

An aerial photograph of an offshore industrial platform, likely a gas processing or storage facility, situated in the middle of the ocean. The platform features several tall, cylindrical towers and a complex network of pipes and structural steel. A large supply vessel with a black hull and a white superstructure is docked at the platform. The sky is clear and blue, and the water is a deep blue. The overall scene conveys a sense of remote industrial activity.

Remote Renewable Energy Hubs

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Menu

- 1. Remote Renewable Energy Hubs**
- 2. Optimization of the Hubs**
- 3. Geopolitics, Finance and Incentives**



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

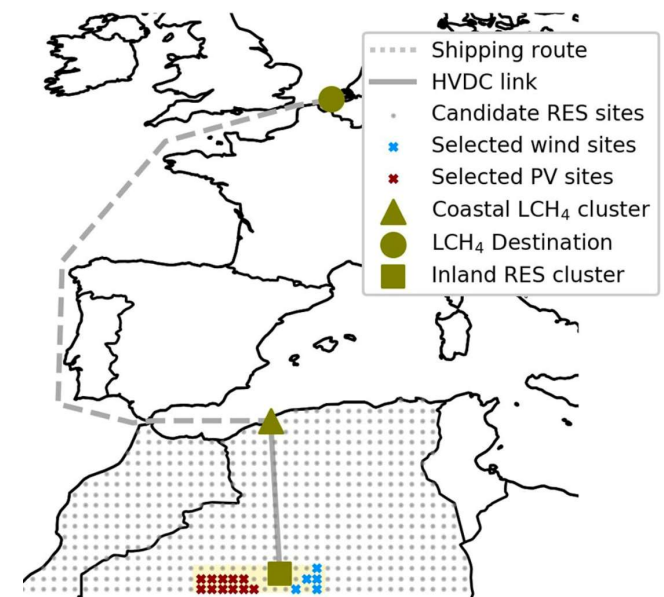
1. Remote Renewable Energy Hubs

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 a 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.

Question: 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

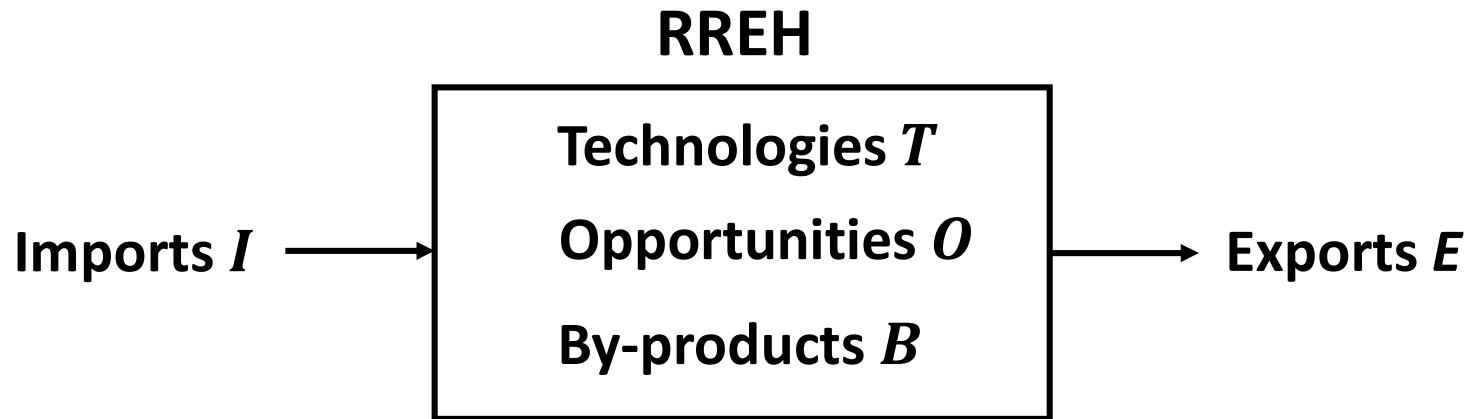
RREH can be built very quickly, in parallel, in many places around the world using the same technology and can **greatly benefit local communities**.

Characteristics of a RREH

An RREH can be characterized by a set of technologies T (e.g. direct air capture (DAC), methanation, wind turbines, solar panels, etc...) which are connected together in order to transform/produce commodities that can be divided into four sets:

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

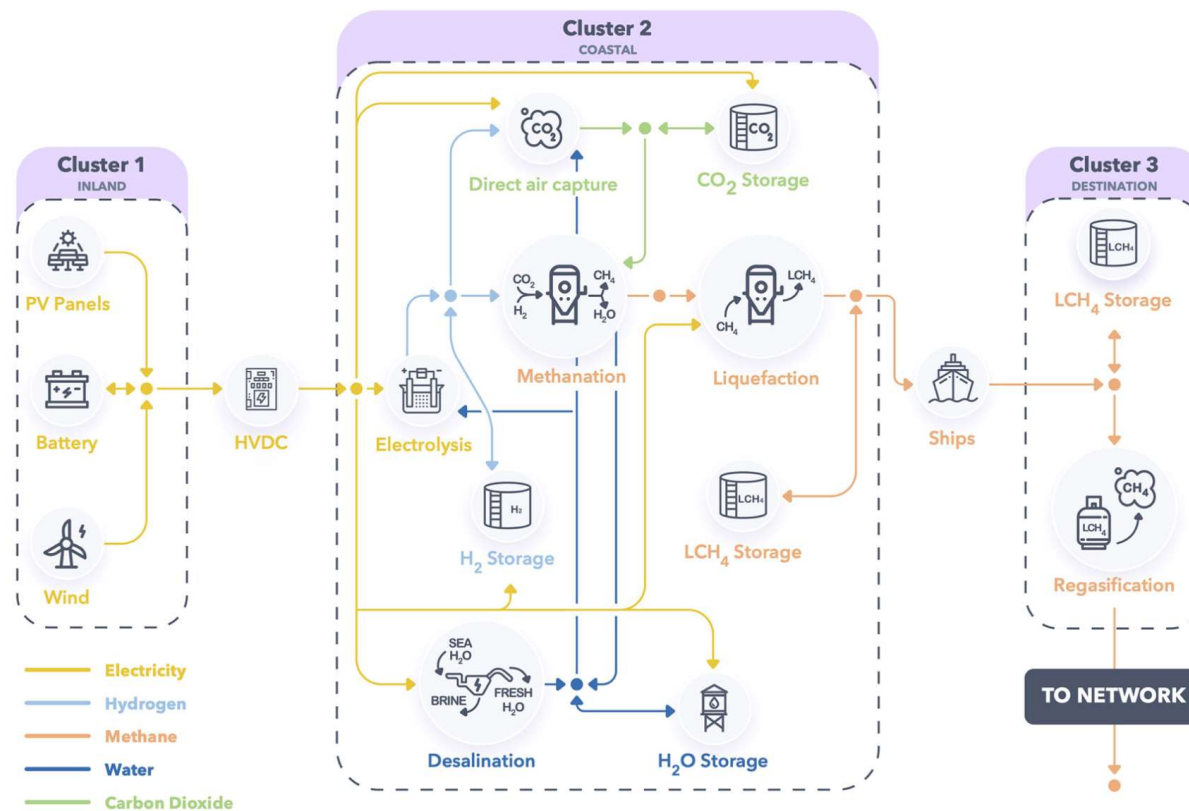
Schematic view of a RREH



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

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

- Set of technologies T described in this picture:



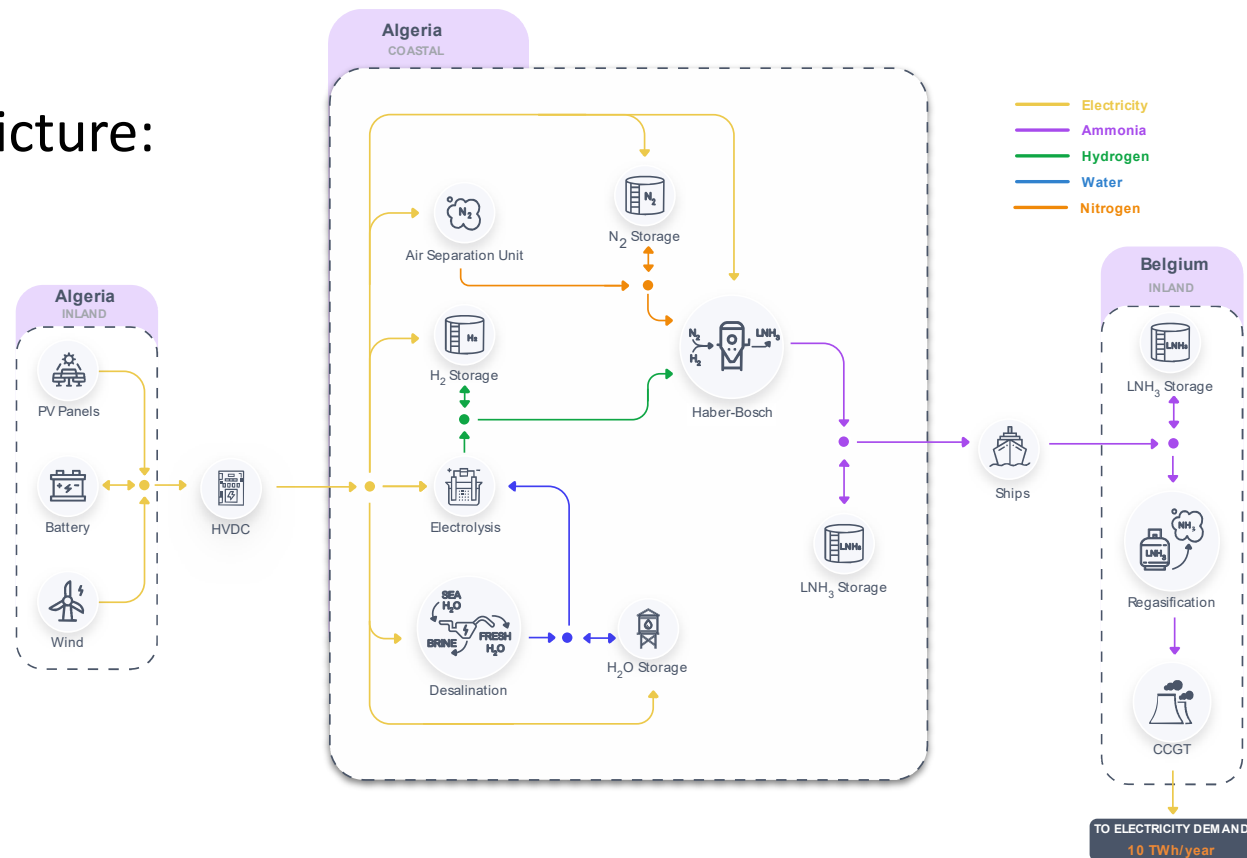
- Set of imports I = sea water (should this be considered as an import?)
 - Set of exports E = CH₄
 - Set of by-products B = heat, O₂
 - Set of exploited local opportunities O = \emptyset
-

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.

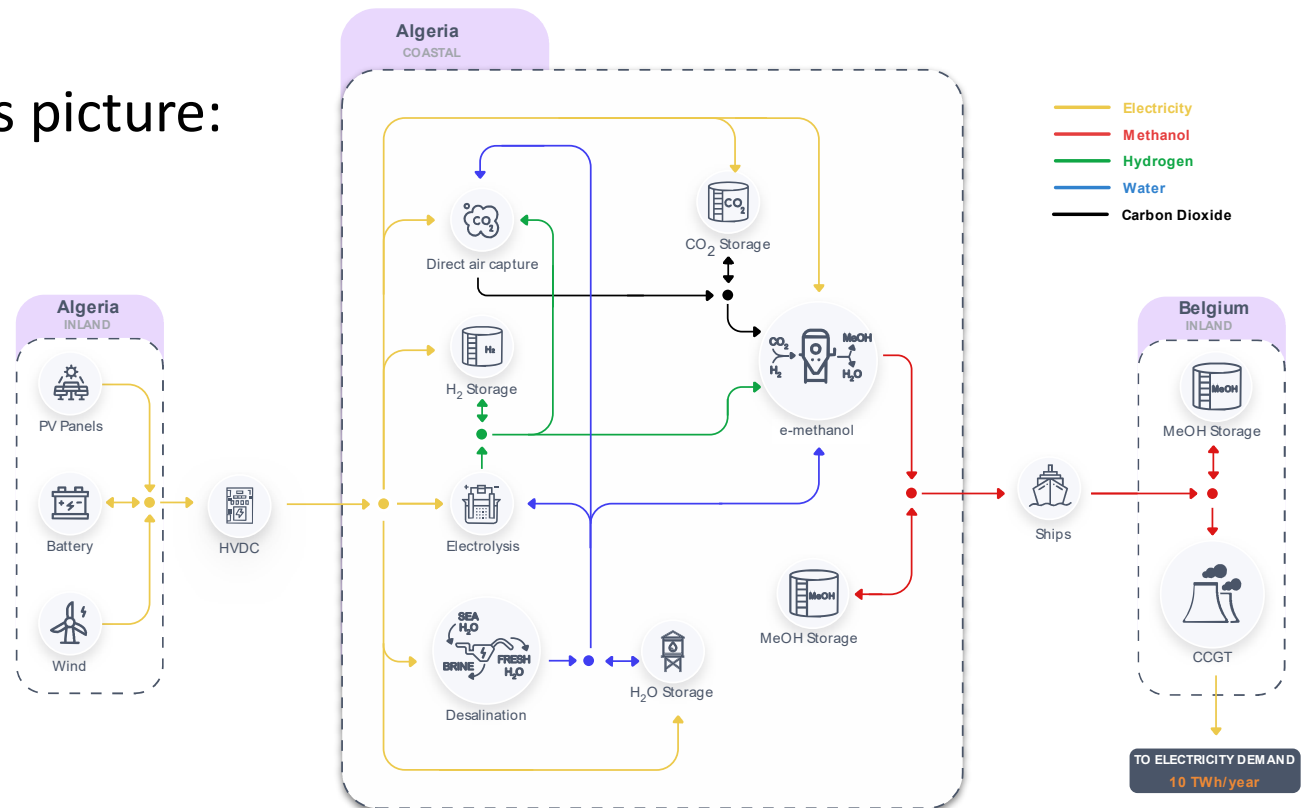
Example 2: Variation of Example 1 for ammoniac production

- Set T described in this picture:
- Set $I =$ sea water
- Set $E = \text{NH}_3$
- Set $B =$ heat, O_2
- Set $O = \emptyset$



Example 3: Variation of Example 1 for methanol production

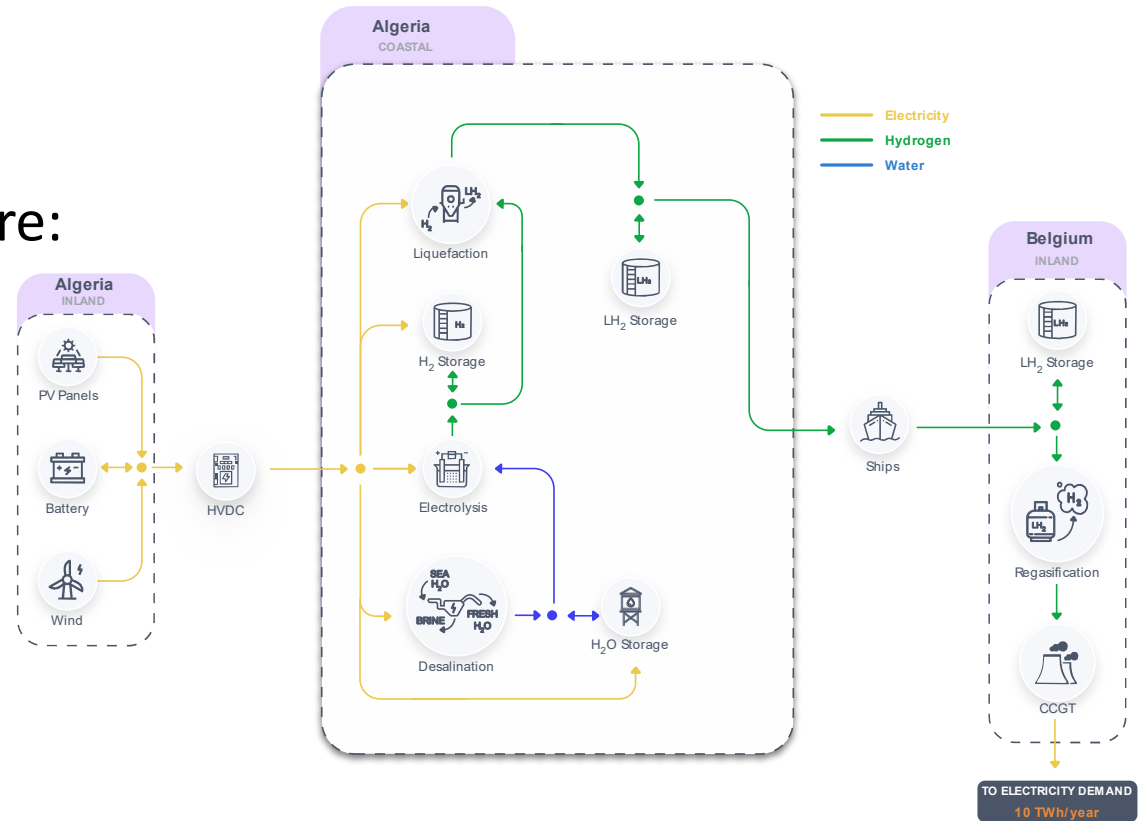
- Set T described in this picture:
- Set $I =$ sea water
- Set $E = \text{CH}_3\text{OH}$
- Set $B =$ heat, O_2
- Set $O = \emptyset$



Example 4: Variation of Example 1 for hydrogen production

- Set T described in this picture:

- Set $I = \emptyset$,
- Set $E = H_2$,
- Set $B = \text{heat, } O_2$
- 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).

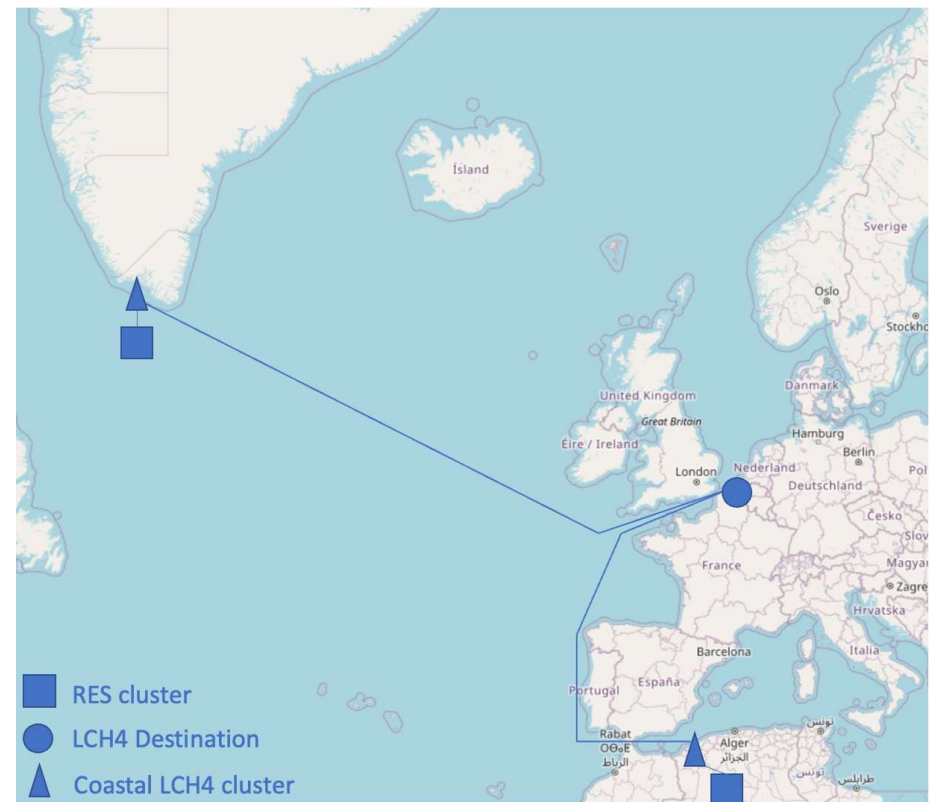
| | CH₄ | NH₃ | CH₃OH | H₂ |
|----------------|-----------------------|-----------------------|-------------------------|----------------------|
| Liquid | 146 | 102 | 140 | 118 |
| Gaseous | 149 | 107 | / | 120 |

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

Example 5: CO₂ Valorization from PCCC in Europe

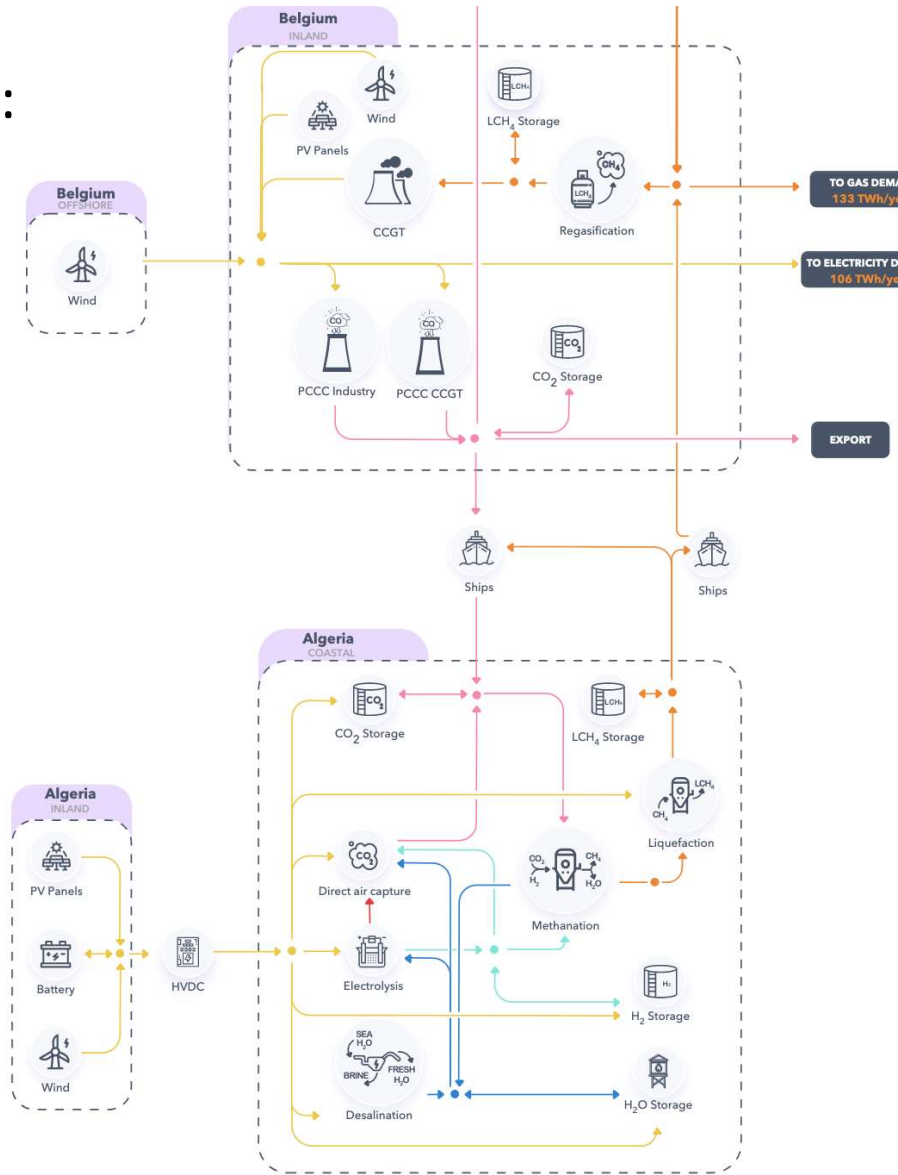
Now, not all the CO₂ used for methanation in Example 1 comes from DAC. There is the possibility of importing CO₂ from PCCC in Northern Europe at a price of 162 €/ton.

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



- Set of technologies T described in this picture:
- Set of imports $I = \text{CO}_2$, sea water
- Set of exports $E = \text{CH}_4$
- Set of by-products $B = \text{heat, O}_2$
- Set of exploited local opportunities $O = \emptyset$

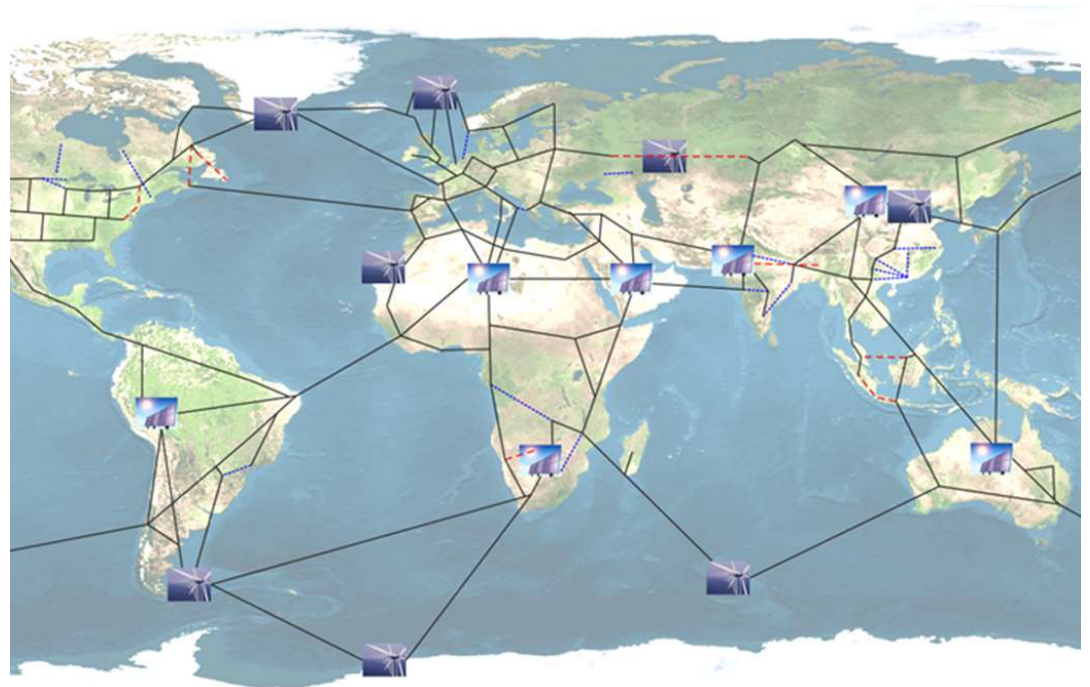
Price of regazified CH4 from an **optimized hub**:
 136€/MWh versus 149€/MWh in Example 1;
 see Dachet et al. (2023a).



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 = electricity
- Set E = electricity
- Set $B = \emptyset$
- Set $O = \emptyset$



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 ($0 \neq \emptyset$)

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 $B = \text{heat, O}_2$.

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).

2. Optimization of the Hubs

What is optimizing a RREH?

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

1. **Sizing**: to 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.

*May be part of the optimisation problem in itself in which case we would have a three-level optimization problem



RREH seen as a set of nodes and hyperedges

We have proposed modelling a hub as set of nodes and hyperedges (Berger et al., 2021).

This modelisation could be used to 'easily' optimize even complex hubs.

Modelisation lead to a new tool GBOML, which is publicly available under the MIT licence (Miftari et al., 2023).

A remote renewable energy hub can be modelled as a set of nodes \mathcal{N} and hyperedges \mathcal{E}

- The nodes in \mathcal{N} contribute to the (linear) objective and local constraints. A node n is defined by
 - internal X^n variables
 - external Z^n variables
 - $F^n(X^n, Z^n) = \sum_{t=1}^T f^n(X^n, Z^n, t)$
- The hyperedges in \mathcal{E} model the constraints between nodes.
- An optimization horizon $T > 0$ with time-steps indexed by $t \in \mathcal{T}$, where $\mathcal{T} = \{1, \dots, T\}$.
- Subject to
 - Equality constraints $h_i(X^n, Z^n, t) = 0$ with $i \in \mathcal{I}$
 - Inequality constraints $g_j(X^n, Z^n, t) \leq 0$ with $j \in \mathcal{J}$

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

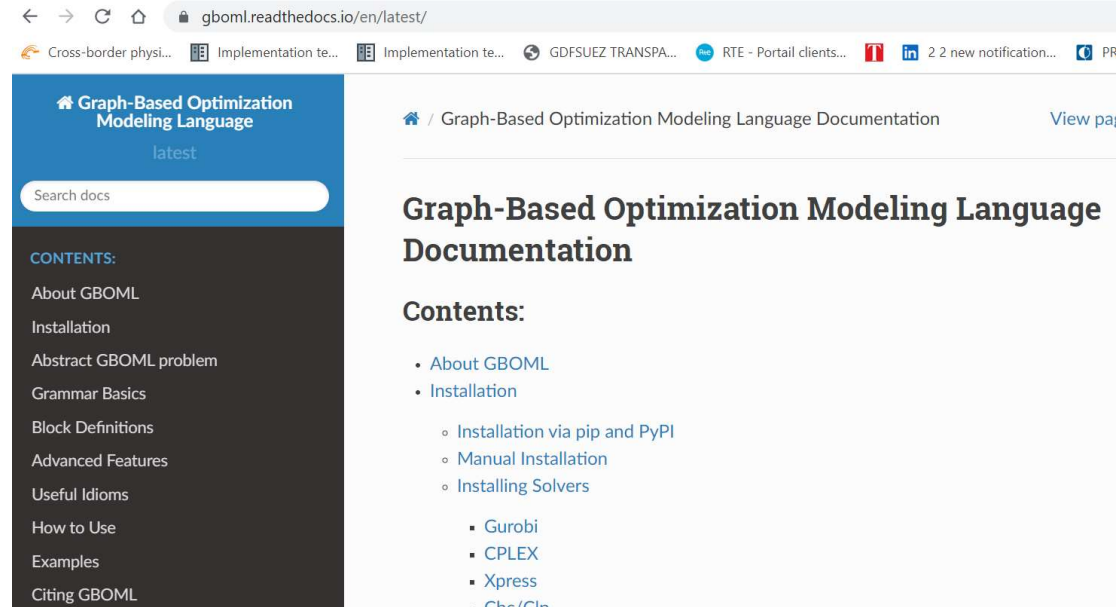
$$\begin{aligned} \text{s.t. } & h_i(X^n, Z^n, t) = 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}, \forall i \in \mathcal{I} \\ & g_j(X^n, Z^n, t) \leq 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}, \forall j \in \mathcal{J} \\ & H^e(Z^e) = 0, \forall e \in \mathcal{E} \\ & G^e(Z^e) \leq 0, \forall e \in \mathcal{E}. \end{aligned}$$

GBOML: The Graph-Based Optimization Modelling Language

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

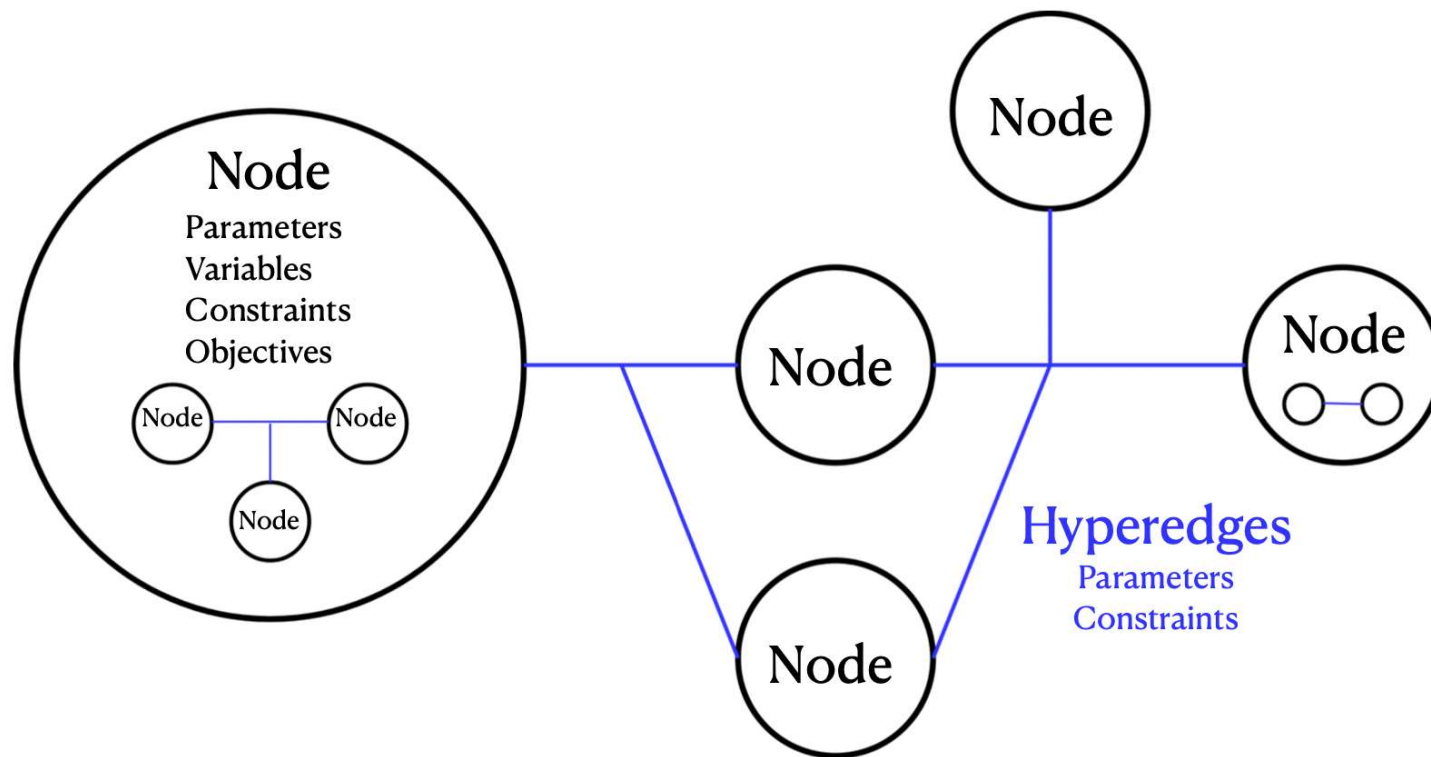
Optimal solution for sizing and operation under several hypotheses:

- Perfect forecast
- All the investment decisions made at the initial time.
- Mixed Integer Linear Modelling.



The screenshot displays the GBOML documentation website. The browser address bar shows the URL `gboml.readthedocs.io/en/latest/`. The page title is "Graph-Based Optimization Modeling Language Documentation". The navigation menu on the left lists the following items: "About GBOML", "Installation", "Abstract GBOML problem", "Grammar Basics", "Block Definitions", "Advanced Features", "Useful Idioms", "How to Use", "Examples", and "Citing GBOML". The main content area shows the "Contents:" section with a list of links: "About GBOML", "Installation", "Installation via pip and PyPI", "Manual Installation", and "Installing Solvers". The "Installing Solvers" section is expanded, showing a list of solvers: "Gurobi", "CPLEX", "Xpress", and "Cbc/Clo".

The hierarchical hypergraph modelling upon which GBMOL relies



Source: Miftari et al. (2023)

Three 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. **Non-Linear behaviour** of the components that significantly complexifies optimization problems.
3. **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 aRREH 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).

3. Geopolitics, Finance and Incentives

Deepening of multilateralism and the end of energy weaponization

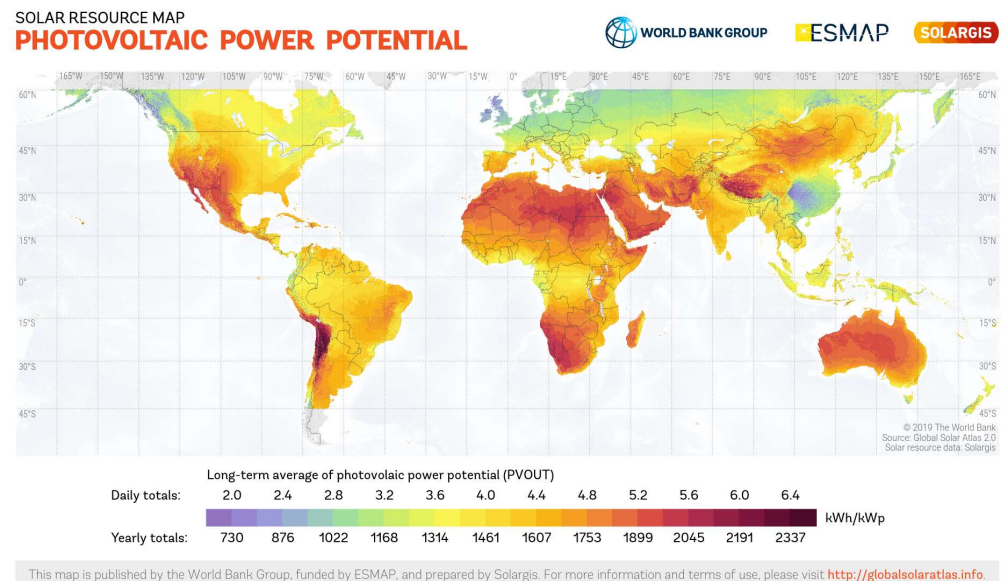
A global grid and the multiplication of RREH numbers will create a complex web of interdependencies between states (ex. depending on variations of demand and supply).

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).

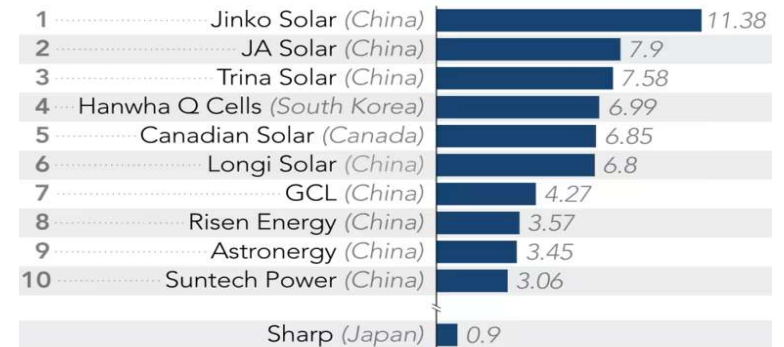


Concentration of resources

No need to worry about the concentration of resources, but attention must be paid to the concentration of 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?

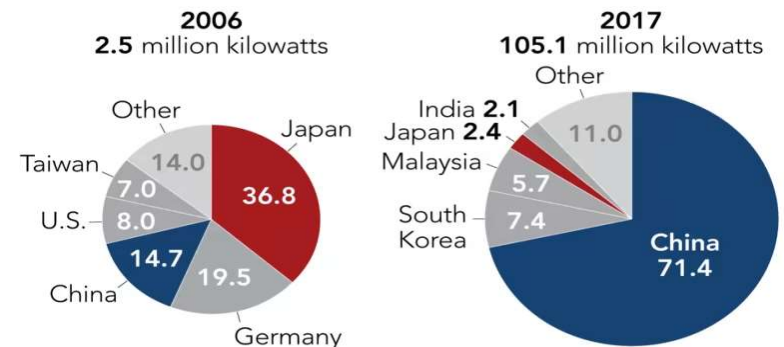
Chinese solar panel makers dominate top-10 list by shipment volume (in millions of kilowatts)



Figures are for 2018 with the exception of Sharp, which is a Nikkei estimate for the fiscal year ended March 2019
Source: IHS Markit

Solar panel production shifts to China

Share of global production (in percent)



Source: RTS Corp.

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

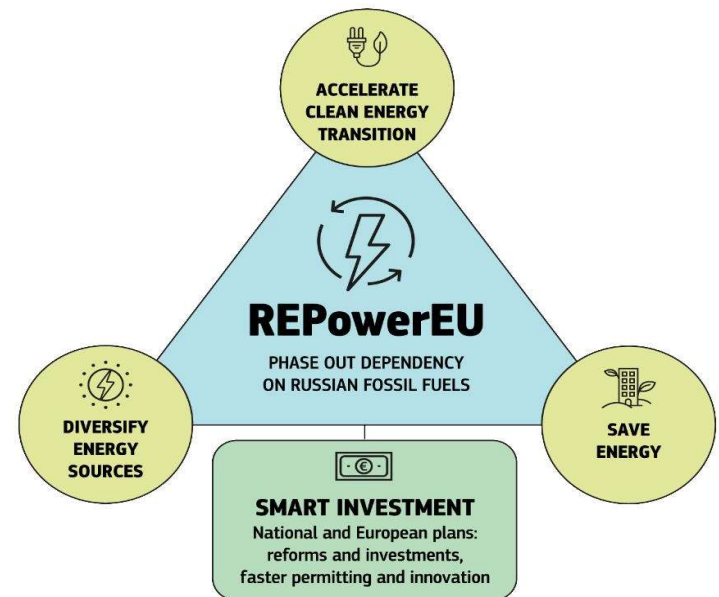
The RREH concept is aligned with six UN SDGs:

- 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 suppliers
- 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

CO2 emissions originating 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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