DESIGN AND MULTI-OBJECTIVE OPTIMIZATION OF CO_2 VALUE CHAINS FOR A NET-NEGATIVE WASTE TO ENERGY SECTOR: A SWISS CASE STUDY

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Abstract

This study investigates the optimal design of CO_2 value chains aimed at decarbonizing the waste to energy (WtE) sector on a national scale and presents the case study of Switzerland. Switzerland has 30 WtE plants that generate a total of 4.2 million tons of CO_2 emissions per year. Half of these emissions are from biogenic sources and half are fossil-based, corresponding to 4.5% of the overall Swiss emissions. On the one hand, this indicates the relevance of decarbonizing the WtE sector. On the other hand, it implies that a net-negative-emissions WtE sector can be achieved by adopting carbon capture and storage (CCS) technologies.

The CO_2 value chains considered here consist in capturing CO_2 at the WtE production sites, transporting it to the storage site, and permanently storing it underground. An optimization problem is formulated to determine the optimal design of the CO_2 value chains in terms of size and location of carbon capture technologies, and structure of the network transporting the CO_2 from the capture to the storage sites. The optimization algorithm is a mixed integer linear program that minimizes the total annual cost and CO_2 emissions of the overall system. Several transport options are assessed, namely truck, train, pipeline and ship, as well as different transport paths.

Keywords: *CO_2 value chain; CO_2 network; waste-to-energy; net-negative emissions; industrial emissions; optimization.*

1. Introduction

Evidences that the anthropogenic alteration of the earth carbon balance is leading to climate change clearly indicate the necessity of finding new routes for energy provision to achieve no-carbon emission by 2050 and keep global warming below 1.5 °C [1]. Within this framework, carbon capture and storage (CCS) proved to be a fundamental technology to achieve net-zero emissions in “hard-to-decarbonize” industrial sectors, such as the cement, steel and chemical industries. At the same time, CCS allows achieving net-negative emissions in sectors such as waste-to-energy (WtE), when energy is produced starting from biogenic waste.

Unlocking this CCS potential relies on the creation of a shared CO_2 infrastructure to connect the emission sources to the CO_2 permanent storage sites, thus decreasing the risk of investment and providing low-cost mitigation measures. In addition to the CO_2 emissions sources and permanent storage sites, the key component of these CO_2 ecosystems will be the CO_2 transport network. Currently, several European CCS projects are focused on building CO_2 storage hubs and clusters in various locations across Europe (e.g., in Norway, in the Netherlands, and in the UK). Among these, the Northern Lights project will most likely be the first one to enter into the operational phase, targeted for 2024-2025, and will make CO_2 storage available to emitters from coastal and central Europe.

The CO_2 transport network may rely on different transportation modes. Nowadays, pipelines are the most common CO_2 transport mode. They are a mature technology that has been in operations since the early 1970s for enhanced oil recovery applications. In some locations, CO_2 transport by ship or barge may be an economically attractive alternative to pipelines. For example, in the perspective of a permanent storage site in the North Sea (in Norway, Netherlands or UK), water transport may be preferred, not only by coastal CO_2 emitters in Northern Europe, but also by those emitters located in the proximity of the Rhine axis that links the largest European seaports to their hinterland. For small CO_2 volumes, road and rail tankers are also viable options. In particular, in the short term and at an early stage of development of a CO_2 network, the use of insulated tankers that can be loaded onto trucks or rails seem the most feasible choice. It becomes evident that developing an optimal network design will be a key challenge to create a mature CCS industry [2].

Switzerland has 30 WtE plants that generate a total of 4.2 million tons of CO_2 emissions per year. Half of these emissions are from biogenic sources and half are fossil-based, corresponding to 4.5% of the overall Swiss

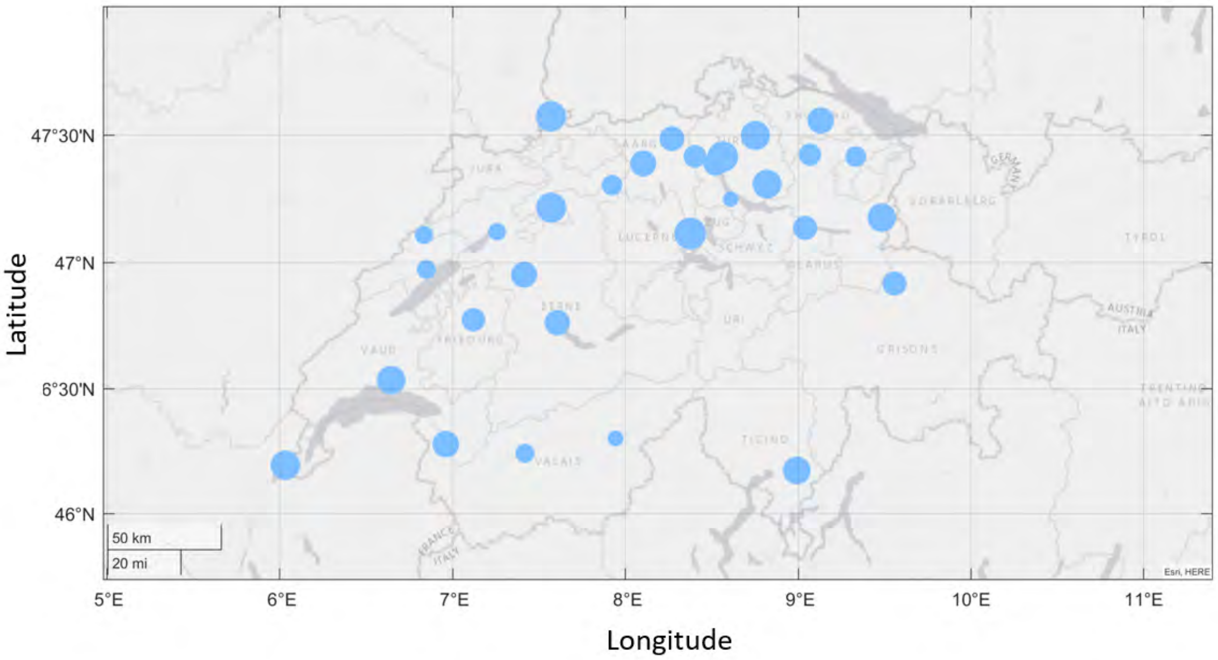

Figure 1. Schematic representation of the location of the Swiss WtE plants.

emissions. On the one hand, this indicates the relevance of decarbonizing the WtE sector. On the other hand, it implies that a net-negative-emissions WtE sector can be achieved with CCS technologies. Focusing on such a Swiss case study, this study investigates the optimal design of CO_2 value chains aimed at decarbonizing the WtE sector on a national scale.

2. System description

The CO_2 network considered here entails capturing CO_2 at the 30 Swiss WtE production sites, transporting it to the storage site, and permanently storing it underground. We evaluate the feasibility of transporting the CO_2 captured from the Swiss WtE plants to a storage site in the North Sea (i.e., the Northern Lights project off the Norwegian shore) via a continental terminal located in the port of Rotterdam, in The Netherlands.

The system components include:

(i) The CO_2 capture sites corresponding to the WtE plants, see Figure 1. An amine-based technology with 90% capture rate and several fractions of exhaust gases treated are considered.

(ii) The Northern Lights CO_2 storage site, where the CO_2 is permanently stored underground;

(iii) The CO_2 transport network that consists of CO_2 paths from capture sites to the permanent storage site. The transport technologies considered in this work are truck, rail, ship, barges and pipelines. Here, we consider a brownfield design for pipelines, i.e., we force the CO_2 pipelines to follow the same route of the installed natural gas pipelines.

Our work aims at defining the *optimal* CO_2 value chain in terms of size and location of CO_2 capture technologies, type and size of CO_2 network connections between all nodes.

3. Optimization problem

The optimal design of the CO_2 value chain is tackled by formulating and solving an optimization problem that minimizes the total annual cost and CO_2 emissions of the system by determining the optimal size and location of CO_2 capture technologies, as well as the optimal structure of the CO_2 network. Such an optimization problem is formulated as a mixed-integer linear program (MILP), which include both continuous, x, and binary variables, y, and can be written in general form as:

$$\min_{x,y}(\boldsymbol{c}_1^{\mathrm{T}}\boldsymbol{x} + \boldsymbol{c}_2^{\mathrm{T}}\boldsymbol{y})$$

$$\text{s.t.}$$

$$\boldsymbol{A_1 x} = \boldsymbol{b_1}, \qquad \boldsymbol{A_2 y} = \boldsymbol{b_2}$$

$$\boldsymbol{x} \geq 0 \in \mathbb{R}^X, \boldsymbol{y} \in \{0,1\}^Y$$

where $\boldsymbol{c}_1$ and $\boldsymbol{c}_2$ represent the cost vectors associated to the continuous and binary decision variables, $\boldsymbol{x}$ and $\boldsymbol{y}$, respectively; $\boldsymbol{A}_1$ and $\boldsymbol{A}_2$ are the corresponding constraint matrices, and $\boldsymbol{b}_1$ and $\boldsymbol{b}_2$ the corresponding constraint known terms; X and Y indicate the dimensions of the vectors $\boldsymbol{x}$ and $\boldsymbol{y}$, respectively. Here, both continuous and binary variables are optimized, with the latter being introduced to model the nonlinearities related to the presence and to the costs of network connections. The optimization problem is based on mathematical tools presented earlier [3,4,5], which are here expanded to describe all relevant features of CO_2 networks.

The input data to the optimization problem are (i) the CO_2 emissions corresponding to the WtE plants (spatially distributed), (ii) the availability of technology and

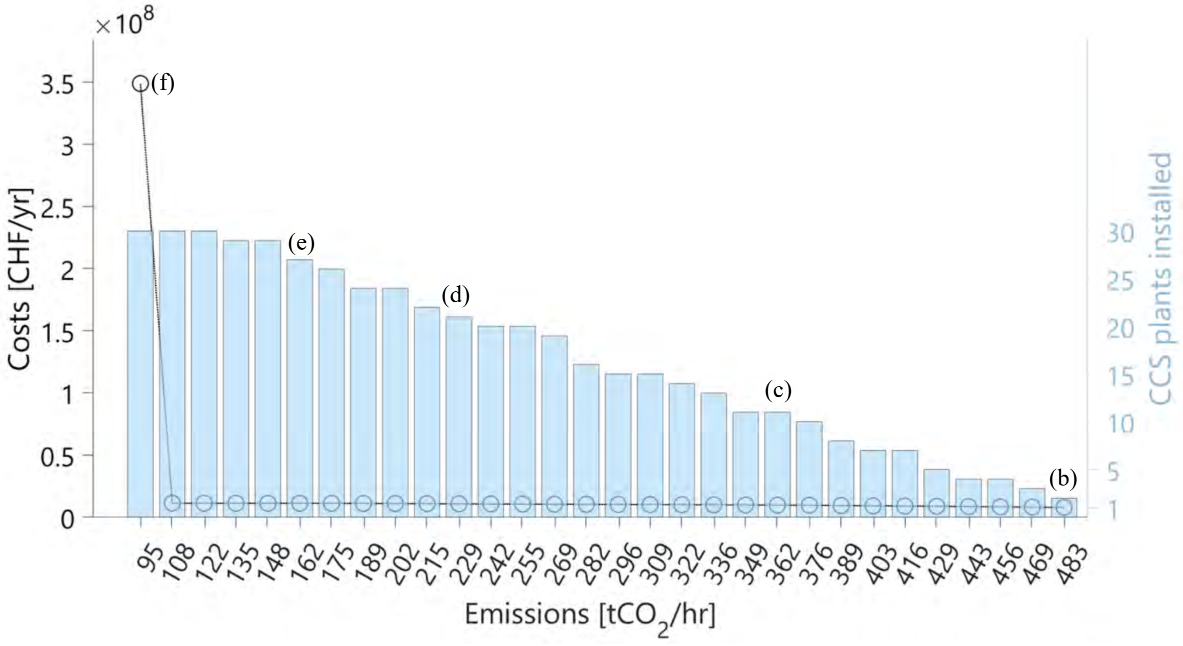

Figure 2. Cost-emissions Pareto front and number of installed capture plants as a function of total CO2 emissions of the system.

network options (including the availability of CO_2 storage sites), (iii) the parameters defining cost and performance of the CO_2 capture and network technologies, (iv) the parameters describing the system configuration.

Based on such input data, the optimization problem determines (i) the selection and size of capture and network technologies, (ii) the CO_2 flow through network technologies, (iii) the energy required to compress and liquefy CO_2 after capture and to transport it.

The optimal solution must comply with mass and energy balances, as well as with the models of the capture and network technologies.

The optimization algorithm minimizes the total annual cost (capital, maintenance, and operational costs) and the total annual CO_2 emissions. This translates in a multi-objective optimization problem, which is solved through the ϵ-constraint method proposed by Mavrotas [8], where the cost is minimized for fixed values of CO_2 emissions.

3. Preliminary results and discussion

Figure 2 shows the cost-emissions Pareto front of the CO_2 value chains for the Swiss WtE plants, and reports the number of capture units installed (right-hand side) along the Pareto front. Two main observations can be made. First, costs and emissions cannot be minimized simultaneously, and a trade-off emerges from these two variables. As the number of capture plants installed, hence the costs, increase, the total emissions decrease. Second, the achievement of the lowest level of emissions (i.e., 95 tCO_2/h) requires a more than threefold increase in costs for only a 12% reduction in emissions. These trends can be further explored by considering the network design emerging for different points along the Pareto front.

Figures 3 and 4 show the CO_2 network design obtained for different points along the Pareto front. Moving towards lower emissions, not only the number of installed capture unit increases but the CO_2 network shifts to transport modes with lower carbon footprint. Case (a) corresponds to the maximum emissions scenario, i.e., no capture plants are installed and there are no costs associated. Designs (b), (c), and (d) mostly rely on train transport from the WtE plants to the Rotterdam terminal, from where CO_2 is transported via ship to the Northern Lights storage facilities. For those emitters without a train connection, transport of CO_2 by truck to the nearest train station is found to be the most viable solution. It can be noted how the model chooses to install first (i.e., for lower costs) capture units at plants that are geographically closer to the Northern Lights storage. In addition, capture units are preferably installed at sites with larger emissions, in order to optimize costs per amount of CO_2 transported. For a further reduction of total emissions (design (e)), the model opts for installing truck connections between the WtE plants and the Swiss terminal corresponding to Basel, from where the CO_2 is transported via barge along the Rhine until Rotterdam, and again by ship to Northern Lights. Barge-based transport, having a smaller carbon footprint than train transport, allows lowering the total emissions and, at the same time, adopting a cheaper transport solution, i.e., truck, at the national level.

Finally, the most stringent emissions reduction level (i.e., total emissions of 95 tCO2/h) is achieved not by installing additional capture units, but by adopting pipelines as the main CO_2 transport mode, at the national and international level (design (f)). Nevertheless, even in this case few connections within Switzerland are forced to adopt truck or train transport due to the limitations on pipeline construction.

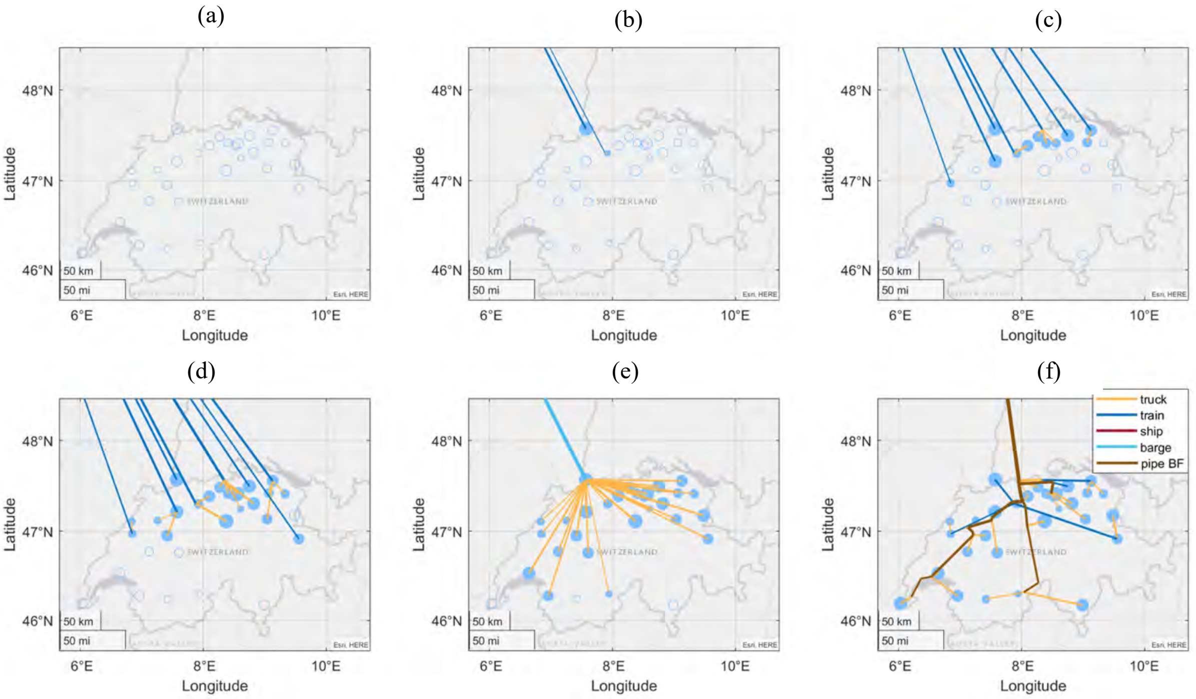

Figure 4. CO_2 network design for different points along the Pareto front (focus on Swiss national network).

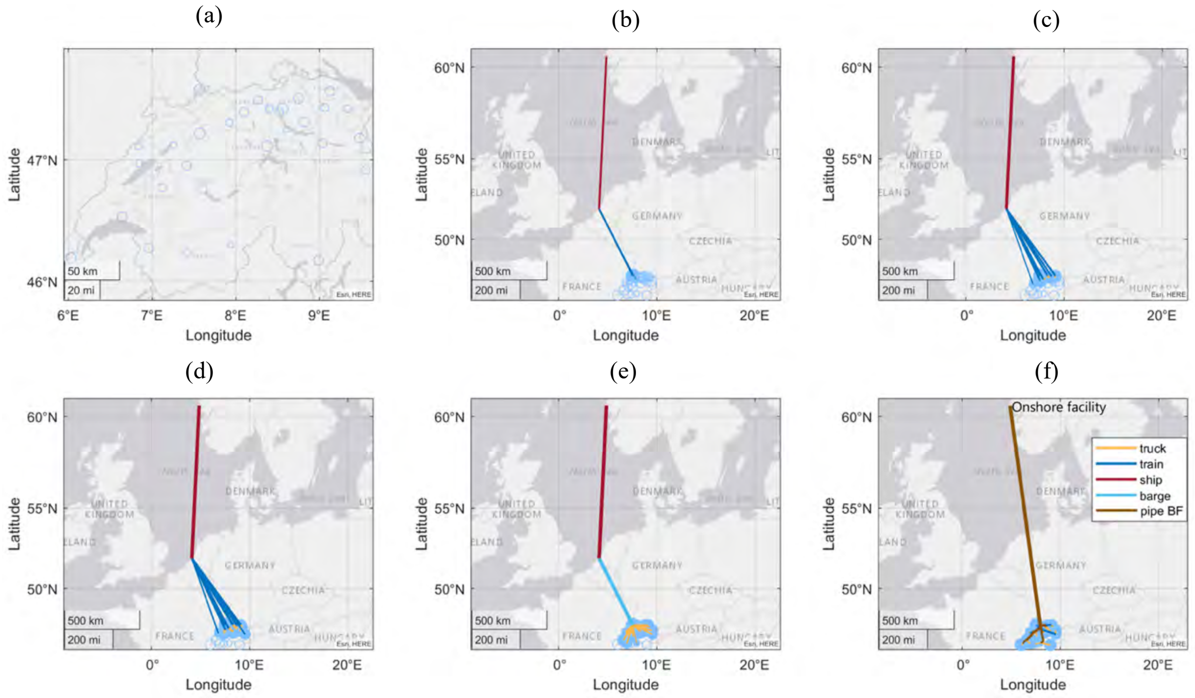

Figure 3. CO_2 network design for different points along the Pareto front (overview on international connection).

4. Conclusions

This work investigates the optimal design of CO_2 value chains aimed at decarbonizing the Swiss waste to energy sector, which comprises 30 WtE plants generating a total of 4.2 million tons of CO_2 emissions per year. The CO_2 value chains considered here consist in capturing CO_2 at the WtE production sites, transporting it to the storage site, and permanently storing it underground. An optimization problem is formulated to determine the optimal design of the CO_2 value chains in terms of size and location of carbon capture technologies, and structure of the network transporting the CO_2 from the capture to the storage sites. Several transport options are assessed, namely truck, train, pipeline and ship, as well as different transport paths.

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References

[1] Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S. Global warming of 1.5 C. An IPCC Special Report on the impacts of global warming of. 2018 Oct 8;1:1-9.

[2] Wei YM, Kang JN, Liu LC, Li Q, Wang PT, Hou JJ, Liang QM, Liao H, Huang SF, Yu B. A proposed global layout of carbon capture and storage in line with a 2° C climate target. Nature Climate Change. 2021 Jan 4:1-7.

[3] P. Gabrielli, M. Gazzani, E. Martelli, and M. Mazzotti, "Optimal design of multi-energy systems with seasonal storage," *Appl. Energy*, vol. 219, pp. 408–424, 2018.

[4] P. Gabrielli, F. Charbonnier, A. Guidolin, and M. Mazzotti, "Enabling low-carbon hydrogen supply chains through use of biomass and carbon capture and storage: A Swiss case study," *Submitted*, 2019.

[5] Gabrielli P, Poluzzi A, Kramer GJ, Spiers C, Mazzotti M, Gazzani M. Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage. Renewable and Sustainable Energy Reviews. 2020 Apr 1;121:109629.

[6] Mavrotas G. Effective implementation of the ε-constraint method in multi-objective mathematical programming problems. Applied mathematics and computation. 2009 Jul 15;213(2):455-65.