Projet DRIVER du Fonds de Transition Energétique octroyé dans le cadre de l'appel de Novembre 2020

Délivrable 2 (D2) : Rapport sur les modélisations de marchés CO2 et d'autres commodités liées au secteur de l'énergie

Délivrable produit par : Université de Liège

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DRIVER

Note : en accord avec les représentants du SPF Economie, il a été convenu lors du *kick-off meeting* du projet DRIVER du 25 Octobre 2021, que les délivrables du projet peuvent être rédigés soit en français soit en anglais moyennant un résumé en français. Le présent document est rédigé de la manière suivante : les deux premières parties (généralités et méthodologies) de ce rapport sont en français, tandis que la deuxième partie (résultats) est conservée en anglais, langue dans laquelle ces résultats ont été publiés.

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I Marchés du Carbone : généralités et approches développées dans le contexte du projet DRIVER

1.1. Donner un prix du carbone : objectifs

L'objectif principal de donner un prix au CO_2 est d'inciter à réduire les émissions de gaz à effet de serre (GES), dont fait partie le CO_2. En donnant une valeur économique aux émissions de CO_2, on espère inciter l'ensemble de des agents économiques à réduire leurs émissions, car cela leur permettrait de minimiser les coûts associés à ces émissions. En outre, donner un prix au CO_2 permet de stimuler l'innovation technologique, en créant une demande pour des alternatives bas carbone : génération d'électricité à partir de ressources renouvelables, technologies favorisant l'accroissement de l'efficacité énergétique, solutions de stockage de carbone.

A court terme, la tarification du CO_2 peut également permettre de générer des revenus qui ont vocation à être réinvestis dans des technologies permettant de répondre à la problématique énergie / climat : projets d'adaptation aux impacts du changement climatique, de développement de technologies bas-carbone, soutien aux pays en développement afin de favoriser des choix de développements (énergétiques, économiques, écologiques) durables[1].

1.2. Externalités

Une externalité se produit lorsque les avantages et/ou les inconvénients d'une activité ne sont pas pris en compte par les parties impliquées dans cette activité, et sont plutôt supportés (en positif ou en négatif) par d'autres parties. Afin d'intégrer les externalités négatives liées aux émissions de polluants, il existe différents instruments, notamment les normes d'émission (*command and control regulation*) ou la fixation d'un prix lié à l'émission de ce polluant (taxe ou système d'échange de quota).

Dans le cas des émissions de CO_2, les externalités négatives se traduisent essentiellement par le réchauffement climatique et ses conséquences : élévation des températures, augmentation de la fréquence des événements météorologiques extrêmes, diminution de la biodiversité, élévation du niveau des océans... Ces coûts environnementaux sont souvent supportés par la société dans son ensemble plutôt que par les émetteurs de GES.

En intégrant le coût des externalités environnementales dans le prix du carbone, on encourage les entreprises et les individus à tenir compte des coûts réels du changement climatique dans leurs décisions économiques[2].

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[1] https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)698890
[2] https://stats.oecd.org/glossary/detail.asp?ID=3215

1.3. Donner un prix au carbone : principales approches

Il y a deux manières principales de donner un prix au CO2, la taxe carbone d'une part, et le système d'échange de quotas d'autre part.

- **Taxe carbone** : l'idée est d'imposer une taxe sur chaque tonne de CO2 émise. Ainsi, les émetteurs sont incités à réduire leurs émissions pour simplement éviter le paiement de cette taxe. Le montant de la taxe devrait idéalement être fixé en fonction du niveau de dommage environnemental estimé causé par les émissions de carbone. Ainsi, les émetteurs prendraient en compte les coûts environnementaux des conséquences de leurs émissions dans leurs calculs économiques.
- **Système de plafonnement et d'échange** (« *cap and trade* ») : un plafond global d'émissions de carbone est fixé. Des quotas d'émissions sont attribués aux entreprises, officialisant ainsi leurs droits d'émettre une certaine quantité de carbone. Les entreprises peuvent vendre ces quotas sur un marché, ou même en acheter d'autres, ce qui fait émerger une valeur économique pour les réductions d'émissions. Concrètement, si une entreprise émet moins que ce que l'allocation lui autorise, elle peut vendre les quotas excédentaires, tandis qu'une entreprise qui émet plus que son allocation devra acheter des quotas supplémentaires. Ainsi, les émetteurs ont une incitation économique à réduire leurs émissions.

L'annexe 1 du présent développe de façon plus détaillée (en anglais) différents aspects des points abordées ci-dessus.

1.4. Approches développées dans le cadre du projet DRIVER

Dans le cadre du projet Driver, une approche innovante est explorée : celle-ci consiste à explorer la possibilité de valoriser le carbone de manière positive, c'est à dire dans un contexte où le CO2 devient une molécule d'intérêt. Plus précisément, on explore ici l'idée de combiner du CO2 avec de l'hydrogène obtenu à partir d'énergie renouvelable (via hydrolyse). Cette approche est développée en partie II pour ce qui concerne les aspects méthodologiques, et en partie III pour ce qui concerne les aspects quantitatifs.

1.5. Principales disséminations scientifiques

- *Towards CO2 valorization in a multi remote renewable energy hub framework.* Victor Dachet, Amina Benzerga, Raphaël Fonteneau, Damien Ernst. Proceedings of ECOS 2023 – The 36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, 25-30 June 2023, Las Palmas de Gran Canaria, Spain.
- *Energy Markets: Carbon Price.* Victor Dachet, Adrien Bolland, Thibaut Théate, Antoine Dubois, Raphaël Fonteneau and Damien Ernst. Talk in the context of the « Energy Market » class, ULiège, November 2023.
- *Remote Renewable Energy Hubs.* Victor Dachet & Damien Ernst. Talk at Total Energies Town Hall, May 2023.
- *E-Fuels Produced In Remote Renewable Energy Hubs: A Cross Vector Analysis*. Antoine Larbanois, Victor Dachet, Raphaël Fonteneau & Damien Ernst (2023). Working paper.

II Valoriser le CO2 dans un schéma de hub énergétique à distance – méthodologie.

Dans cette deuxième partie, nous proposons un cadre d'optimisation basé sur un schéma dans lequel on valorise des ressources d'énergie renouvelable situées dans des hubs énergétiques à distance – approche qu'on désigne par l'acronyme multi-RREH, de l'anglais *Remote Renewable Energy Hub*.

Ce cadre permet une valorisation du CO2 en utilisant des technologies de capture du carbone. Cette valorisation repose sur l'idée que le CO2 collecté dans l'atmosphère ou après combustion peut être combiné avec de l'hydrogène pour produire du méthane synthétique. L'hydrogène est obtenu par électrolyse de l'eau en utilisant des énergies renouvelables (ER). Ces énergies renouvelables sont générées dans des RREH, qui sont des endroits où les ER sont abondantes et peu coûteuses (par exemple, l'énergie solaire photovoltaïque dans le désert du Sahara ou l'énergie éolienne au Groenland).

Ce schéma d'optimisation est évalué dans le cadre d'une association entre la Belgique et 2 hubs énergétiques situés l'un dans le désert du Sahara, l'autre au niveau des côtes du Groenland. Cette évaluation est en réalité une analyse technico-économique qui permet, entre autres, de mettre en évidence l'intérêt de capturer le CO2 par capture postcombustion plutôt qu'uniquement par capture directe de l'air pour la synthèse de méthane dans les RREH. Ce choix permet une réduction notable de 9,2 % du coût total du système dans notre scénario de référence. Par ailleurs, ce schéma permet de déterminer un seuil de prix du CO2 au-dessus duquel les technologies de capture du CO2 pourraient jouer un rôle pivot dans le processus de décarbonation des industries. Par exemple, ce seuil de prix peut fournir des informations pertinentes pour étalonner le système européen d'échange de quotas d'émission (EU Emission Trading System) afin de favoriser l'émergence des multi-RREH.

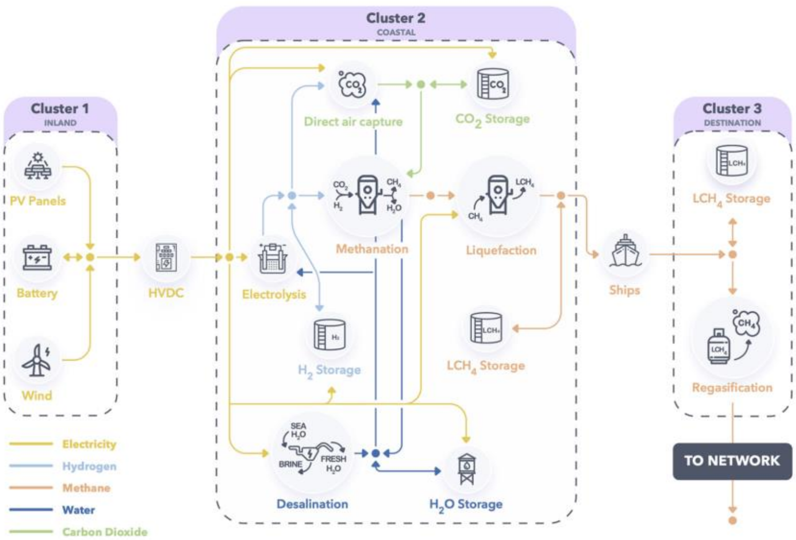

Figure 1 : le modèle « Remote Energy Hub » originel

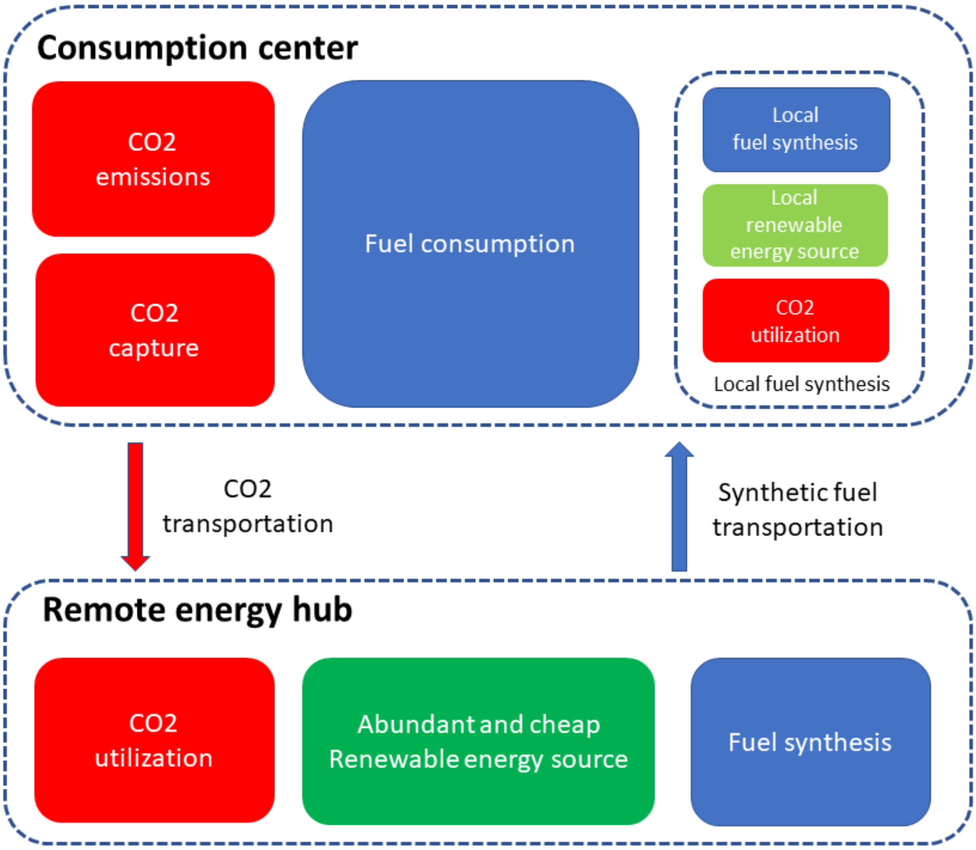

Figure 2: le concept RREH

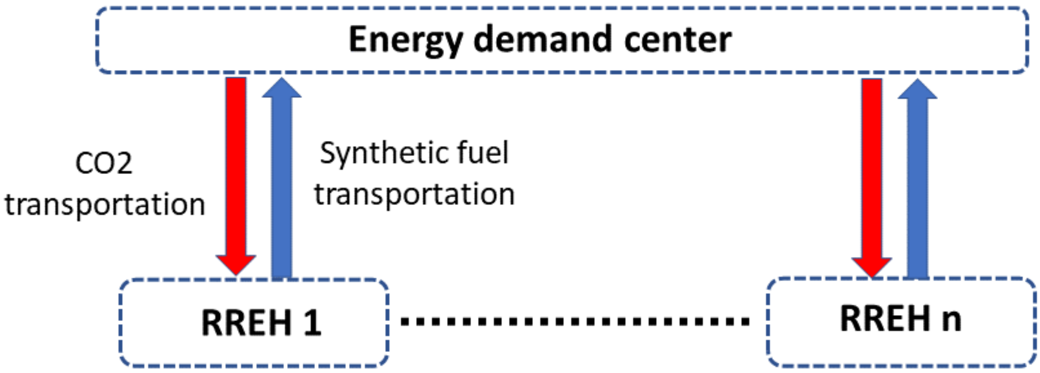

Figure 3 : schéma de la structure multi-RREH

2.1. Introduction et approches connexes

Alors que le monde entier est engagé dans un processus de réduction des émissions de gaz à effet de serre, la capture du CO2 apparaît de plus en plus comme un élément crucial pour limiter le réchauffement climatique. Une fois capturé, le CO2 peut être soit stocké (CCS - ***Carbon Capture and Storage***), soit valorisé (CCU - ***Carbon Capture and Utilisation***), par exemple par la production de méthane synthétique. Dans cet article, nous nous concentrons sur le CCU, où le CO2 est considéré comme un ingrédient nécessaire dans le processus de production de méthane synthétique, avec l'hydrogène vert, c'est-à-dire l'hydrogène obtenu par électrolyse à partir d'énergies renouvelables.

Dans l'approche présentée ici, fondée sur l'approche « ***Remote Renewable Energy Hub*** » (RREH)[3] , l'idée consiste à proposer une approche multicentres et multi-sources de CO2. Le CO2 est potentiellement capturé à la fois par des technologies de capture du carbone post-combustion (PCCC) et de capture directe de l'air (DAC). L'hydrogène est produit par électrolyse à partir d'énergies renouvelables dans un RREH, qui est particulièrement bien adapté à la production d'énergie renouvelable bon marché et abondante (par exemple, l'énergie solaire dans le désert du Sahara ou l'énergie éolienne au Groenland). Le concept RREH repose également sur l'idée suivante : certains endroits présentent une forte consommation d'énergie sans disposer de beaucoup de ressources d'énergie renouvelable (par exemple, l'Europe). À l'inverse, certains endroits disposent d'une énergie renouvelable abondante tout en n'ayant presque pas de demande d'énergie. Dans sa formulation originale, le concept RREH suggère d'utiliser les technologies DAC pour alimenter la demande de CO2 au RREH. Dans cet article, nous incluons les technologies PCCC comme alternative aux technologies DAC : en plus ou en remplacement de la capture dans l'atmosphère, le CO2 émis dans les endroits à forte consommation d'énergie peut être transporté vers les RREH pour être combiné avec de l'hydrogène vert pour produire du méthane synthétique neutre.

Nous proposons une méthodologie pour évaluer la faisabilité technico-économique de l'exportation de CO2 vers des RREH où du méthane synthétique neutre en CO2 serait généré à l'aide de H2 vert produit localement. Nous formalisons un problème d'optimisation dans lequel les sources de CO2 sont "mises en concurrence" afin de fournir du CO2 aux unités de méthanation des RREH. Cette méthodologie est basée sur une modélisation linéaire du système énergétique belge, incluant la demande de gaz et d'électricité, et les principaux émetteurs de CO2. Nous nous appuyons sur des approches publiées précédemment pour développer notre approche[3], et, en particulier, nous utilisons le langage GBOML[4] pour modéliser le système énergétique et l'optimiser.

Notre méthodologie est évaluée dans le contexte belge : nous considérons les émissions de CO2 belges et la demande de gaz et d'électricité belge. Le CO2 peut être capturé en Belgique par capture du carbone post-combustion (PCCC) ou dans des RREH par capture directe de l'air (DAC). Le méthane synthétique neutre en CO2 sera produit dans un centre d'énergie distant d'où il sera expédié pour servir la demande de gaz belge. Nous dérivons un coût d'émission de CO2 afin d'avoir un système à émission neutre. Nous déterminons également une valeur de perte de charge (c'est-à-dire un prix associé à un manque de service énergétique) afin de répondre à la demande d'énergie en tout temps. Plusieurs scénarios

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[3] Mathias Berger, David-Constantin Radu, Ghislain Detienne, Thierry Deschuyteneer, Aurore Richel, and Damien Ernst. Remote renewable hubs for carbon-neutral synthetic fuel production. Frontiers in Energy Research, 2021. doi: 10.3389/fenrg.2021.671279.

[4] Bardhyl Miftari, Mathias Berger, Hatim Djelassi, and Damien Ernst. GBOML: Graph-Based Optimization Modeling Language. Journal of Open Source Software, 7(72):4158, 2022. doi: 10.21105/joss.04158. URL https://doi.org/10.21105/joss.04158.

sont étudiés avec différents prix des émissions de CO2, l'allocation ou non de l'énergie non desservie et le forcing d'un RREH donné.

Ce travail est principalement lié aux sujets suivants qui pourraient jouer un rôle important dans la décarbonation profonde de nos sociétés :

(i) les approches de type « ***Global Grid*** »,
(ii) les technologies de ***power-to-X***, les systèmes énergétiques intégrés et les hubs énergétiques,
(iii) les marchés de quotas de CO2.

Les approches de type ***Global Grid***[5,6,7] exploitent l'idée de récolter l'énergie renouvelable là où elle est abondante afin d'alimenter la demande d'électricité des zones fortement consommatrices. Ces approches ont principalement été orientées vers des solutions utilisant le vecteur « électricité » pour rapatrier l'énergie vers les zones de forte consommation. Elles ont notamment suscité un intérêt particulier avec le concept DESERTEC[8] qui se concentre sur les ressources d'énergie solaire du Sahara pour répondre à la demande d'électricité européenne. Plus récemment, les vents du nord de l'Europe et du Groenland ont également été identifiés comme des ressources prometteuses à valoriser dans le contexte Global Grid[9]. Les configurations ressources-demande combinant plusieurs types de ressources ainsi que plusieurs fuseaux horaires au niveau de la demande présentent de meilleurs résultats[6].

Les approches de type « systèmes multi-énergies »[10,11] exploitent l'idée que des possibilités d'optimisation supplémentaires sont offertes lorsque les demandes et production d'énergie sont optimisés conjointement au-delà des vecteurs énergétiques. Les technologies de type *power-to-X*, en particulier les technologies *power-to-CH4* utilisant l'hydrolyse et l'énergie renouvelable pour produire du H2[12], offrent une solution neutre en CO2 pour

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[5] Spyros Chatzivasileiadis, Damien Ernst, and Goran Andersson. The global grid. Renewable Energy, 57: 372–383, 2013.
[6] J. Yu, K. Bakic, A. Kumar, A. Iliceto, L. Beleke Tabu, J.L. Ruaud, J. Fan, B. Cova, H. Li, Damien Ernst, Raphael Fonteneau, M. Theku, G. Sanchis, M. Chamollet, M. Le Du, Y. Zhang, S. Chatzivasileiadis, David-Constantin Radu, Mathias Berger, M. Stabile, F. Heymann, M.A. Dupré La Tour, Miguel Manuel de Villena Millan, and M. Ranjbar. Global electricity network - feasibility study. Technical report, October 2019.
URL https://e-cigre.org/publication/775-global-electricity-network-feasibility-study.
[7] Zhenya Liu. Global energy interconnection. Academic Press, 2015.
[8] Tobias Samus, Bastian Lang, and Holger Rohn. Assessing the natural resource use and the resource efficiency potential of the DESERTEC concept. Solar Energy, 87:176–183, 2013.
[9] David Radu, Mathias Berger, Antoine Dubois, Raphael Fonteneau, Hrvoje Pandzic, Yury Dvorkin, Quentin Louveaux, and Damien Ernst. Assessing the impact of offshore wind siting strategies on the design of the european power system. Applied Energy, 305:117700, 2022.
[10] Marie Munster, Daniel Moller Sneum, Rasmus Bramstoft, Fabian Buhler, Brian Elmegaard, Spyros Giannelos, Goran Strbac, Mathias Berger, David-Constantin Radu, Damian Elsaesser, Alexandre Oudalov, and Antonio Iliceto. Sector coupling: Concepts, state-of-the-art and perspectives. Technical report, January 2020.
URL https://www.etip-snet.eu/sector-coupling-concepts-state-art-perspectives/.
[11] Mark O'Malley, Benjamin Kroposki, Bryan Hannegan, Henrik Madsen, Mattias Andersson, William D'haeseleer, Mark F McGranaghan, Chris Dent, Goran Strbac, Suresh Baskaran, et al. Energy systems integration. defining and describing the value proposition. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2016.
[12] Manuel Gotz, Jonathan Lefebvre, Friedemann Mors, Amy McDaniel Koch, Frank Graf, Siegfried Bajohr, Rainer Reimert, and Thomas Kolb. Renewable power-to-gas: A technological and economic review.

répondre à la demande de gaz, mais aussi un moyen de stocker de vastes quantités d'énergie issues de sources renouvelables[13]. Récemment, *Berger et al.* ont proposé un cadre de modélisation[14] pour évaluer la viabilité technico-économique de la production de carburants synthétiques neutres en carbone à partir d'électricité renouvelable dans des zones reculées où les ressources renouvelables de haute qualité sont abondantes. Il convient de mentionner que l'idée de centres énergétiques existait avant les travaux de Berger et al. [15,16,17], mais les travaux de *Berger et al*. ont introduit l'idée de produire l'énergie à distance du point de vue de la demande. L'approche proposée ici s'inscrit dans cette lignée.

Etant donné que ce travail vise à donner une valeur au CO2, il est étroitement lié au système d'échange de quotas d'émission de l'Union Européenne (EU ETS). Le système EU ETS, qui est décrit sur le site web de la Commission Européenne[18] mais également par Howarth N. Brohé *et al*[19], est un système « *cap and trade* ». Le système fixe un plafond (*cap*) à la quantité totale de certains gaz à effet de serre (GES) que peuvent émettre les installations incluses dans le périmètre ETS. Dans le cadre de ce plafond, les installations reçoivent des quotas d'émission, qui peuvent être échangés (*trade*) entre elles. Le nombre total de quotas disponibles est limité afin de garantir leur valeur, et le plafond est progressivement réduit au fil du temps afin de réduire les émissions totales. Si une installation ne parvient pas à couvrir entièrement ses émissions, elle s'expose à de lourdes amendes. À l'inverse, si une installation réduit ses émissions, elle peut soit conserver le surplus de quotas pour une utilisation future, soit le vendre à une autre installation qui n'a pas réussi à couvrir ses propres émissions. Ce mécanisme d'échange vise à réduire les émissions de GES, et à encourager les investissements dans des solutions à faibles émissions de GES dès que ces dernières sont plus rentables.

2.2. Cœur de l'approche : valoriser le CO2 dans un schéma multi-hub énergétiques

Le concept de centre d'énergie renouvelable à distance (RREH) a été introduit pour la première fois par Berger et al[20], où les auteurs proposent un hub dans lequel du CH4 est

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Renewable Energy, 85:1371–1390, 2016. ISSN 0960-1481. doi: https://doi.org/10.1016/j.renene.2015.07.066. URL https://www.sciencedirect.com/science/article/pii/S0960148115301610.

[13] Herib Blanco and Andr´e Faaij. A review at the role of storage in energy systems with a focus on power to gas and long-term storage. Renewable and Sustainable Energy Reviews, 81:1049–1086, 2018. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2017.07.062. URL https://www.sciencedirect.com/science/article/pii/S1364032117311310.

[14] Mathias Berger, David-Constantin Radu, Ghislain Detienne, Thierry Deschuyteneer, Aurore Richel, and Damien Ernst. Remote renewable hubs for carbon-neutral synthetic fuel production. Frontiers in Energy Research, 2021. doi: 10.3389/fenrg.2021.671279.

[15] Martin Geidl, Gaudenz Koeppel, Patrick Favre-Perrod, Bernd Klockl, Goran Andersson, and Klaus Frohlich. Energy hubs for the future. IEEE power and energy magazine, 5(1):24–30, 2006.

[16] Mohammad Mohammadi, Younes Noorollahi, Behnam Mohammadi-Ivatloo, and Hossein Yousefi. Energy hub: From a model to a concept–a review. Renewable and Sustainable Energy Reviews, 80:1512–1527, 2017.

[17] Hadi Sadeghi, Masoud Rashidinejad, Moein Moeini-Aghtaie, and Amir Abdollahi. The energy hub: An extensive survey on the state-of-the-art. Applied Thermal Engineering, 161:114071, 2019.

[18] https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

[19] Howarth N. Brohé A., Eyre N. Carbon Markets. Routledge, 2009.
doi: https://doi.org/10.4324/9781849770699.

[20] Mathias Berger, David-Constantin Radu, Ghislain Detienne, Thierry Deschuyteneer, Aurore Richel, and

synthétisé à partir d'hydrogène et de CO_2 capturé dans l'air (DAC). Ce concept a émergé dans le contexte des approches Global Grid[5] et des systèmes multi-énergies. Ces approches visent à optimiser la production et l'utilisation des énergies renouvelables (ER) en (i) recherchant des gisements d'énergie(s) renouvelable(s) abondants et bon marché, (ii) en tirant parti de la complémentarité quotidienne et saisonnière des énergies renouvelables, et (iii) en utilisant des technologies de type *power-to-gas* pour mieux gérer les fluctuations de production des énergies renouvelables et répondre à la demande de carburants synthétiques, ces derniers se substituant aux molécules actuellement dérivées des énergies fossiles.

Dans l'article original[20], l'unité de méthanation est alimentée en CO_2 par une unité DAC, et la demande d'énergie est satisfaite par un unique RREH situé en Algérie. Cependant, dans l'approche présentée ici, nous proposons d'étudier la faisabilité de valoriser le CO_2 capturé par des techniques de capture post-combustion (PCCC) au niveau du Centre de Demande d'énergie (EDC). Par ailleurs, nous nous écartons de l'article original en introduisant une approche multi-RREH, dans laquelle l'EDC sert de « fournisseur de CO_2 » à un ensemble de RREH multiples, notés $RREH_1$, ... , $RREH_h$. Chaque hub $RREH_i$ ($1 \leq i \leq h$) a ses propres caractéristiques, telles que le type d'énergie renouvelable, le potentiel, la distance à l'EDC et les moyens de transport du CO_2 depuis l'EDC, ce qui en pratique peut affecter sa compétitivité propre.

Afin d'illustrer les concepts discutés ci-dessus, nous avons élaboré un modèle de système multi-RREH à partir des hypothèses suivantes :

(i) Le centre de demande d'énergie (EDC) considéré est la Belgique, incluant ses demandes en gaz et en électricité, ainsi que ses émissions de CO_2,

(ii) Deux RREH potentiels : le premier situé dans le désert du Sahara avec accès aux ressources solaires et éoliennes, et le second situé au Groenland, bénéficiant des champs éoliens de haute qualité de la région. Un schéma détaillé de ce système est représenté à la Figure 5 : le modèle multi-RREH. Similairement à l'approche**Erreur ! Signet non défini.**, nous avons utilisé le langage GBOML[21], un langage récemment développé et adapté à l'optimisation des systèmes énergétiques pour modéliser le système.

Nous notons que le code du modèle GBOML incluant 2 hubs énergétiques ainsi que EDC est disponible en ligne[22] et peut être facilement étendu pour ajouter des RREH et des EDC supplémentaires.

Damien Ernst. Remote renewable hubs for carbon-neutral synthetic fuel production. Frontiers in Energy Research, 2021. doi: 10.3389/fenrg.2021.671279.

[21] Bardhyl Miftari, Mathias Berger, Hatim Djelassi, and Damien Ernst. GBOML: Graph-Based Optimization Modeling Language. Journal of Open Source Software, 7(72):4158, 2022. doi: 10.21105/joss.04158. URL https://doi.org/10.21105/joss.04158.

[22] https://gitlab.uliege.be/smart_grids/public/gboml/-/tree/master/examples

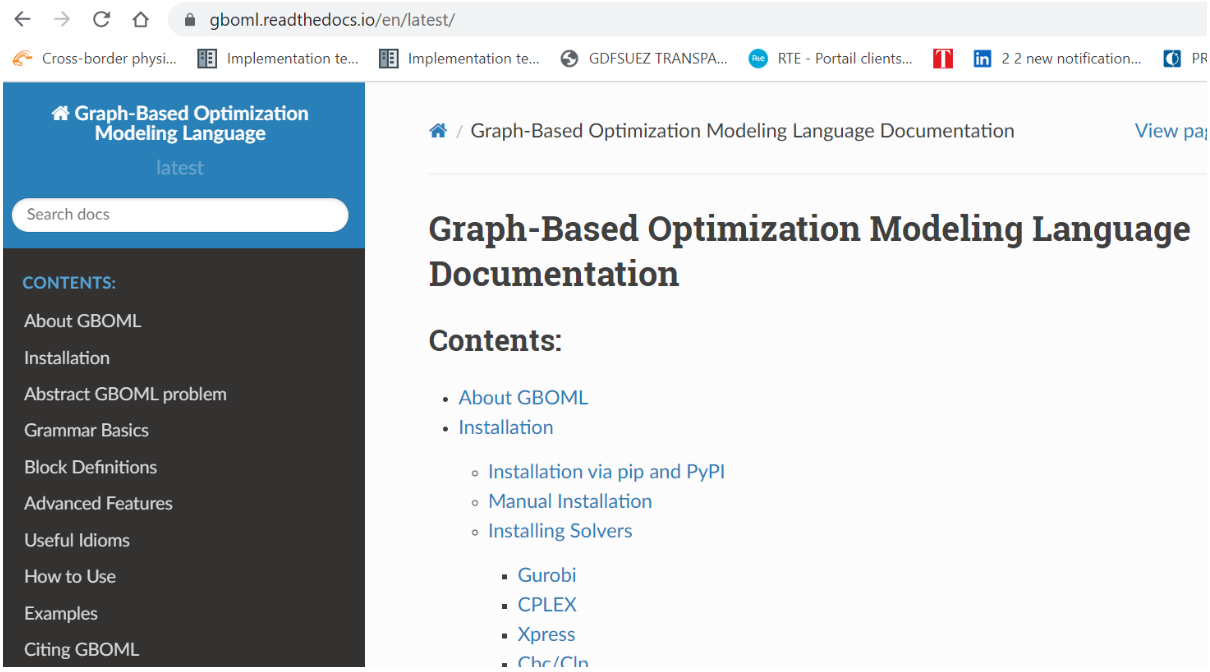


Figure 4 : GBOML est un outil spécifiquement conçu pour la modélisation et l'optimisation de systèmes (énergétiques) complexes. Source : https://gboml.readthedocs.io/en/latest/

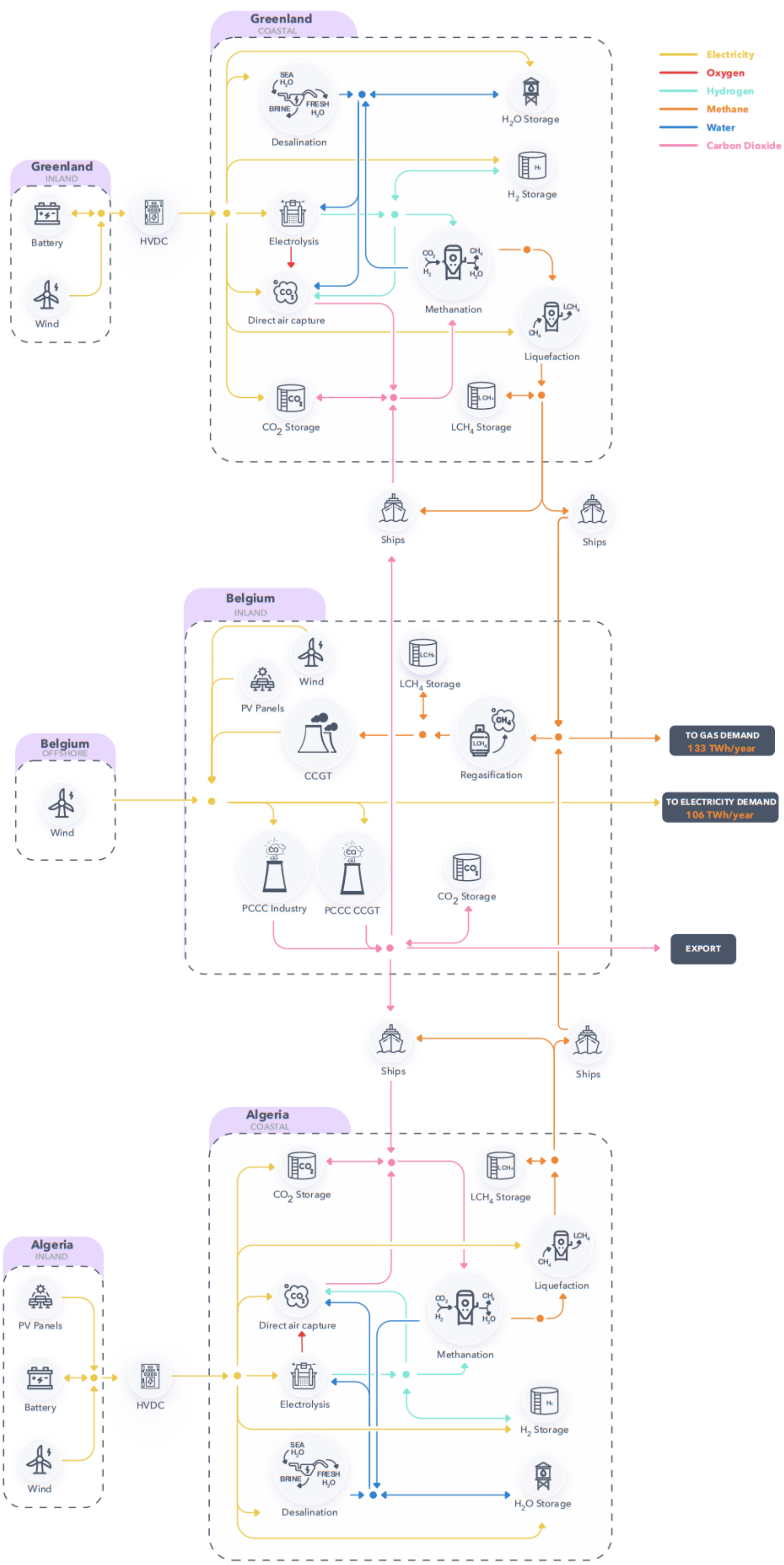


Figure 5 : le modèle multi-RREH

2.3. Eléments de modélisation

Cette section donne un aperçu du travail de formalisation du modèle d'optimisation qui sous-tend le modèle de système multi-énergies proposé dans ce travail. Le langage GBOML[23], un langage récemment développé et dédié à la modélisation et l'optimisation des systèmes multi-énergies en utilisant la notion de graphes, est utilisé pour construire ce modèle. Le problème d'optimisation est assimilé à un problème d'optimisation sur des graphes, où le système multi-énergies est considéré comme un ensemble de nœuds *N* qui contribuent à l'objectif (linéaire) et aux contraintes locales, et les arêtes E sont utilisées pour modéliser les contraintes qui lient les nœuds entre eux, par exemple entre les RREH et l'EDC dans le cas de notre problème.

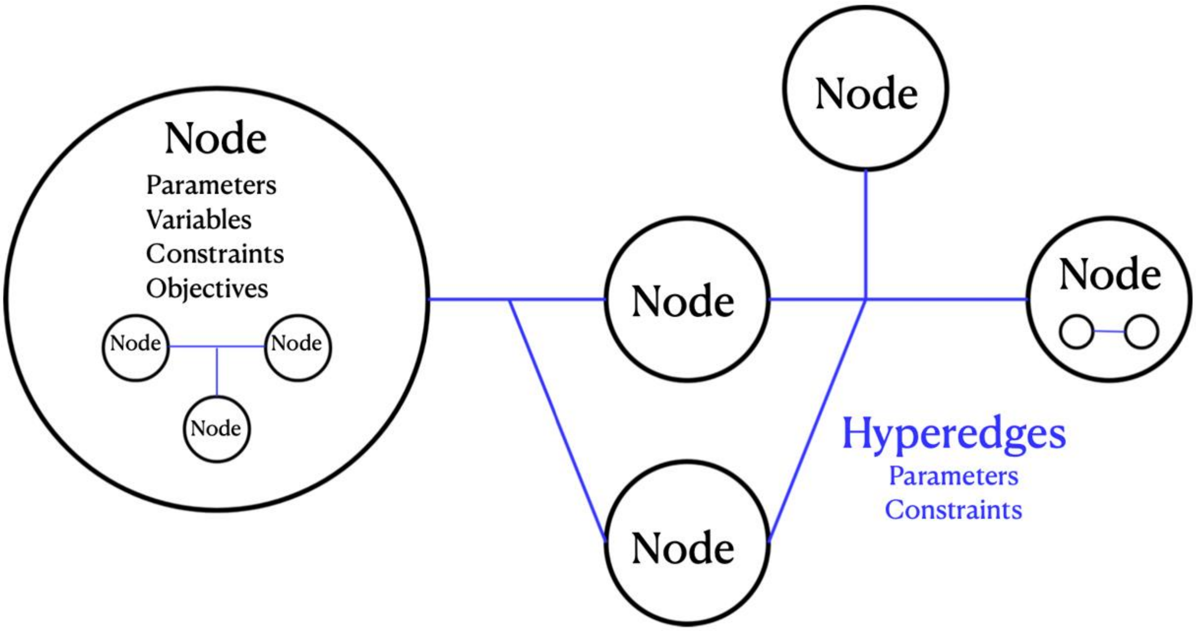


Figure 6 : La modélisation hiérarchique des hypergraphes sur laquelle repose le langage GBMOL

Le formalisme employé dans ce travail suit celui introduit Berger *et al*[24]. L'ensemble du système est défini par des ensembles de nœuds *N* et d'arêtes *E*. L'horizon d'optimisation est noté *T*, avec des pas de temps indexés par t ∈ T, où *T* = {1, ... , *T*}.

Un nœud $n \in N$ est défini par des variables internes X^n et externes Z^n, où les variables internes décrivent les caractéristiques spécifiques de l'unité, telles que la puissance nominale installée. Des contraintes d'égalité $h_i(X^n, Z^n, t) = 0$ avec $i \in I$ et des contraintes

[23] Bardhyl Miftari, Mathias Berger, Hatim Djelassi, and Damien Ernst. GBOML: Graph-Based Optimization Modeling Language. Journal of Open Source Software, 7(72):4158, 2022. doi: 10.21105/joss.04158. URL https://doi.org/10.21105/joss.04158.

[24] Mathias Berger, David-Constantin Radu, Ghislain Detienne, Thierry Deschuyteneer, Aurore Richel, and Damien Ernst. Remote renewable hubs for carbon-neutral synthetic fuel production. Frontiers in Energy Research, 2021. doi: 10.3389/fenrg.2021.671279.

d'inégalité g_j (X^n, Z^n, t) ≤ 0 avec j ∈ *J* sont utilisées pour chaque pas de temps t ∈ *T* afin de modéliser les contraintes opérationnelles.

Chaque nœud *n* dispose d'une fonction de coût associée :

$$F^n(X^n, Z^n) = \sum_{t=1}^{T} f^n(X^n, Z^n, t)$$

dont le but est de décrire les dépenses d'investissement (CAPEX) et les dépenses opérationnelle (OPEX).

Enfin, des contraintes d'égalité et d'inégalité sur les arêtes peuvent être définies comme $H^e(Z^e) = 0$ et $G^e(Z^e) \leq 0$ avec e ∈ E afin de modéliser les lois de conservation et les plafonds relatives aux différentes grandeurs qui interviennent dans le problème.

Finalement, le modèle s'écrit :

$$\begin{aligned}
\min \quad & \sum_{n=1}^{N} F^n(X^n, Z^n) \\
\text{s.t.} \quad & h_i(X^n, Z^n, t) = 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}, \forall i \in \mathcal{I} \\
& g_j(X^n, Z^n, t) \leq 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}, \forall j \in \mathcal{J} \\
& H^e(Z^e) = 0, \forall e \in \mathcal{E} \\
& G^e(Z^e) \leq 0, \forall e \in \mathcal{E}.
\end{aligned}$$

Les principales hypothèses sous-jacentes à notre modèle sont les suivantes :

- **Planification et exploitation centralisées** : une seule entité est responsable de toutes les décisions d'investissement et d'exploitation,
- **Prévisions et connaissances parfaites du futur** : il est supposé que les séries temporelles de demande, ainsi que les séries temporelles liées à la météorologie, sont connues à l'avance pour l'ensemble de l'horizon d'optimisation, c'est-à-dire pour ∀t ∈ {1, ... , T},
- **Permanence des décisions d'investissement** : les décisions d'investissement aboutissent au dimensionnement des capacités d'installation au début de l'horizon temporel. Les capacités restent fixes pendant toute la période d'optimisation, c'est-à-dire pour ∀t ∈ {1, ... , T},
- **Modélisation linéaire** : toutes les technologies et leurs interactions sont modélisées à l'aide de relations linéaires,
- **Agrégation spatiale** : Les demandes et la production d'énergie à chaque nœud sont représentées par des points uniques. La topologie des réseaux énergétiques nécessaires pour répondre à ces demandes et productions n'est *localement* pas modélisée. Cela peut être perçu comme une généralisation de l'hypothèse de la *plaque de cuivre* utilisée dans le cadre des *power systems*.

Dans notre problème, toutes les fonctions de coût et les contraintes sont des transformations affines des entrées. Plus de détails sur les contraintes de chaque technologie sont disponibles dans les articles ici référencés [25,26]. Enfin, la fonction « objectif » locale correspondant au CAPEX est modélisée avec un coût moyen pondéré uniforme du capital (WACC) de 7% pour chaque technologie. Ainsi, le CAPEX est calculé à l'aide de la formule suivante :

$$\zeta^n = \mathrm{CAPEX}_n \times \frac{\mathrm{w}}{(1-(1+\mathrm{w})^{-\mathrm{L}_n})}$$

Où L_n indique la durée de vie de la technologie *n* et *w* le WACC. Par conséquent, ζ^n représente le coût annualisé de l'investissement dans la technologie *n*.

Un plafond sur les émissions nettes de CO2 (c'est-à-dire les rejets moins le CO2 capturé de l'atmosphère) est ajouté au modèle. Ce dernier est défini comme suit :

$$\sum_{t\in\mathcal{T}}\left(\sum_{a\in\mathcal{A}} q^{a}_{co2,t} - \sum_{c\in\mathcal{C}} q^{c}_{co2,t}\right) \leq \kappa_{co2}\nu$$

où *A* et *C* représentent les ensembles de technologies qui rejettent du CO2 dans l'atmosphère et celles qui captent du CO2 directement de l'atmosphère, respectivement. *κCO2* représente le plafond de CO2 en kilotonnes par an, et *v* représente le nombre d'années couvertes par l'horizon d'optimisation. La variable duale associée à l'équation ci-dessus permet de dériver un coût du CO2 en C/t. Une explication détaillée des variables duales en tant que coûts marginaux en programmation linéaire peut être trouvée dans l'ouvrage de Bertsimas & Tsitsiklis au chapitre 4[27].

III Valoriser le CO2 dans un schéma de hub énergétique à distance – premiers résultats.

Cette troisième partie est dédiée à la présentation de résultats chiffrés. La méthodologies multi-RREH est déployée dans un cas concret faisant intervenir la Belgique (comme EDC), et 2 hubs énergétiques, l'un situé au Groenland, l'autre dans le désert du Sahara.

[25] Mathias Berger, David Radu, Raphael Fonteneau, Thierry Deschuyteneer, Ghislain Detienne, and Damien Ernst. The role of power-to-gas and carbon capture technologies in cross-sector decarbonization strategies. Electric Power Systems Research, 180:106039, 2020. ISSN 0378-7796.
doi: https://doi.org/10.1016/j.epsr.2019.106039 .
URL https://www.sciencedirect.com/science/article/pii/S037877961930358X .

[26] Mathias Berger, David-Constantin Radu, Ghislain Detienne, Thierry Deschuyteneer, Aurore Richel, and Damien Ernst. Remote renewable hubs for carbon-neutral synthetic fuel production. Frontiers in Energy Research, 2021. doi: 10.3389/fenrg.2021.671279.

[27] Dimitris Bertsimas and John N. Tsitsiklis. Introduction to Linear Optimization. Athena Scientific, 1997. ISBN 978-1886529199.

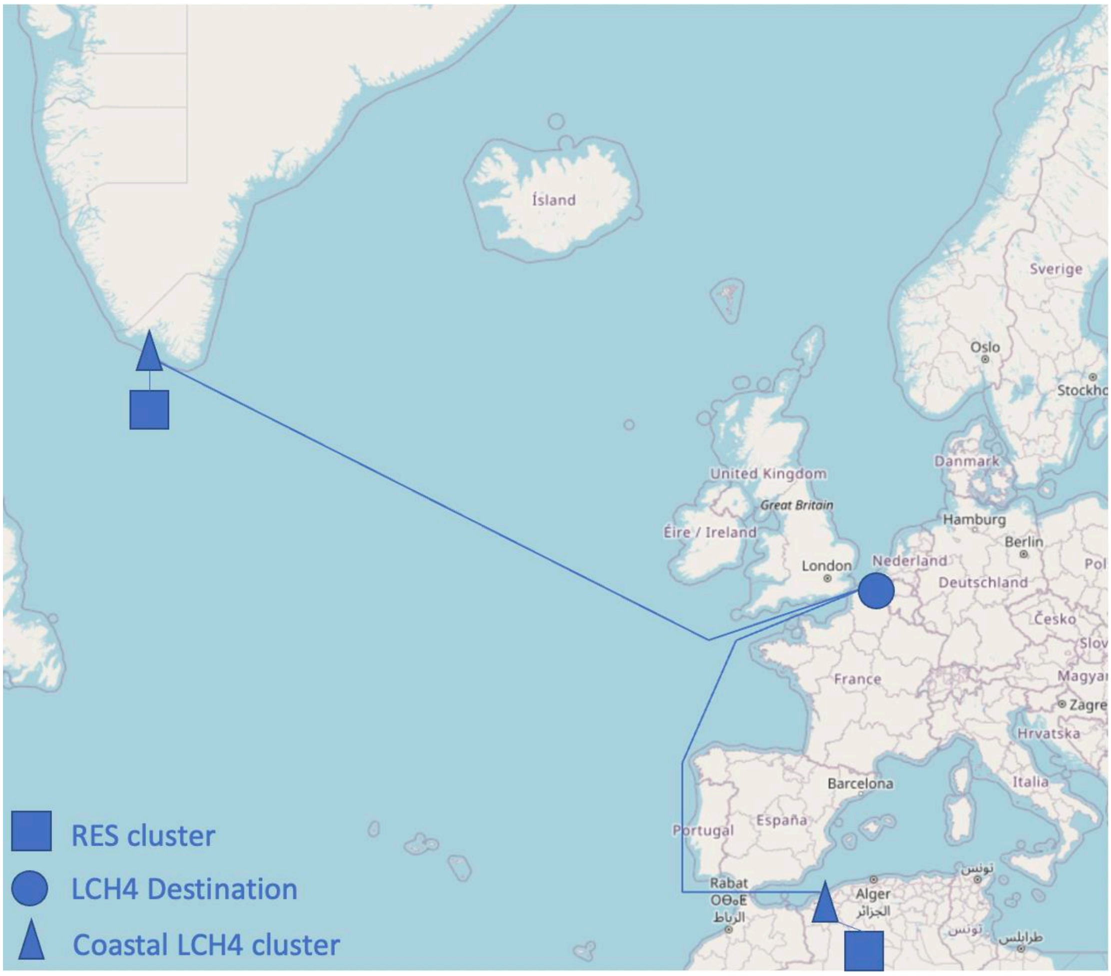


Figure 7 : un modèle double RREH

3.1. Data

The data cover 2 years: 2015 and 2016. It is used to characterize energy demand as well as load factors for renewable energy sources.

3.1.1. Renewable generation profiles

In order to determine the generation profiles of variable energy sources in Belgium we use the data from the transmission system operator (TSO) of Belgium[28]. The profiles for the RREH located in Algeria are extracted with the same methodology as in Berger *et al*[29]. For the RREH situated in Greenland, the profiles of renewable energy are extracted thanks to the MAR model[30] and given a power curve for an offshore wind turbine MHI VestasOffshore V164-9.5MW.

[28] Elia. Power generation, 2022. URL https://www.elia.be/en/grid-data/power-generation .

[29] Mathias Berger, David-Constantin Radu, Ghislain Detienne, Thierry Deschuyteneer, Aurore Richel, and Damien Ernst. Remote renewable hubs for carbon-neutral synthetic fuel production. Frontiers in Energy Research, 2021. doi: 10.3389/fenrg.2021.671279.

[30] X. Fettweis, J. E. Box, C. Agosta, C. Amory, C. Kittel, C. Lang, D. van As, H. Machguth, and H. Gallee.

3.1.2. Energy consumption

The energy consumption data is collected for two energy vectors: gas[31] and electricity[32] with the same methodology as Berger et al[33]. In Figure 8 : Daily aggregated profiles of electricity and natural gas demand covering the years 2015 and 2016, the data corresponding to the two years 2015 and 2016 is represented, where the signal is daily aggregated. In some cases, gas usage is shifted towards electricity needs, as described in Berger *et al*[33, section 4.2.2]. This shift is due to the use of heat pumps, which can help decarbonize heating in Europe. For both energy vectors, industrial and heating demands are taken into account.

The peak power demand is equal to 60.13 GWh/h for both gas and electricity. The energy demand for electricity ranges from 6.42 to 20.29 GWh/h, while that for gas ranges from 5.51 to 39.84 GWh/h. The total energy demand is on average 106.45 TWh/year and 132.65 TWh/year for electricity and gas, respectively.

Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model. The Cryosphere, 11(2):1015–1033, 2017. doi: 10.5194/tc-11-1015-2017.
URL https://tc.copernicus.org/articles/11/1015/2017/.

[31] Fluxys. Flow data – ex-post domestic exit point information, 2022.
URL https://gasdata.fluxys.com/fr/transmission-ztp-trading-services/flow-data/ .

[32] Elia. Load and load forecasts – total load, 2022. URL https://www.elia.be/en/grid-data/load-and-load-forecasts.

[33] Mathias Berger, David Radu, Raphael Fonteneau, Thierry Deschuyteneer, Ghislain Detienne, and Damien Ernst. The role of power-to-gas and carbon capture technologies in cross-sector decarbonisation strategies. Electric Power Systems Research, 180:106039, 2020. ISSN 0378-7796.
doi: https://doi.org/10.1016/j.epsr.2019.106039 .
URL https://www.sciencedirect.com/science/article/pii/S037877961930358X.

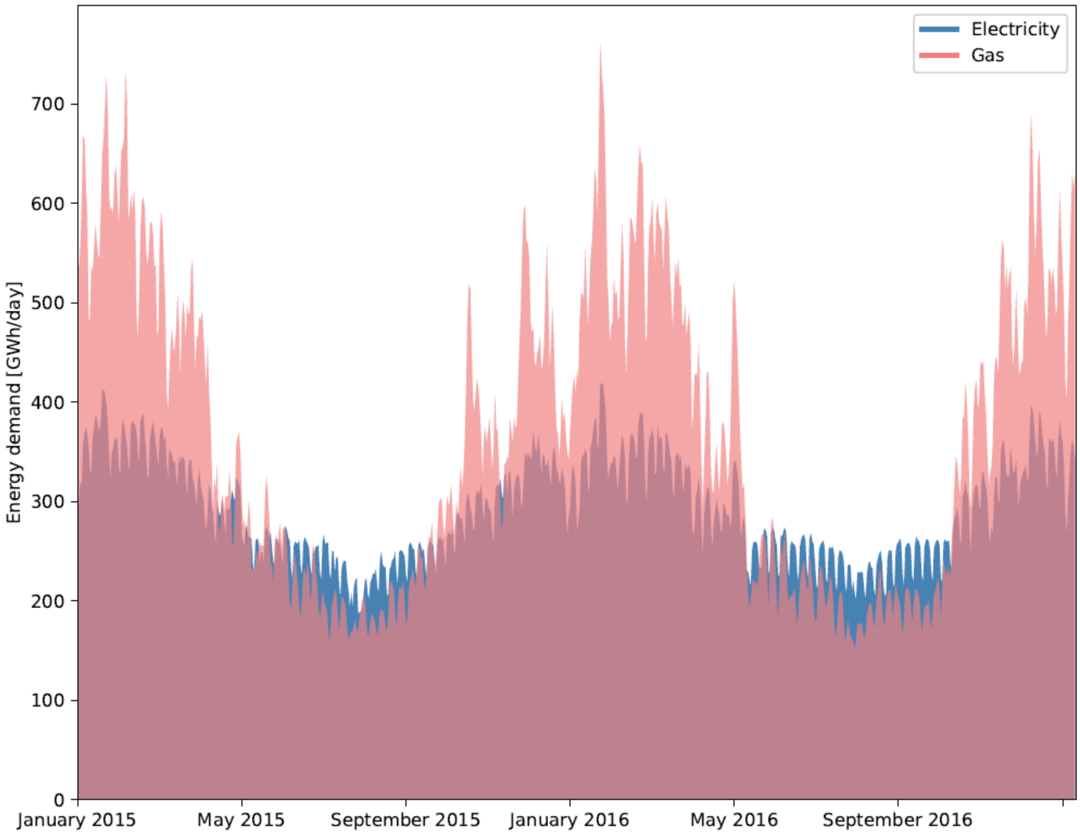


Figure 8 : Daily aggregated profiles of electricity and natural gas demand covering the years 2015 and 2016

3.2. Model Configuration

Our model consists of 3 main components (see Fig. 1) Figure 5 : le modèle multi-RREH : the energy demand center located in Belgium and 2 Remote Renewable Energy Hubs (RREHs) situated in Algeria and Greenland. The RREH in Algeria is modeled as described in Berger *et al*[34] with the same techno-economic parameters. The distinction is made with the inclusion of the CO2 connection between Belgium and Algeria. The RREH in Greenland is similarly modeled, with the exception of the removal of the photovoltaic potential and the modification of the high-voltage direct current (HVDC) line to a length of 100 km rather than 1000 km.

The transportation of CO2 is achieved through the use of boats, which have a CAPEX of 5MC/kt, a lifespan of 40 years, and an average daily energy consumption of 0.0150 GWh/day. CO2 transport data was obtained from the Danish Energy Agency[35]. The loading and traveling time for these boats are assumed identical to those for liquefied methane carriers[34], i.e. 24 and 116 hours, respectively. In order to fill the tank of CO2 carriers with

[34] Mathias Berger, David-Constantin Radu, Ghislain Detienne, Thierry Deschuyteneer, Aurore Richel, and Damien Ernst. Remote renewable hubs for carbon-neutral synthetic fuel production. Frontiers in Energy Research, 2021. doi: 10.3389/fenrg.2021.671279

[35] Danish Energy Agency. Technology data for carbon capture, transport and storage, 2023. URL : https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-carbon-capture-transport-and.

fuel (liquefied methane), these tanks are loaded when unloading the CO2 at the RREH. Indeed, at the RREH, synthetic CH4 is available without having undergone any additional transport-related losses. Except for the storage facilities, liquefaction of CO2 has been excluded from the model. Sideways analyses have confirmed that this assumption has a negligible impact on the optimal objective.

Belgium is modeled with an electricity and gas demand as depicted in Figure 8 : Daily aggregated profiles of electricity and natural gas demand covering the years 2015 and 2016, with various means of production, including wind power, solar power, and a combined cycle gas turbine. The solar potential is limited to 40GW. The wind potential is equal to 8.4 GW and 8 GW for onshore and offshore capacities, respectively. The technoeconomic parameters of each technology deployed in Belgium follow those in Berger et al [36].

We have also added a CO2 source that is equivalent to 40Mt CO2/year, which corresponds to the energy sectors and industrial processes greenhouse gases in Belgium in 2019 [37, Table 4.1.1 (pp. 165- 166)]. We assume that we can install post-carbon capture technologies (PCCC) in these sectors.

In terms of carbon capture technologies, the model has access to direct air capture installed at the RREHs, as well as a PCCC in Belgium on the 40Mt of CO2 per year and a PCCC installation on the CCGT.

As stated in Berger *et al.*[38], the cost of PCCC is 3150MC/kt/h of CAPEX. The variable operating and maintenance costs (VOM and FOM) have been neglected in this analysis. However, a demand of 0.4125GWhel/ktCO2 of electricity is required. The expected lifetime is assumed to be 20 years. Similarly, according to Berger et al.[39] [3], the cost of DAC is equal to 4801.4 MC/kt/h of CAPEX. Similar to PCCC, VOM and FOM are ignored. The operational requirements for DAC are 0.1091GWhel/ktCO2 of electricity, 0.0438ktH2/ktCO2 of di-hydrogen, and 5.0ktH20/ktCO2 of water. The expected lifetime is assumed to be 30 years.

[36] Mathias Berger, David Radu, Raphael Fonteneau, Thierry Deschuyteneer, Ghislain Detienne, and Damien Ernst. The role of power-to-gas and carbon capture technologies in cross-sector decarbonisation strategies. Electric Power Systems Research, 180:106039, 2020. ISSN 0378-7796.
doi: https://doi.org/10.1016/j.epsr.2019.106039.
URL https://www.sciencedirect.com/science/article/pii/S037877961930358X .

[37] European Commission and Directorate-General for Energy. EU energy in figures : statistical pocketbook 2021. Publications Office of the European Union, 2021. doi: doi/10.2833/511498.

[38] Mathias Berger, David Radu, Raphael Fonteneau, Thierry Deschuyteneer, Ghislain Detienne, and Damien Ernst. The role of power-to-gas and carbon capture technologies in cross-sector decarbonisation strategies. Electric Power Systems Research, 180:106039, 2020. ISSN 0378-7796.
doi: https://doi.org/10.1016/j.epsr.2019.106039.
URL https://www.sciencedirect.com/science/article/pii/S037877961930358X.

[39] Mathias Berger, David-Constantin Radu, Ghislain Detienne, Thierry Deschuyteneer, Aurore Richel, and Damien Ernst. Remote renewable hubs for carbon-neutral synthetic fuel production. Frontiers in Energy Research, 2021. doi: 10.3389/fenrg.2021.671279.

3.3. Results

In this section, we explore several scenarios. We describe the variables that are used to differentiate the scenarios

1. Cost or Cap on CO2: either a cap is set of 0 t/year or a price at 80€/t or 0€/t
2. Cost of energy not served (ENS): either energy not served is not allowed or a penalty of 3000€/MWh is imposed for each unit of unproduced energy.
3. Forcing or not the use of a given RREH.

Table 1 : Scenarios' parameters

Scenario	Cap on CO2 (kt)	Cost of CO2 (M€/kt)	ENS	Cost of ENS (k€/MWh)	Objective (M€)
1.	0.0	0.0	No	-	83742.61
2.	0.0	0.0	Yes	3.0	80778.02
3.	No	0.08	Yes	3.0	78872.94
4.	No	0.0	Yes	3.0	76323.94
5.	0.0	0.0	No	-	111209.95

The results are generated with 5 scenarios:

1. Scenario 1: This scenario seeks to avoid energy scarcity, whatever the cost. Therefore, no ENS is allowed. In addition, a hard constraint is set on CO2 emissions: a cap on CO2 is set.
2. Scenario 2: This scenario follows the same assumptions as scenario 1 except that it leverages the constraint on energy not served. The cost associated to electricity not served is equal to 3000€/MWh, which is a standard value in the electricity context[40].
3. Scenario 3: This scenario leverages the constraint on CO2 emissions, and does not force the avoidance of energy not served but is penalized by 3000€/MWh not served. A penalty is associated with any CO2 emission in the atmosphere in the form of a fee equal to 80€/t - a value that reflects the current price of CO2 in the EU-ETS trading system[41].
4. Scenario 4: This scenario follows the same assumptions as scenario 3, with the difference that the cost of CO2 is equal to 0€/MWh. The aim is to showcase the system's configuration in the absence of any considerations for CO2 emissions.
5. Scenario 5: This scenario follows the same assumptions as scenario 1, with the difference that the only available RREH is in Greenland.

These scenarios summarized in Table 1 : Scenarios' parameters vary in their degree of constraint. Scenario 1 is the most restrictive, with a cap on CO2 emissions and no allowance for energy not served. Scenario 2 allows for energy not served, while scenarios 3 and 4

[40] Thomas Schroder and Wilhelm Kuckshinrichs. Value of lost load: An efficient economic indicator for power supply security? A literature review. Frontiers in Energy Research, 3, 2015. ISSN 2296-598X. doi: 10. 3389/fenrg.2015.00055. URL https://www.frontiersin.org/articles/10.3389/fenrg.2015.00055

[41] Trading Economics. EU carbon permits, 2023. URL https://tradingeconomics.com/commodity/carbon.

remove the cap and replace it with CO2 prices of 80€ and 0€ per ton, respectively. Finally, scenario 5 requires the use of the RREH in Greenland, with parameters identical to those of scenario 1.

3.4. Analyses and discussion

In this section, we introduce and discuss the results in detail. We choose to present a cross-scenario analysis in the light of key indicators and statistics extracted from the model.

3.4.1. Total cost

The results indicate that the costs associated with enabling the hub in Algeria are substantially lower than those in Greenland, as depicted in Figure 9 : (a) : Breakdown of costs per scenario and per cluster (Belgium (BE), Algeria (DZ), and Greenland (GL)). (b) : Breakdown of costs per scenario per asset function. Flexibility covers storage capacities, CO2 Infra covers CO2 capture, storage, and transport (a) where nothing is built in the Greenland hub from scenarios 1 to 4, despite it being available for use. This disparity in costs can be attributed to the over-dimensioning of flexibility assets, particularly the storage capacities, as illustrated in Figure 9 : (a) : Breakdown of costs per scenario and per cluster (Belgium (BE), Algeria (DZ), and Greenland (GL)). (b) : Breakdown of costs per scenario per asset function. Flexibility covers storage capacities, CO2 Infra covers CO2 capture, storage, and transport(b). This is mainly explained to electricity generated solely through wind available in Greenland, whereas both solar and wind electricity are obtainable in Algeria. This implies that the flexibility assets have to take the lead in maintaining a minimum of electricity delivery required in the electrolysis power plant.

Furthermore, a reduction in total costs is observed in the first four scenarios with respect to the objective. This is explained with the order on the scenarios based on their degree of constraint with scenario 1 being the most constrained and scenario 4 being the least.

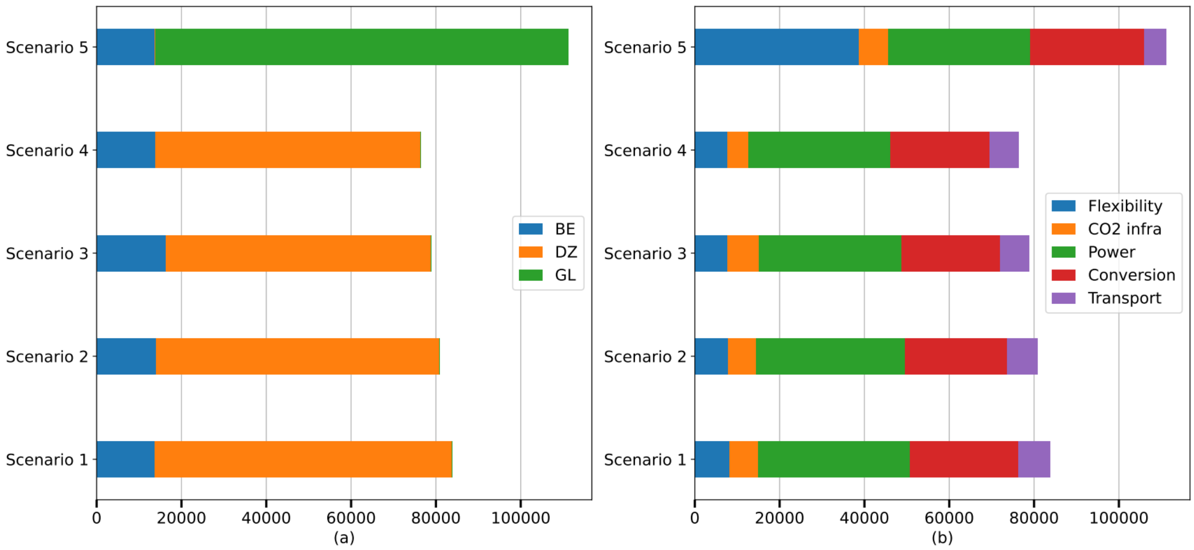


Figure 9 : (a) : Breakdown of costs per scenario and per cluster (Belgium (BE), Algeria (DZ), and Greenland (GL)). (b) : Breakdown of costs per scenario per asset function. Flexibility covers storage capacities, CO2 Infra covers CO2 capture, storage, and transport

3.4.2. Power installation capacities

All power capacities installations are displayed in Table 2 : Total Power installation in GW per scenario.. The potential in Belgium of solar energy is never reached while for both wind offshore and onshore the potential is reached in all scenarios.

From scenario 1 to scenario 2, the only difference being the allowance of ENS, there is an increase in the installation of controllable energy production assets. Indeed, there is a shift in capacity from CCGT to solar energy in Belgium between the first scenario and the second.

Comparing scenario 1 and 5, solar energy in Belgium is more expensive than importing CH4 from the RREH in Algeria. Importing from Greenland is more expensive and leads to an increase in power capacity installation in Belgium for solar, but it does not reach the maximum potential.

Another interesting comparison can be made with the work of Berger *et al*[42], where the capacity installation in the hub for the reference scenario is 4.3GW of solar and 4.4GW of wind. In our case, the reference scenario 1 displays 100.51GW and 103.62GW, respectively. The power installation capacity is multiplied by approximately 23 while providing, on average, 282TWh/year of gas (HHV) to serve the gas demand and part of the electricity demand in Belgium, which is 28.2 times the gas production in the original paper.

Table 2 : Total Power installation in GW per scenario.

Scenario	Wind onshore BE	Wind offshore BE	Solar BE	CCGT BE	Wind GL	Wind DZ	Solar DZ
1	8.40	8.0	10.56	22.69	0.00	103.62	100.51
2	8.40	8.0	15.35	17.95	0.00	98.43	95.47
3	8.40	8.0	14.95	17.83	0.00	93.32	90.32
4	8.40	8.0	14.72	17.82	0.00	93.28	90.28
5	8.40	8.0	17.48	19.58	129.43	0.00	0.00

3.4.3. CO2 installations (transport, capture)

In Table 3 : Capacity, in kt/h, of CO2 capture technology and transport by hub and per scenario, the capacities of the CO2 capture units and the installations of transport capacity per scenario are displayed. Each time PCCC is activated, we recall that capturing CO2 is the only means to create gas in our system, and thus a minimum installation is required to support the demand. On the other hand, the DAC is only activated when a CO2 cap is set. PCCC has an efficiency of CO2 capture set to 90%, which means that a direct air capture technology asset is necessary to recover the remaining 10% of emissions in the atmosphere. This leads to a direct consequence, which is that when the DAC is available, the capacity of transport decreases because CO2 is locally available in the hub. However, the cost of CO2 capture by PCCC added to transport of CO2 is cheaper than the cost of DAC in the RREH. The only way

[42] Mathias Berger, David-Constantin Radu, Ghislain Detienne, Thierry Deschuyteneer, Aurore Richel, and Damien Ernst. Remote renewable hubs for carbon-neutral synthetic fuel production. Frontiers in Energy Research, 2021. doi: 10.3389/fenrg.2021.671279.

to put PCCC out of business would be to have a distance between the hub and the energy demand center so long that the transport cost would increase too much.

Due to the higher concentration of CO2 in manufacturing smoke compared to the air, PCCC will likely always be cheaper than DAC, even with significant improvements in the DAC process. As a result, the operational costs associated with the energy required for PCCC will be lower than those of DAC.

Table 3 : Capacity, in kt/h, of CO2 capture technology and transport by hub and per scenario

Scenario	PCCC	PCCC CCGT	DAC DZ	DAC GL	Carrier DZ	Carrier GL
1	4.11	2.62	1.30	0.00	8.030	0.000
2	4.11	2.07	1.47	0.00	7.142	0.000
3	4.11	1.80	0.00	0.00	9.694	0.000
4	3.76	2.06	0.00	0.00	0.701	0.000
5	4.11	2.40	0.00	1.35	0.000	7.564

3.4.4. Cost of CO2 derived and Cap of CO2.

From the first, second, and fifth scenarios, we are able to derive a shadow price thanks to the CO2 cap constraint. These correspond to approximately 162.77€/tCO2 for the first and second scenarios and 235.65€/tCO2 for the fifth scenario. This shows that given the system considered, i.e., Belgium and RREHs, putting a price of CO2 equal to 162.77€ would avoid these emissions in the atmosphere and activate the export of CO2 to Norway for storage purposes. In scenario 3, where a price of 80€/tCO2 is set, there is a net balance in the atmosphere of approximately 15Mt/year. In scenario 4, where no price is fixed, there is a net balance in the atmosphere which is equivalent to 16Mt/year.

We would like to emphasize that the CO2 cap in our model only considers the emissions from the industrial and energy sectors, which are fully modeled. It does not account for a part of the emissions resulting from the gas demand served. Of this demand, 32% is attributed to industrial needs, which are included in the statistics of the 40 Mt of CO2 emitted per year (see section 3.2. Model Configuration), while the remaining 68% is due to heating and is not covered by our cap. This heating gas demand translates to approximately 12.3 Mt of CO2 emitted per year.

3.4.5. Cost of CH4 derived

To estimate the cost of CH4 production, we first subtract from the optimal objective function the cost of the means of electricity production in Belgium (PV, on/off shore wind, CCGT), the cost of unserved energy (when applicable), and the cost related to export of CO2 for sequestration. All of these costs are substracted because they do not refer directly to the cost of producing synthetic methane. Then, we divide the obtained cost by the total energy content (HHV) in CH4 produced at the output of the regasification power plant in Belgium.

These methane costs, listed in Table 4 : Estimation of methane price by retrieving the costs of power installations in Belgium, costs of unserved, are compared to the price of 147.9€/MWh of methane (HHV) obtained by Berger *et al*[43]. Our scenarios achieve a lower cost for gas production (except for Greenland). This demonstrates that PCCC, which uses smoke with a high concentration of CO2 combined with transport, is more cost-effective than having only access to a DAC unit, as previously mentioned.

In our system, no fossil gas is available for import to Belgium; only synthetic gas produced from CO2 capture is used. If fossil gas were still available for import, our model would seek to minimize costs and import as much cheap gas as possible while staying within our carbon budget.

Table 4 : Estimation of methane price by retrieving the costs of power installations in Belgium, costs of unserved

Scenario	1	2	3	4	5
[€/MWh]	136	137.19	133.89	129.27	192.00

3.4.6. ENS cost discussion

The cost of unserved energy is a fixed parameter in scenarios 2, 3, and 4, but not in scenarios 1 and 5. Instead, a hard constraint is imposed to ensure that electricity demand is always met, resulting in a shadow price associated with the constraint. The maximum shadow price values for scenarios 1 and 5 are 913,640€/MWh and 1,075,913€/MWh, respectively. This is attributed to the peak in electricity and gas demand observed on January 18th at 18:00 (as shown in Figure 10 : Evening of January 18th leading to the maximum shadow price associated with the hard constraint), where renewable energy load factors were low. Thus, all energy demand had to be supplied by the Combined Cycle Gas Turbine (CCGT) and gas resources.

[43] Mathias Berger, David-Constantin Radu, Ghislain Detienne, Thierry Deschuyteneer, Aurore Richel, and Damien Ernst. Remote renewable hubs for carbon-neutral synthetic fuel production. Frontiers in Energy Research, 2021. doi: 10.3389/fenrg.2021.671279.

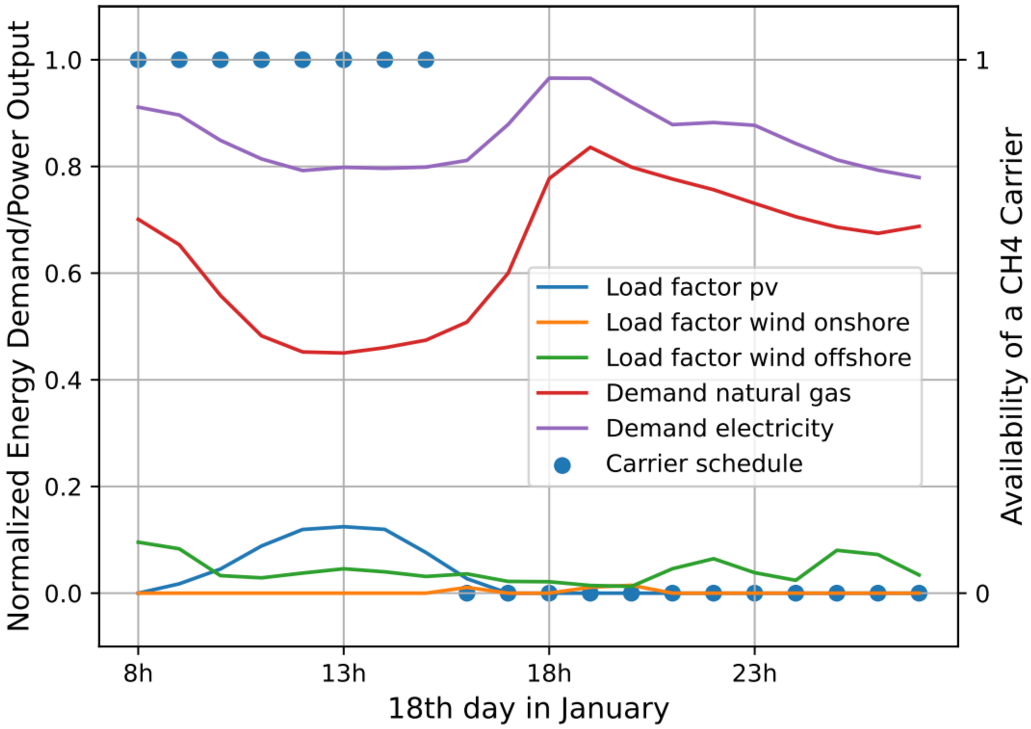


Figure 10 : Evening of January 18th leading to the maximum shadow price associated with the hard constraint

IV. Conclusions partielles, recherches en cours et futures

L'approche de valorisation « positive » du CO2 présentée dans les partie II (méthodologie) et III (résultats quantitatifs) permet de calculer des valeurs seuils pour le CO2 à partir desquels le schéma {RREH, PCCC} devient économiquement pertinent. Ces valeurs seuils dépendent des hypothèses de coûts des différentes technologies qui interviennent dans la modélisation. Nous avons entamé des discussions avec l'UCLouvain afin de quantifier l'impact des incertitudes sur les paramètres technologiques sur le « shadow price » du CO2 en sortie du modèle RREH. Ces recherches sont toujours en cours. Aussi, l'approche décrite ici se concentre sur la production de méthane synthétique, mais d'autres possibilités de valorisation du CO2 existent, notamment au travers de la production de méthanol. Un article scientifique est actuellement en cours d'écriture sur le sujet.

La suite de ce rapport présente 3 annexes : un exposé au sujet du prix du carbone, un article scientifique présenté à la conférence ECOS 2023, et enfin un exposé sur les RREH présenté chez Total Energie.

Annexes 1 : Energy Markets: Carbon Price

Annexe 2 : Towards CO2 valorization in a multi remote renewable energy hub framework

Annexe 3 : Remote Renewable Energy Hubs

Energy Markets: Carbon Price

Author: Victor Dachet

Adrien Bolland, Thibaut Théate, Antoine Dubois, Raphaël Fonteneau and Damien Ernst

Course Overview

Carbon Price

Carbon Price

Main goal:

Decrease GHG emissions in Europe by setting a price.

This price must represent the externalities.

Source: https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)698890

Externalities : A Definition

Externalities refers to situations when the effect of **production or consumption** of goods and services **imposes costs or benefits on others** which are **not reflected in the prices** charged for the goods and services being provided.

Source: https://stats.oecd.org/glossary/detail.asp?ID=3215

Market Failure

Externalities either positive or negative that are not taken into account lead to respesctively underconsumption and overconsumption. This implies what we call a market failure.

E.g.: The overconsumption of fossil fuels.

Negative Externalities

The price of an externality is the difference between the marginal social cost (MSC) and the marginal private cost (MPC).

MPC + MEC = MSC

with MEC : marginal external costs

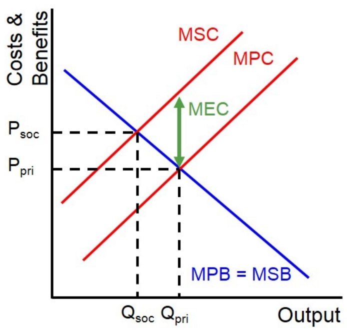


Figure source: https://www.ezyeducation.co.uk/ezyeconomicsdetails/ezylexicon-economic-glossary/741-marginal-external-cost.html

Property Rights

Definition:

Property rights define the theoretical and legal ownership of resources and how they can be used. Property can be owned by individuals, businesses, and governments. These rights define the benefits associated with ownership of the property.

Source: https://www.investopedia.com/terms/p/property_rights.asp

Transactions

Definition:

A transaction is a completed agreement between a buyer and a seller to exchange goods, services, or financial assets in return for money.

Source: https://www.investopedia.com/terms/t/transaction.asp

Coase Theorem

Thrm - If **transactions costs are low** and **property rights are clearly defined**, private bargains will ensure that the market equilibrium is efficient even if there are externalities

- Often conditions are not met
- Suggests a solution – the creation of new markets:

  If governments can define property rights and reduce transaction costs markets can be used to control externality problems.

Source: Carbon Markets: An International Business Guide by Arnaud Brohé, Nick Eyre and Nicolas Howarth
https://www.youtube.com/watch?v=00HPak2RLlQ

Marginal Abatment Cost:

An abatement cost is a cost borne by firms when they are required to remove and/or reduce undesirable nuisances or negative by-products created during production.

It is the cost to reduce one more unit of an environmental negatives (e.g. the cost to reduce one ton of CO2).

Source: https://www.investopedia.com/terms/a/abatementcost.asp

Policy Mechanisms

How to set up a price on carbon?

Four ways to consider carbon externalities:

1. Baseline and Credit
2. Command-and-control regulation
3. Carbon Tax
4. Carbon Market: cap and trade mechanism

In this lecture, we will focus on the 2 last and more specifically on carbon markets.

Source: https://en.wikipedia.org/wiki/Emissions_trading

Baseline and Credit

You fix a baseline on emissions for a given sector. Then the actors which produce a good or a service with higher emissions must buy allowances from actors producing with less emissions than the baseline.

Command-and-Control Regulation

Command—and—control policy refers to environmental policy that relies on regulation (permission, prohibition, standard setting and enforcement) as opposed to financial incentives, that is, economic instruments of cost internalisation.

Source: https://stats.oecd.org/glossary/detail.asp?ID=383

Carbon Tax

This is a price mechanism. You fix a price on a given quantity of emission.

Then, the market will find an optimal quantity to emit.

Cap and Trade mechanism

This is a quantity instrument. You fix the maximum total amount of emissions and you sell by auction the allowances to emit.

Then, the market will find a price for this given volume of emissions.

Similarities between cap & trade and carbon tax

- Reduce emissions by encouraging lowest-cost emissions reductions (without prior knowledge on where these reductions will occur).
- Encourage investors and entrepreneurs to develop new low-carbon technologies.
- Generate government revenue

Source: https://www.wri.org/insights/carbon-tax-vs-cap-and-trade-whats-better-policy-cut-emissions

Advantages of a Carbon Tax

- Stable carbon prices, so energy producers and entrepreneurs can make investment decisions without fear of fluctuating regulatory costs.

Source: https://www.wri.org/insights/carbon-tax-vs-cap-and-trade-whats-better-policy-cut-emissions

Advantages of Cap and Trade

- By setting an emissions cap that declines over time, a cap-and-trade policy can increase certainty that emissions will fall below the predetermined emissions targets.
- Automatic response to inflation

Source: https://www.wri.org/insights/carbon-tax-vs-cap-and-trade-whats-better-policy-cut-emissions

Historic Context

Historic Context

Kyoto Protocol (signed in 1997) establishes 3 market-based mechanisms:

1. International Emissions Trading
2. Clean Development Mechanism (CDM)
3. Joint implementation (JI)

entered into force in 2005.

Source: https://unfccc.int/kyoto_protocol

Clean Development Mechanism (CDM) and Joint Implemenation (JI)

CDM and **JI** are the two project-based mechanisms which feed the carbon market.

The **CDM** involves investment in **emission reduction** or removal enhancement projects **in developing countries** that contribute to their sustainable development, while **JI** enables **developed countries** to carry out emission reduction or removal enhancement projects in other developed countries.

CDM: earn saleable certified emission reduction (CER) credits, each equivalent to one tonne of CO2, which can be counted towards meeting Kyoto targets.

JI: to earn emission reduction units (ERUs) from an emission-reduction or emission removal project in another Annex B Party, each equivalent to one tonne of CO2, which can be counted towards meeting its Kyoto target.

Source: https://unfccc.int/process/the-kyoto-protocol/mechanisms

International Emissions Trading

The allowed emissions are divided into assigned amount units **(AAUs).**

Emissions trading, as set out in Article 17 of the Kyoto Protocol, allows countries that have emission units to spare - emissions permitted them but not "used" - to sell this excess capacity to countries that are over their targets.

Other traded units:

- A removal unit **(RMU)** on the basis of land use, land-use change and forestry (LULUCF) activities such as reforestation
- An emission reduction unit **(ERU)** generated by a joint implementation project
- A certified emission reduction **(CER)** generated from a clean development mechanism project activity

Source: https://unfccc.int/process/the-kyoto-protocol/mechanisms/emissions-trading

International Emissions Trading

Transfers and acquisitions of these units are tracked and recorded through the registry systems under the Kyoto Protocol.

An international transaction log ensures secure transfer of emission reduction units between countries.

The commitment period reserve

In order to address the concern that Parties could "oversell" units, and subsequently be unable to meet their own emissions targets, each Party is required to maintain a reserve of ERUs, CERs, AAUs and/or RMUs in its national registry. This reserve, known as the "commitment period reserve", should not drop below 90 per cent of the Party's assigned amount or 100 per cent of five times its most recently reviewed inventory, whichever is lowest

Source: https://unfccc.int/process/the-kyoto-protocol/mechanisms/emissions-trading

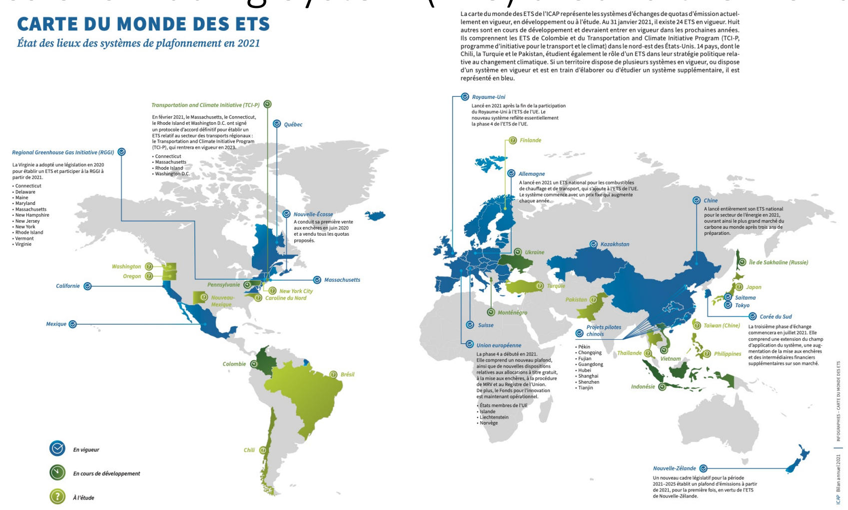
Kyoto Protocol: Critics

- Caps reflect more a political negotiation than an optimization of environmental considerations. There was a lack of ambition.
- Lack of transparency and liquidity of the carbon market.
- Withdrawal of the Canada in 2011 due to oil sand development.
- No ratification by the US the biggest polluter country at that time (2nd one since 2006).
- Critics on the CDM:
  1 - High transaction costs for small scale projects (too long procedures often done by consultant in developed countries).
  2 - Geographical distribution of the projects (More than 85% of the issued credits from 5 countries (China, India, Brazil, South Korea and Mexico).
  3 - Overall climate impact, at best, neutral.
- At least, first steps of an international collaboration to fight climate change when the consensus was weaker than today.

Source: Carbon Markets: An International Business Guide by Arnaud Brohé, Nick Eyre and Nicolas Howarth and https://ourworldindata.org/co2-emissions

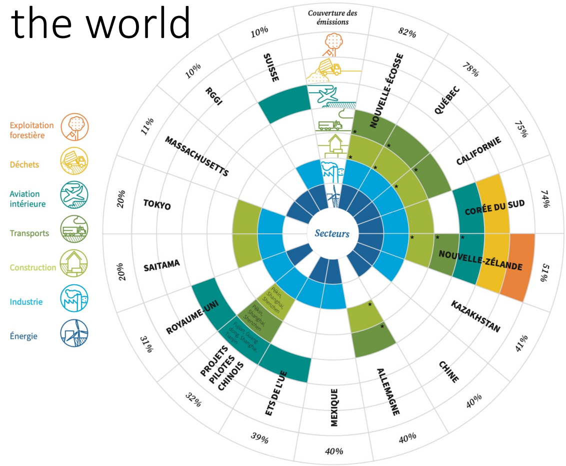
World Overview

Emissions Trading System (ETS) around the world



Source: https://icapcarbonaction.com/en/publications/emissions-trading-worldwide-icap-status-report-2021

ETS around the world



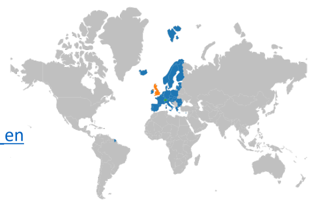
Nowadays, 16% of the world GHG emissions are covered by an ETS

Source: https://icapcarbonaction.com/en/publications/emissions-trading-worldwide-icap-status-report-2021

European Emissions Trading System

EU Emissions Trading System

- operates in all EU countries plus Iceland, Liechtenstein and Norway (EEA-EFTA states),
- limits emissions from around 10,000 installations in the power sector and manufacturing industry, as well as airlines operating between these countries,
- covers around 40% of the EU's greenhouse gas emissions.



Source: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

Figure source: https://en.wikipedia.org/wiki/European_Union_Emissions_Trading_System

EU-ETS: cap and trade

The EU-ETS works on the 'cap and trade' principle. A cap is set on the total amount of certain greenhouse gases that can be emitted by the installations covered by the system. The cap is reduced over time so that total emissions fall.

Within the cap, installations buy or receive emissions allowances, which they can trade with one another as needed. The limit on the total number of allowances available ensures that they have a value.

After each year, an installation must surrender **enough allowances to cover fully its emissions**, otherwise heavy fines are imposed. If an installation reduces its emissions, it can keep the spare allowances to cover its future needs or else sell them to another installation that is short of allowances.

Source: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

GHG Covered by the EU-ETS

- Carbon dioxide (CO2)
- Nitrous Oxyde (N2O)
- Perfluorocarbons (PFCs)

Source: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

Link between Kyoto and European ETS

The European ETS was developed in order to achieve Kyoto protocol goals.

The European ETS recognises ERU and CER to allocate some ETS allowances.

Source: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32004L0101

Birth of the European Emission Trading System (ETS)

- Phase 1: 2005 - 3-year pilot phase
- Phase 2: (2008-2012) – First commitment period of the Kyoto Protocol. ETS covered aviation since 2012.
- Phase 3: (2013-2020) Broadened the scope to more sectors and gases, single EU-wide cap, auctioning default method for distributing allowances, harmonised the rules for free allocation.
- Phase 4: (2021-Now)

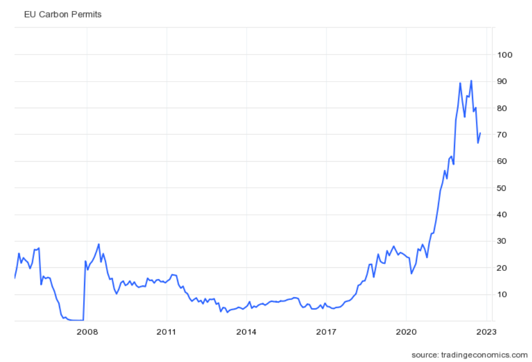
Source: https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)698890

Historical Data ETS Prices

Some statistics:

Lowest price: 0.01€

Highest Price: 99.22€



Historical Data ETS Prices

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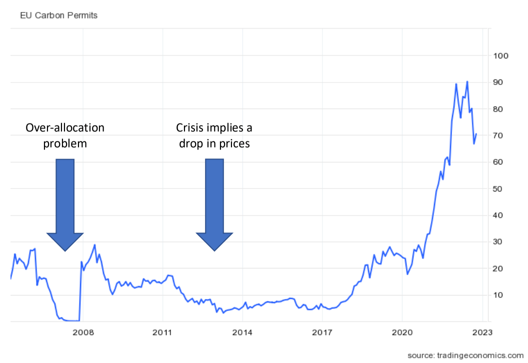


Market Stability Reserve (MSR)

It started to operate in January 2019 as a response to the **over-supply of allowances** since 2009, a result of the **economic crisis** and **high imports of international credits**, which led to **lower carbon prices**.

The MSR allows for better matching of the supply of allowances to be auctioned with the demand. Under the revision of the EU ETS in 2018, the MSR intake rate (the percentage of the total number of allowances in circulation which is put in the reserve) until the end of 2023 was doubled from 12 % to 24 %, and the minimum amount of allowances placed in the MSR was doubled from 100 to 200 million. Moreover, from 2023 the allowances held in the MSR above the total number of allowances auctioned during the previous year should no longer be valid.

Source: https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)698890

Risk of Carbon Leakage

Carbon leakage refers to the situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints. This could lead to an increase in their total emissions. The risk of carbon leakage may be higher in certain energy-intensive industries.

Source: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/carbon-leakage_en

Carbon Border Adjustment Mechanism (CBAM)

The CBAM would initially apply to imports in five emissions-intensive sectors deemed at greater risk of carbon leakage: cement, iron and steel, aluminium, fertilisers, and electricity. The CBAM charge would cover imports of these goods from all third countries, except those participating in the ETS or a linked mechanism.

The price of the CBAM certificates would be directly linked to the weekly price of EU ETS allowance.

Source: https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698889/EPRS_BRI(2022)698889_EN.pdf

In practice

The auction is hosted by EEX the market operator which ensures the reliability of the exchanges.

Who may participate in Emissions Auctions?

- Compliance buyers (operators of stationary installations, aircraft operator)
- Investment firms and credit institutions
- Business groupings of compliance buyers

They have to fulfil admission requirements according to EU and EEX rules:

- Establishment in the EU
- Hold a nominated holding account in the Union registry
- Hold a nominated bank account

Source: https://www.eex.com/en/markets/environmental-markets/eu-ets-auctions

Overview of the auction process

9:00-11:00 am CET	~11:01 am CET	~11:05 am CET	Auction Day + 1 ECC Business day	Upon Request
Bidding window: • Products: i. T3PA (Spot EU Allowances for Phase 4 of the EU ETS, lot size: 500 EUA) ii. EAA3 (Spot EU Aviation Allowances for Phase 4 of the EU ETS, lot size: 500 EUAA) • Bids could be submitted, modified and withdrawn during the bidding window • Bids could be submitted directly in the Auction System (see Video Tutorial) or indirectly via EEX Helpdesk or via Intermediary • Bids are submitted without seeing other participant's bids	Determination of the auction clearing price: • Bids are sorted in descending order of the price bid • Tied bids are sorted through random selection according to an algorithm • Bid volumes are added, starting with the highest bid • The price at which the summed up bid volumes match or exceed the volume of allowances auctioned sets the auction clearing price for all successful bidders Publication: • Main Auction Results in the Auction System and on the Website	Publication: • Detailed Auction Results on the Website (link to the dedicated auction website)	Payment: • From the Clearing Member of a Trading Member to ECC • From ECC to the Auctioneer Delivery (internal): • Transfer of allowances within the ECC Union Registry Account from the Auctioneer (Seller) to the Trading Member (potentially an Intermediary*) having been successful in the Emissions Auction (Buyer)	Delivery (external): • Transfer of allowances from the ECC Union Registry Account to the Union Registry Account of the Trading Member

Source: https://www.eex.com/en/markets/environmental-markets/eu-ets-auctions

Auction process: clearing price

Example: Auction for 1 million EUAs

Order book
after close of bidding window phase

Bidder	Price	Volume
A	82.00 €	500,000
B	86.00 €	600,000
C	84.00 €	300,000
D	85.00 €	800,000
E	85.00 €	500,000
F	95.00 €	10,000
Total		2,710,000

Order book
sorted by price

Bidder	Price	Volume	Allocation
F	95.00 €	10,000	10,000
B	86.00 €	600,000	600,000
D	85.00 €	800,000	*390,000
E	85.00 €	500,000	0
C	84.00 €	300,000	0
A	82.00 €	500,000	0
Total		2,710,000	1,000,000

Source: https://www.eex.com/en/markets/environmental-markets/eu-ets-auctions

Example of Volume planned to be auctioned in 2022

Volume 2022	States	Details
333,205,500	25 EU Member States and 3 EEA EFTA States, Innovation Fund and Modernisation Fund	Weekly auctions on Mondays, Tuesdays and Thursdays
84,230,000	Germany	Weekly auctions on Fridays
62,916,000	Poland	Bi-weekly auctions on Wednesdays
2,037,500	UK in respect of generation of electricity in Northern Ireland	23 February 2022: 1,108,500 EUA (volume of 2021) 21 September 2022: 929,000 EUA (volume of 2022)

Source: https://www.eex.com/en/markets/environmental-markets/eu-ets-auctions

Influence on power markets

What carbon price to make fossil fuel power plants out of business ?

Ref. fossil tech.	Coal with CCS			Nuclear		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
	8% capital cost	5% capital cost	12.5% capital cost	8% capital cost	5% capital cost	12.5% capital cost
Gas CCGT 8% capital cost	Carbon price 85€/tCO2	Carbon price **50 €/tCO2**	Carbon price 120€/tCO2	Carbon price 60 €/tCO2	Carbon price **20€/tCO2**	Carbon price 132€/tCO2
Coal plant 8% capital cost	Carbon price 35€/t	Carbon price **20€/t**	Carbon price 54€/t	Carbon price 30€/t	Carbon price **12.5 €/t**	Carbon price 60€/t

Source: Finon 2017 cfr https://www.carbonpricingleadership.org/open-for-comments/tag/Commission

Clean Spark Spread and Clean Dark Spread

Definition:

$$Clean\ Spark\ Spread = P_e - \frac{P_g}{\eta_{el}} - P_c\, I_{gas}$$

With P_e electricity price, P_g gas price, η_{el} efficiency, P_c the carbon price and I_{gas} the gas emissions intensity.

If Clean Spark Spread > Clean Dark Spread :

⇒ Gas-based production more interesting than coal-based

Sources: Carbon Markets: An International Business Guide by Arnaud Brohé, Nick Eyre and Nicolas Howarth and https://en.wikipedia.org/wiki/Spark_spread

Clean Spark Spread and Clean Dark Spread

Figure 8: Evolution du *clean spark spread* (efficacité PCS 50 %) et du *clean dark spread* (efficacité de 42 %) pour les contrats à terme année +1 (Cal +1)

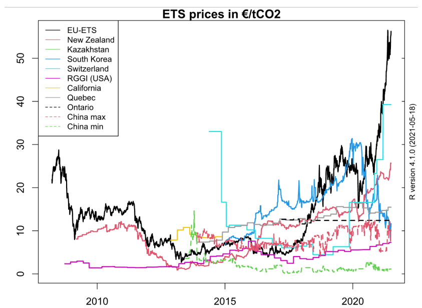
Source: https://www.creg.be/fr/publications/etude-f2289

Assessment of the ETS

Do Carbon Markets work in practice?

Prices are too low to achieve Paris agreement by 2030. Stern and Stiglitz estimated a range between 50 and 100 $ / t CO2 to decarbonate the economy.

The prices were too low to create enough incentives to decarbonate industries but are rising… Wait and see ?



Source: https://en.wikipedia.org/wiki/Carbon_price#/media/File:ETS-allowance-prices.svg

Source: The economist https://www.youtube.com/watch?v=m5ych9oDtk0

Conclusion

- The goal of putting a price is to internalize the price of externalities
- Market-based mechanism is a quantity policy instrument
- The Kyoto Protocol is the “father” of the EU-ETS
- 16% of the GHG emissions worldwide are covered by an ETS
- The EU-ETS is a market based on the cap-and-trade mechanism
- The prices are rising: it may become a real incentive soon
- Clean Spark Spread and Clean Dark Spread are profitability measures of respectively Gas and Coal power plant.

Vocabulary

- Auction = enchère
- Emission allowance = droit d'émission

References

- Carbon Markets: An International Business Guide by Arnaud Brohé, Nick Eyre and Nicolas Howarth
- Energie: Economie et politiques by Jean-Pierre Hansen and Jacques Percebois seconde édition.

Towards CO2 valorization in a multi remote renewable energy hub framework

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Abstract:

In this paper, we propose a multi-RREH (Remote Renewable Energy Hub) based optimization framework. This framework allows a valorization of CO2 using carbon capture technologies. This valorization is grounded on the idea that CO2 gathered from the atmosphere or post combustion can be combined with hydrogen to produce synthetic methane. The hydrogen is obtained from water electrolysis using renewable energy (RE). Such renewable energy is generated in RREHs, which are locations where RE is cheap and abundant (e.g., solar PV in the Sahara Desert, or wind in Greenland). We instantiate our framework on a case study focusing on Belgium and 2 RREHs, and we conduct a techno-economic analysis. This analysis highlights, among others, the interest of capturing CO2 via Post Combustion Carbon Capture (PCCC) rather than only through Direct Air Capture (DAC) for methane synthesis in RREH. By doing so, a notable reduction of 9.2% is observed in the total cost of the system under our reference scenario. In addition, we use our framework to derive a carbon price threshold above which carbon capture technologies may start playing a pivotal role in the decarbonation process of our industries. For example, this price threshold may give relevant information for calibrating the EU Emission Trading System so as to trigger the emergence of the multi-RREH.

Keywords:

CO2 Valorization, Energy Hub, Multi-Energy Systems, Optimization of Energy Systems, Sector Coupling.

1. Introduction

While the whole world is engaged in a process to decrease greenhouse gas emissions, capturing CO2 appears more and more as a crucial element to limit global warming. Once it is captured, CO2 may be either stored (CCS - Carbon Capture and Storage), either valorized (CCU - Carbon Capture and Utilisation), for instance through synthetic methane generation. In this article, we focus on CCU, where CO2 is seen as a required ingredient in the process of generating synthetic methane, together with *green* hydrogen, i.e. hydrogen obtained from renewable energy-based electrolysis.

In this paper, we build on top of the Remote Renewable Energy Hub (RREH) approach [3] to propose a multi-hub, multi CO2 sources approach. CO2 is captured using both Post-Combustion Carbon Capture (PCCC) and Direct Air Capture (DAC) technologies. Hydrogen is produced from electrolysis using renewable energy in a RREH which is particularly well-suited for producing cheap and abundant renewable energy (e.g., solar energy in the Sahara desert, or wind energy in Greenland). The RREH concept also relies on the following idea: some locations show large amount of energy consumption while not having lots of renewable energy resources (e.g., Europe). On the opposite, some places have abundant renewable energy while having almost no energy demand. In its original formulation, the RREH concept suggests to use DAC technologies to feed the CO2 demand at the RREH. In this paper, we include PCCC technologies as an alternative to DAC technologies: in addition or replacement to being captured in the atmosphere, CO2 emitted in energy intensive locations may be transported to the RREHs to be combined with green hydrogen for producing neutral synthetic methane.

We propose a methodology for assessing the technico-economic feasibility of exporting CO2 into RREH where synthetic CO2-neutral methane would be generated using locally produced green H2. We formalise an optimisation problem where CO2 sources are in "competition" to provide CO2 to the methanation units in the RREHs. This methodology is based on a linear program modelling of Belgium energy system, including gas and electricity demand, and main CO2 emitters. We rely on previously published approaches to develop our approach Berger et al. [3], and, in particular, we use the GBOML language Miftari et al. [17] to model the energy system and to optimize it.

Our methodology is evaluated in the Belgian context: we consider Belgian CO2 emissions and Belgian gas and electricity demand. CO2 may be captured using Post Combustion Carbon Capture (PCCC) in Belgium or DAC in RREH locations. CO2 neutral synthetic methane will be produced in a remote energy hub from where it would be shipped back to serve the Belgian gas demand. We derive a CO2 emission cost in order to have a neutral emission system. We also determine a value of lost load (*i.e.* a price associated with a lack of energy service) in order to serve the energy demand at all times. Several scenarios are studied with different prices of CO2 emissions, allocation or not of unserved energy and forcing of a given RREH.

2. Related Work

This work is mainly related with the following topics that may play an important role in the deep decarbonation of our societies: (i) global grid approaches, (ii) power-to-X technologies, multi-energy systems and and energy hub approaches, and (iii) CO2 quotas markets.

Global Grid (GG) approaches [7], [25], sometimes referred to as Global Energy Interconnection approaches [16], are related with the idea of harvesting renewable energy from abundant and potentially remote renewable energy fields to feed the electricity demand in high demand centres. These approaches have mainly been oriented towards solutions using the electricity vector to repatriate energy from energy hubs, and have received a growing interest starting from the DESERTEC concept [23] that focuses on Sahara solar energy resources from the Sahara desert to serve the European electricity demand. More recently, wind from Northern Europe and Greenland has also been identified as a promising resource to be valued within the GG context [21]. Resource and demand configurations combining several types of resources as well as demand time zones show better results [25].

Multi-energy systems approaches [19, 20] exploit the benefits of integrating energy demand and generation, as well as infrastructure. Power-to-X technologies, in particular power-to-CH4 technologies using hydrolysis and renewable energy for producing H2 [15], offer a CO2 neutral solution to serve gas demand, but also a way to store vast quantities of energy issues from renewable sources [5]. Recently, Berger et al. have proposed a modeling framework [3] for assessing the techno-economics viability of carbon-neutral synthetic fuel production from renewable electricity in remote areas where high-quality renewable resources are abundant. Let us mention that the idea of energy hubs was preexisting the work of Berger et al. [14, 18, 22], however the contribution of Berger et al. is the introduction of remote energy production, far from the demand. Our contribution is in line with the latter.

As this work aims to enhance the value of CO2, it is closely linked to the European Union Emissions Trading System (EU ETS). The EU ETS system, which is described on the European Commission's website [1] and in [6], is a 'cap and trade' program. The system sets a cap on the total amount of certain greenhouse gases (GHG) that can be emitted by the facilities covered by the ETS. Within the cap, facilities are given emissions allowances, which can be traded with one another. The total number of allowances available is limited to ensure that they have value, and the cap is gradually reduced over time to lower total emissions. If a facility fails to cover its emissions fully, it faces substantial fines. Conversely, if a facility reduces its emissions, it can either retain the surplus allowance for future use or sell it to another facility that has not succeeded in covering its own emissions. This trading mechanism aims to reduce GHG emissions as soon as it becomes the most cost-effective solution and encourage investments in low GHG emissions solutions.

3. CO2 Valorisation in a Multi-Remote Renewable Energy Hubs Approach

The Remote Renewable Energy Hub concept was first introduced in [3] where the authors proposed a hub for synthesizing CH4 based on hydrogen and CO2 captured from the air thanks to a methanation unit. This concept has emerged within the context of global grid [7] and multi-energy systems approaches. These approaches aim at optimising the generation and utilisation of renewable energy (RE) by both (i) looking for abundant and cheap RE fields, (ii) taking advantage of daily/seasonal complementary of RE, as well as (iii) using power-to-gas technologies for better addressing RE generation fluctuations and meet e-fuels demand to act as a substitute for molecules derived nowadays from fossil fuels.

In the original article [3], the methanation unit was supplied with CO2 by a Direct Air Capture unit, and the energy demand was fulfilled by a single RREH located in Algeria. However, in this paper, we propose to investigate the feasibility of valorizing CO2 captured through Post Combustion Capture techniques at the energy demand center (EDC). Additionally, we deviate from the original paper by introducing a multi-RREH approach, wherein the EDC serves as a CO2 provider to a set of multiple RREHs, denoted as $RREH_1, \dots, RREH_h$. Each hub $RREH_i (1 \leq i \leq h)$ has its unique characteristics, such as renewable energy type, potential, distance from the EDC, and means of CO2 transport from the EDC, which can affect its competitiveness.

In order to illustrate the concepts discussed above, we have developed a model for a multi-RREH system

[1] https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

based on the following assumptions: (i) the EDC is Belgium, encompassing its gas and electricity demands as well as its CO2 emissions, (ii) there are two RREHs: one situated in the Sahara desert with access to solar and wind resources, and another in Greenland benefiting from the high-quality wind fields in the region. A detailed schematic of the resulting system is shown in Fig. 1. Similar to [3], we employed the GBOML language [17], a recently developed language tailored for energy system optimization (refer to section 4. for more information), to model the system.

We note that the GBOML model code with two RREHs and one EDC system is available online[2] and can be easily extended to add additional RREHs and EDCs.

4. Modelling

This section provides insight into the optimization framework that underlies the multi-energy system model proposed in this work. The GBOML language introduced in [17], a recently developed language dedicated to modeling graph-based optimization of multi-energy systems, is utilized to build this model. The optimization problem can be viewed as optimization on graphs, where a multi-energy system is considered as a set of nodes $\mathcal{N}$ that contribute to the (linear) objective and local constraints, and hyperedges $\mathcal{E}$ are used to model the constraints between nodes, such as those between RREHs and the EDC in our context.

The formalism employed in this work follows that introduced in [3]. The entire system is defined by sets of nodes $\mathcal{N}$ and hyperedges $\mathcal{E}$. The optimization horizon is denoted by T, with time-steps indexed by $t \in \mathcal{T}$, where $\mathcal{T} = \{1, \dots, T\}$.

A node $n \in \mathcal{N}$ is defined by internal X^n and external Z^n variables, where internal variables describe the specific characteristics of the unit, such as the nominal power capacity installed in the asset. Equality constraints $h_i(X^n, Z^n, t) = 0$ with $i \in \mathcal{I}$ and inequality constraints $g_j(X^n, Z^n, t) \leq 0$ with $j \in \mathcal{J}$, are employed for each $t \in \mathcal{T}$ to model operational constraints.

Each node n has an associated cost function $F^n(X^n, Z^n) = \sum_{t=1}^{T} f^n(X^n, Z^n, t)$ that typically represents the capital expenditure and operational expenditure, i.e., CAPEX and OPEX, respectively.

Finally, equality and inequality constraints on hyperedges can be defined as $H^e(Z^e) = 0$ and $G^e(Z^e) \leq 0$ with $e \in \mathcal{E}$ to model the laws of conservation and caps on given commodities.

One can read this type of problem as:

$$\begin{aligned} \min \quad & \sum_{n=1}^{N} F^n(X^n, Z^n) \\ \text{s.t.} \quad & h_i(X^n, Z^n, t) = 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}, \forall i \in \mathcal{I} \\ & g_j(X^n, Z^n, t) \leq 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}, \forall j \in \mathcal{J} \\ & H^e(Z^e) = 0, \forall e \in \mathcal{E} \\ & G^e(Z^e) \leq 0, \forall e \in \mathcal{E}. \end{aligned} \tag{1}$$

The main assumptions underlying our model are the following:

- Centralised planning and operation: In this framework, a single entity is responsible for making all investment and operation decisions.
- Perfect forecast and knowledge: It is assumed that the demand curves, as well as weather time series, are available and known *in advance* for the entire optimisation horizon, i.e., $\forall t \in \{1, \dots, T\}$.
- Permanence of investment decisions: Investment decisions result in the sizing of installation capacities at the beginning of the time horizon. Capacities remain fixed throughout the entire optimisation period, i.e., $\forall t \in \{1, \dots, T\}$.
- Linear modelling of technologies: All technologies and their interactions are modelled using linear equations within this framework.
- Spatial aggregation: The energy demands and generation at each node are represented by single points. The topology of the embedded network required to serve this demand locally is not modelled in this approach. This can be viewed as an extension of the copper plate modelling approach used in electrical power systems.

In our problem, all cost functions and constraints are affine transformation of the inputs. More details on the constraints of each technology can be found in [2], [3]. Additionnaly, the local objective function corresponding

[2] https://gitlab.uliege.be/smart_grids/public/gboml/-/tree/master/examples

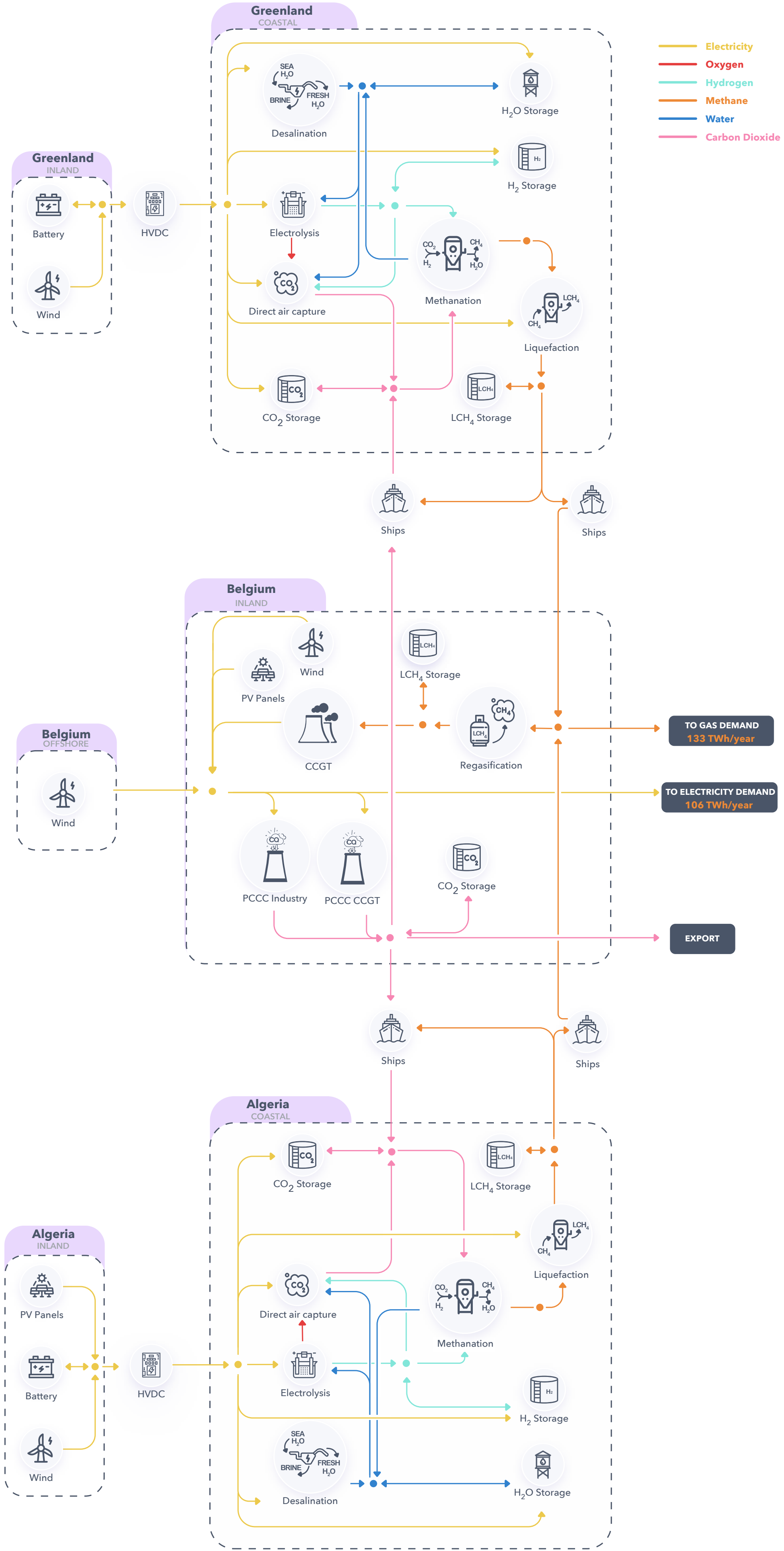

Figure 1: A schematic illustration of the remote energy hub. CO2 being captured, it may be used to synthesize fuel either locally either in a remote energy hub where renewable energy may be cheaper and more abundant.

to the CAPEX is modelled with a uniform weighted average cost of capital (WACC) of 7% for each technology. Thus, the CAPEX is computed using the following formula:

$$\zeta^n = \mathrm{CAPEX}_n \times \frac{\mathrm{w}}{(1 - (1 + \mathrm{w})^{-\mathrm{L}_n})} \tag{2}$$

with L_n the lifetime of technology n and w the WACC. Hence, ζ^n represents the annualised cost of investing in technology n.

Moreover, a cap on the net CO2 emissions (*i.e.* release in minus captured from the atmosphere) is added to the model. This latter is defined as

$$\sum_{t \in \mathcal{T}} (\sum_{a \in \mathcal{A}} q^a_{co2,t} - \sum_{c \in \mathcal{C}} q^c_{co2,t}) \leq \kappa_{co2} \nu \tag{3}$$

with $\mathcal{A}$ and $\mathcal{C}$ representing the sets of technologies that release CO2 into the atmosphere and those that capture CO2 directly from the atmosphere, respectively, κ_{co2} represents the CO2 cap in kilotons per year, and ν represents the number of years covered by the optimization horizon. The shadow price, or marginal cost, which is the dual variable associated with (3) allows for the derivation of a CO2 cost in €/t. A detailed explanation of dual variables as marginal costs in linear programming can be found in [4, Chapter 4].

5. Case Study: Belgium

This case study is focused on Belgium with two remote renewable energy hubs: one located in Algeria and another one located in Greenland. We will analyse the techno-economic feasibilty of the system while responding to an energy demand composed only of electricity and gas in Belgium.

5.1. Data

The data cover 2 years: 2015 and 2016. It is used to characterize energy demand as well as load factors for renewable energy sources.

Renewable generation profiles

In order to determine the generation profiles of variable energy sources in Belgium we use the data from the transmission system operator (TSO) of Belgium [11]. The profiles for the RREH located in Algeria are extracted with the same methodology as in [3]. For the RREH situated in Greenland, the profiles of renewable energy are extracted thanks to the MAR model [12] and given a power curve for an offsore wind turbine MHI Vestas Offshore V164-9.5MW.

Energy consumption

The energy consumption data is collected for two energy vectors: gas ([13]) and electricity ([10]) with the same methodology as in [2]. In Fig. 2, the data corresponding to the two years is represented, where the signal is daily aggregated. In some cases, gas usage is shifted towards electricity needs, as described in [2, section 4.2.2]. This shift is due to the use of heat pumps, which can help decarbonize heating in Europe. For both energy vectors, industrial and heating demands are taken into account.

The peak power demand is equal to 60.13 GWh/h for both gas and electricity. The energy demand for electricity ranges from 6.42 to 20.29 GWh/h, while that for gas ranges from 5.51 to 39.84 GWh/h. The total energy demand is on average 106.45 TWh/year and 132.65 TWh/year for electricity and gas, respectively.

5.2. Model Configuration

Our model consists of three main components (see Fig. 1): the energy demand center located in Belgium and two Remote Renewable Energy Hubs (RREHs) situated in Algeria and Greenland. The RREH in Algeria is modeled as described in [3] with the same techno-economic parameters. The distinction is made with the inclusion of the CO2 connection between Belgium and Algeria. The RREH in Greenland is similarly modeled, with the exception of the removal of the photovoltaic potential and the modification of the high-voltage direct current (HVDC) line to a length of 100 km rather than 1000 km.

The transportation of CO2 is achieved through the use of boats, which have a CAPEX of 5M€/kt, a lifespan of 40 years, and an average daily energy consumption of 0.0150 GWh/day. CO2 transport data was obtained from [1]. The loading and traveling time for these boats are assumed identical to those for liquefied methane carriers [3], *i.e.* 24 and 116 hours, respectively. In order to fill the tank of CO2 carriers with fuel (liquefied methane), these tanks are loaded when unloading the CO2 at the RREH. Indeed, at the RREH, synthetic CH4 is available without having undergone any additional transport-related losses. Except for the storage facilities, liquefaction of CO2 has been excluded from the model. Sideways analyses have confirmed that this assumption has a negligible impact on the optimal objective.

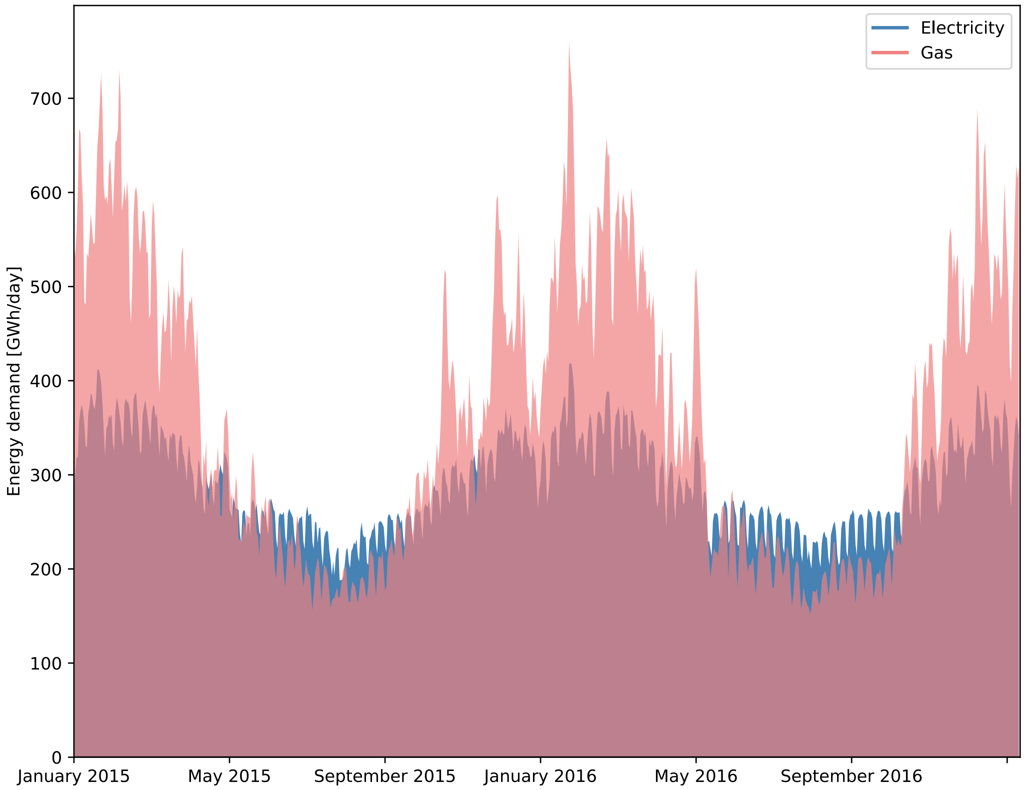

Figure 2: Daily aggregated profiles of electricity and natural gas demand covering the years 2015 and 2016 spanned by the optimisation.

Belgium is modeled with an electricity and gas demand as depicted in Fig. 2, with various means of production, including wind power, solar power, and a combined cycle gas turbine. The solar potential is limited to 40GW. The wind potential is equal to 8.4 GW and 8 GW for onshore and offshore capacities, respectively. The techno-economic parameters of each technology deployed in Belgium follow those in [2].

We have also added a CO2 source that is equivalent to 40Mt CO2/year, which corresponds to the energy sectors and industrial processes greenhouse gases in Belgium in 2019 [8, Table 4.1.1 (pp. 165- 166)]. We assume that we can install post-carbon capture technologies (PCCC) in these sectors.

In terms of carbon capture technologies, the model has access to direct air capture installed at the RREHs, as well as a PCCC in Belgium on the 40Mt of CO2 per year and a PCCC installation on the CCGT.

As stated in [2], the cost of PCCC is 3150M€/kt/h of CAPEX. The variable operating and maintenance costs (VOM and FOM) have been neglected in this analysis. However, a demand of 0.4125GWh_{el}/kt_{CO2} of electricity is required. The expected lifetime is assumed to be 20 years.

Similarly, according to [3], the cost of DAC is equal to 4801.4 M€/kt/h of CAPEX. Similar to PCCC, VOM and FOM are ignored. The operational requirements for DAC are 0.1091GWh_{el}/kt_{CO2} of electricity, 0.0438kt_{H2}/kt_{CO2} of di-hydrogen, and 5.0kt_{H20}/kt_{CO2} of water. The expected lifetime is assumed to be 30 years.

5.3. Results

In this section, we explore several scenari. We describe the variables that are used to differentiate the scenari

1. Cost or Cap on CO2: either a cap is set of 0 t/year or a price at 80€/t or 0€/t
2. Cost of energy not served (ENS): either energy not served is not allowed or a penalty of 3000€/MWh is imposed for each unit of unproduced energy.
3. Forcing or not the use of a given RREH.

Scenario	Cap on CO2 (kt)	Cost of CO2 (M€/kt)	ENS	Cost ENS (k€/MWh)	Objective (M€)
1	0.0	0.0	No	-	83742.61
2	0.0	0.0	Yes	3.0	80778.02
3	No	0.08	Yes	3.0	78872.94
4	No	0.0	Yes	3.0	76323.94
5	0.0	0.0	No	-	111209.95

Table 1: Scenari parameters.

The results are generated with 5 scenari:

Scenario 1: This scenario seeks to avoid energy scarcity, whatever the cost. Therefore, no ENS is allowed. In addition, a hard constraint is set on CO2 emissions: a cap on CO2 is set.

Scenario 2: This scenario follows the same assumptions as scenario 1 except that it leverages the constraint on energy not served. The cost associated to electricity not served is equal to 3000€/MWh, which is a standard value in the electricity context [24].

Scenario 3: This scenario leverages the constraint on CO2 emissions, and does not force the avoidance of energy not served but is penalized by 3000€/MWh not served. A penalty is associated with any CO2 emission in the atmosphere in the form of a fee equal to 80€/t - a value that reflects the current price of CO2 in the EU-ETS trading system [9].

Scenario 4: This scenario follows the same assumptions as scenario 3, with the difference that the cost of CO2 is equal to 0€/MWh. The aim is to showcase the system's configuration in the absence of any considerations for CO2 emissions.

Scenario 5: This scenario follows the same assumptions as scenario 1, with the difference that the only available RREH is in Greenland.

These scenari summarized in Table 1 vary in their degree of constraint. Scenario 1 is the most restrictive, with a cap on CO2 emissions and no allowance for energy not served. Scenario 2 allows for energy not served, while scenarios 3 and 4 remove the cap and replace it with CO2 prices of 80€ and 0€ per ton, respectively. Finally, scenario 5 requires the use of the RREH in Greenland, with parameters identical to those of scenario 1.

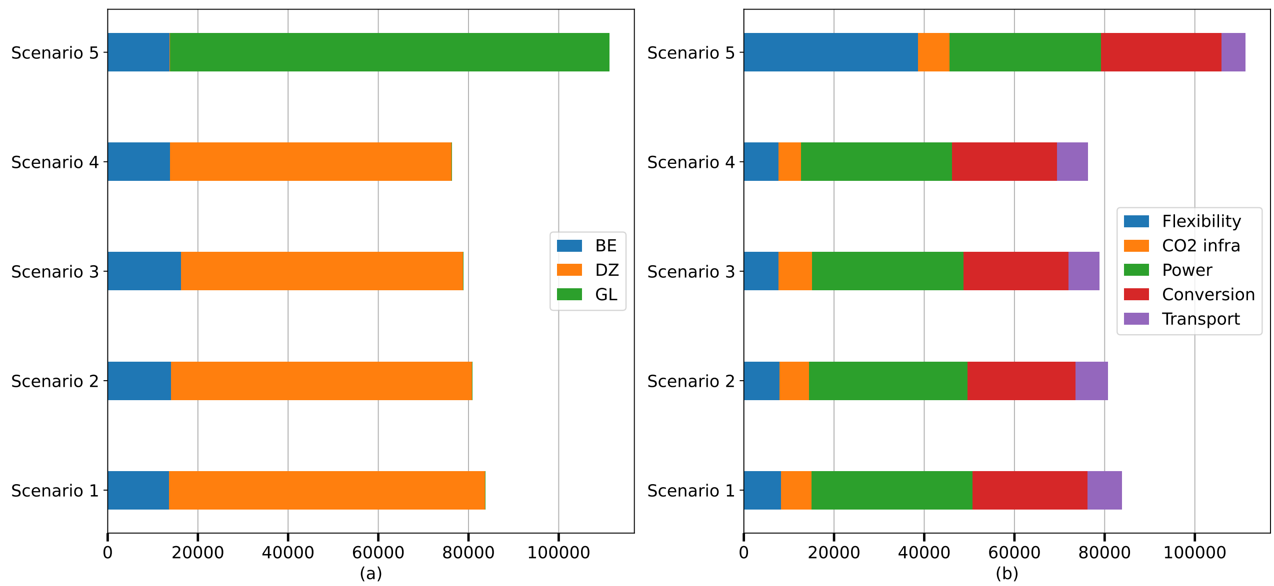

Figure 3: (a): Breakdown of costs per scenario and per cluster (Belgium (BE), Algeria (DZ), and Greenland (GL)). (b): Breakdown of costs per scenario per asset function. Flexibility covers storage capacities, CO2 Infra covers CO2 capture, storage, and transport, Power covers means of electricity production, Conversion covers all assets that convert one commodity into another and Transport HVDC lines and CH4 carriers.

5.4. Analyses and Discussion

In this section, we introduce and discuss the results in detail. We choose to present a cross-scenario analysis in the light of key indicators and statistics extracted from the model.

Total cost.

The results indicate that the costs associated with enabling the hub in Algeria are substantially lower than those in Greenland, as depicted in Fig. 3 (a) where nothing is built in the Greenland hub from scenarios 1 to 4, despite it being available for use. This disparity in costs can be attributed to the over-dimensioning of flexibility assets, particularly the storage capacities, as illustrated in Fig. 3 (b). This is mainly explained to electricity generated solely through wind available in Greenland, whereas both solar and wind electricity are obtainable in Algeria. This implies that the flexibility assets have to take the lead in maintaining a minimum of electricity delivery required in the electrolysis power plant.

Furthermore, a reduction in total costs is observed in the first four scenarios with respect to the objective. This is explained with the order on the scenari based on their degree of constraint with scenario 1 being the most constrained and scenario 4 being the least.

Power installation capacities.

All power capacities installations are displayed in Table 2.

The potential in Belgium of solar energy is never reached while for both wind offshore and onshore the potential is reached in all scenari.

From scenario 1 to scenario 2, the only difference being the allowance of ENS, there is an increase in the installation of controllable energy production assets. Indeed, there is a shift in capacity from CCGT to solar energy in Belgium between the first scenario and the second.

Comparing scenario 1 and 5, solar energy in Belgium is more expensive than importing CH4 from the RREH in Algeria. Importing from Greenland is more expensive and leads to an increase in power capacity installation in Belgium for solar, but it does not reach the maximum potential.

Another interesting comparison can be made with the work of [3], where the capacity installation in the hub for the reference scenario is 4.3GW of solar and 4.4GW of wind. In our case, the reference scenario 1 displays 100.51GW and 103.62GW, respectively. The power installation capacity is multiplied by approximately 23 while providing, on average, 282TWh/year of gas (HHV) to serve the gas demand and part of the electricity demand in Belgium, which is 28.2 times the gas production in the original paper.

Scenario	Wind onshore BE	Wind offshore BE	Solar BE	CCGT BE	Wind GL	Wind DZ	Solar DZ
1	8.40	8.00	10.56	22.69	0.00	103.62	100.51
2	8.40	8.00	15.35	17.95	0.00	98.43	95.47
3	8.40	8.00	14.95	17.83	0.00	93.32	90.32
4	8.40	8.00	14.72	17.82	0.00	93.28	90.28
5	8.40	8.00	17.48	19.58	129.43	0.00	0.00

Table 2: Total Power installation in GW per scenario.

CO2 installations (transport, capture).

In Table 3, the capacities of the CO2 capture units and the installations of transport capacity per scenario are displayed. Each time PCCC is activated, we recall that capturing CO2 is the only means to create gas in our system, and thus a minimum installation is required to support the demand. On the other hand, the DAC is only activated when a CO2 cap is set. PCCC has an efficiency of CO2 capture set to 90%, which means that a direct air capture technology asset is necessary to recover the remaining 10% of emissions in the atmosphere. This leads to a direct consequence, which is that when the DAC is available, the capacity of transport decreases because CO2 is locally available in the hub. However, the cost of CO2 capture by PCCC added to transport of CO2 is cheaper than the cost of DAC in the RREH. The only way to put PCCC out of business would be to have a distance between the hub and the energy demand center so long that the transport cost would increase too much.

Due to the higher concentration of CO2 in manufacturing smoke compared to the air, PCCC will likely always be cheaper than DAC, even with significant improvements in the DAC process. As a result, the operational costs associated with the energy required for PCCC will be lower than those of DAC.

Cost of CO2 derived and Cap of CO2.

From the first, second, and fifth scenarios, we are able to derive a shadow price thanks to the CO2 cap constraint. These correspond to approximately 162.77€/tCO2 for the first and second scenarios and 235.65€/tCO2

Scenario	PCCC	PCCC CCGT	DAC DZ	DAC GL	Carrier DZ	Carrier GL
1	4.11	2.62	1.30	0.00	8.030	0.000
2	4.11	2.07	1.47	0.00	7.142	0.000
3	4.11	1.80	0.00	0.00	9.694	0.000
4	3.76	2.06	0.00	0.00	9.701	0.000
5	4.11	2.40	0.00	1.35	0.000	7.564

Table 3: Capacity, in kt/h, of CO2 capture technology and transport by hub and per scenario.

for the fifth scenario. This shows that given the system considered, i.e., Belgium and RREHs, putting a price of CO2 equal to 162.77€ would avoid these emissions in the atmosphere and activate the export of CO2 to Norway for storage purposes. In scenario 3, where a price of 80€/tCO2 is set, there is a net balance in the atmosphere of approximately 15Mt/year. In scenario 4, where no price is fixed, there is a net balance in the atmosphere which is equivalent to 16Mt/year.

We would like to emphasize that the CO2 cap in our model only considers the emissions from the industrial and energy sectors, which are fully modeled. It does not account for a part of the emissions resulting from the gas demand served. Of this demand, 32% is attributed to industrial needs, which are included in the statistics of the 40 Mt of CO2 emitted per year (see subsection 5.2.), while the remaining 68% is due to heating and is not covered by our cap. This heating gas demand translates to approximately 12.3 Mt of CO2 emitted per year.

Cost of CH4 derived

To estimate the cost of CH4 production, we first subtract from the optimal objective function the cost of the means of electricity production in Belgium (PV, on/off shore wind, CCGT), the cost of unserved energy (when applicable), and the cost related to export of CO2 for sequestration. All of these costs are substracted because they do not refer directly to the cost of producing synthetic methane. Then, we divide the obtained cost by the total energy content (HHV) in CH4 produced at the output of the regasification power plant in Belgium.

These methane costs, listed in Table 4, are compared to the price of 147.9€/MWh of methane (HHV) obtained by [3]. Our scenarios achieve a lower cost for gas production (except for Greenland). This demonstrates that PCCC, which uses smoke with a high concentration of CO2 combined with transport, is more cost-effective than having only access to a DAC unit, as previously mentioned.

In our system, no fossil gas is available for import to Belgium; only synthetic gas produced from CO2 capture is used. If fossil gas were still available for import, our model would seek to minimize costs and import as much cheap gas as possible while staying within our carbon budget.

Scenario	1	2	3	4	5
[€/MWh]	136.00	137.19	133.89	129.27	192.00

Table 4: Estimation of methane price by retrieving the costs of power installations in Belgium, costs of unserved energy, and costs of exporting CO2 for storage purposes.

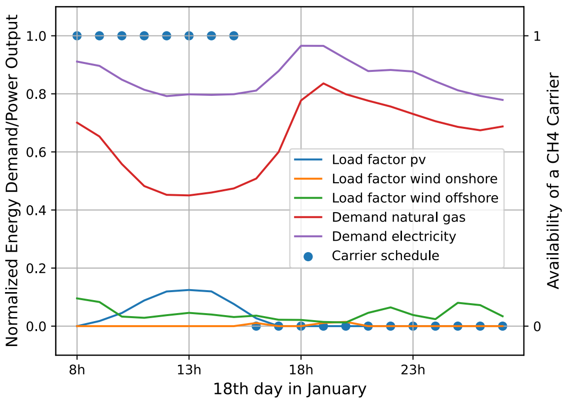

Figure 4: Evening of January 18th leading to the maximum shadow price associated with the hard constraint on energy not served in scenarios 1 and 5.

ENS cost discussion

The cost of unserved energy is a fixed parameter in scenarios 2, 3, and 4, but not in scenarios 1 and 5. Instead, a hard constraint is imposed to ensure that electricity demand is always met, resulting in a shadow price associated with the constraint. The maximum shadow price values for scenarios 1 and 5 are 913,640€/MWh and 1,075,913€/MWh, respectively. This is attributed to the peak in electricity and gas demand observed on January 18th at 18:00 (as shown in Figure 4), where renewable energy load factors were low. Thus, all energy demand had to be supplied by the Combined Cycle Gas Turbine (CCGT) and gas resources.

6. Conclusion

In this work, we present our framework of multi remote energy hubs with capture of CO2 enabled in an energy demand center and its valorization by synthesizing methane in remote renewable energy hubs. We demonstrate the feasibility of serving the energy demand at the horizon 2050 of an entire country with only renewable energy and gas power plant fueled by synthetic methane while decarbonizing the energy and industry sectors on a case study implying Belgium as energy demand center and two RREHs: Greenland and Algeria. Our reference scenario exhibits a gas price of 136.0€/MWh instead of 149.7€/MWh in [3] where only direct air capture was available in the RREH in order to feed CO2 into the methanation process. This shows the potential of Post Combustion Carbon Capture installations in the context of remote renewable energy hubs supply chains. We also derive a cost of CO2 of 163€ per ton in order to avoid any emission in the industrial and energy sector in Belgium. Finally, our model effectively captures the "competition" between different RREHs and is able to select exactly in which investments should be prioritized. In our simulations, the investments were made only for the RREH located in Algeria. In this respect, it would be interesting to study further how the different devices structuring the RREH in Greenland should be modified to become competitive with the RREH located in Algeria. This could be done for example by modifying the wind turbines selected for the Greenland hub so that they can operate with higher nominal wind speeds and higher cut-off speeds in order to better exploit the strong winds in this area.

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Appendix A Glossary

BE	Belgium
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
DAC	Direct Air Capture
DZ	Algeria
EDC	Energy Demand Center
ENS	Energy Not Served
ETS	Emission Trading System
GBOML	Graph Based Optimzation Modeling Language
GL	Greenland
HHV	Higher Heating Value
OPEX	Operational Expenditure
PCCC	Post Combustion Carbon Capture
PV	Photovoltaic
RE	Renewable Energy
RREH	Remote Renewable Energy Hub
RES	Renewable Energy Sources

Nomenclature

Sets and indices

$\mathcal{E}, e$ set of hyperedges and hyperedge index

$\mathcal{G}$ hypergraph with node set $\mathcal{N}$ and hyperedge set $\mathcal{E}$

$\mathcal{I}^n, i$ set of external variables at node n, and variable index

$\mathcal{N}, n$ set of nodes and node index

$\mathcal{T}, t$ set of time periods and time index

Parameters

$\nu \in \mathbb{N}$ number of years spanned by optimisation horizon

$\kappa_i \in \mathbb{R}_+$ maximum flow capacity of commodity i

$\zeta^n \in \mathbb{R}_+$ annualised CAPEX of node n (flow component)

Variables

$q^n_{it} \in \mathbb{R}_+$ flow variable i of node n at time t

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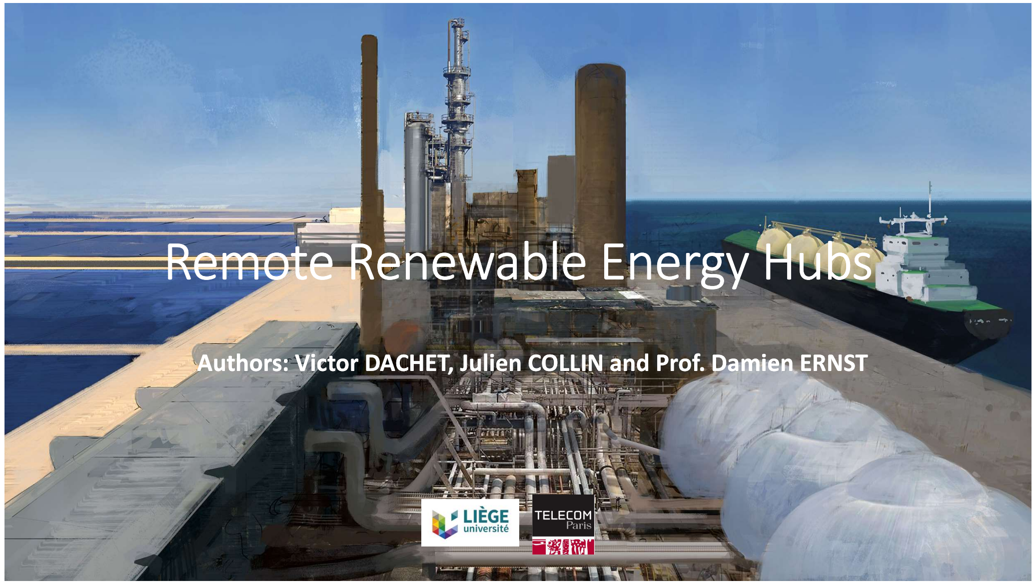


Menu

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

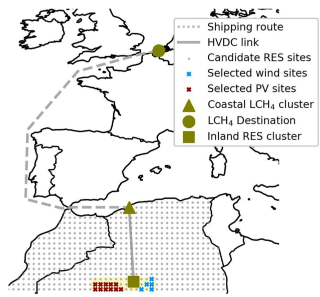
Artist's representation of a remote energy hub in Greenland.

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.



<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

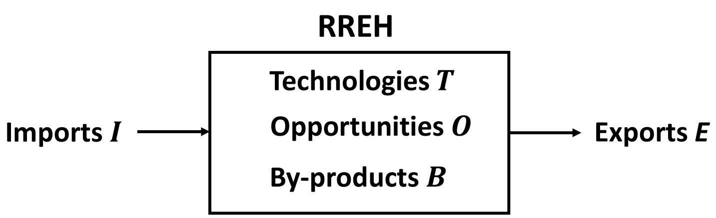
RREH can be built very quickly, in parallel, in many places around the world using the same technology and can **greatly benefit local communities**.

Characteristics of 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, amoniac, hydrogen, electricity
- By-products B: e.g. heat, oxygen
- Locally exploited oportunities O: e.g. potable water, fertilizer, electricity, heat.

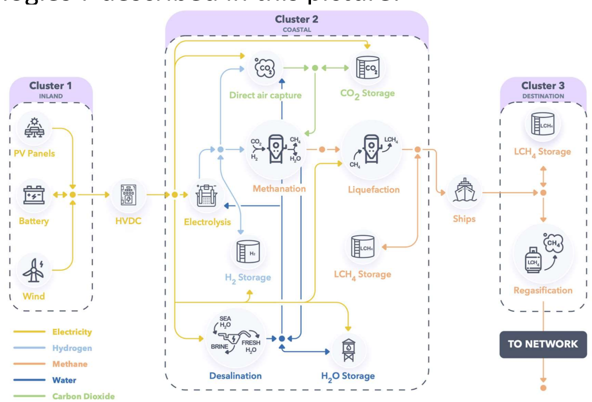
Schematic view of a RREH



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:



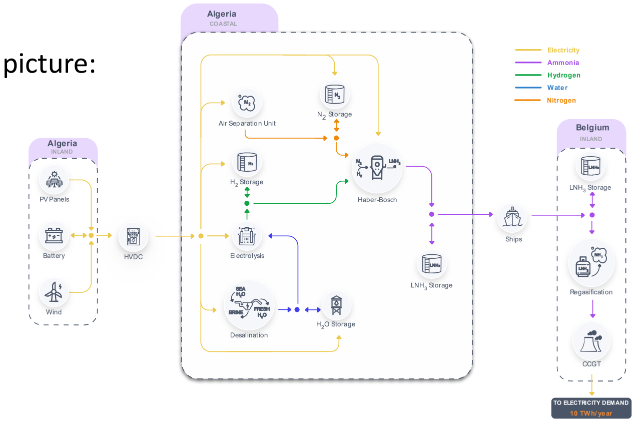
- Set of imports I = sea water (should this be considered as an import?)
- Set of exports E = CH4
- Set of by-products B = heat, O2
- Set of exploited local opportunities O = ø

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 ammoniac production

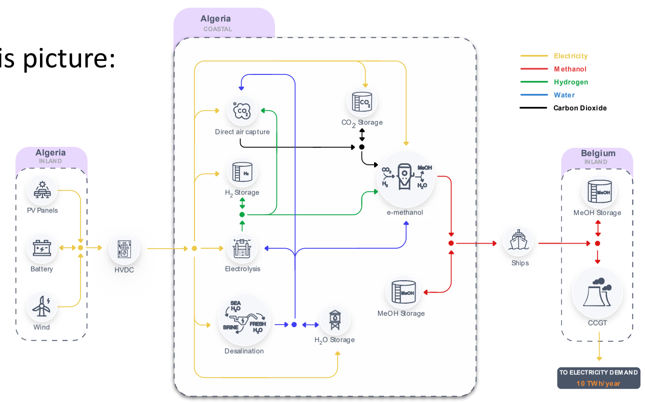
- Set T described in this picture:



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

Example 3: Variation of Example 1 for methanol production

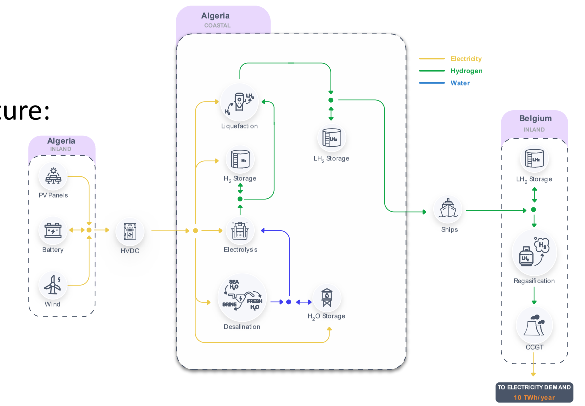
- Set T described in this picture:



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

Example 4: Variation of Example 1 for hydrogen production

- Set T described in this picture:



- Set I = ø,
- Set E = H2,
- Set B = heat, O2
- Set O = ø

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

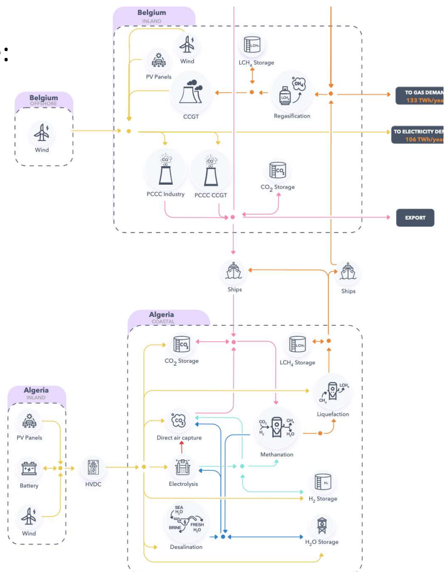
Cost in Euros per MWh for the different energy-rich molecules. WACC of 7% for investments.

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.

- Set of technologies *T* described in this picture:



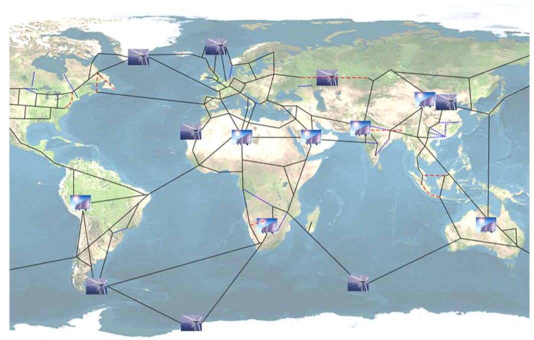
- Set of imports *I* = **CO2**, sea water
- Set of exports *E* = CH4
- Set of by-products *B* = heat, O2
- Set of exploited local opportunites *O* = ø

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 ≠ ∅)

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).

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 $\mathcal{T} = \{1, \ldots, T\}$.
- 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 $j \in \mathcal{J}$

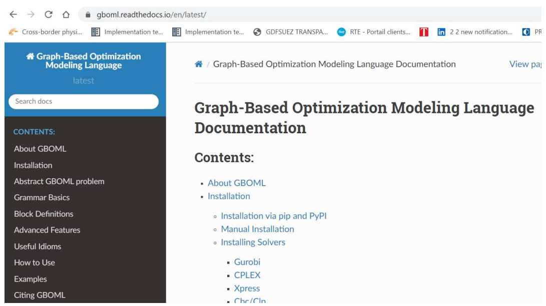
$$
\begin{aligned}
\min \quad & \sum_{n=1}^{N} F^n(X^n, Z^n) \\
\text{s.t.} \quad & h_i(X^n, Z^n, t) = 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}, \forall i \in \mathcal{I} \\
& g_j(X^n, Z^n, t) \leq 0, \forall n \in \mathcal{N}, \forall t \in \mathcal{T}, \forall j \in \mathcal{J} \\
& H^e(Z^e) = 0, \forall e \in \mathcal{E} \\
& G^e(Z^e) \leq 0, \forall e \in \mathcal{E}.
\end{aligned}
$$

GBOML: The Graph-Based Optimization Modelling Language

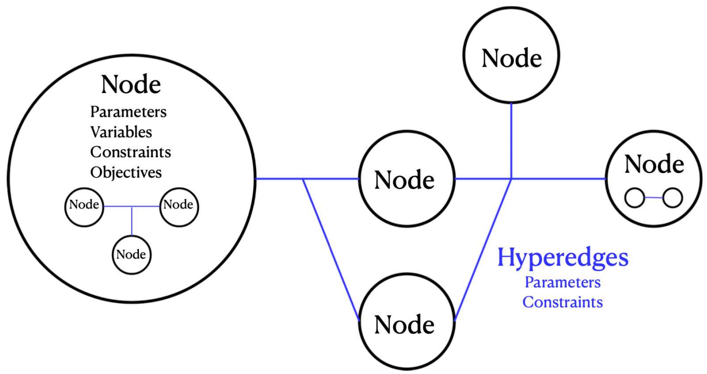
GBOML is a tool specifically designed for the **Modelling** and the **Optimization** of complex (energy) systems.

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 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

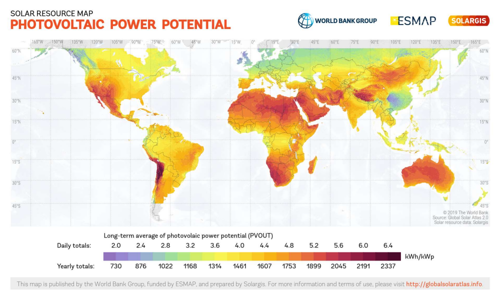
A global grid and the multiplication of RREH numbers will create a complex web of interdependencies between states (ex. depending on variations of demand and supply).

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.

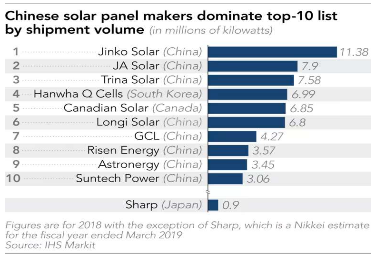
With RREHs there is a way to promote democratization and strengthen the EU's role as a 'Normative Power' (Manners, 2002).

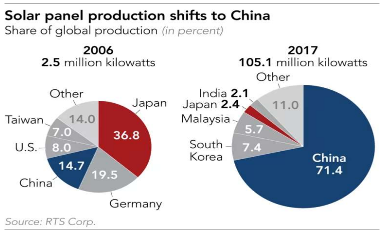


Concentration of resources

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?





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

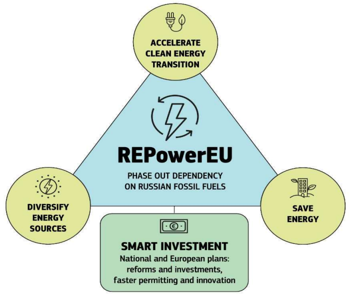
The RREH concept is aligned with six UN SDGs:

- 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.



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.

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.

Carbon Pricing and Incentives

CO2 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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