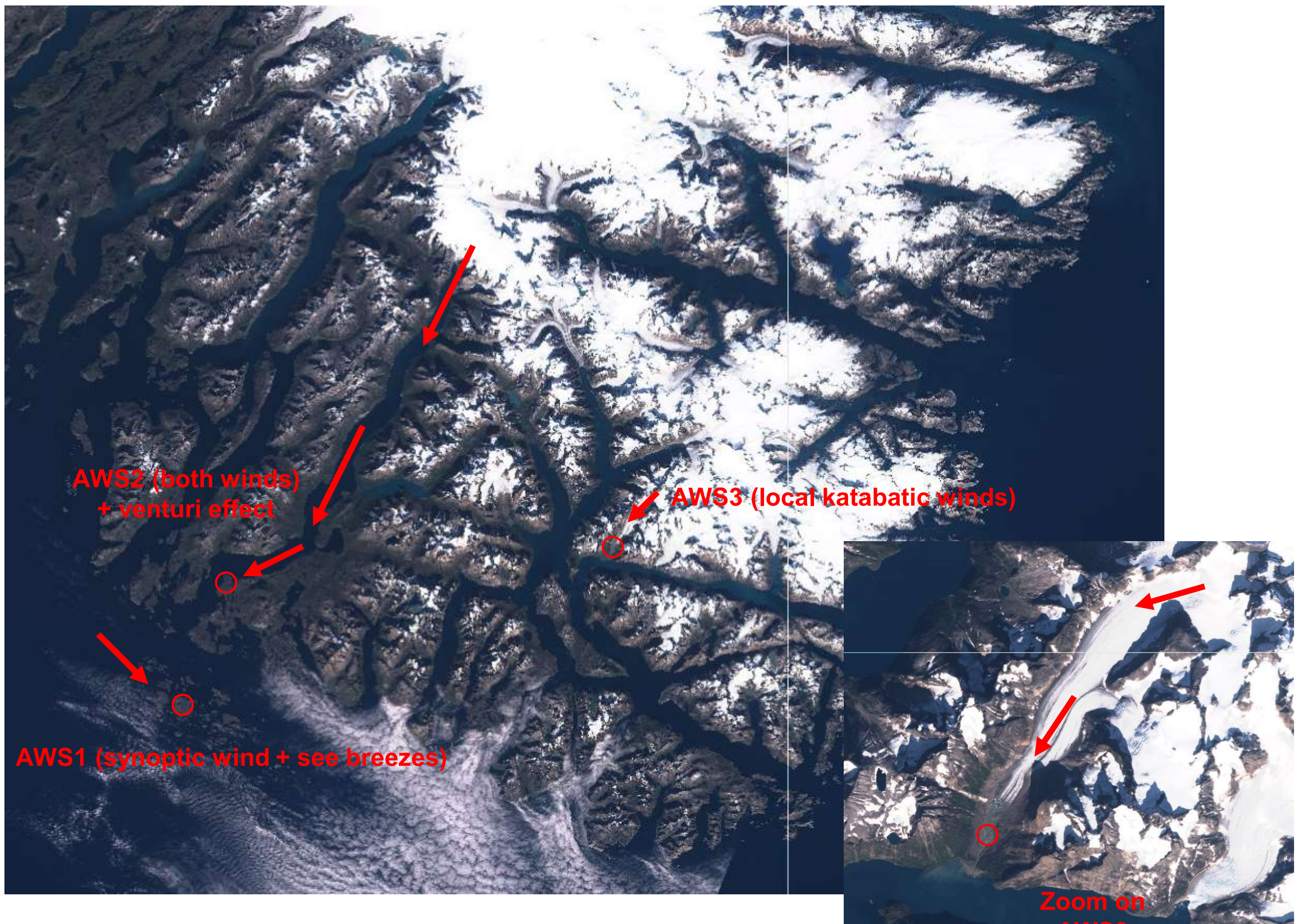
Mean wind speed at 100m (km/h)

Weather stations

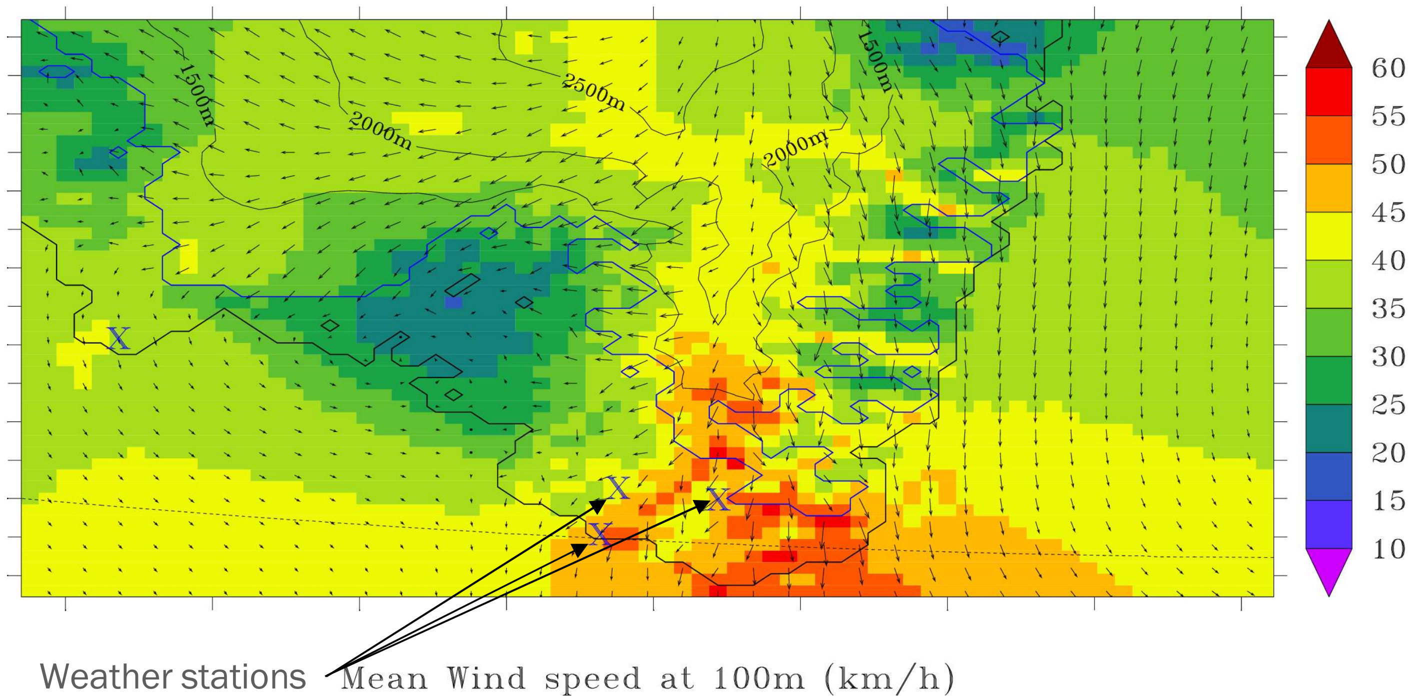
Goal of the project: installing three weather stations in the South-East of Greenland.
The wind in this area has never been properly measured before!

The team:
Dr. Xavier Fettweis, Michaël Fonder and Prof. Damien Ernst

# Location of the weather stations



# Winds at those locations




Weather stations

# Vaisala’s AWS310 stations

Description of AWS310 stations:

- 4 sensors:
    - i. Anemometer for wind speed
    - ii. Weathervane for wind direction
    - iii. Thermometer
    - iv. Humidity sensor
- Satellite antenna for data transfer
- 10m mast with three guy wires
- Battery with photovoltaic panel for lengthy operations in complete autonomy

Our AWS310s are also synonyms for an epic delivery:

- Packages weighing more than 350kg for a total volume of 2m³ divided in seven boxes for each station
- A total delivery delay of three months

# Departure from Saint-Malo

# Northabout : a  boat designed for polar expeditions

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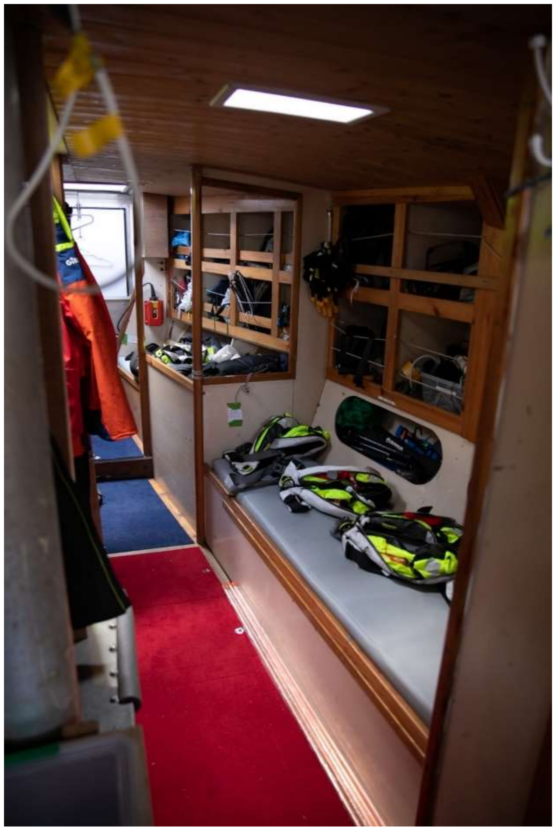

- 10 bunks
- Sufficient food for 3 months
- 15m length, 18m mast
- Reinforced aluminium hull
- Extra-large fuel tanks

Photos © Studio

# Final preparations in Roscoff

# Crossing the Atlantic

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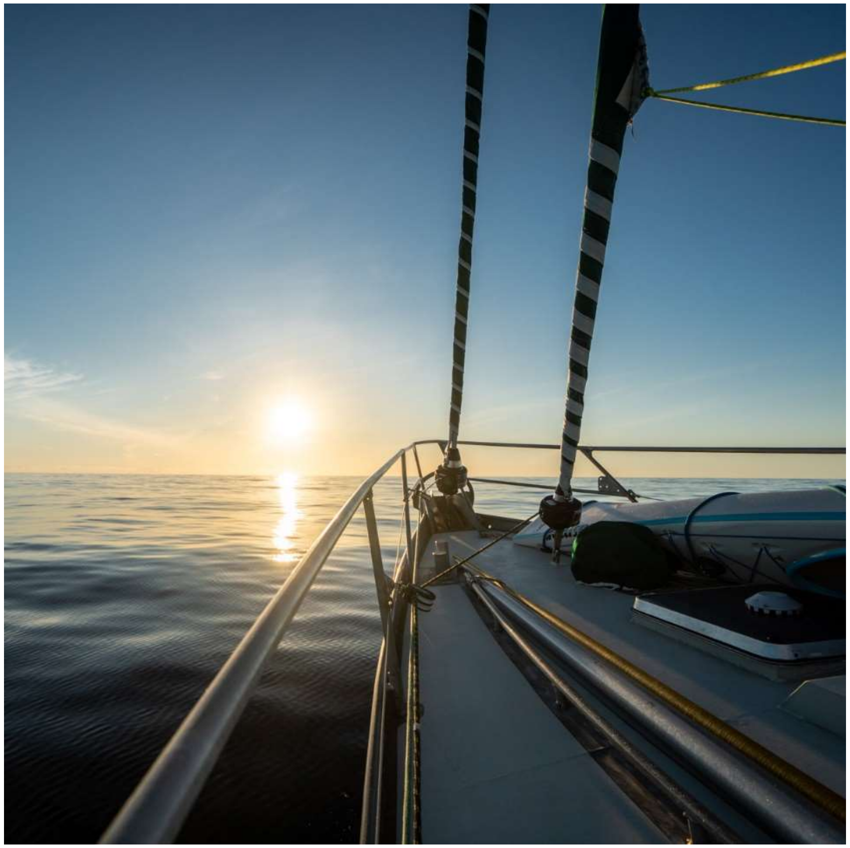

# Crossing the Atlantic

*(artist representation)*

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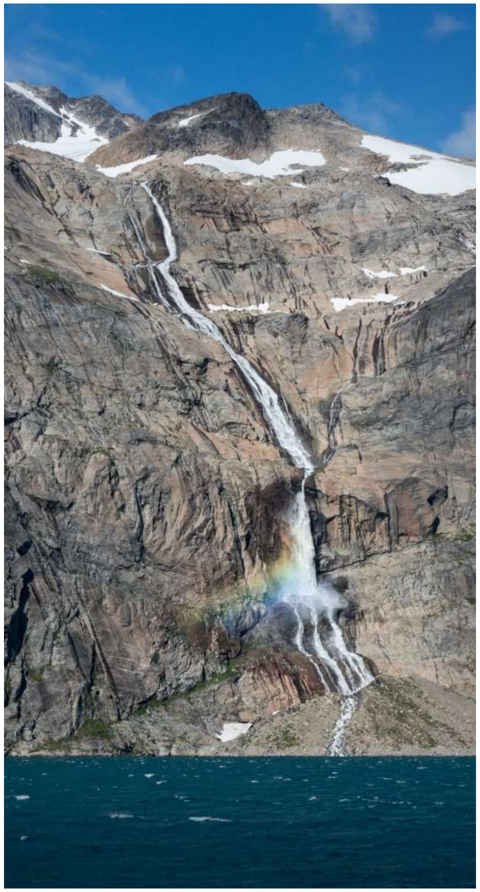
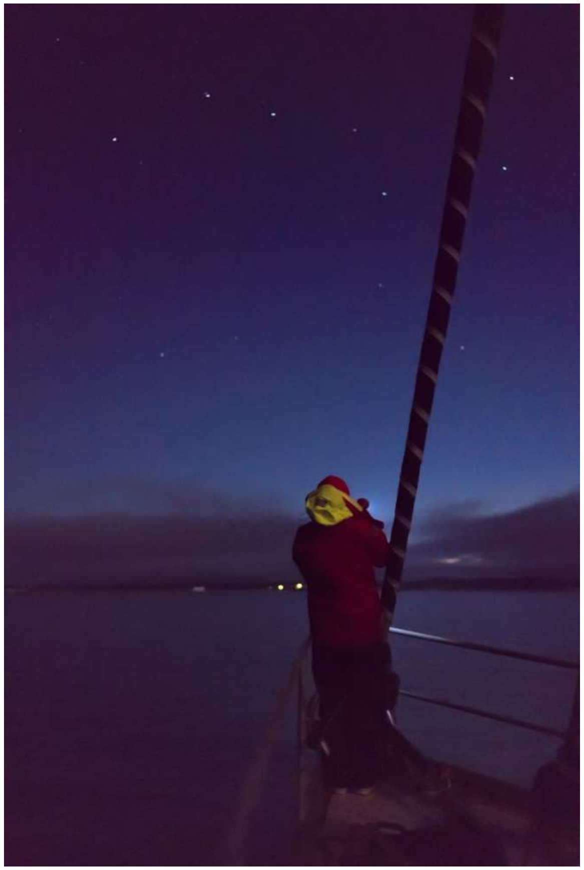
# Snapshots of life onboard


# Arrival in Greenland

# Sailing challenges in Greenland

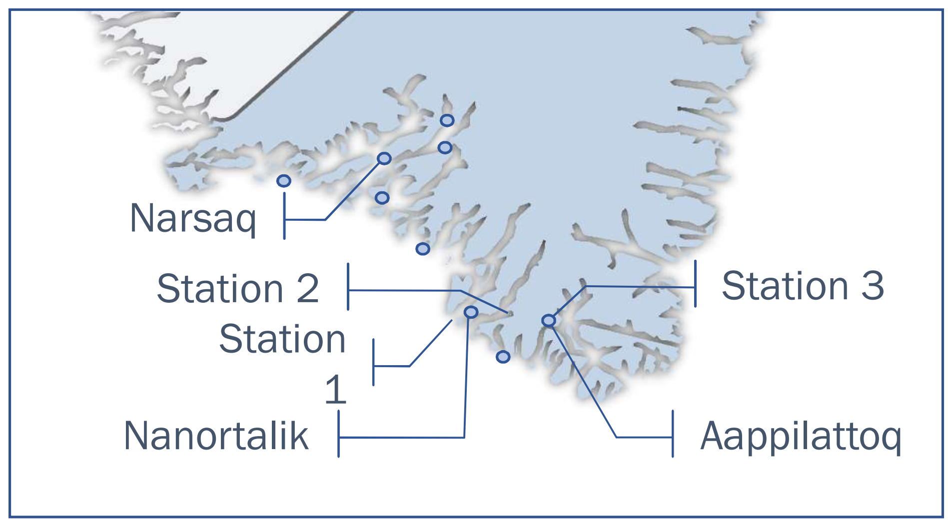


Icebergs are everywhere!

Lack of concentration could lead to catastrophic damage.

# Our stops in South Greenland

- Delivery and blank test of the stations in Narsaq
- Use of Nanortalik as operational base for Stations 1 and 2
- Use of Aappilattoq as operational base for Station 3 and maintenance



# Narsaq : Incoming boxes

# Installing a station is easier said than done!

Installing a station is a challenging task:

- Planning all details on the boat
- Transferring everything ashore
- Finding the right spot for the station
- Getting everything on site
- Starting the installation, hoping for the best
- Dealing with unpredictable weather

*Photos © Julien Fumard*

# Transporting a station ashore

# Finalizing the installation of Station 1

# Aappilattoq, our last sheltered stop

# Unforseen need for early maintenance

All stations encountered some critical issues a few days after their installation

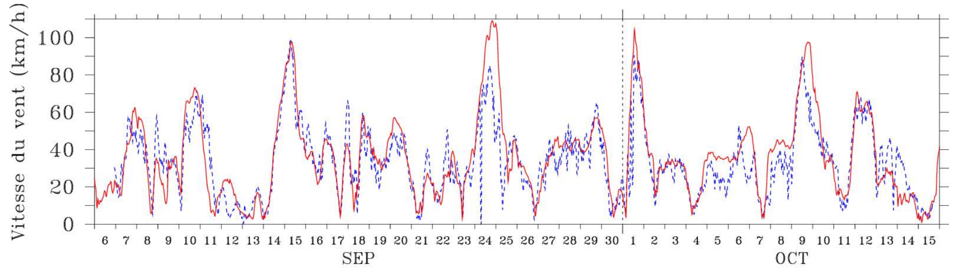
Need for going back to the installations sites for repairs!  Done by hiring a local fisherman.

# All 3 stations are now operational and sending data

# First comparison: MAR vs observations

**AWS1**

1 observation every 20m
from 6 SEP 2020 to 15 OCT 2020

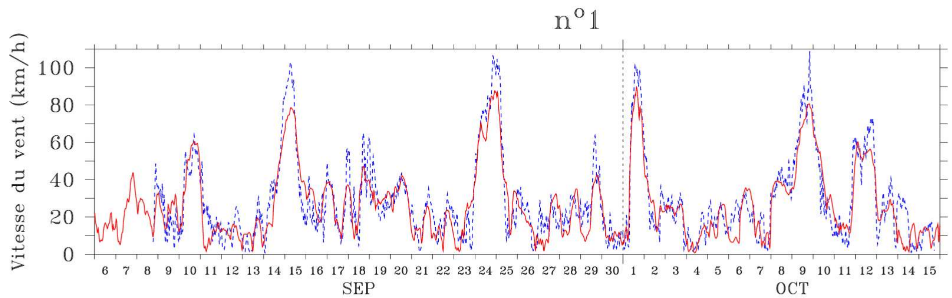



Correlation: 0.87
Bias=+2.4km/h
RMSE=11km/h

Mean: 34±20km/h

**AWS2**

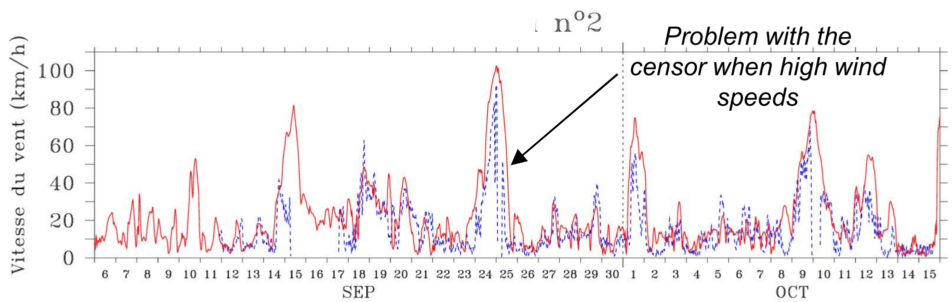
Wind measured at 10m




Correlation: 0.9
bias=-2km/h
RMSE=10km/h

Mean: 29±23km/h

**AWS3**



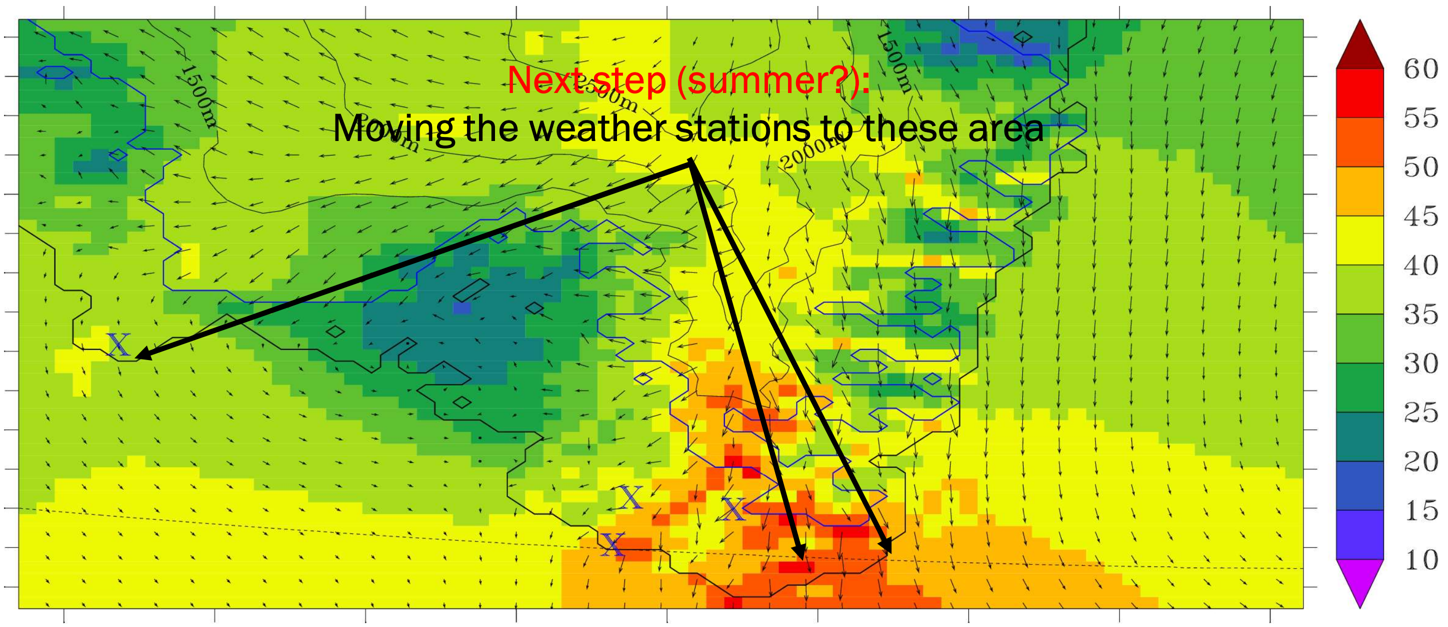

Correlation: 0.86
bias=+4km/h
RMSE=11km/h

Mean: 17±17km/h

MAR is able to simulate both spatial and temporal variability observed until now at the 3 stations

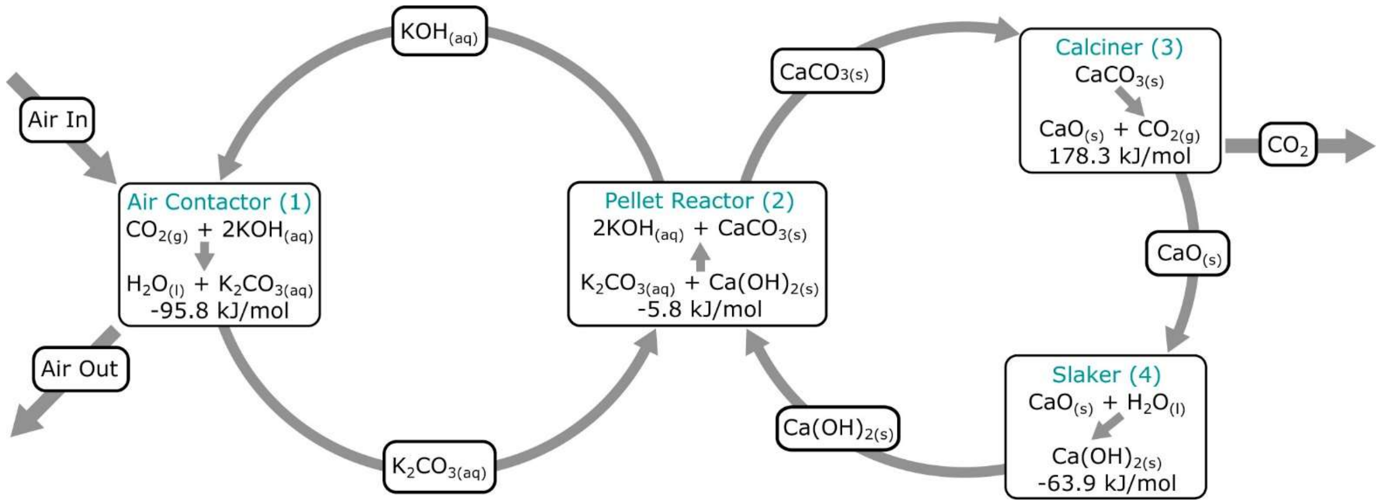
# Katabata 2?

First observations confirm the MAR results over the South of Greenland and the high wind speed in this area. Weather stations could be installed in other locations.




Mean Wind speed at 100m (km/h)

# Direct air $CO_2$ capture




Process commercialized by Carbon Engineering for capturing $CO_2$. Air exits with a $CO_2$ concentration of around 110 ppm. Energy required per ton of $CO_2$ captured and compressed at 150 bars: around 1.4 MWh of heat (at a temperature of more than 600 °C for the calciner – provided now by burning natural gas) and 0.4 MWh of electricity.

Source: https://carbonengineering.com/

# What can be done with this $CO_2$?

1. Storing $CO_2$ underground.

2. Synthesize synthetic green fuels with high energy density using hydrogen produced from water electrolysis and renewable electricity.
Example: the Sabatier reaction for producing $CH_4$

$$CO_2 + 4\,H_2 \xrightarrow[\text{pressure}]{400\ ^\circ C} CH_4 + 2\,H_2O \qquad \Delta H = -165.0 \text{ kJ/mol}$$

3. Transform $CO_2$ into graphite (pure coal) using, for example, the Bosch reaction, and building a mountain of coal.

High-temperature heat input can help optimise Solutions 2. and 3.


- Pierre Demet -

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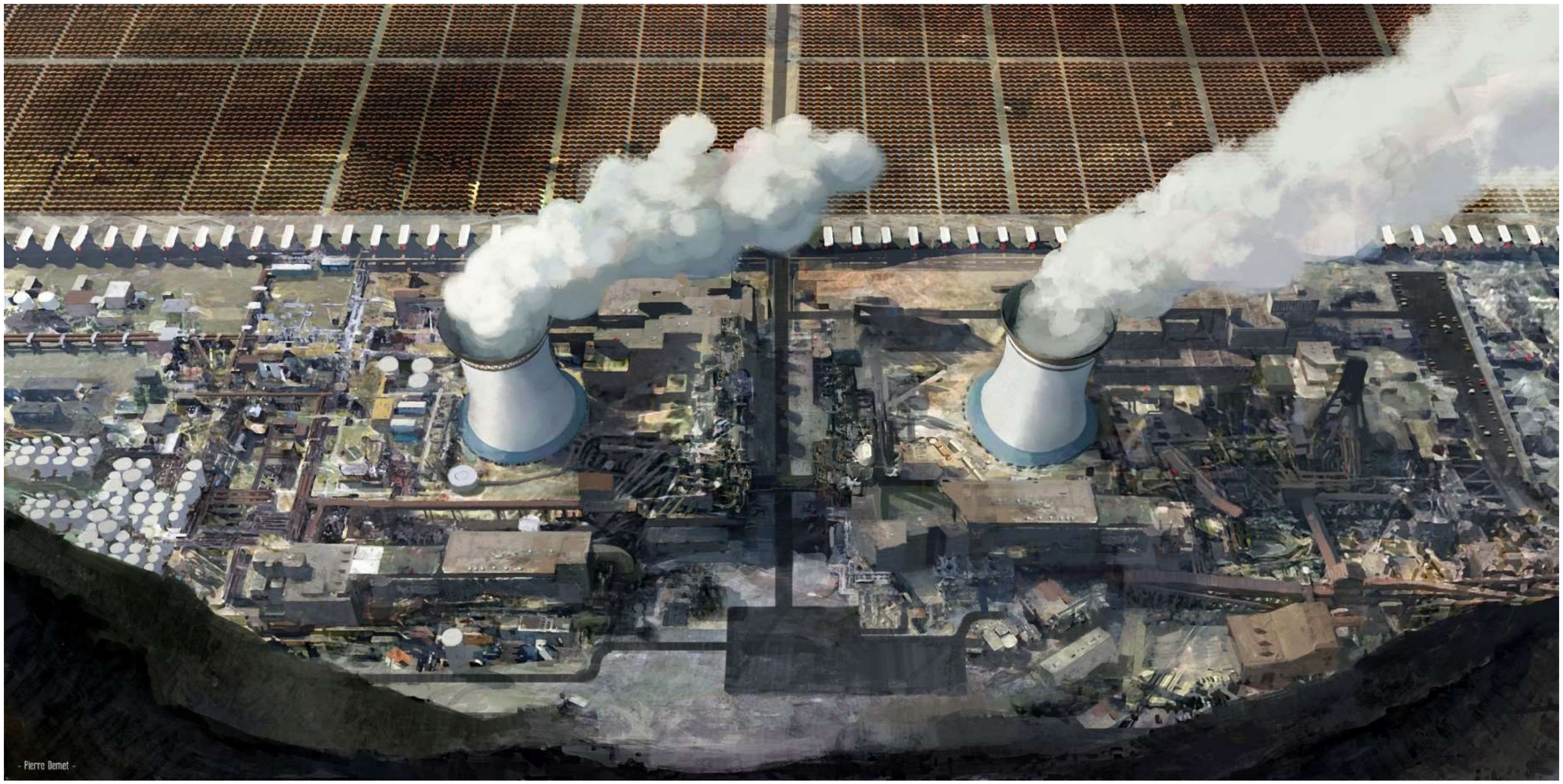


# Energy needed to return to 280 ppm

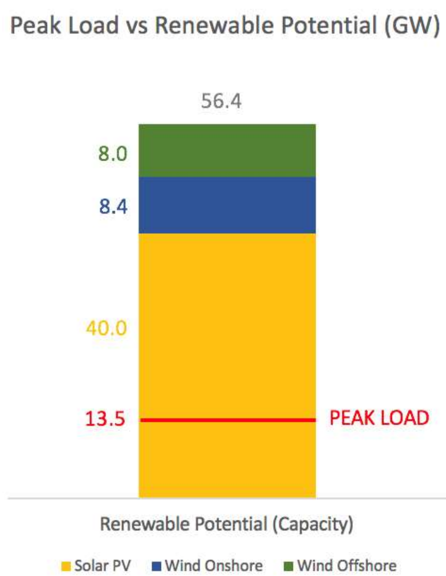
There are around 3.25 x 1012 tons of $CO_2$ in the atmosphere. To return to preindustrial levels (280 ppm), (412−280)/412 * 3.25 x 1012=1.04 x 10exp(12) tons of $CO_2$ have to be removed from the atmosphere.

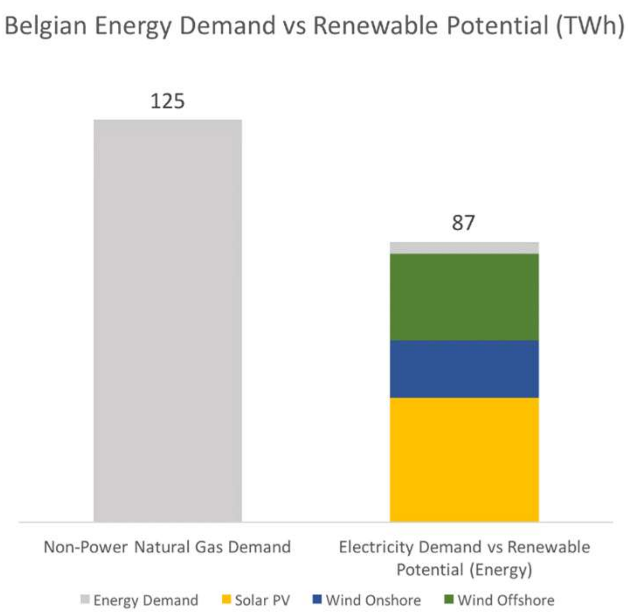
Removing 1 ton of $CO_2$ from the atmosphere requires (1.4+0.4)=1.8 MWh.

One ton of graphite generates 8.9 MWh when combusted. Due to the energy conservation principle, transforming one ton of $CO_2$ into graphite and $O_2$ would at least require 12/((2∗16+12)) * 8.9 = 2.42 MWh of energy.

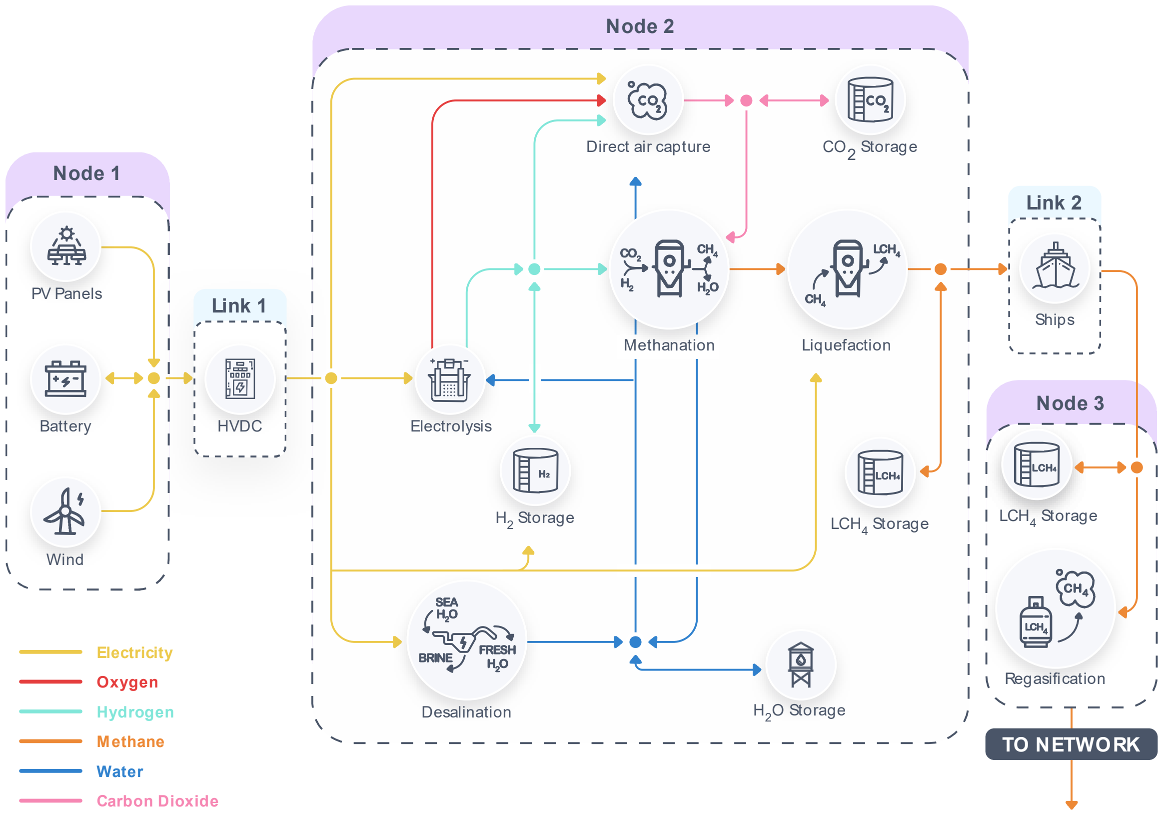
Transforming 1.05 x 1012 of $CO_2$ into graphite would require a minimum of 4,431,000 TWh of energy. This is 40 times our annual final energy consumption.

# Wouldn't it be nice to be able to import 125 TWh of cheap synthetic green $CH_4$ in Belgium?



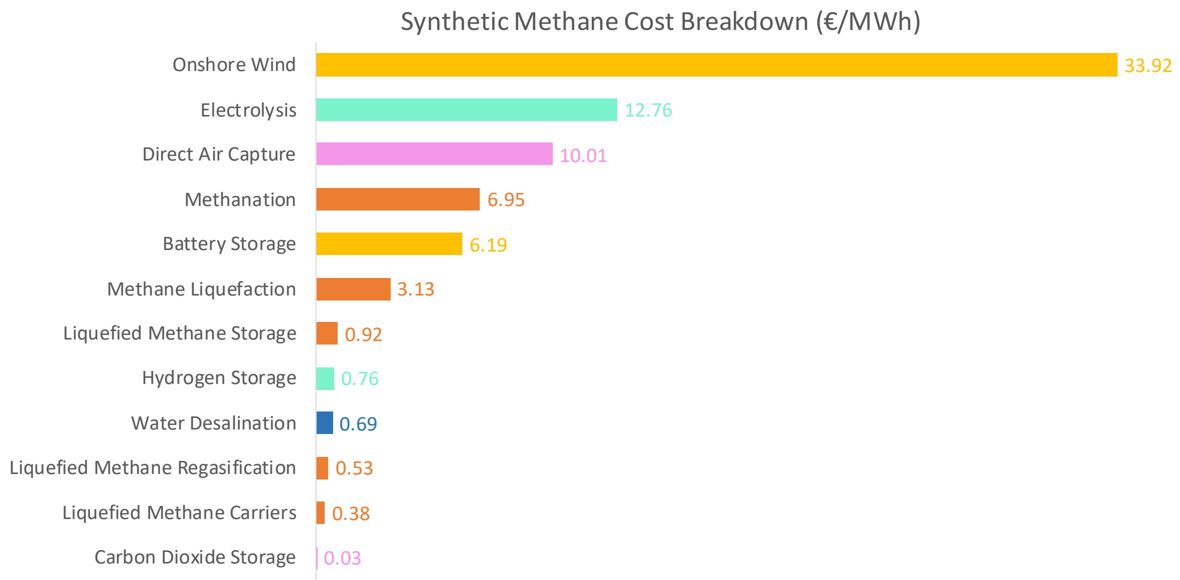
# Remote renewable energy hub



*Artist representation of an infrastructure where solar energy and direct capture of $CO_2$ in the air are used to produce green $CH_4$. The green gas is then liquefied and shipped to consumption centers.*

*Artist representation of a remote energy hub placed in Greenland.*

# Remote renewable energy hub in Greenland: cost breakdown




Methane comes at a price 76.4 €/MWh in Zeebrugge.

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