SUSTAINABLE CARBON SOURCES FOR BIOFUEL PRODUCTION IN RENEWABLE ENERGY FUTURE

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1 Introduction

Mitigating and preventing anthropogenic climate change is globally one of the largest and most important undertakings of this century. The energy sector is major challenge for this initiative, as it is the source of roughly two thirds of the world's greenhouse gas emissions [1]. To overcome this obstacle, a structural change of the energy sector can thus be anticipated. By 2040, roughly one third of the world's electricity production would come from renewable sources, with the most aggressive increase in wind power, hydropower and solar PV. [1]

As the share of intermittent electricity production from wind and solar increases, so does the need for power stabilization. Hydrogen is an unique substance in the sense that it enables energy storage and stabilization both in the short and long time scales. Short term stabilization can be achieved by adjusting the electrolyser operation according to the available excess electricity from intermittent sources. Long term storage is enabled by the produced hydrogen, as it can be stored either directly, or converted to a synthetic hydrocarbon. Hydrocarbons have the benefit of better connectivity with existing infrastructure and easier handling. On the other hand, the manufacturing of hydrocarbons requires a source of carbon for the conversion process.

The goal of this paper is to describe the potential sustainable sources of carbon for large scale synthetic fuel production on a national scale in Finland, and to identify the necessary infrastructural requirements for the circulation of carbon in such a system. A renewable energy scenario for Finland for the year 2050 is used to derive the necessary background information, i.e. the amount of synthetic methane required, as well as the quantity of CO_2 available from power generation facilities. These values are then distributed to different regions and the necessity of transportation and storage is evaluated. Temporal variation of the consumption and production of carbon dioxide is taken into account, so that potentially problematic periods of the year can be identified. This approach enables the comparison of large system scale decisions considering facility placement, integration and infrastructural demands.

2 Methodology

A model has been developed in this work which incorporates a simplified carbon balance on a regional level. A nodal network is used as the model's base, which enables this regional tracking of CO_2 balance and storage. The following sections introduce the model in detail, starting with a description of the environment that is modelled.

2.1 Energy scenario

The boundary values for this work are extracted mainly from a 100% renewable energy scenario for Finland in 2050 by Child and Breyer [2], which contains heat, electricity and transport demand for private households and industry. In the scenario, a large portion of electricity is produced by using wind (105 TWh), followed by photovoltaics (40 TWh) and hydropower (20 TWh). The scenario has a large installed capacity of electrolysers (23.5 GW), which stabilizes electricity production while also manufacturing hydrogen. Over 35% of electricity is used in the electrolysis process, so the proportion of installed electricity production capacity to indispensable consumption is rather high. On the other hand, this enables the system to be completely renewable, as the energy demand can also be met during suboptimal times of wind and solar production. The produced hydrogen is subsequently methanised and fed to the natural gas grid. Finally, the synthetic methane (30 TWh) is used in combined heat and power production.

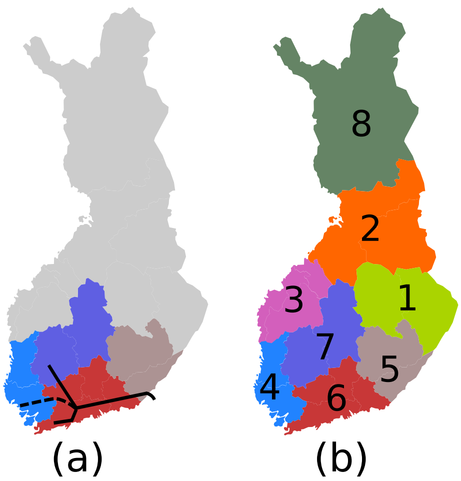
2.2 Sources of carbon dioxide

The potential sources for carbon dioxide have been divided into six technological categories for this work: industry, district heat (DH), gas turbines (GT), direct air capture (DAC), biogas and power-to-gas (PtG) consumption. Each of these technologies has a characteristic operation curve for every hour of the year, which has been derived from the energy scenario by Child and Breyer. For district heat, the operation curve has been slightly altered to match with the geographical variation in the length of the heating season, but otherwise all regions have identical operation curves for each category.

Industrial sources are mainly pulp mills and waste incinerators. Not all sources from the industry are completely biogenic, but it is assumed that these plants have some biogenic or recycled components available. District heat facilities are not run during summer. Gas turbines are not used as a source of CO_2 in this work, as their operation is highly variable, and available CO_2 quantity is low. The CO_2 from biogas originates from field biomass (nearly 70% of CO_2), wastewater treatment facilities, foodstuff wastes and manure. CO_2 is extracted during the upgrading process of raw biogas. Biogas-based CO_2 and direct air capture have been simplified to have a constant production of CO_2 throughout the year. The energy, investment and operations costs of all capture methods have not been considered in this work.

2.3 Locations

The model is based on a nodal network, with each node representing a given location of Finland as illustrated in figure 2.1. A fraction of total installed capacity is placed inside each node. The total capacity is derived from the energy scenario by Child and Breyer, and the ratios which divide the capacity between nodes have been presented in figure 2.1. The ratios for industrial sources are based on emissions of current existing facilities, weighing biogenic emissions by 75% and fossil by 25%. The assumption made in this procedure is that that the location of industrial sites and power generation plants would be relatively unchanged in 2050. Similar approach has been done for district heat, but instead weighing the share of current district heat facility emissions by 75% and estimated population distribution in 2040 by 25%. Biogas potential has been estimated based on maximum technically feasible amount in Finland, including field biomass [3].



Fraction of capacity in node

Node	Industry	DH	Biogas
1	0.06	0.07	0.09
2	0.13	0.11	0.09
3	0.09	0.12	0.15
4	0.08	0.13	0.15
5	0.34	0.10	0.13
6	0.08	0.27	0.23
7	0.09	0.15	0.13
8	0.13	0.06	0.04
Total	1	1	1

Figure 2.1: (a) Nodes which are connected to the natural gas grid. Dashed line represents a planned pipeline, others already exist. (b) Calculation nodes and ratios distributing the installed capacity between nodes. These ratios remain unchanged in this work

2.4 Scenarios

Two types of scenarios are studied in this work. The first type investigates the effects of regional distribution of PtG capacity. This is done by comparing centralized and decentralized systems, meaning that PtG capacity would be concentrated equally to only two regions in the centralized case (nodes 5 and 6), or between all regions in the decentralized case. In the base scenario, nodes 4, 5, 6 and 7 have equal PtG capacity. These nodes were chosen because of the existence of natural gas grid in those nodes. The decentralized system has PtG units in regions where natural gas grid does not exist, but the produced amounts of synthetic fuels are rather low, so it is reasonable to assume that such amounts could be absorbed by local consumption. The actual size of each individual PtG unit is not limited or modelled, but rather the total installed capacity in each node, obscuring the unit size concept.

The second type of scenarios explores the differences between carbon dioxide sources. One case captures a larger proportion of CO_2 directly from air, while reducing the amount captured from industrial plants and district heat facilities. The other variation increases the amount of captured CO_2 from industrial plants and district heat facilities, while still maintaining the same PtG demand for CO_2. This means that a larger portion of the captured CO_2 is vented, as storage capacity is optimized according to PtG demand. Table 2.1 shows the total captured CO_2 amount for all the scenarios.

Table 2.1: Sources of carbon dioxide in different scenarios

Scenario	Industry	DH	DAC	Biogas Mt CO_2	GT	Total	PtG
Maximum available	7.21	10.34		1.2	0.73	19.48	-6.11
Base	2.06	3.26	0	1.2	0	6.52	-6.11
Centralized	2.06	3.26	0	1.2	0	6.52	-6.11
Decentralized	2.06	3.26	0	1.2	0	6.52	-6.11
High DAC	1.01	2.31	2.01	1.2	0	6.53	-6.11
High CO_2	2.81	4.44	0	1.2	0	8.45	-6.11

3 Results

Figure 3.1 shows the temporal variation in the CO_2 yield with different sources for the base scenario (a), and the corresponding total balance of CO_2 capture and consumption (b). Two distinct deficits in CO_2 can be seen, one slightly smaller during late May, and the other in late August and September. Largest deficit of CO_2 coincides with low CO_2 yield from DH.

3.1 Storage

For the storage level, one year period has been investigated, and the initial storage level is iterated to match with the year's end. Figure 3.2 shows the annual total storage level in all scenarios. Storage level decreases rapidly in late May and September, as can be expected

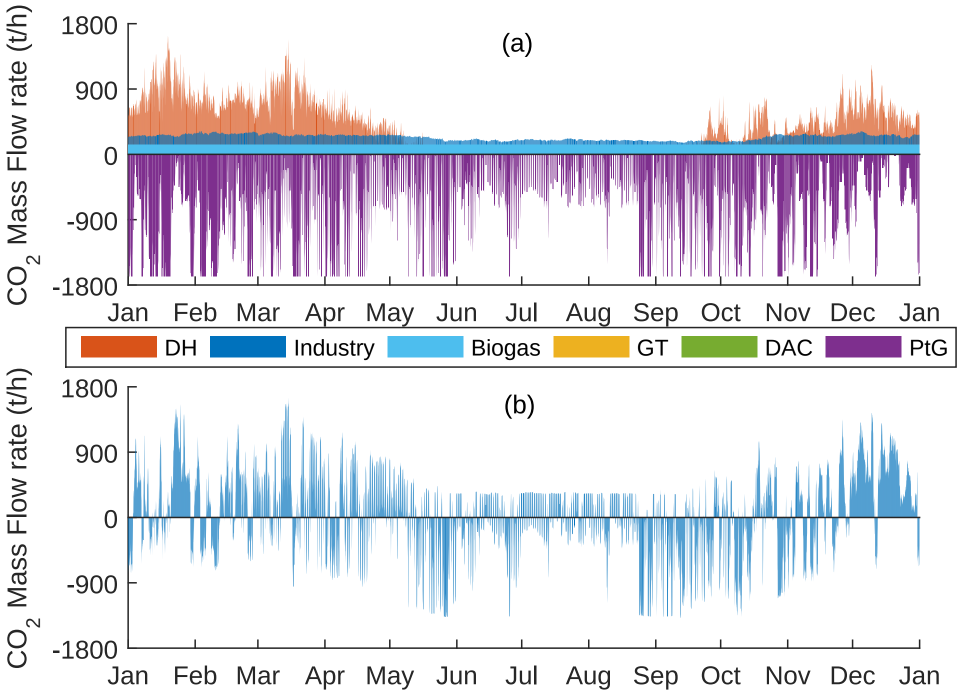


Figure 3.1: (a) Captured CO_2 in the base scenario, with sources distinguished by different colors. (b) Total balance for base scenario, i.e. hourly sum of the sources shown in (a)

from earlier observations. Nearly all storages reach a minimum value in mid-November, during which time PtG capacity was high and DH yield experienced a small dip. High CO_2 scenario reached the minimum value slightly earlier, however, in mid-October. This is explained by the higher relative share of DH in the scenario, so the system is more vulnerable to variations in DH operation. Once the DH operation ramps up during the autumn, it is now able to carry the system over the mid-November dip.

In the high DAC scenario, the production of CO_2 is spread out move evenly throughout the year. This results in overall smaller storage requirement. In the high CO_2 scenario, the captured CO_2 amount is larger during every time step, so naturally this results in a smaller required storage size. The required storage size could be decreased to an arbitrary value by increasing the amount of CO_2 captured. A worst case scenario for the storage size can be calculated by using DH as the only source of CO_2, as it has the highest volatility of the currently considered sources. Doing this gives a storage size of 2000 kilotons. This reveals that for an optimized system, an ideal mixture of capture, storage and transport is required. To store 1000 kilotons of CO_2, roughly 30 tanks would be required, assuming all the tanks are 30 meters high and 38 meters in diameter. This gives in idea of the scale of the system.

The storage level in the centralized scenario is slightly lower during the early year than in the base scenario, but catches up later in the year. The likely reason for this is that a larger portion of consumed CO_2 originates from DH, and the storages are being filled more slowly by the steady biogas production. The yearly storage demand remain roughly the same, however, so the difference is mitigated later. In the decentralized scenario, larger portion of biogas based CO_2 can be used *directly* as the PtG capacity is more spread out, which results in slightly smaller storage size.

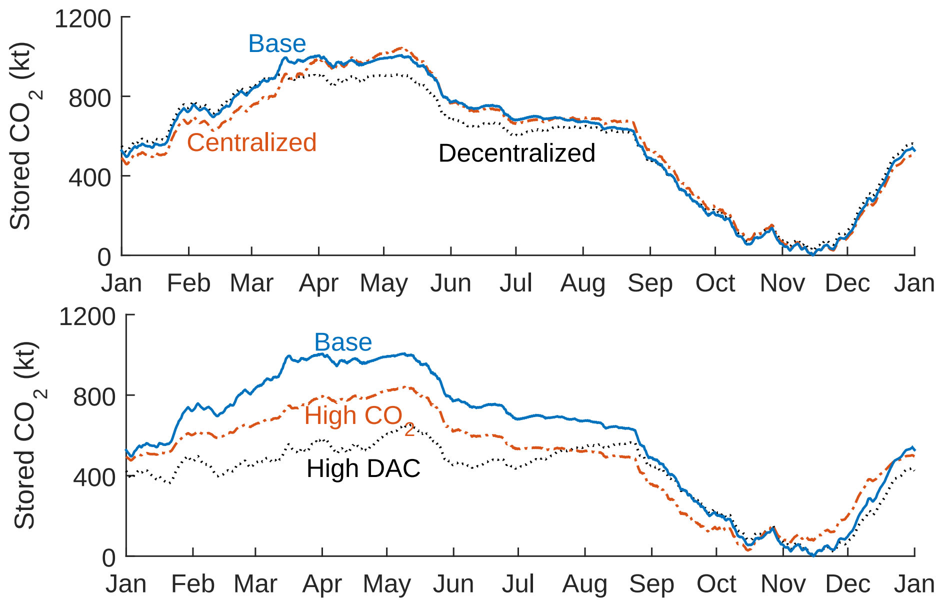


Figure 3.2: Storage level during the year in different scenarios

3.2 Transport

Table 3.1 shows the main transport results calculated in this work. For the high DAC scenario, the CO_2 yield is distributed more evenly during the year, which reduces transport demand. For the high CO_2 scenario, transport demand is also smaller. This is logical as each node produces more CO_2 and transport is thus less critical. Nodes 4 and 7 required imports in the high CO_2 scenario, and these nodes have less overall installed capacity as was seen earlier in figure 2.1. The average shipment size is considerably larger with the centralized scenario, and this is caused by the larger PtG capacity in the nodes.

Figure 3.3 shows how the transportation of CO_2 occurs during the year for the base scenario. If a single truck is assumed to be able to carry 25 tons of CO_2, transporting a moderate 40 kilotons of CO_2 per week would require over 200 shipments daily. However,

Table 3.1: Amount of CO_2 transported in different scenarios

Scenario	Transferred CO_2 (kt)	Total distance (1000 km)	Average distance (km)	Average shipment (t)	Vented CO_2 (kt)
Base	975	1335	218	160	411
Centralized	2435	1422	196	336	411
Decentralized	0	0	0	0	411
High DAC	500	508	165	163	426
High CO_2	118	81	110	161	2344

the model does not predict future demand, but transfers are done instantly when storage capacity reaches the lower limit. If the transfers required by the base scenario could be distributed evenly, a small gas carrier LPG tanker with 20 000 m^3 capacity would need to shipped weekly, which seems more feasible.

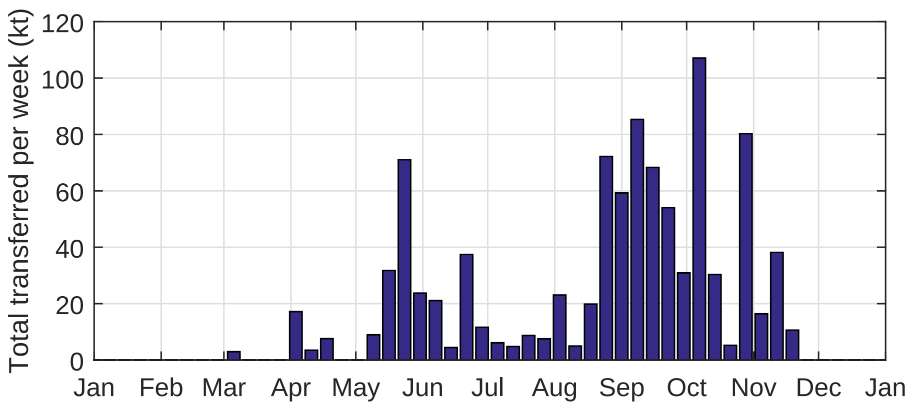


Figure 3.3: Weekly transport demand for the base scenario

4 Discussion

Conceptually, this model aligns itself between large scale system analyses and individual plant studies. The model could easily be extended, for instance by including costs for storage, transportation and capture. Increasing the level of detail in the nodal network could help pinpoint the locations of CO_2 capture sites to minimize the cost of transport and storage. Other important gases, such as hydrogen or oxygen, could also be taken into account by the model.

The temporal variation of CO_2 production between regions might not be very large, as was shown in the cases presented in this work. Thus, seasonal transfer over long distances does not seem viable, but instead focus should be on utilizing as many sources locally as possible. This means that the PtG capacity should be distributed according to the available low cost CO_2, which would also spread the distribution of electrolyser units and electricity consumption more evenly. On the other hand, the distribution of the produced synthetic fuels could be more difficult in regions without access to natural gas network.

The scenario and model parameters could be improved in further studies. For instance, the production of CO2 from biogas and DAC could be changed from constant to hourly varying production. Also, the placement of PtG units could be restricted by additional variables, e.g. electric grid or unit size restrictions. The role of different CO_2 sources should be taken into account in the scenarios, as for example DAC has a large footprint [4], so it could be better suited for small specialized units in remote locations.

5 Summary

The model developed for this work was used to assess the circulation of carbon in a system which produces large amounts of synthetic fuels. For this study, the model included basic components for storage, geographical distribution of sources and simplified transportation. The results given by the model are logical and coherent. There are some aspects which could be included in the model, such as cost calculations and more detailed capture processes.

Transportation of CO_2 in large quantities over long distances does not seem feasible. Instead, focus should be put on intelligent distribution of PtG units according to available CO_2 and minimizing the transport distances. If transport is required over different counties, pipe transport seems competetive for PtG applications due to the high quantities transferred.

To produce the targeted 30 TWh of methane annually, a total storage capacity of roughly 1 million tons would be required for CO_2, which is a moderate amount considering that 6.1 million tons is required annually. However, more realistic assumption in the CO_2 capture process could increase the storage size. Storage size can be decreased by increasing the capture capacity, but this leads to an optimization problem between storage size, capture capacity and transport.

Acknowledgement

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