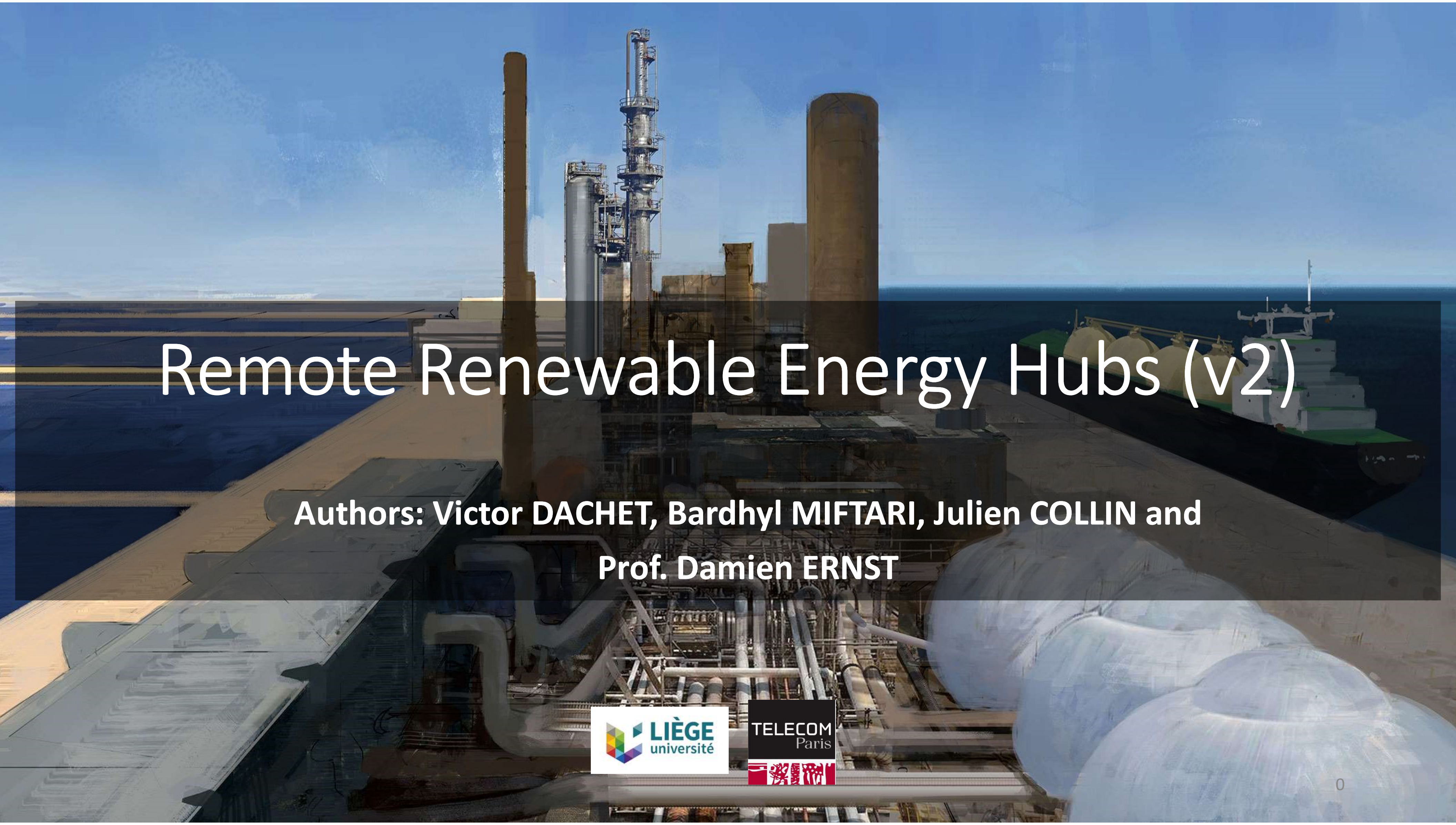

Remote Renewable Energy Hubs (v2)

Authors: Victor DACHET, Bardhyl MIFTARI, Julien COLLIN and Prof. Damien ERNST

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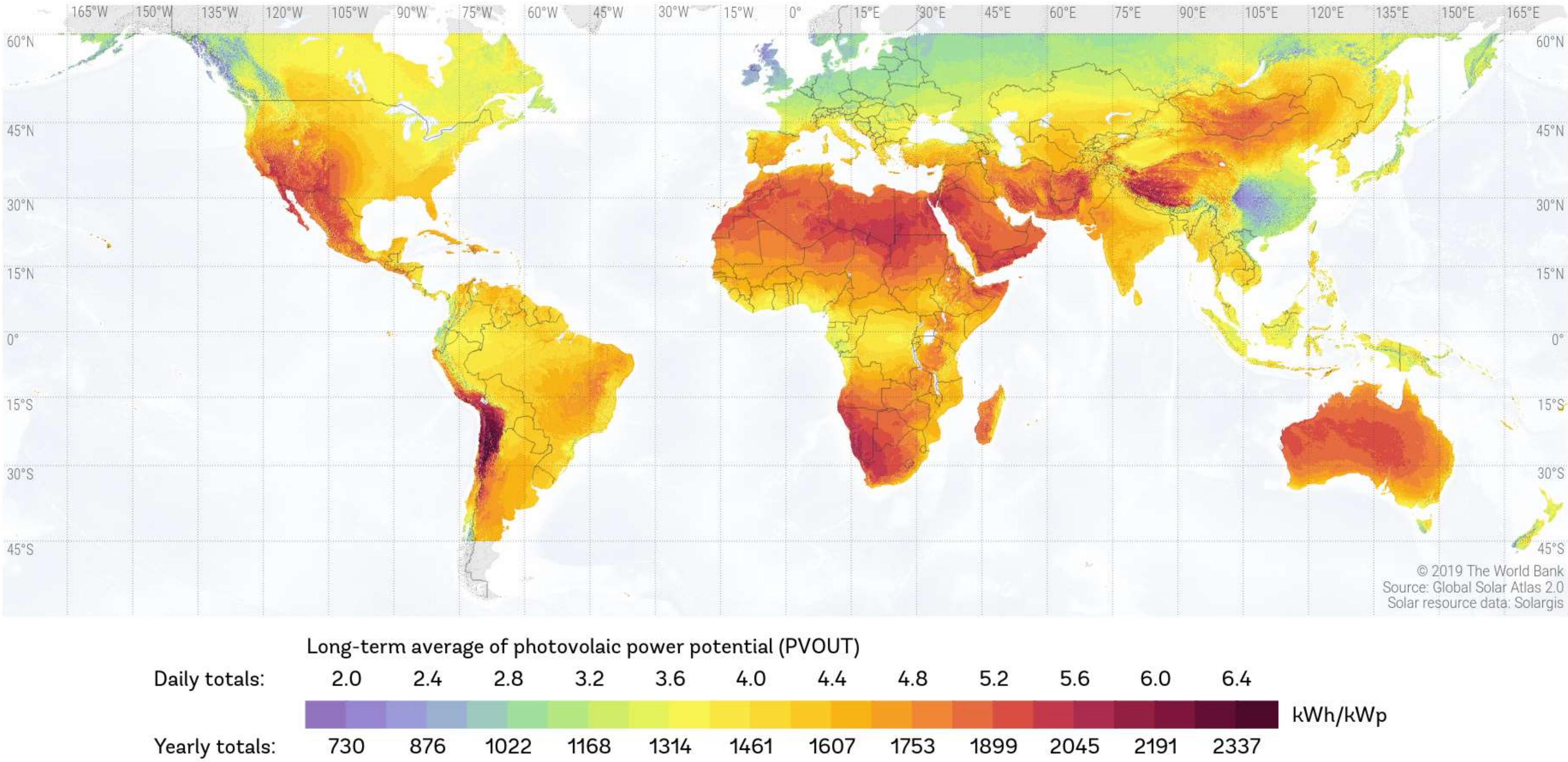
Artist's representation of a remote energy hub in Greenland.

Introduction

SOLAR RESOURCE MAP

PHOTOVOLTAIC POWER POTENTIAL



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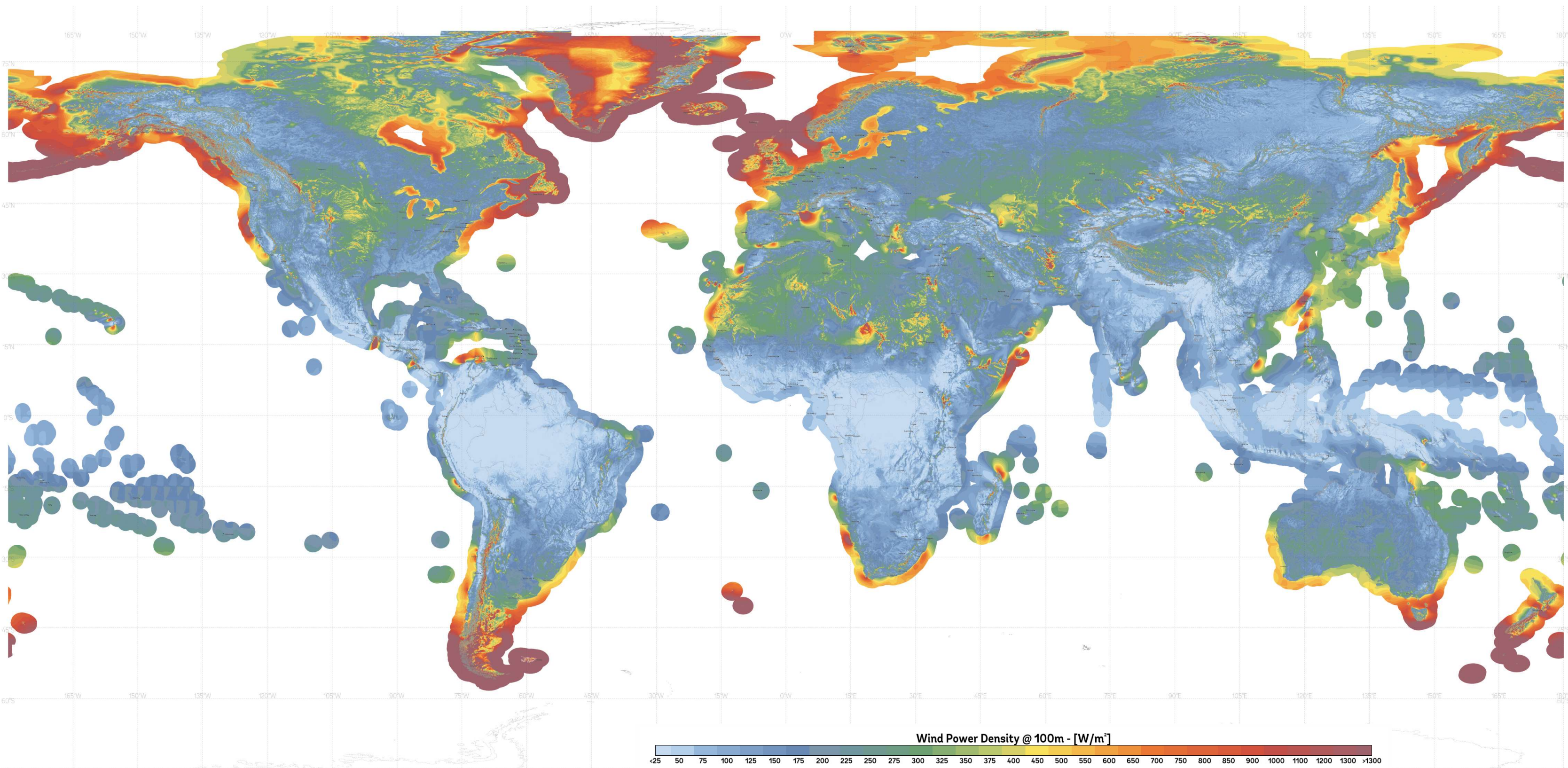
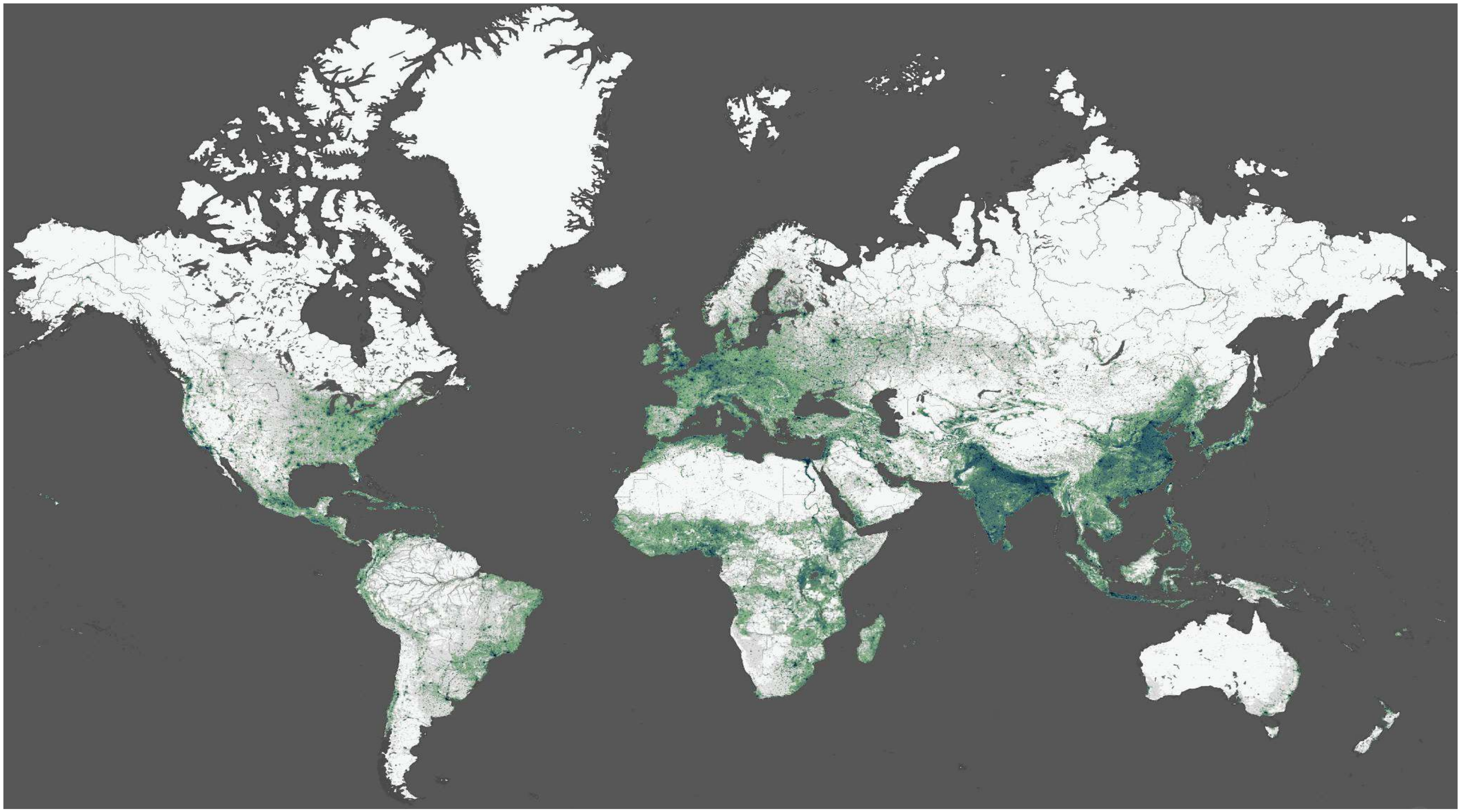
WIND RESOURCE MAP

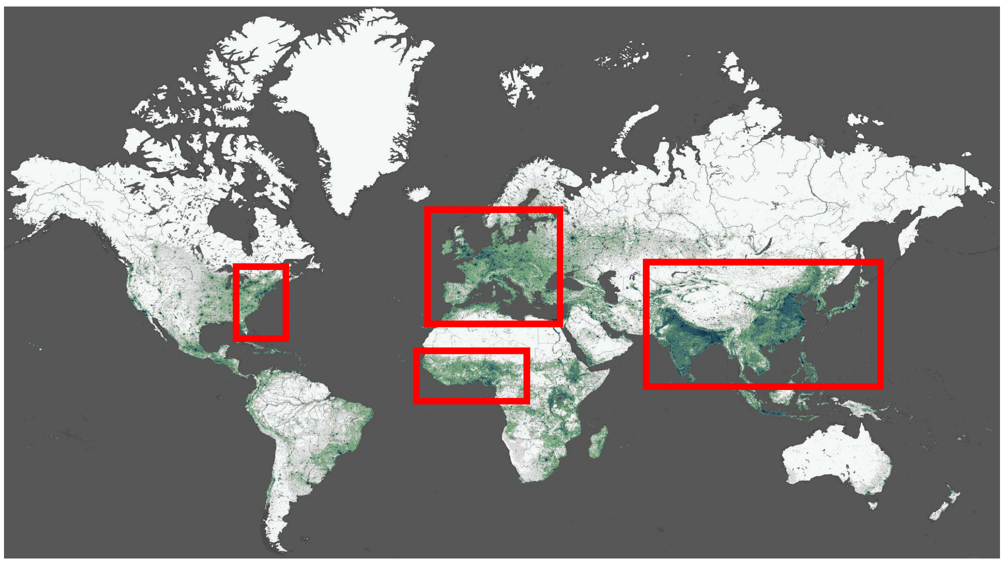
WIND POWER DENSITY POTENTIAL



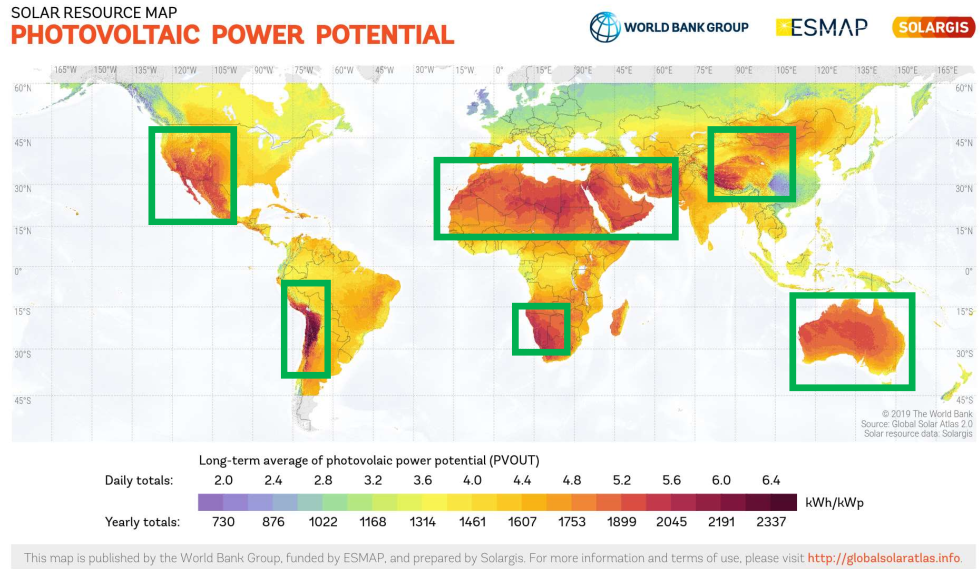
World population density

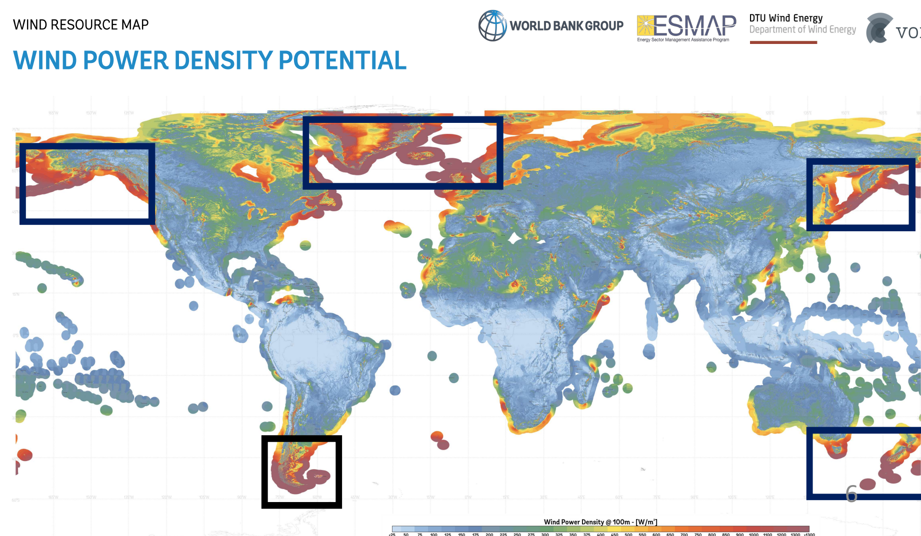


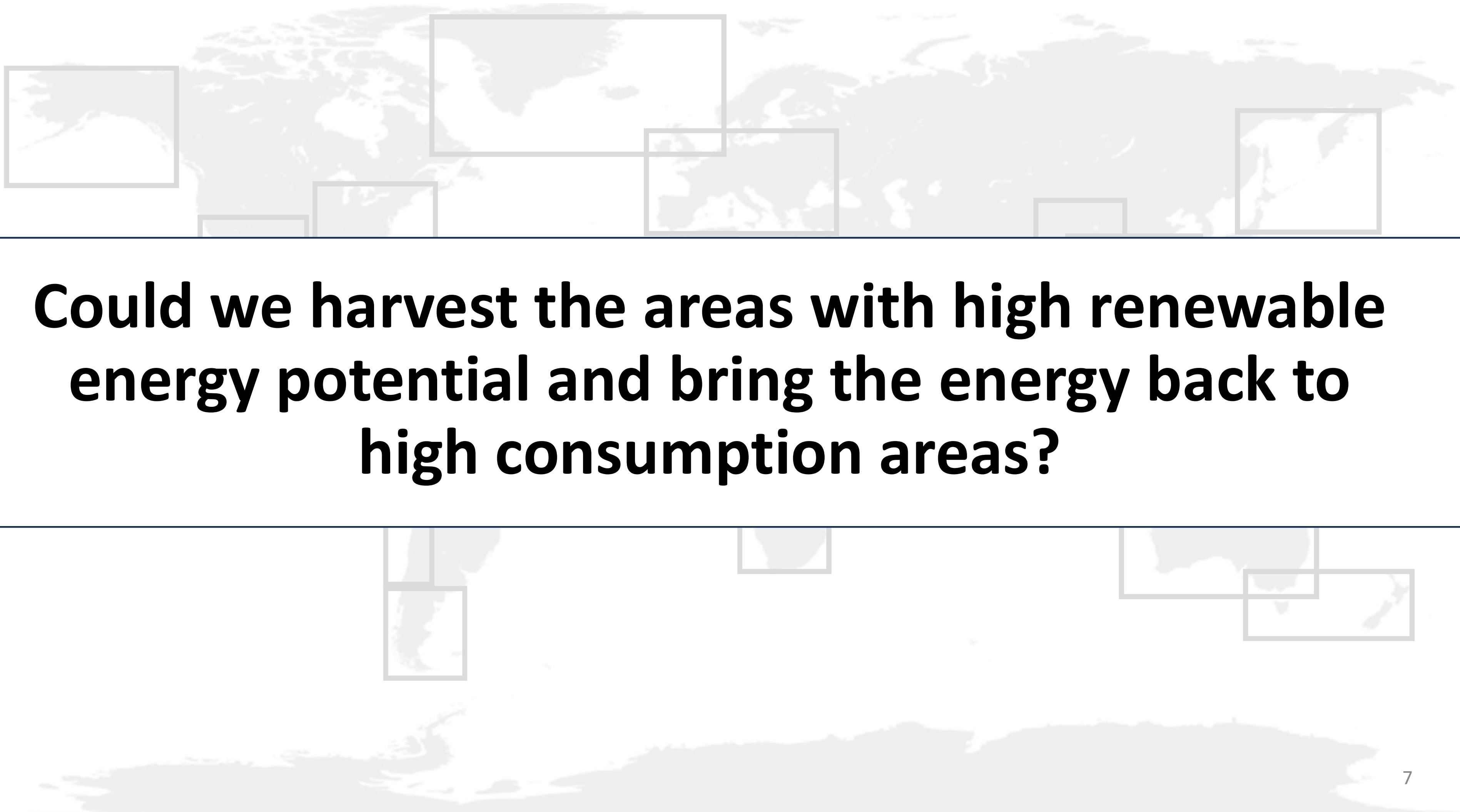
Mismatch



- High population density
- High photovoltaic power potential
- High wind power density potential







Could we harvest the areas with high renewable energy potential and bring the energy back to high consumption areas?

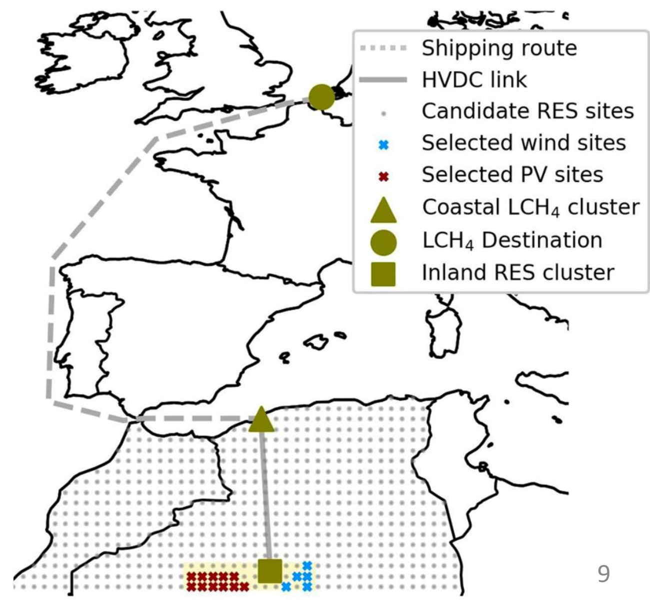
Remote Renewable Energy Hubs

Remote Renewable Energy Hub: definition

A Remote Renewable Energy Hub (RREH) is an energy hub located far away from large load centres where abundant, high-quality renewable energy is harvested.

An example of an RREH where solar and wind energy is collected in the Algerian desert, carried to the shore via an HVDC link, transformed into carbon-neutral CH4 and then shipped to Europe.

<u>Question:</u> What is the exact perimeter of the RREH?



Why RREH?

The potential of renewable energy production near load centres is often limited and of lower quality. Thus, RREH may create new opportunities for decarbonizing economies.

There is the possibility of producing decarbonized fuels in RREH such as H2 or NH3 but also **non-decarbonized but CO2-neutral fuels** using, for example, a combination of direct air capture (DAC), electrolysis and Fischer-Tropsch technologies.

RREH can be built very quickly, in parallel, in many places around the world using the same technology and can **greatly benefit local communities**.

Characteristics of an RREH (1/2)

An RREH can be characterized by

(i) L a set of **locations**;

(ii) $G = (N, V)$ a **graph of technologies** where N is a set of nodes which represent technologies (e.g. direct air capture (DAC), methanation, wind turbines, solar panels, etc…) which are connected together through hyperedges (or vertices) V;

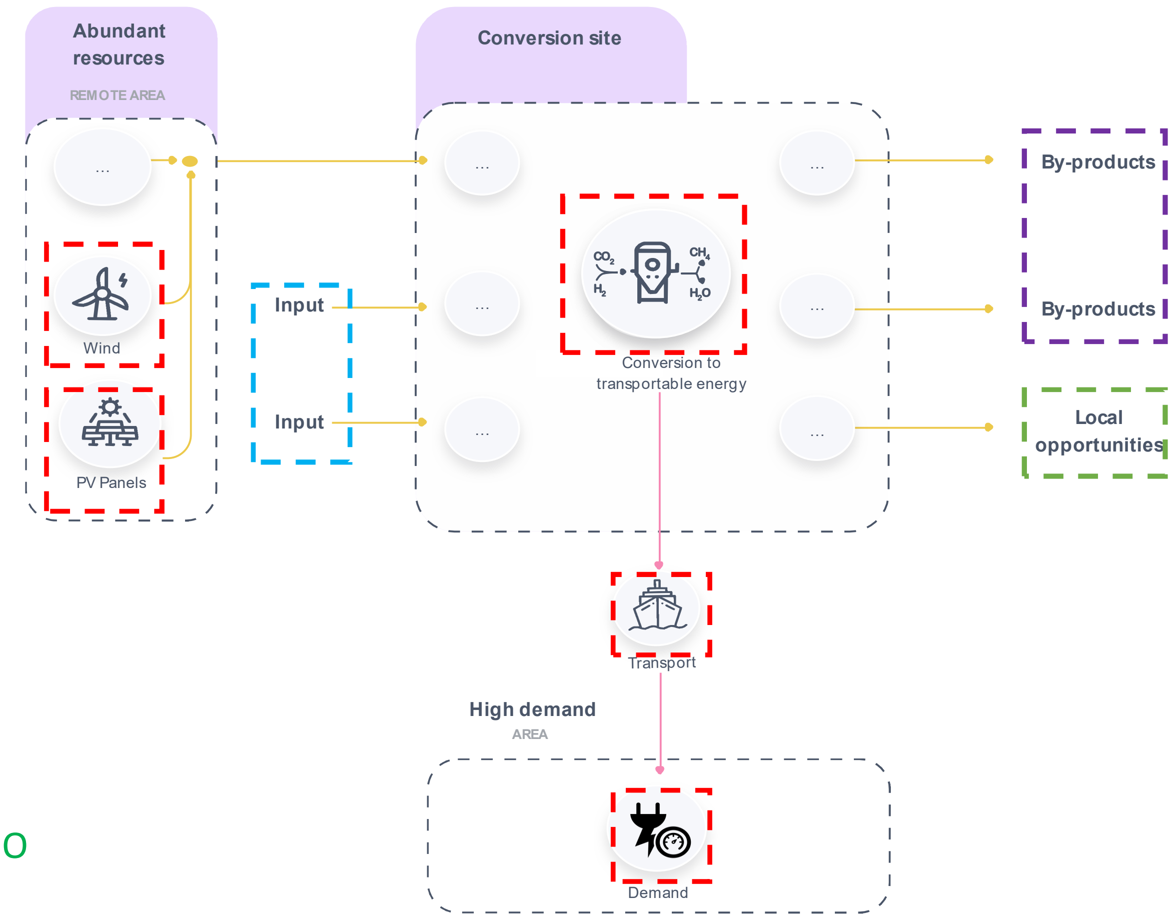
(iii) S an **operational strategy**.

Characteristics of an RREH (2/2)

These 3 key elements (L, G, S) enable the processing/production of commodities that can be divided into four sets:

- Imports I : e.g. CO2, sea water;
- Exports E: e.g. methane, methanol, amoniac, hydrogen, electricity;
- By-products B: e.g. heat, oxygen;
- Locally exploited opportunities O: e.g. potable water, fertilizer, electricity, heat.

Schematic view of an RREH

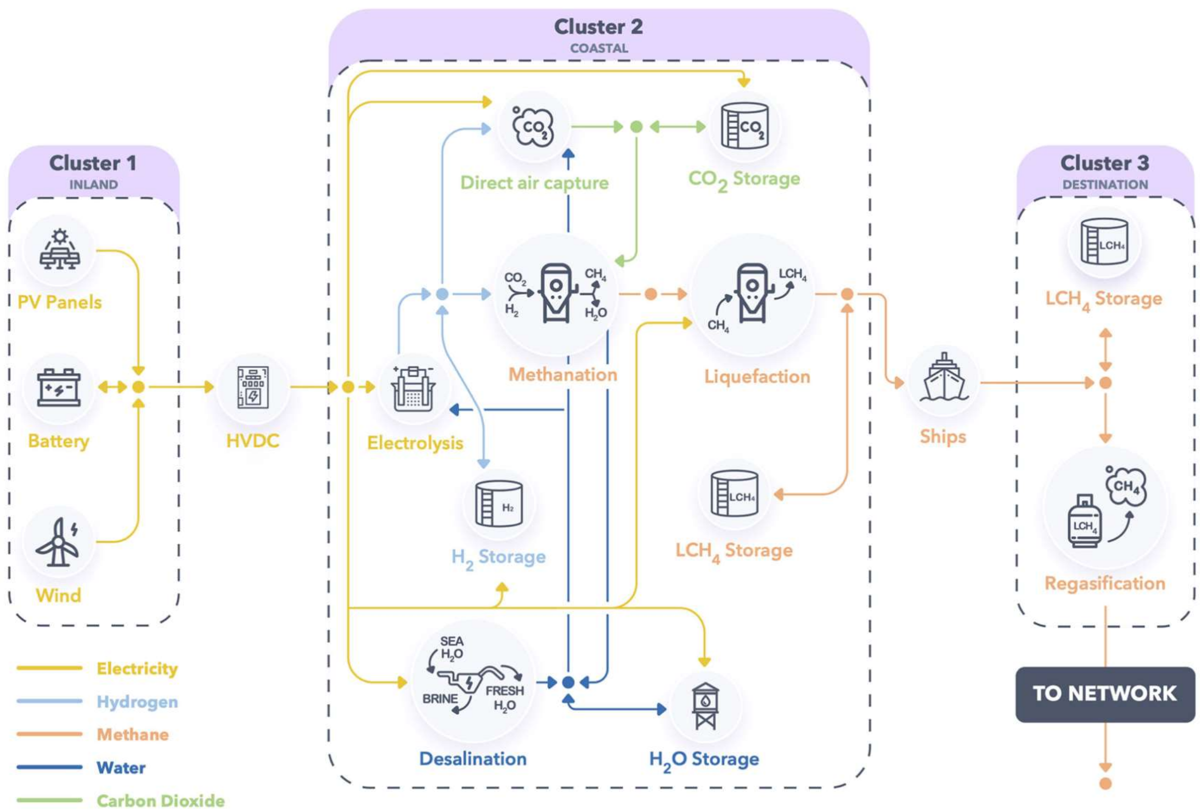


Technologies N
Hyperedges V
Imports I
By-products B
Local opportunities O

Example 1: A hub in the desert for carbon-neutral fuel

Let us go back to the RREH in the Algerian desert.

- Graph of technologies *G* described in this picture:



- Set of imports *I* = sea water (should this be considered as an import?)
- Set of exports *E* = CH4
- Set of by-products *B* = heat, O2
- Set of exploited local opportunities *O* = ø

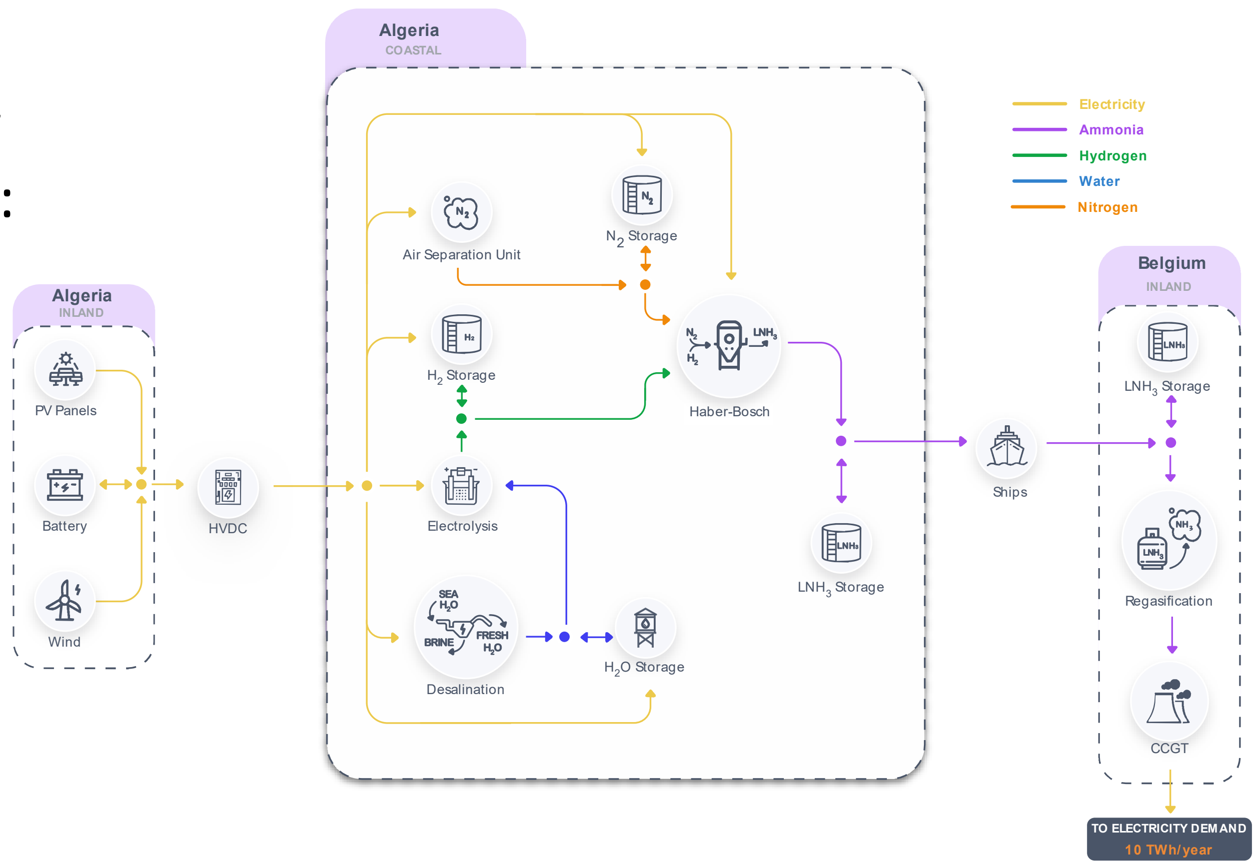
Price of regazified CH4 in Zeebrugge (Zeebrugge) in an **optimized hub**: 149€/MWh HHV (Berger et al., 2021).

Price may be reduced (i) with the decrease in technological costs (ii) by exploiting local opportunities (selling electricity, pure water, etc., locally) (iii) by using Post-Combustion Carbon Capture (PCCC) in addition to DAC; see Example 5.

Example 2: Variation of Example 1 for ammonia production

- Graph of technologies *G* described in this picture:

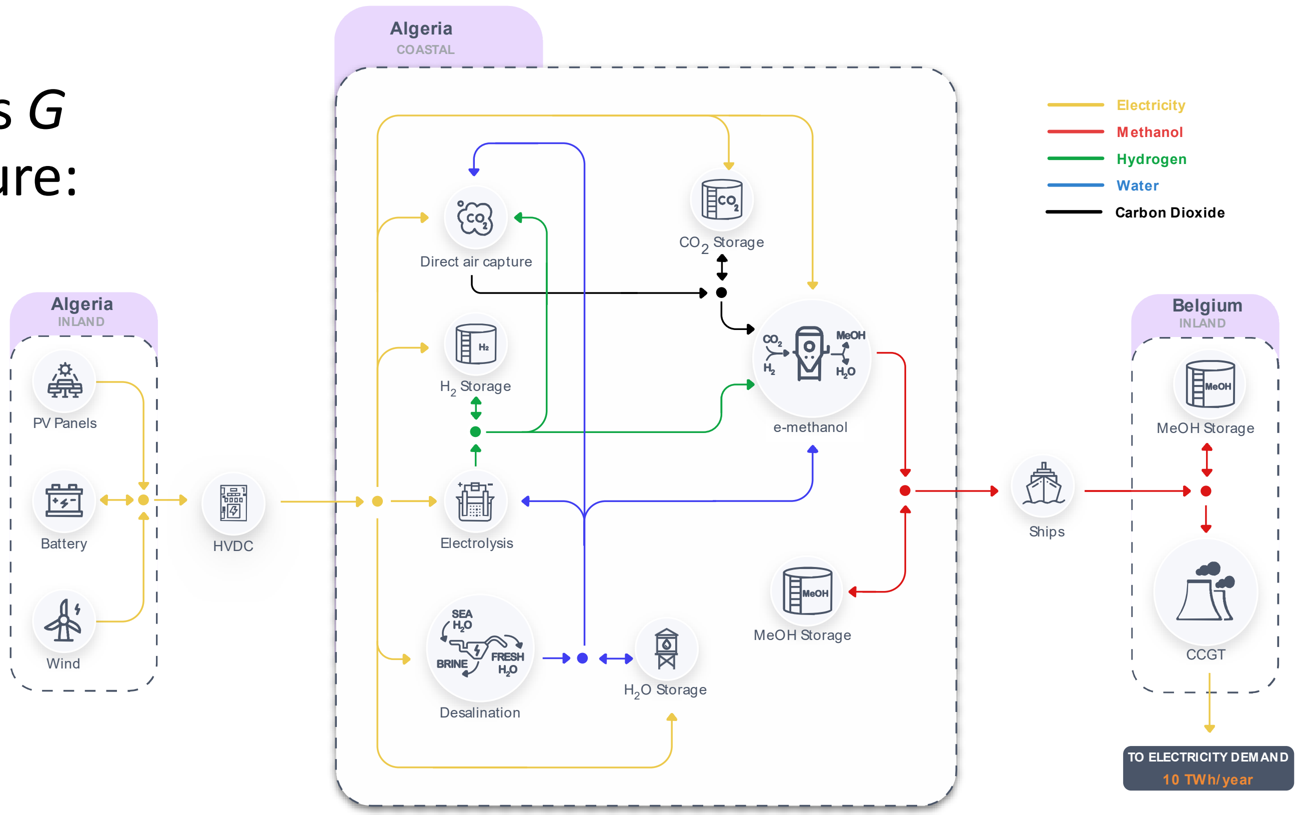
- Set *I* = sea water
- Set *E* = NH3
- Set *B* = heat, O2
- Set O = ø



Example 3: Variation of Example 1 for methanol production

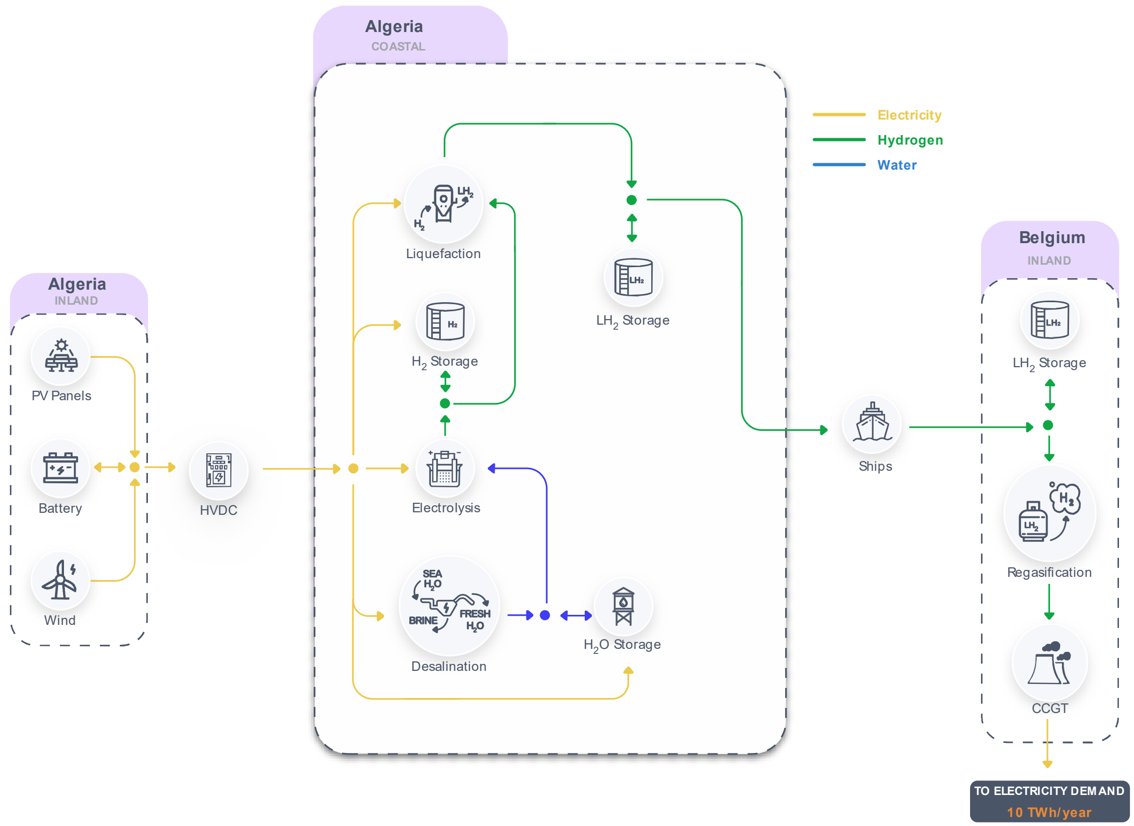
- Graph of technologies *G* described in this picture:

- Set *I* = sea water
- Set *E* = CH3OH
- Set *B* = heat, O2
- Set *O* = ø



Example 4: Variation of Example 1 for hydrogen production

- Graph of technologies *G* described in this picture:



- Set $I = \emptyset$,
- Set E = H2,
- Set B = heat, O2
- Set $O = \emptyset$

What is the best molecule to synthesize in hubs?

We have optimized the different hubs corresponding to Examples 1 to 5 and computed the cost in MWh for producing and transporting the energy-rich molecules to Belgium. Cheapest e-fuel is **NH3**, see Dachet et al. (2023b).

	CH4	NH3	CH3OH	H2
Liquid	**146**	**102**	**140**	**118**
Gazeous	**149**	**107**	/	**120**

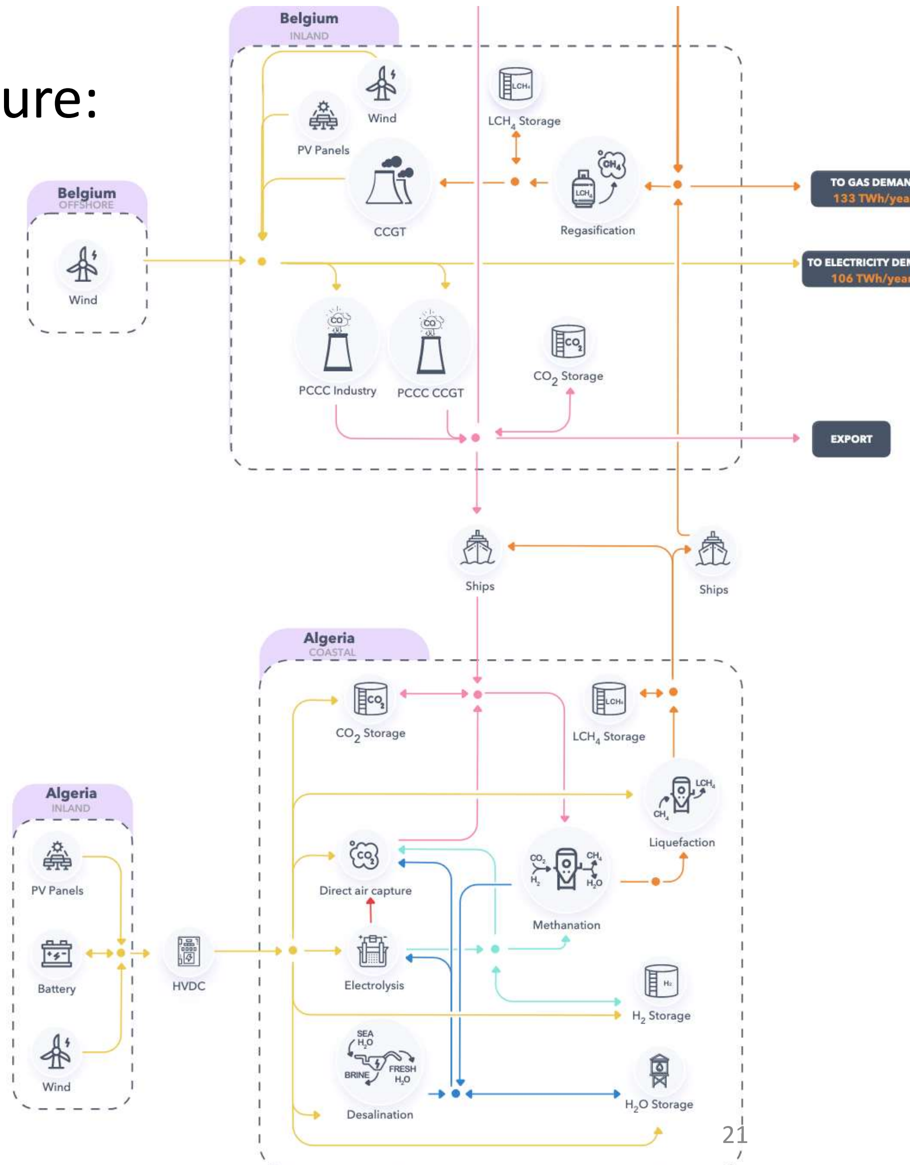
Cost in Euros per MWh for the different energy-rich molecules. WACC of 7% for investments.

Example 5: CO2 Valorization from PCCC in Europe

Now, not all the CO2 used for methanation in Example 1 comes from DAC. There is the possiblity of importing CO2 from PCCC in Northern Europe at a price of 162 €/ton.

This the « shadow value of CO2 » established through centralized optimisation in a multi-renewable energy hub setting for CH4 production.

- Graph of technologies *G* described in this picture:



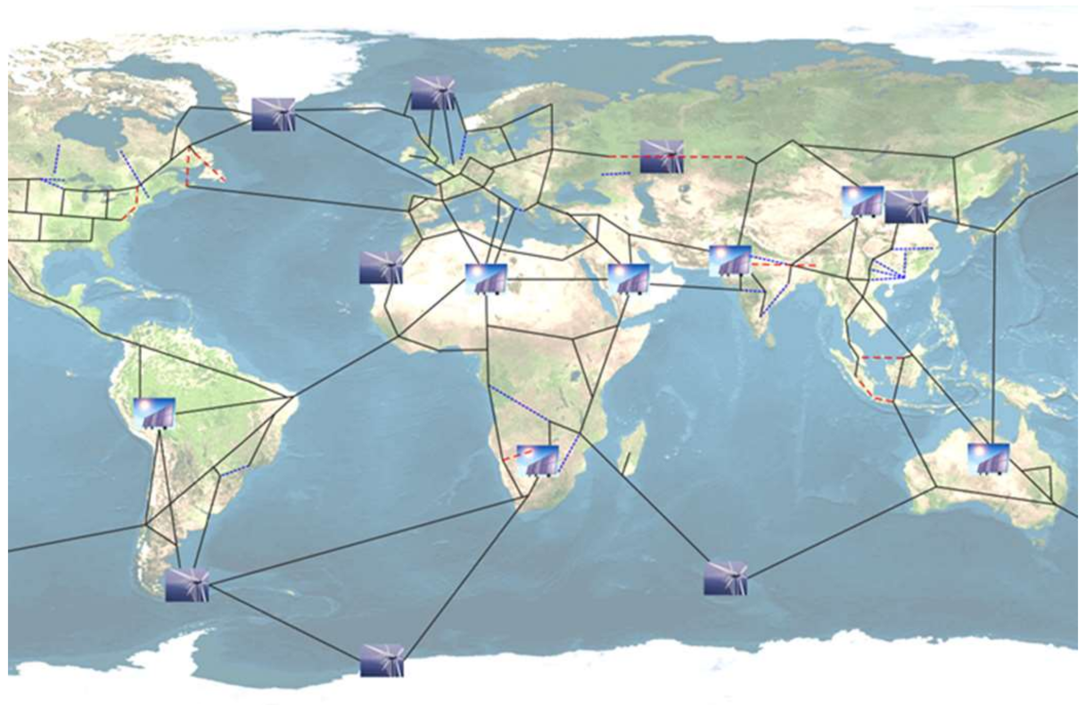
- Set of imports *I* = **CO2**, sea water
- Set of exports *E* = CH4
- Set of by-products *B* = heat, O2
- Set of exploited local opportunites *O* = ø

Price of regazified CH4 from an **optimized hub**: 136€/MWh versus 149€/MWh in Example 1; see Dachet et al. (2023a).

Example 6: the global grid seen as a set of connected hubs

The global grid can be seen as a set of connected hubs with sets:

- Set *I* = electricty
- Set *E* = electricity
- Set *B* = ø
- Set *O* = ø



For more information on the original Global Grid research paper, see Chatzivasileiadis et al. (2013).

Example 7: A ‘smart’ multi-energy vector hub

A **smart multi-energy vector hub** could combine Haber Bosch, methanation, methanolisation and electrolysis processes in a smart way to take advantage of each technology in order to produce different molecules.

The production level of each molecule would be adapted to market price signals.

Challenges for designing, building and operating such hubs.

Exploiting local opportunities in sunny areas (O ≠ ø)

RREHs are likely to be developed in sunny areas where there is often very little access to fresh water.

They could be used to produce fresh water together with nitrogen fertilizers and electricity for developing local agriculture and helping (often impoverished) communities to thrive.

Irrigation carousel in the Wadi Rum desert in Jordan.

Valorizing the by-products B

The hubs reviewed for producing energy-rich molecules had a set of by-products B = heat, O2.

Valuing these by-products could help improve the business cases for these hubs.

The heat by-product of a renewable energy hub placed in cold and windy Greenland could, for example, be used for heating buildings.

Artistic representation of a 'Dubai of Greenland' which would emerge thanks to the significant wind resources of the country, see e.g. Radu et al. (2019).

Optimization of the Hubs

What is optimizing an RREH?

Once the location of a hub as been found* and its graph of technologies chosen, the process of optimizing consists of optimizing its:

1. **Sizing**: find the optimal component dimensions of the hubs (e.g., what is the size of the battery in MWh, the power of the electrolyser);
2. **Operational strategy**: given the constraints associated with each component, how to optimally control the hub to satisfy constraints and maximize profits.

It is important to **optimize both elements at the same time**. Indeed there is an interdependance between the optimal sizing and the optimal operational strategy.

Mixed-Integer Linear Programs (**MILPs**) can be used for carrying out such a combined optimisation.

*may be part of the optimisation problem in itself in which case we would have a three-level optimization problem or even a fourth-level if you also optimize the graph of techologies.

Mixed-Integer Linear Programming in brief

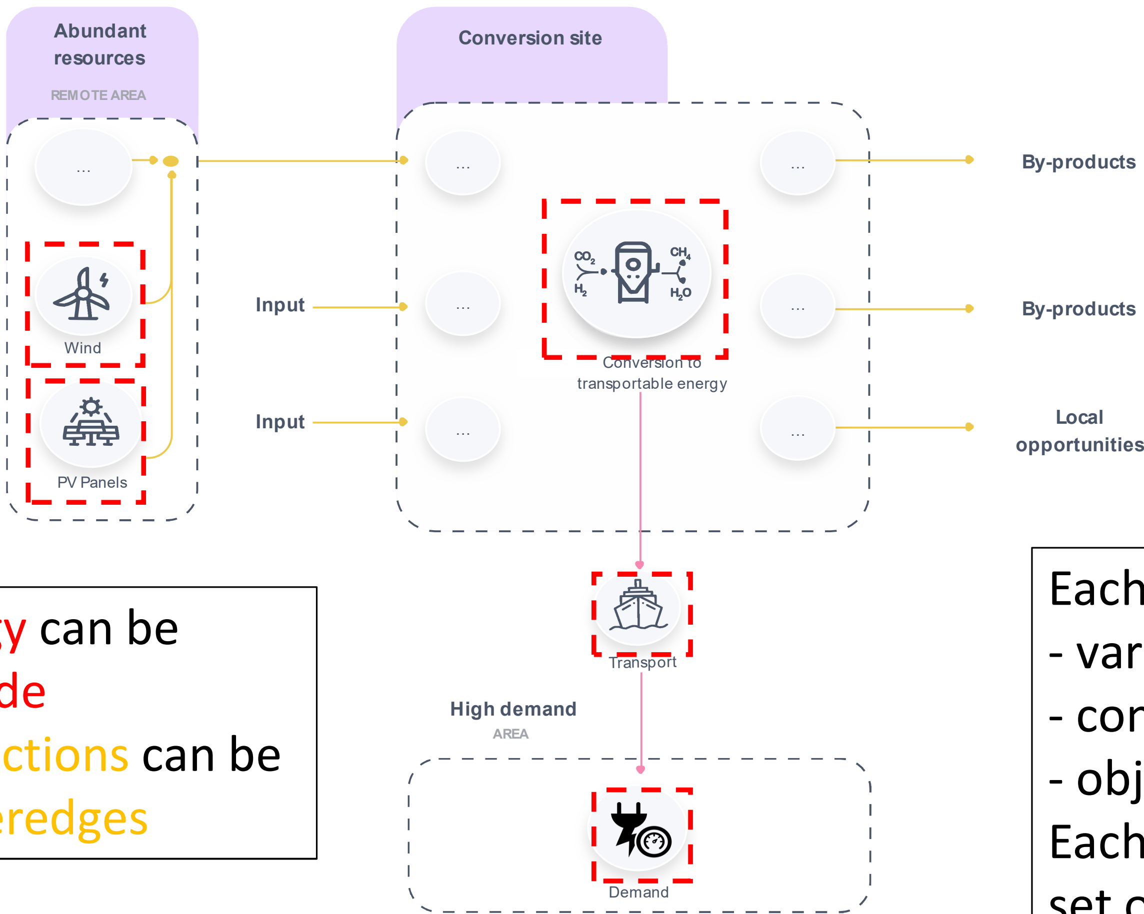
MILPs are optimization problems expressed using variables, constraints and an objective function. In linear optimization, the problems are written as,

$$\begin{aligned} &min\ \ c^t\, x \\ &s.t.\ Ax \leq b \end{aligned}$$

where x is made-of integer and continuous variables.

MILP can deal with large problems. Non-linearities can also be modelled by those problems using piece-wise linear functions.

Optimizing a RREH



- Each technology can be viewed as a node
- The interconnections can be viewed as hyperedges

Each node has its own set of
- variables,
- constraints, and,
- objectives

Each hyperedge has its own set of constraints

Optimizing a RREH

For every node we must :

- Minimize its objective
- Such that we respect all its constraints

For every hyperedge we must :

- Respect its constraints

Overall, we want to

$$\min \sum_{n}^{\text{all nodes}} \text{objectives}_n$$

$s.t.$ all the constraints of all nodes are respected
all the constraints of all hyperedges are respected

Optimizing a RREH

Minimize the sum over all the objectives of every node

$$\min \quad \sum_{n=1}^{N} F^n(X^n, Z^n)$$

Respect every node constraint for every time-step

$$\text{s.t.} \quad h_i(X^n, Z^n, t) = 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}, \forall i \in \mathcal{I}$$

$$g_j(X^n, Z^n, t) \leq 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}, \forall j \in \mathcal{J}$$

Respect every hyperedge constraint

$$H^e(Z^e) = 0, \forall e \in \mathcal{E}$$

$$G^e(Z^e) \leq 0, \forall e \in \mathcal{E}.$$

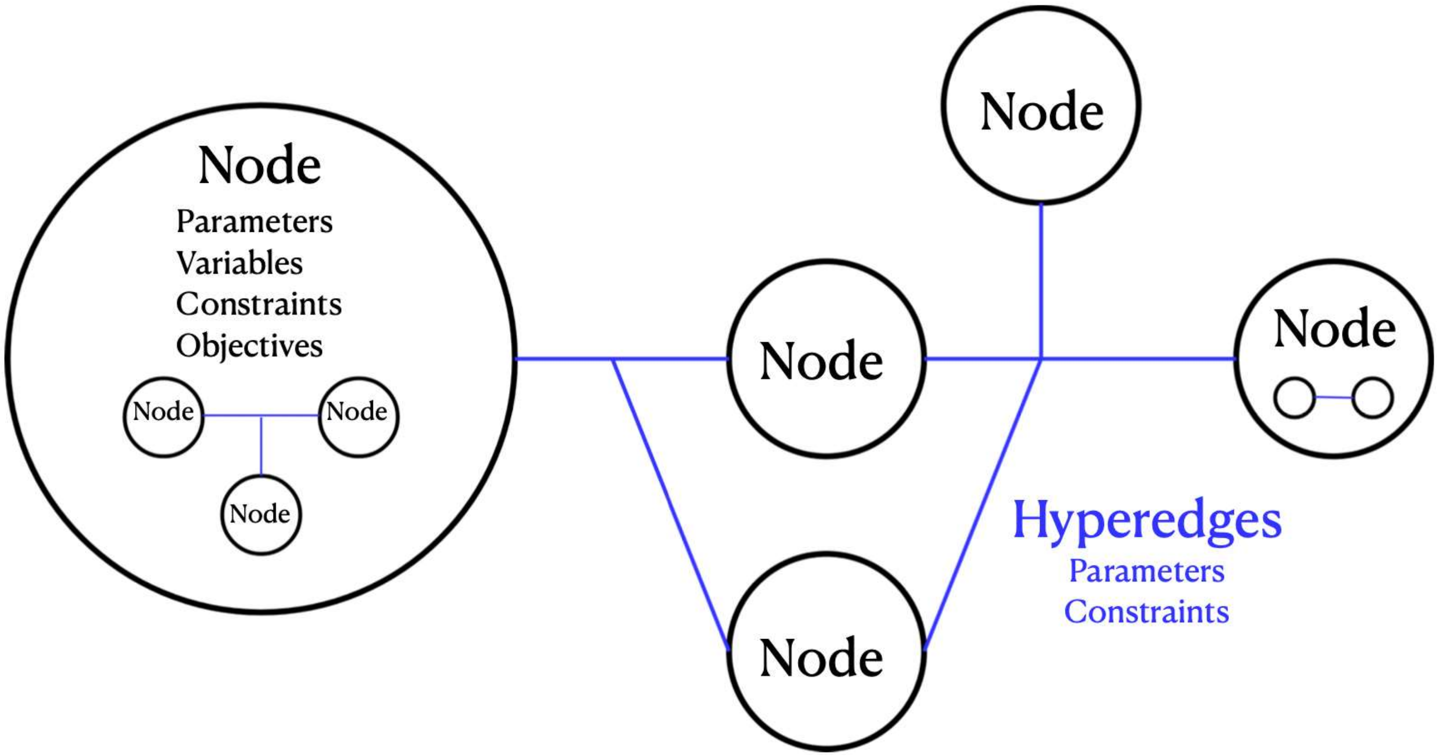
GBOML: The Graph-Based Optimization Modelling Language

GBOML is a tool specifically designed for the **Modelling** and the **Optimization** of complex (energy) systems.

GBOML **exploits** the hypergraph structure of problems:

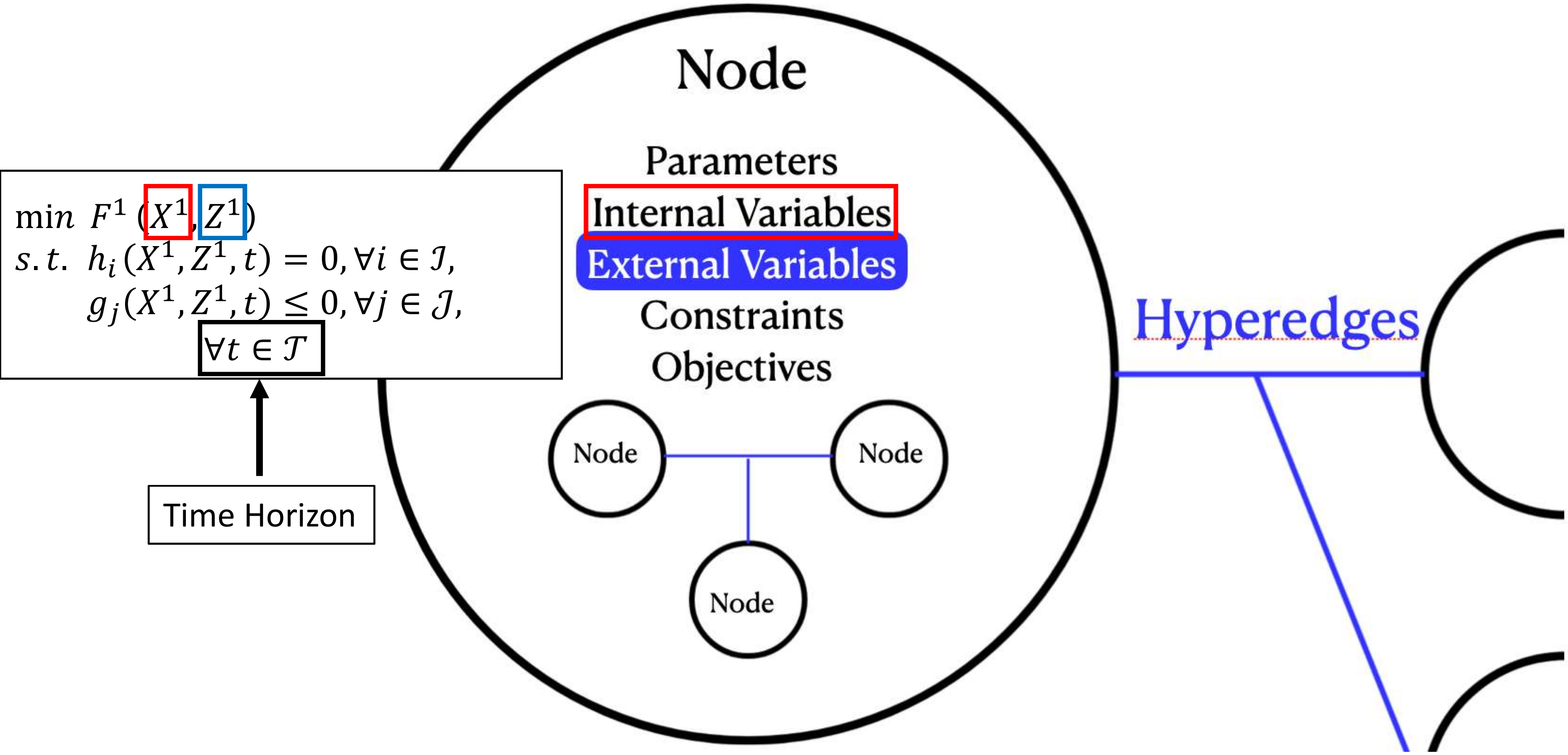
- It enables the definition of **reusable templates** that can be imported;
- It supports **model assembling**;
- It uses structure **to build models faster**;
- It interfaces with various (open-source and commercial) **solvers** and **structure exploiting methods**;
- It supports also **hierarchical** hypergraph structures.

The hierarchical hypergraph



Source: Miftari et al. (2023)

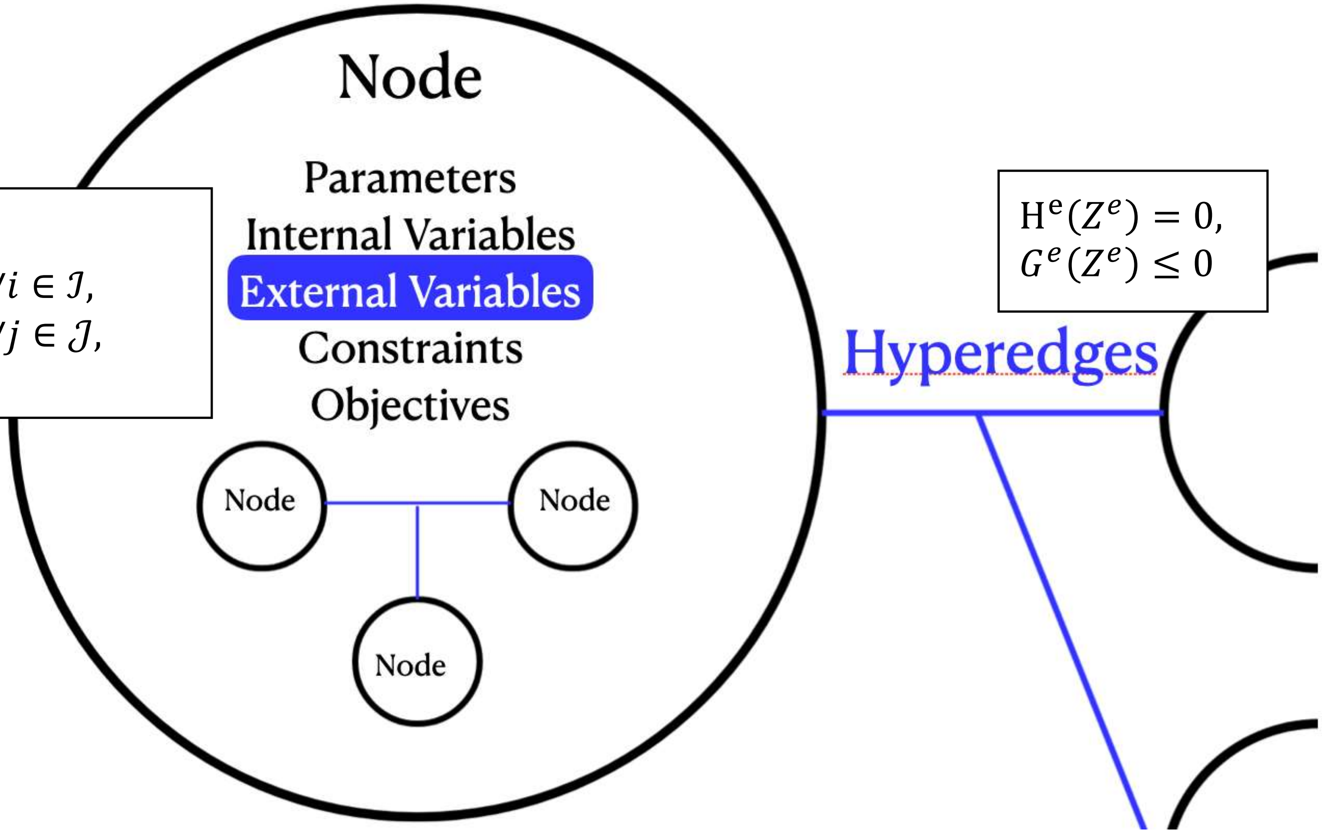
The hierarchical hypergraph



Source: Miftari et al. (2023)

The hierarchical hypergraph

$$\min\ F^1(X^1, Z^1)$$
$$s.t.\ \ h_i(X^1, Z^1, t) = 0, \forall i \in \mathcal{I},$$
$$g_j(X^1, Z^1, t) \leq 0, \forall j \in \mathcal{J},$$
$$\forall t \in \mathcal{T}$$



$$\mathrm{H}^{\mathrm{e}}(Z^e) = 0,$$
$$G^e(Z^e) \leq 0$$

Source: Miftari et al. (2023)

Two existing challenges for optimizing a hub

1. **Uncertainty:** how to take into account uncertainty related, for example, to the cost of commodities, the renewable energy profiles, the cost of technologies.

2. **Optimizing the technology:** how can we determine what improvements should be made to the technology to optimize the economy of hubs? For example, designing windmills with higher cut-out speed and rated output speed may significantly improve the economics of an RREH located in windy Greenland; see Radu et al. (2019).*

* We are currently using Reinforcement Learning (RL) techniques as a way to solve these challenges, see e.g. Boland et al. (2022).

Geopolitics, Finance and Incentives

Deepening of multilateralism and the end of energy weaponization

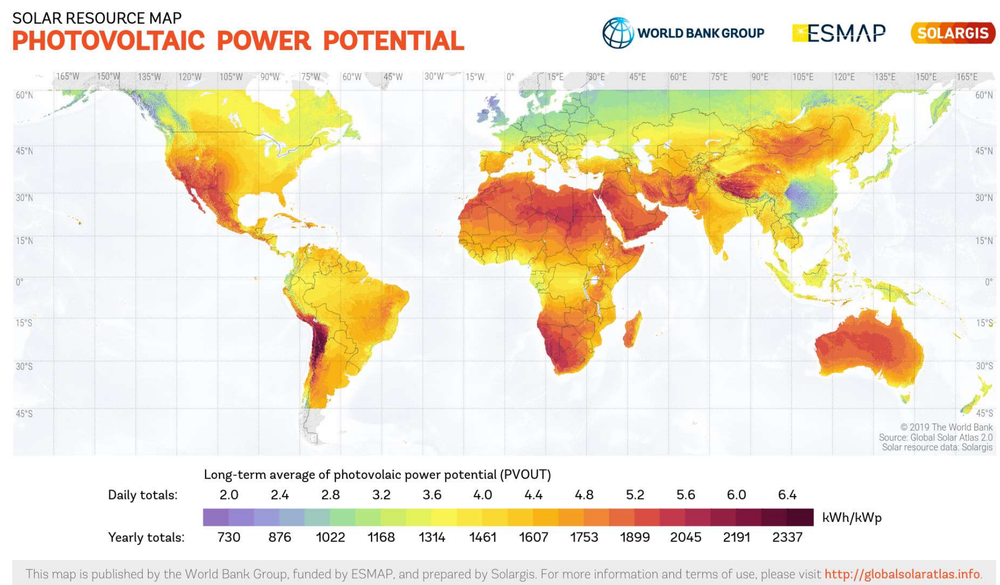
A global grid and the multiplication of RREH numbers will create a complex web of interdependencies between states (ex. depending on variations of demand and supply).

The abundance of wind and solar energy resources makes it possible to avoid having hubs used as a political energy weapon as is currently the case for gas and oil, where limited resources are located in specific countries (Bordoff and O'Sullivan (2023)).

Promotion of democratic regimes through a strategic establishment of RREH

Wind and solar resources are abundant in stable and democratic parts of the world.

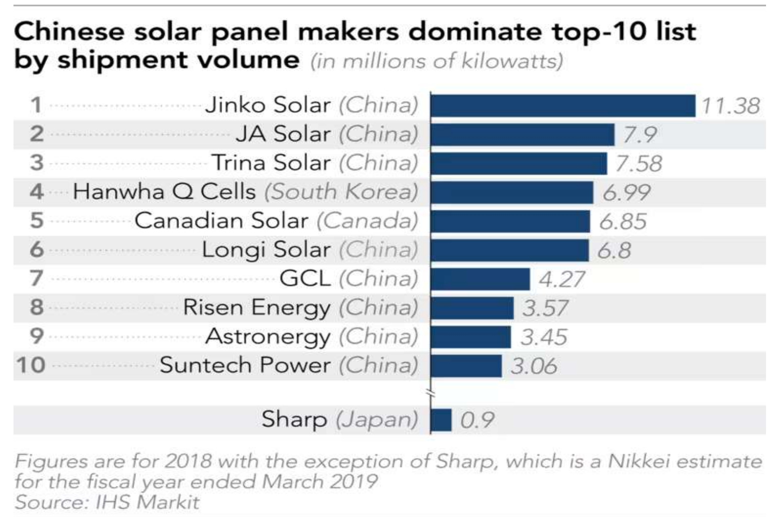
With RREHs there is a way to promote democratization and strengthen the EU's role as a 'Normative Power' (Manners, 2002).

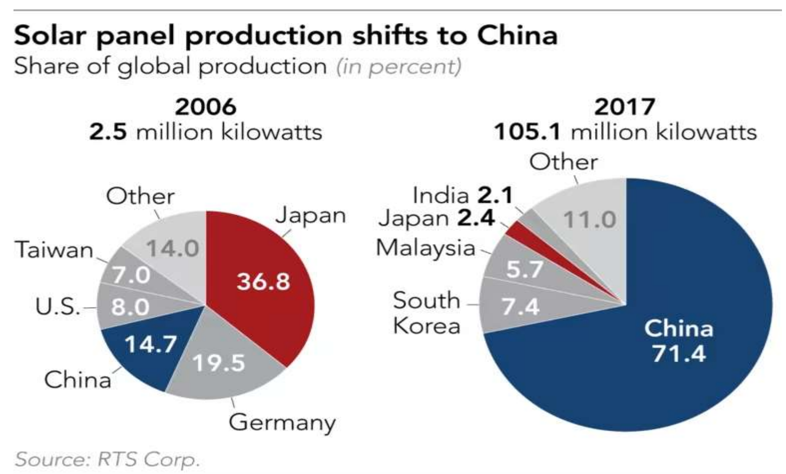


Concentration of resources

No need to worry about the concentration of solar/wind resources, but attention must be paid to the concentration of technological resources needed for the fabrication of renewable technologies and manufacturing chains (IEA, 2022).

How to efficiently diversify supply chains to avoid over-reliance over a few technology-producing countries?





Consideration of the local environment when developing RREHs

Establishing RREHs in the Global South must not be a colonialist nor a plundering endeavour.

Valorization of local opportunities and by-products in countries developing such hubs is important.

Importance of fairness, respect of local realities of communities and sustainable development.

Kirkuk oil field (Iraq) in 1932. The oil extracted from this field at the time mainly benefited the United Kingdom. This is an example of energy colonialism that should not be reproduced with RREH.

United Nations Sustainable Development Goals (UN SDGs)

UN SDGs (Gymiah et al., 2023):

- Set of 17 interconnected goals adopted by all United Nations Member States in 2015
- Aim to address the world's most pressing social, economic, and environmental challenges by 2030.

RREHs and UN SDGs

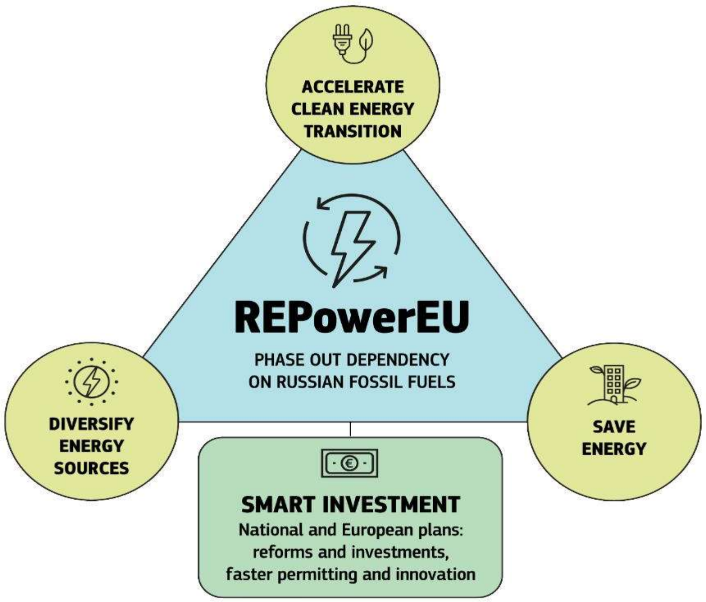
The RREH concept is aligned with six UN SDGs:

- SDG 6: Clean water and sanitation;
- SDG 7: Affordable and clean energy;
- SDG 8: Decent work and economic growth;
- SDG 9: Industry, innovation and infrastructure;
- SDG 12: Responsible production and consumption;
- SDG 13: Climate action.

REPowerEU

REPowerEU (European Commission, 2022):

- In the context of the war in Ukraine, a plan has been designed to save energy, produce clean energy and diversify energy supplies;
- In the short term: diversification of energy supplies and supplier;
- On the mid term (to execute before 2027): financial and juridic measures to build new infrastructures and energy systems.



RREHs and REPowerEU

Several objectives of an RREH and REPowerEU match, namely:

- Diversification of energy supplies;
- Accelerating the rollout of renewables;
- Reduction of fossil fuel reliance and consumption. Example: reduction of reliance on Russian natural gas.

However, the EU did not consider the possibility of importing carbon-neutral natural gas or other synthetic fossil fuels from renewable hubs. REPowerEU places too much emphasis on hydrogen, and not enough on other carbon-neutral outputs that can be produced in RREHs.

New regulatory and monitoring mechanisms will have to be put in place (e.g., amendment of Directive (EU) 2018/2001 *on the promotion of the use of energy from renewable sources*).

The proposal of the European Parliament and the Council for a Regulation *on the internal markets for renewable and natural gases and for hydrogen* is heading in the right direction.

Carbon Pricing and Incentives

CO_2 emissions orginating from carbon-neutral fuel produced in RREHs should not be englobed in the ETS & CBAM schemes.

Increase in production and trade of carbon-neutral fuels may lead to an over-supply of carbon credits and thus will drive their prices down.

Conclusion

- **RREHs offer magnificent opportunities for rapidly transitioning to low-carbon economies.**
- Possibility to take advantage of local opportunities for farming and water.
- GBOML can be used to model and help for the optimization of RREH.
- Identifying the optimal hubs is a complex optimization task, especially if multi-energy vector hubs are considered.
- Opportunity to deepen multilateralism and achieve normative objectives at both UN and EU levels.

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