Remote Renewable Energy Hubs: a Taxonomy

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Abstract

Serving the energy demand with renewable energy is hindered by its limited availability near load centres (i.e. places where the energy demand is high). To address this challenge, the concept of Remote Renewable Energy Hubs (RREH) emerges as a promising solution. RREHs are energy hubs located in areas with abundant renewable energy sources, such as sun in the Sahara Desert or wind in Greenland. In these hubs, renewable energy sources are used to synthetise energy molecules. To synthesize one or several given energy molecule, a specific hub configuration must be designed, which means choosing a set of technologies that are interacting with each other as well as defining how there are integrated in their local environment. The plurality of technologies that may be employed in RREHs results in a large diversity of hubs. In order to characterize this diversity, we propose in this paper a taxonomy for accurately defining these hubs. This taxonomy allows to better describe and compare designs of hubs as well as to identify new ones. This could contribute to their cost efficiency and to improve their local integration.

Keywords: Energy Sytems, Remote Renewable Energy Hub, Renewable Energy, Taxonomy

1. Introduction

To decarbonize their energy supply, load centers, i.e., geographical zones with high energy demand, will have to rely on large amounts of renewable energy. Nevertheless, renewable energy produced locally in those load centers, such as Belgium, may be insufficient to cover all energy needs for various reasons [1], such as: (i) limited space to install renewable energy assets and (ii) low-quality renewable energy sources. To address these limitations, Remote Renewable Energy Hubs (RREHs), i.e., energy hubs situated away from those load centers where renewable energy is abundant, offer a solution to the lack of local renewable resources. RREHs have spurred significant research on possible hub development around the globe [1, 2, 3]. They can rely on power-to-X technologies that present a dual advantage [4, 5, 6]. They offer a CO_2-neutral solution to meet energy demand and a means of storing energy generated by renewable sources [7].

Different models of RREHs have been proposed in the literature. Hashimoto et al. [3] proposed a RREH, where CH_4 was produced in Egypt to deliver methane to Japan. However, no techno-economic analysis of the supply chains was carried out. Then, Fasihi and Bogdanov [8] and Fasihi et al. [9] proposed a techno-economic analysis for the production of CH_4 in Northern Africa and delivery in Finland. In Verkehrswende et al. [10], the authors investigate a similar supply chain with delivery in Germany. Berger et al. [11] proposed a techno-economic analysis of a supply chain between the Sahara desert in Algeria and Belgium as a load centre. Dachet et al. [2] performed a techno-economic analysis of introducing a loop involving the export of CO_2 from Belgium to the RREH defined in Berger et al. [11] as proposed by Hashimoto et al. [3]. They highlight the potential of post-combustion carbon capture (PCCC) in Belgium to valorise CO_2 in a RREH. They also investigated another RREH located in Greenland, which has also been proposed as an energy hub for Europe with complementary wind regimes [12, 13]. Fonder et al. [14] explore the same idea with PCCC technologies in complement of Direct Air Capture (DAC) devices to produce CO_2 in a RREH located in Morocco. Verleysen et al. [15] have studied a case of RREH exporting NH_3 from Morocco to Belgium. They assessed that the cost of a RREH would be lower than an ammonia hub in Belgium. Moreover, uncertainties on CAPEX and OPEX technology costs have also been taken into account in [15]. Larbanois et al. [16] compared four energy vectors, namely hydrogen (H_2), ammoniac (NH_3),

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methanol (CH_3OH), and methane (CH_4) synthesized in Algeria to meet an energy demand in Belgium.

It is worth noticing that the global grid approach [17, 18, 19], is closely related to the concept of RREH. Indeed, a global grid would allow to collect renewable energy where it is the most abundant and to meet an electricity demand far away from the harvested zone. The DESERTEC project [20] that repatriates renewable energy through electric cables to Europe is an example of a project to develop a global grid. The global grid approach can be seen as the interconnection of load centres and RREHs around the world with electricity as an export commodity.

There exists a combinatorial number of possibilities to design a hub due to all the technologies that can be considered. This implies a large diversity of hubs, making it difficult to compare different hubs, even if they are located in the same place or aimed at producing the same energy vectors. Indeed, RREHs producing the same energy vectors may also differ in their import commodities which complexifies again their comparison and their description. Moreover, in the literature, there is often a lack of clarity regarding whether the valorization of local opportunities and by-products inherent to this type of infrastructure is taken into account. To address these problems, we propose a taxonomy to better characterize RREHs.

This taxonomy aims to provide a tool for describing and comparing RREH models. Moreover, it may be useful for those seeking to improve the design of new hubs. It also offers new prospects for enhancing the local integration of these hubs.

We define the concept of RREH in the next section. In Section 3, we present our taxonomy and illustrate it with an academic example. In Section 4, we apply the taxonomy to two hubs studied in the literature, demonstrating its effectiveness in describing and comparing hubs. In Section 5, we propose a practical procedure for using the taxonomy to identify new hubs. Finally, Section 6 concludes the paper.

2. Definition and Concept

Definition 1. *An **energy hub** integrates input and output of commodities, conversion, and storage functionalities, enabling coupling between different energy systems.*

An energy hub can also encompass production/consumption units, and transportation infrastructure, allowing the exchange of multiple energy carriers.

This definition has been adapted from [21], omitting references to sustainable energy. In both definitions, an offshore wind farm or an onshore solar farm are considered as energy hubs whereas this new definition also encompasses an offshore petroleum platform. In this regard, we distinguish the concept of energy hub from the concept of a *renewable energy hub* which is defined in the following way:

Definition 2. *A **renewable energy hub** is an energy hub that relies on renewable energy sources for energy production.*

Energy hubs can be located anywhere on Earth. However, it makes sense to distinguish energy hubs that are located in remote areas, far from the main centres of population. Notably due to their remote nature, numerous geographical zones with high renewable energy density are yet to be exploited. Additionally, setting energy hubs away from population centres allows the deployment of large infrastructures without impacting the lives of citizens. This leads us to define and focus on what we denote as Remote Renewable Energy Hubs.

Definition 3. *A **Remote Renewable Energy Hub** (RREH) is a renewable energy hub located in a remote area.*

In this definition, we acknowledge that remoteness is a subjective notion, but this is an intentional choice: it allows for the inclusion under the taxonomy described in the following sections of a broad range of energy hubs. Moreover, it underscores the necessity of transportation for the energy produced.

3. Taxonomy

This section formally defines the taxonomy, and, in particular, explains the purpose of each of its components in the context of a RREH. The first part introduces generic mathematical elements that are not related to any particular hub in subsection 3.1. The second part, subsection 3.2, uses these generic mathematical elements to derive elements of the taxonomy tailored to any specific hub. To illustrate this, a hypothetical RREH in Greenland is considered. This RREH generates renewable electricty from wind turbines that is used to power an electrolyser. The H_2 produced by the electrolyzer is subsequently transported via a pipeline to Iceland. A visual representation of this hypothetical hub is provided in Figure 1.
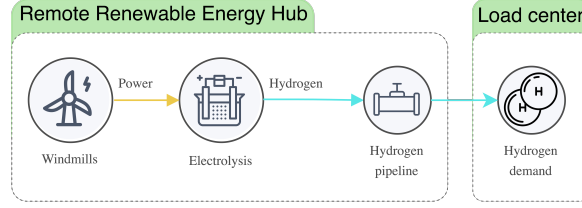
2

Figure 1: RREH located in Greenland exporting H$_2$ towards North America.

3.1. Generic mathematical elements

There are four generic elements associated to a hub, namely $C, \mathcal{L}, \mathcal{T}$ and $\mathcal{H}$. Those are defined hereafter.

- C: the set of all commodities that can be exchanged between technologies typically composed of chemical components, electricity and heat.

- $\mathcal{L}$: the set of locations and their specificities in terms of renewable energy potential and energy demand. An element $l \in \mathcal{L}$ is characterised by the triplet $l = (L, P_l, D_l)$ where L is a location and P_l and D_l are respectively the renewable potential and the demand associated with the location L. A location characterised by a high demand and low renewable potential is referred to as a load centre.

- $\mathcal{T}$: the set of all possible technologies. A technology $t \in \mathcal{T}$, associated with a name n, can be seen as a function processing input commodities $C_t^{in} \subseteq C$ and converting them into output commodities $C_t^{out} \subseteq C$, represented as a 3-tuple $t = (n, C_t^{in}, C_t^{out})$. Included in the set of technologies $\mathcal{T}$, there are three specific technologies:

  (i) $t^{im} = (\text{import}, \emptyset, C_{t^{im}}^{out})$ models the imported commodities;
  (ii) $t^{ex} = (\text{export}, C_{t^{ex}}^{in}, \emptyset)$ models the exported commodities;
  (iii) $t^{op} = (\text{opportunity}, C_{t^{op}}^{in}, \emptyset)$ models the locally exploited commodities;

- $\mathcal{H}$: the set of possible flows of commodities. In this set each element $h = (c, \mathcal{T}^{out}, \mathcal{T}^{in}) \in \mathcal{H}$ is made of three components: a commodity $c \in C$, a set of technologies $\mathcal{T}^{out} \subseteq \mathcal{T}$ that output the commodity c and a set of technologies $\mathcal{T}^{in} \subseteq \mathcal{T}$ that have as input the commodity c coming from the technologies in $\mathcal{T}^{out}$. Therefore, h denotes a flow of commodity c from each technology contained in $\mathcal{T}^{out}$ to each technology contained in $\mathcal{T}^{in}$. One can observe that the edges follow the convention of hyperedges in this work. This simplifies the taxonomy's readability by reducing the number of edges

that need to be defined. Specifically, a single hyperedge represents $|\mathcal{T}^{out}| \times |\mathcal{T}^{in}|$ edges where $|X|$ corresponds to the cardinality of the set X.

3.2. Elements of the taxonomy tailored to a specific hub

Now that the generic mathematical elements have been introduced, any RREH r can be formalised as a 7-tuple $r = (\mathcal{L}_r, \mathcal{G}_r, C_r, \mathcal{E}_r, \mathcal{I}_r, \mathcal{B}_r, O_r)$ can be characterised by its components:

- $\mathcal{L}_r \subseteq \mathcal{L}$: a set of locations associated with the technologies in the hub. Indeed, to model a RREH, a location or several must be identified. The location determines the RREH's potential in terms of resource availability such as solar, wind, hydropower or geothermia. Moreover, the geographical location of the RREH will influence its competitiveness in the closest load centres.

  In the example provided in Figure 1, the set of locations includes only one location in Greenland that has a high renewable energy potential in wind and a low energy demand due to the low density population. Therefore,

$$\mathcal{L}_r = \{l_1\},$$

  where

$$l_1 = (\text{Greenland, high wind potential,}$$

  low energy demand).

- $\mathcal{G}_r = (\mathcal{T}_r, \mathcal{H}_r)$: a graph that mathematically formalises the technologies and commodity flows, represented as $\mathcal{T}_r \subseteq \mathcal{T}$ and $\mathcal{H}_r \subseteq \mathcal{H}$. These technologies $\mathcal{T}_r$ are situated in locations depicted in $\mathcal{L}_r$. The relationships between these components form a graph structure, with $\mathcal{T}_r$ denoting the nodes and $\mathcal{H}_r$ representing the edges. Defining $\mathcal{G}_r$ is called designing a RREH. Therefore, designing a RREH consists of finding the technologies (*i.e.* the nodes in $\mathcal{T}$) that compose the RREH and the flows of

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commodities between these technologies (*i.e.* the edges in $\mathcal{H}$).

In our Greenland example (cfr. Figure 1), the graph of technologies is defined as:

$\mathcal{T}_r = \{$

$\quad$ (Wind$_{l_1}$, $\{\emptyset\}$, $\{$electricity$\}$),

$\quad$ (import$_{l_1}$, $\{\emptyset\}$, $\{H_2O\}$),

$\quad$ (Electrolyser$_{l_1}$, $\{$electricity, $H_2O\}$,

$\quad$ $\{H_2, O_2\}$),

$\quad$ (export$_{l_1}$, $\{H_2\}$, $\{\emptyset\}$)

$\quad \}$

$\mathcal{H}_r = \{$

$\quad$ (Electricity, $\{$Wind$_{l_1}\}$, $\{$Electrolyser$_{l_1}\}$),

$\quad$ (H_2O, $\{t_{l1}^{im}\}$, $\{$Electrolyser$_{l_1}\}$),

$\quad$ (O_2, $\{$Electrolyser$_{l_1}\}$, $\emptyset$),

$\quad$ (H_2, $\{$Electrolyser$_{l_1}\}$, $\{t_{l1}^{ex}\}$)

$\quad \}$.

- $\mathcal{C}_r \subseteq \mathcal{C}$: the set of commodities within the RREH. $\mathcal{C}_r$ can be derived from $\mathcal{G}_r$.

  In our Greenland example (cfr. Figure 1),

  $\mathcal{C}_r = \{$electricity, H_2O, H_2, $O_2\}$.

- $\mathcal{E}_r \subseteq \mathcal{C}_r$: the set of exported commodities. These commodities are input in $t^{ex} \in \mathcal{T}_r$ that are exported to a load centre (*i.e.* to a location $L' \notin \mathcal{L}_r$) in a selected carrier, such as electricity, liquid or gaseous hydrogen. The so-called design process entails determining the necessary processes for producing the exported commodities in $\mathcal{E}_r$.

  In our Greenland example (cfr. Figure 1),

  $\mathcal{E}_r = \{H_2\}$.

- $\mathcal{I}_r \subseteq \mathcal{C}_r$: the set of imported commodities. These commodities are outputted by $t^{im} \in \mathcal{T}_r$. The design of the RREH may also be influenced by the availability of imported commodities in the hub (*i.e.* to a location in $\mathcal{L}_r$). Indeed, it is not necessary to produce all required commodities in close proximity to the RREH. For instance, as demonstrated by Dachet et al. [2], importing CO_2 from the load centre rather than relying on DAC technologies can lead to a reduction in the total system cost. In our Greenland example (cfr. Figure 1), $\mathcal{I}_r = \{H_2O\}$.

- $\mathcal{B}_r \subseteq \mathcal{C}_r$: the set of byproduct commodities. Among all the commodities within the RREH (*i.e.* in $\mathcal{C}_r$), some are byproducts that are never used in any process. More specifically, these byproducts are commodities output by a technology $t \in \mathcal{T}_r$ but not involved into any edge composed of this commodity output by t and included in the input set of any technology $t' \in \mathcal{T}_r$. These byproduct commodities are never used within the RREH however they could be valorised by re-designing the RREH to input them into an existing technology of the hub or a new technology not already considered. Another possibility is to valorize those commodities in a market.

  In our Greenland example (cfr. Figure 1),

  $\mathcal{B}_r = \{O_2\}$.

- $\mathcal{O}_r \subseteq \mathcal{C}_r$: the set of locally exploited opportunities. This set entails the commodities that are input in $t^{opportunity} \in \mathcal{T}_{L'}$ that are exported to meet a local demand (*i.e.* to a location $L' \in \mathcal{L}_r$). In fact, all the commodities within the RREH can represent opportunities for local development, thereby facilitating local integration of the RREH.

  In our Greenland example (cfr. Figure 1), no produced commodity has been used to meet a local demand, hence $\mathcal{O}_r = \emptyset$.

A schematic view of these sets and graph is given in Figure 2 where the set of imported commodities $\mathcal{I}_r$ is processed by the graph of technologies $\mathcal{T}_r$ and the commodities flows $\mathcal{H}_r$ in the RREH producing local opportunities $\mathcal{O}_r$ and by-products $\mathcal{B}_r$ and exporting commodities included in the set of exports $\mathcal{E}_r$.

4. Instantiation

In this section, the taxonomy will be exemplified using a hub located in Algeria, as studied in the literature [1]. This will highlight how the taxonomy can be used to easily describe hubs. Then, a second example from the literature [16] will be presented using the taxonomy to demonstrate how the taxonomy can ease the comparison between them.

The first RREH r_1, coming from [11], is composed of renewable energy production (solar and wind) that powers an electrolyzer to produce hydrogen. From this hydrogen and CO_2 captured via DAC, a methanation process produces methane (CH_4) that is liquefied and exported by boats to Belgium. This RREH is divided into two connected parts: one located in the Sahara desert for
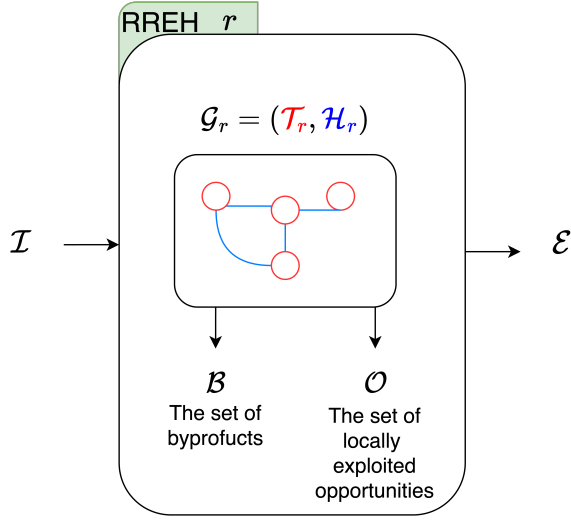
Figure 2: Schematic view of a RREH with the different sets which define it.

harnessing renewable energy and a second one located on the Algerian coast responsible for the synthesis and export of methane to Belgium. These two parts are connected via a High Voltage Direct Current (HVDC) link. In the taxonomy, this RREH would be expressed as:

- $\mathcal{L}_{r_1} = \{l_1, l_2, l_3\}$
  where
  l_1 = (Sahara desert,
  high renewable potential, low demand),
  l_2 = (Algerian coast, high renewable potential,
  medium demand)},
  l_3 = (From Sahara desert to the coast,
  high renewable potential, low demand)

- $\mathcal{G}_{r_1} = (\mathcal{T}_{r_1}, \mathcal{H}_{r_1})$ is represented in Figure 3 and comprehensively detailed in Table 2.

- $C_{r_1} = \{\text{electricity}, CH_4(g), CH_4(l), H_2, H_2O, CO_2, O_2, \text{heat}\}$

- $\mathcal{E}_{r_1} = \{CH_4\}$

- $\mathcal{I}_{r_1} = \{\text{sea water, air}\}$

- $\mathcal{B}_{r_1} = \{O_2, \text{heat}\}$

- $O_{r_1} = \{\}.$

The comprehensive description is available in Table 2.

The second RREH r_2, coming from [16], is composed of renewable energy production (solar and wind) that

powers an electrolyzer to produce hydrogen. From this hydrogen and nitrogen (N2) produced via an Air Separation Unit (ASU), an Haber-Bosch process synthesizes ammoniac (NH_3) in liquid form that is exported by boats to Belgium. This RREH is located and divided at the same locations than the other ones.

The expression of this second hub is avalaible in Table 1 and the comprehensive description is available in Table A.3. The Table 1 also highlights the key differences between these two hubs. As an example, the main differences between these hubs, besides the exported commodity, are the byproducts. The hub exporting CH_4 does not produce Argon whereas the hub exporting NH_3 does.

5. Design and Local Integration

In this section, a systematic approach is proposed to guide the design process - specifically, identifying the technologies that constitute the RREH and the connections among them - as well as the local integration of a hub. Each step of this approach is then discussed with reference to existing literature on hubs. The approach is as follows:

1. **Define Export Commodities**: identify the export set $\mathcal{E}_r$ to establish which commodities (e.g., methane, methanol, electricity) the RREH will produce for export.

2. **Select locations**: from all the locations available worldwide, identify those suitable for energy harvesting and transport to define your set $\mathcal{L}_r$.

3. **Construct Technology Graph**: develop a potential technology graph $\mathcal{G}_r$ to describe the required technologies and commodities for producing the items in $\mathcal{E}_r$.

4. **Consider Imports**: assess potential import commodities $\mathcal{I}_r$, especially those scarce locally but obtainable from elsewhere, to potentially reduce the number of technologies required to produce commodities within the RREH for its operation.

5. **Assess Byproducts**: evaluate byproducts $\mathcal{B}_r$ as potential resources that can be integrated into the RREH design to optimize commodity reuse and reduce operational costs.

6. **Identify Local Opportunities**: use C_r that list available commodities and determine locally valuable ones. One may valorize these and add these to the set O_r to strengthen local integration.

7. **Optimize**: based on the results of step 1-6, optimize the hubs based on your objective criteria and assess the results. If the results are not deemed to

Table 1: Characteristics of Remote Renewable Energy Hubs r_1 and r_2.

	r_1	r_2
$\mathcal{L}_r$	$\{l_1, l_2, l_3\}$ l_1 = (Sahara desert, high renewable potential, low demand), l_2 = (Algerian coast, high renewable potential, medium demand), l_3 = (From Sahara desert to the coast, high renewable potential, low demand)	Same as $\mathcal{L}_{r_1}$
$\mathcal{G}_r$	$(\mathcal{T}_{r_1}, \mathcal{H}_{r_1})$ (See Figure 3 and Table 2)	$(\mathcal{T}_{r_2}, \mathcal{H}_{r_2})$ (See Figure A.4 and Table A.3)
C_r	$(\{$electricity$, CH_4(g), CH_4(l), H_2, H_2O, CO_2,$ $O_2,$ heat$\})$	$(\{$electricity$, NH_3, H_2, H_2O, N_2,$ $O_2,$ heat$, Ar\})$
$\mathcal{E}_r$	$\{CH_4\}$	$\{NH_3\}$
$\mathcal{I}_r$	$\{$sea water, air$\}$	Same as $\mathcal{I}_{r_1}$
$\mathcal{B}_r$	$\{O_2,$ heat$\}$	$\{O_2,$ heat$, Ar\}$
O_r	$\{\}$	Same as O_{r_1}

be satisfactory, repeat the different steps to identify another hub design.

Step 1 may involve several considerations to determine which molecule to export, including which commodities are easiest to transport over a given distance and the infrastructure available in the load center to meet demand (e.g., CH_4 or H_2 networks).

Step 2, selecting locations, can be approached qualitatively by examining renewable energy potential maps or by identifying existing infrastructure, such as gas terminals, dedicated to the selected export molecule. Alternatively, it can be conducted more quantitatively using combinatorial optimization methods, such as those proposed by Radu et al. [13], to determine optimal locations for energy production.

Step 3 requires consulting the scientific literature to identify the chemical and physical processes necessary for producing a given export molecule. For instance, [16] proposes hubs exporting ammonia, hydrogen, or methanol, each requiring a unique design.

Step 4 may help reduce production costs. For example, [2] demonstrates that importing CO_2 captured at the load center lowers the cost of methane synthesis compared to solely local production via DAC facilities.

Step 5 can also reduce operational costs, as shown by Dauchat et al. [22], who reuse process-generated heat and provide a detailed analysis of its valorization within an RREH, resulting in cost reductions. Additionally, this step may highlight the need for new components, such as Heat Recovery Steam Generators to reduce overall costs [22].

Step 6 helps to prevent project failure, as noted in [23]. Additionally, it can decrease the overall RREH costs, for example, by using the oxygen byproduct from electrolysis to meet the demand of local hospitals. It may also consist in oversizing desalination capacity to benefit from economies of scale to provide water in water-scarce regions. Finally, this step may also highlight the need for new components, such as a water pipe to supply water to nearby farming installations.

Finally, Step 7 advises repeating the steps to refine the RREH design based on criteria such as local integration, number of required processes, or identifying several promising designs to further analysis with modeling and optimization.

6. Conclusion

This article introduces a definition of the concept of RREH and a taxonomy to characterize them. It also shows the use of this taxonomy on two examples. This taxonomy can enhance communication within the scientific community as well as fostering research on RREH integration and improved designs.

More specifically, its systematic approach to characterizing RREHs enables more effective comparisons and, if coupled with an optimization procedure, can help identify technologies and interconnections that minimize production costs. It can also help identify missing components of particular interest that contribute to building these RREHs, such as a heat network installation to recover part of the heat from the byproduct set.

Table 2: Expression of the full taxonomy where the graph of technologies and flows of commodities $\mathcal{G}_r$ is described by its set of nodes and edges $(\mathcal{T}_r, \mathcal{H}_r)$.

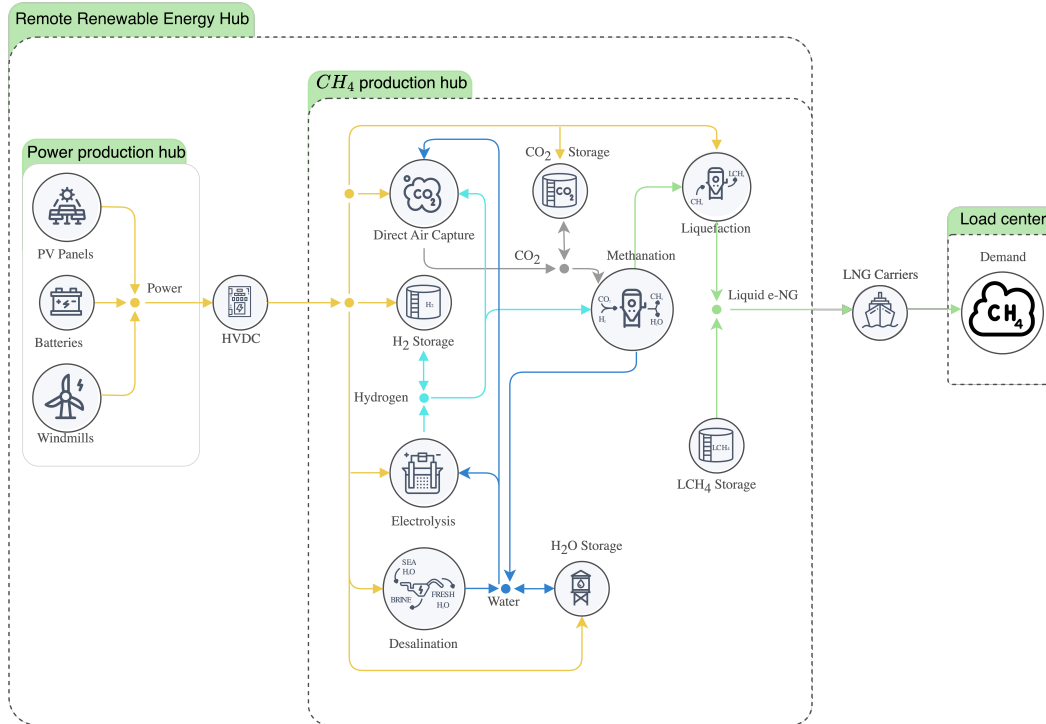| Set	Description
$\mathcal{L}_r$	$\{l_1, l_2, l_3\}$ where l_1 = (Sahara desert, high renewable potential, low demand), l_2 = (Algerian coast, high renewable potential, medium demand)}, l_3 = (From Sahara desert to the coast, high renewable potential, low demand)
$\mathcal{T}_r$	$\{(PV_{l_1}, \{\emptyset\}, \{\text{electricity}\})$, $(\text{Wind}_{l_1}, \{\emptyset\}, \{\text{electricity}\})$, $(\text{Battery}_{l_1}, \{\text{electricity}\}), \{\text{electricity}\})$, $(\text{HVDC}_{l_3}, \{\text{electricity}\}, \{\text{electricity}\})$, $(\text{Electrolyser}_{l_2}, \{\text{electricity}, H_2O\}, \{H_2, O_2\})$, $(\text{Desalination}_{l_2}, \{\text{electricity}, \text{Sea Water}\}, \{H_2O\})$, $(H_2\text{-Storage}_{l_2}, \{\text{electricity}, H_2\}, \{H_2\})$, $(\text{DAC}_{l_2}, \{\text{electricity}, H_2O\}, \{CO_2\})$, $(CO_2\text{-Storage}_{l_2}, \{\text{electricity}, CO_2\}, \{CO_2\})$, $(\text{Methanation}_{l_2}, \{CO_2, H_2\}, \{CH_4(g), H_2O\})$, $(CH_4\text{-Liquefaction}_{l_2}, \{\text{electricity}, CH_4(g)\}, \{CH_4(l)\})$, $(CH_4\text{-Storage}_{l_2}, \{CH_4(l)\}, \{CH_4(l)\})$, $(\text{export}_{l_2}, \{CH_4\}, \{\emptyset\})\}$
$\mathcal{H}_r$	$\{(\text{Electricity}, \{\text{Wind}_{l_1}, \text{Battery}_{l_1}, PV_{l_1}\}, \{\text{Battery}_{l_1}, \text{HVDC}_{l_1}\})$, $(\text{Electricity}, \{\text{HVDC}_{l_1}\}$, $\quad\quad \{\text{Battery}_{l_2}, \text{Electrolyser}_{l_2}, \text{Desalination}_{l_2}, H_2\text{-Storage}_{l_2}, DAC_{l_2}, CO_2\text{-Storage}_{l_2}\})$, $(H_2O, \{H_2\text{-Storage}_{l_2}, \text{Desalination}_{l_2}, \text{Methanation}_{l_2}\}$, $\quad\quad \{H_2\text{-Storage}_{l_2}, \text{Electrolyser}_{l_2}, DAC_{l_2}\})$, $(H_2, \{H_2\text{-Storage}_{l_2}, \text{Electrolyser}_{l_2}\}, \{H_2\text{-Storage}_{l_2}, \text{Methanation}_{l_2}, DAC_{l_2}\})$, $(CH_4(g), \{\text{Methanation}_{l_2}\}, \{CH_4\text{-Liquefaction}_{l_2}\})$, $(CH_4(l), \{CH_4\text{-Liquefaction}_{l_2}, CH_4\text{-Storage}_{l_2}\}, \{CH_4\text{-Storage}_{l_2}, t^{ex}\})$, $(O_2, \{\text{Electrolyser}_{l_2}\}, \emptyset)$, $(\text{Heat}, \{\text{Electrolyser}_{l_2}\}, \emptyset)$, $(\text{Heat}, \{\text{Methanation}_{l_2}\}, \emptyset)$, $(\text{Heat}, \{CH_4\text{-Liquefaction}_{l_2}\}, \emptyset)\}$
C_r	$\{\text{Electricity}, CH_4(g), CH_4(l), H_2, H_2O, CO_2, O_2, \text{Heat}\}$
$\mathcal{E}_r$	$\{CH_4\}$
$\mathcal{I}_r$	$\{\text{sea water, air}\}$
$\mathcal{B}_r$	$\{O_2, \text{Heat}\}$
O_r	$\{\}$

Figure 3: RREH located in Algeria exporting CH$_4$ to a load center situated in Belgium, adapted from [11].

While our taxonomy can already be exploited as it is, we believe there are still relevant avenues for enriching it. Although this paper centers on technical factors, incorporating in the taxonomy financial aspects — such as different financing models or profit-sharing mechanisms — could broader its scope.

Acknowledgements

Competing interests

The authors declare no competing interests.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT and Bard in order to correct the readiness, grammar and spelling of the writing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Appendix A. Example 2

Table A.3: Expression of the full taxonomy where the graph of technologies and flows of commodities $\mathcal{G}_r$ is described by its set of nodes and edges $(\mathcal{T}_r, \mathcal{H}_r)$.

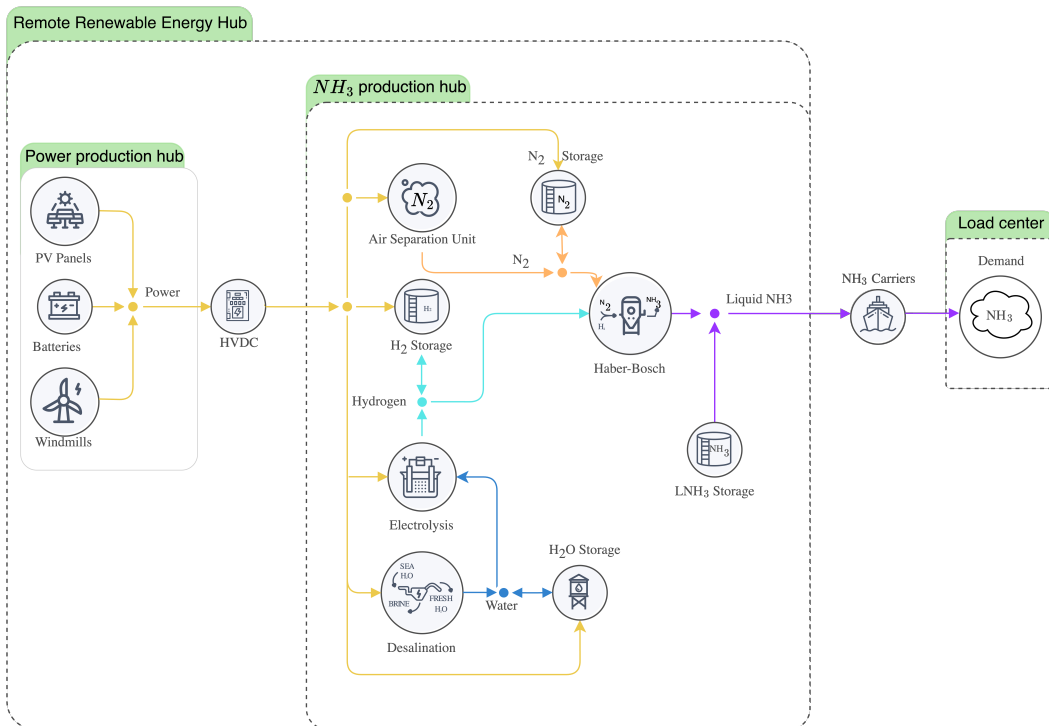| Set	Description
$\mathcal{L}_r$	$\{l_1, l_2, l_3\}$ where l_1 = (Sahara desert, high renewable potential, low demand), l_2 = (Algerian coast, high renewable potential, medium demand)}, l_3 = (From Sahara desert to the coast, high renewable potential, low demand)
$\mathcal{T}_r$	$\{(PV_{l_1}, \{\emptyset\}, \{\text{electricity}\}),$ $(\text{Wind}_{l_1}, \{\emptyset\}, \{\text{electricity}\}),$ $(\text{Battery}_{l_1}, \{\text{electricity}\}, \{\text{electricity}\}),$ $(\text{HVDC}_{l_3}, \{\text{electricity}\}, \{\text{electricity}\}),$ $(\text{Electrolyser}_{l_2}, \{\text{electricity}, H_2O\}, \{H_2, O_2\}),$ $(\text{Desalination}_{l_2}, \{\text{electricity, Sea Water}\}, \{H_2O\}),$ $(H_2\text{-Storage}_{l_2}, \{\text{electricity}, H_2\}, \{H_2\}),$ $(\text{Air Separation Unit}_{l_2}, \{\text{electricity}\}, \{N_2, Ar\}),$ $(N_2\text{-Storage}_{l_2}, \{\text{electricity}, N_2\}, \{N_2\}),$ $(\text{Haber Bosch}_{l_2}, \{N_2, H_2\}, \{NH_3\}),$ $(NH_3\text{-Storage}_{l_2}, \{NH_3\}, \{NH_3\}),$ $(\text{export}_{l_2}, \{NH_3\}, \{\emptyset\})\}$
$\mathcal{H}_r$	$\{(\textbf{Electricity}, \{\text{Wind}_{l_1}, \text{Battery}_{l_1}, PV_{l_1}\}, \{\text{Battery}_{l_1}, \text{HVDC}_{l_1}\}),$ $(\textbf{Electricity}, \{\text{HVDC}_{l_1}\},$ $\{\text{Battery}_{l_2}, \text{Electrolyser}_{l_2}, \text{Desalination}_{l_2}, H_2\text{-Storage}_{l_2}, DAC_{l_2}, CO_2\text{-Storage}_{l_2}\}),$ $(\textbf{H}_2\textbf{O}, \{H_2\text{-Storage}_{l_2}, \text{Desalination}_{l_2}, \text{Methanation}_{l_2}\},$ $\{H_2\text{-Storage}_{l_2}, \text{Electrolyser}_{l_2}\}),$ $(\textbf{H}_2, \{H_2\text{-Storage}_{l_2}, \text{Electrolyser}_{l_2}\}, \{H_2\text{-Storage}_{l_2}, \text{Haber Bosch}_{l_2}\}),$ $(\textbf{NH}_3, \{\text{Haber Bosch}_{l_2}, NH_3\text{-Storage}_{l_2}\}, \{NH_3\text{-Storage}_{l_2}, t^{ex}\}),$ $(\textbf{O}_2, \{\text{Electrolyser}_{l_2}\}, \emptyset),$ $(\textbf{Ar}, \{\text{Air Separation Unit}_{l_2}\}, \emptyset),$ $(\textbf{Heat}, \{\text{Electrolyser}_{l_2}\}, \emptyset),$ $(\textbf{Heat}, \{\text{Haber-Bosch}_{l_2}\}, \emptyset),$
$\mathcal{C}_r$	$\{\text{Electricity}, NH_3, H_2, H_2O, N_2, O_2, \text{Heat}, Ar\}$
$\mathcal{E}_r$	$\{NH_3\}$
$\mathcal{I}_r$	{sea water, air}
$\mathcal{B}_r$	$\{O_2, \text{Heat}, Ar\}$
$\mathcal{O}_r$	{}

Figure A.4: RREH located in Algeria exporting NH$_3$ to a load center situated in Belgium, adapted from [16].