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CCS IN THE EUROPEAN ENERGY TRANSITION TO CLIMATE NEUTRALITY

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Abstract

The transition of the European energy system to reach climate neutrality by 2050 will require a development and deployment of technologies capable of decarbonizing the energy system in an unprecedented scale. Increased sector integration through electrification and system-wide application of hydrogen necessitates the coherent consideration of all energy sectors for transition planning and facilitation through an improved policy framework. The *Hydrogen for Europe* study has applied energy system models to analyse the potential role of hydrogen in all sectors, and in co-existence with electricity and other energy carriers. The current work focuses on the role of CCS as it emerged from this analysis, and how limitations in deployment rate of CCS impacts the energy transition. It was shown that limits on both the annual CO$_2$ injection rate and minimum usage of renewable energy significantly affects the chosen route for hydrogen production.

Keywords: *CCS, Energy transition, Energy system models, Electrolyser*

1. Introduction

The *Hydrogen for Europe* study was initiated in 2020 to provide new knowledge on the role of hydrogen in reaching the EU Green Deal aim of climate neutrality by 2050. EU policies have been in a rapid development from stating that "for Europe to lead the world towards climate neutrality means achieving it by 2050" [1] in 2018, to launching the EU Green Deal a year later and in 2020 submitting to the European Parliament the legislative proposal for an EU Climate Law that enshrines the 2050 climate neutrality target in EU legislation. An EU hydrogen strategy [2] was also released in 2020. In the strategy, hydrogen was acknowledged for its ability to complement electrification in decarbonizing all the sectors of the European energy system. The strategy emphasises hydrogen's role as provider of seasonal storage and as energy carrier that can be distributed to remote demands. The strategy concludes that hydrogen is an important part of the energy transition Europe must undergo to meet the 2050 climate neutrality goal of the European Green Deal.

Several studies have investigated the potential role of hydrogen in the sectors of the European energy system. One of the most comprehensive analyses to date is "A Clean Planet for All" [3], the vision paper launched by the EU commission in 2018. The Hydrogen Roadmap Europe (2019) [4], published by Fuel Cells and Hydrogen Joint Undertaking also provides a comprehensive overview of the potential use of hydrogen to cover the European energy demands. Still, there are significant knowledge gaps in terms of how to optimally foster and support a hydrogen market optimized for minimum transition costs for the society. These questions are related to in which sectors hydrogen will play the most significant role in decarbonizing and how hydrogen should be produced over the entire timespan from today and until 2050.

As part of the *Hydrogen for Europe* study we have shown that the assumptions related to deployment of CO$_2$ storage has a significant influence on the development of carbon capture and storage (CCS) and the hydrogen market in Europe. We will hence present in the current paper an overview of the role of CCS in the transition of the European energy system to carbon-neutrality and how annual storage constraints impact the production of hydrogen from natural gas reforming with CCS. To this end, Section 2 will elaborate the demand for CCS in Europe while Section 3 will present recent research on potential annual CO$_2$ injection rate. Section 4 will present the methodology in the *Hydrogen for Europe* study and Section 5 will present the impact of modelling assumptions on CCS.

2. The need for CCS in the transition to climate neutrality in Europe

Analyses by the IEA identified a clear need for CCS if we are to reach the Paris agreement at a global level [5]. The demand for CCS however differs between the continents due to the current state of the energy system. As an example, CCS could be a vital option for the power sector in Asia due to the possibility of retrofitting coal power generation plants with a long remaining lifetime, the situation is quite different in Europe where a large share of the coal power capacities are near end of lifetime. Some European countries have also decided a general phasing out of coal power, which adds to the reduced capacity. Hence, the role and level of CCS in Europe is uncertain.

Looking at the European energy system from a high-level, the demand for storage of CO$_2$ stems from four needs in decarbonizing the energy system:

- Capture of CO_2 emissions from the industry sector; certain industries such as cement production have no other decarbonization options than CO_2-capture due to inherent process emissions.
- Decarbonization of the power system; a sharp increase of variable renewable power is expected in the power sector. This increases the demand for power capacities with the ability to stabilize the power supply and to bridge seasonal variations. Part of this demand could be covered by power production with integrated CCS.
- Carbon Dioxide Removal (CDR) technologies that can compensate for hard to abate CO_2 emissions. Power and hydrogen production from biomass with integrated CO_2 capture (BECCS) and direct air capture (DACS) of CO_2 have the CDR capability and all rely on the possibility to store the captured CO_2 permanently.
- Production of hydrogen from natural gas with integrated capture of CO_2; these technologies allow producing large quantities of hydrogen within the next decades with accompanying low emission rates of CO_2 based on existing technology and independent of a decarbonised power system. This can give a head start to the development of a European hydrogen market and can facilitate the introduction of increasing production of hydrogen from variable renewables.

The deployment of CCS within the industry, power and hydrogen sectors, as well as for CDR, depends upon several factors including (i) growth rates for industries depending on CCS for CO_2 mitigation, (ii) the need for compensating remaining emissions by CDR, (iii) the competitiveness of CCS relative to other mitigation options, and (iv) limitations in the utilization of CCS due to constraints on the up-scaling of annual injection rates or total storage potential. In particular, the latter limitations could, if present, cause a competition between the sectors for access to storage of CO_2.

3. Limitations for CO_2 storage deployment in Europe

For CO_2 storage in Europe, there are two main physical limitations: the total storage volumes available and the accessible injection rate in terms of CO_2 injected per year. The potential for CO_2 storage is to some degree known in Europe, for example through the establishment of the JRC CO_2 storage database. Geological storage atlases for Norway and the UK conclude that they have the possibility to store 70 Gt each on their continental shelves. The storage potential on the Dutch continental shelf is estimated to be 1.7 Gt.

The main limiting factor for CCS deployment is thus how fast potential sites for CO_2 storage and corresponding infrastructure can be made available. This has to a very small degree been assessed. As part of the review of the EU SET-Plan, the current European plans for CO_2 storage by 2030 has been assessed to 50 Mt/a. Ringrose and Meckel [6] estimated the potential for scale-up of CO_2 storage in three offshore regions including the Norwegian continental shelf. Figure 1 shows the results of Ringrose and Meckel for the Norwegian continental shelf, which form the basis for the chosen injections rate in the *Hydrogen for Europe* study.

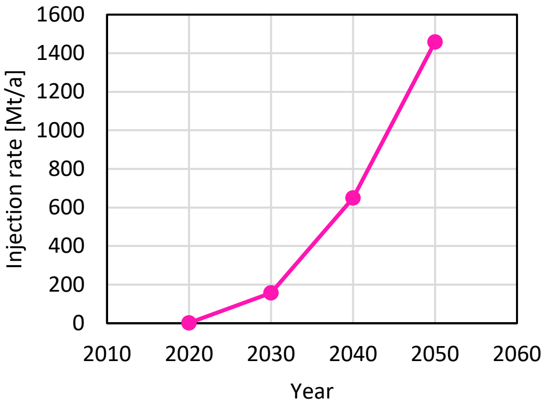

Figure 1: Injection rate on the Norwegian continental shelf (adapted from Ringrose and Meckel [6]).

4. The Hydrogen for Europe study

The *Hydrogen for Europe* study [7] is based upon a framework consisting of two state-of-the-art energy system models: A detailed European energy system model (MIRET-EU), and a more aggregated model to include endogenous learning (Integrate Europe). Technical assumptions as well as baseline assumptions such as demand growth and fossil fuel prices are heavily based upon the databases provided by the Joint Research Centre. The chosen set of policy assumptions is aligned with the existing EU policies and the Green Deal. Hydrogen production technologies such as water electrolysis, natural gas reforming with integrated capture of the produced CO_2 and pyrolysis are all under rapid development. Hence, it has been of high importance in the *Hydrogen for Europe* study to include the most recent performance and cost data for these technologies as well as expectations for future cost reductions to ensure a technology neutral approach.

The model framework includes all aspects of the European energy system, including energy supply, conversion and end-use demand. The coverage of each of the demands and the production of energy carriers such as electricity and hydrogen are not pre-determined, but rather a result of the optimization. The optimization objective is minimizing the total costs for the entire energy system over the considered period from 2020 to 2050. In total 27 European countries are included in the study, of which 3 countries are non-EU members.

Two different scenarios have been established within the study to assess different potential transition paths to climate-neutrality. The *Technology Diversification (TD)* scenario is characterised by its policy framework that consists of the existing policy framework together with a climate law that binds the considered countries to a reduction in greenhouse gas emissions of 55 % compared to 1990 level in 2030 and net-zero emissions by 2050. In the second scenario, the *Renewables Push (RP)* scenario, the renewable energy directive is renewed and set targets for shares of renewables in gross final energy consumption to 40 %, 60 %, and 80 % in 2030, 2040, and 2050, respectively. In both scenarios, annual CO_2 injection to permanent storage is restricted to 1 Gt until 2040, with a subsequent increase to 1.4 Gt by 2050.

In the current analysis, we will consider results from the *TD* and *RP* scenarios, in addition to results from a sensitivity analysis of the *TD* scenario where the CO_2 injection rate is unrestricted (*TD-S*). We will show how the CO_2 deployment varies between these scenarios, and how this affects the markets for electricity and hydrogen.

5. Results

Figure 2 shows the different annual injection rates of CO_2 to permanent storage. We can draw two important conclusions from this figure:

1. The *TD* scenario is constrained in both 2040 and 2050. This can be deduced from the sensitivity (*TD-S*), where the injection rate is increased by 20 % and 30 % respectively as the relevant constraint is removed.
2. Requiring an increased share of renewable energy in the gross final energy (*RP*) leads to non-binding CO_2 injection rate constraints.

Hence, considerable differences in the captured CO_2 from the individual sectors is expected. It should also be noted that the cost optimal injection rates are higher in 2030 and 2040 compared to the study by Ringrose and Meckel [6], highlighting the importance of a fast increase in the annual injection rate.

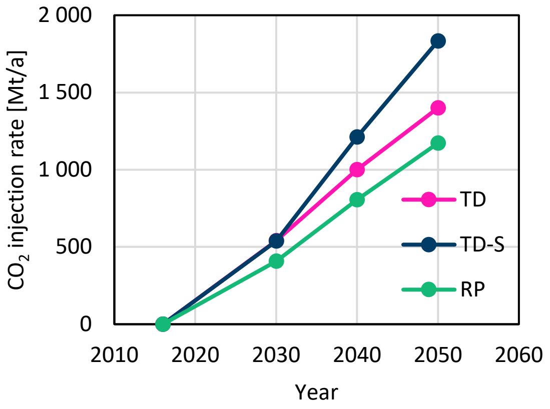

Figure 2: Annual injection of CO_2 to permanent storage.

Figure 3 illustrates the on-grid power generation for each scenario. On-grid power generation in TD and TD-S scenarios are almost identical. However, total power generation in the RP scenario is approximately 7 % higher for 2030, which corresponds to the extra renewable energy needed in that scenario for that year. The alternative to extra renewable power generation would be increased utilization of biomass, but the available biomass resources are limited. Hence, extra renewable power generation from solar PV and wind power is required for achieving the 40 % share. For 2040 and onwards the on-grid power generation is near equal for the three scenarios.

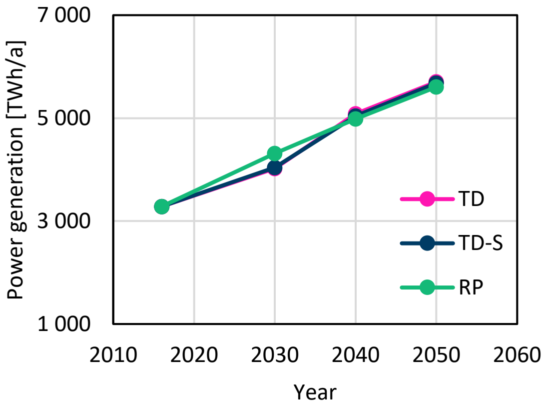

Figure 3: On-grid power generation in Europe excluding power for hydrogen production.

Until 2040, total hydrogen production is largely unaffected by the chosen scenario as shown in Figure 4. By 2050 the differences are more pronounced and partly stem from an increased usage of hydrogen in e-fuels in the *RP* scenario. The cause for this behavior is most likely again the target for renewable share in final energy demand, as e-fuels are considered as renewable, if the hydrogen is produced from renewable energy sources. Increased availability of injection capacity for CO_2 also increases the hydrogen production.

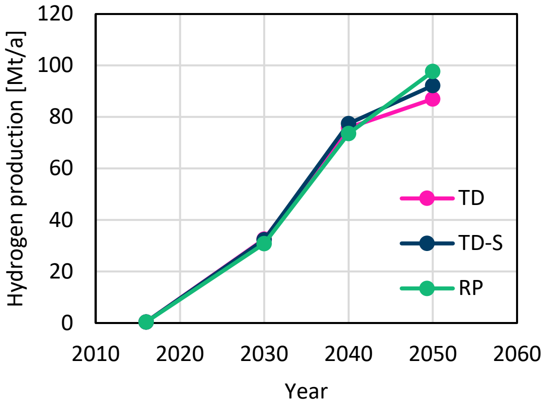

Figure 4: Hydrogen production in Europe.

Figure 5 illustrates the CO_2 captured from the industry sector. Although there are differences between the scenarios, it is not straight-forward to explain them. It is not unexpected, that the *TD-S* scenario results in the highest amount of CO_2 captured, as it also corresponds to the unconstrained CO_2 injection rate. However, less CO_2 is captured in the industry sector in the *TD* scenario than the *RP* scenario although the total CO_2 injection is higher. The constraint related to a higher share of renewables in gross final energy consumption in the *RP* scenario gives the possibility to the industry to keep using fossil-fuel based technologies, thus higher amounts of CO_2 emissions than in *TD*. A small decrease is observed in 2050 in all scenarios due to the increase of renewables with the carbon neutrality constraint. The past investments are at the end of their lifetime by 2040-2050, and that new investments are not based on fossil-fuel consumption, and hence, do not require CCS.

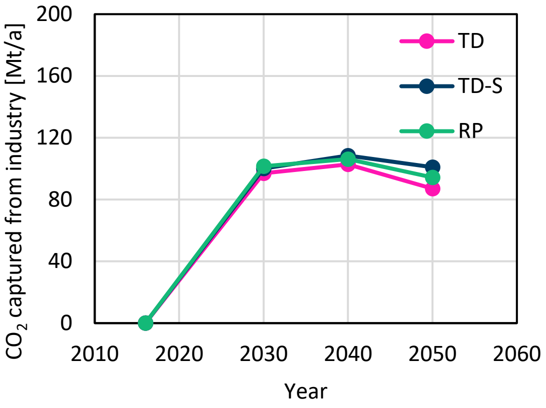

Figure 5: Captured CO_2 in the industry sector.

Figure 6 illustrates the CO_2 captured in the power sector. This includes both CO_2 captured from biomass (BECCS) and from fossil fuels. While there is no significant difference in 2030 between the *TD* scenario and its sensitivity, we see a major difference in both 2040 and 2050. This difference corresponds to 166 Mt/a and is mostly caused by a significant investment in BECCS and natural gas + CCS in the sensitivity due to the unconstrained CO_2 injection rate. The *TD* scenarios compensate the reduced investments in carbon capture technologies through increased investments in nuclear and variable renewable power. The *RP* scenario requires higher CO_2 capture from the power sector than the *TD* scenario, specifically due to the requirement of flexible power generation which is mostly provided through electricity generation *via* BECCS. The CO_2 intensity of BECCS is higher than for NG+CCS. Hence, the amount of captured CO_2 is higher per generated electricity.

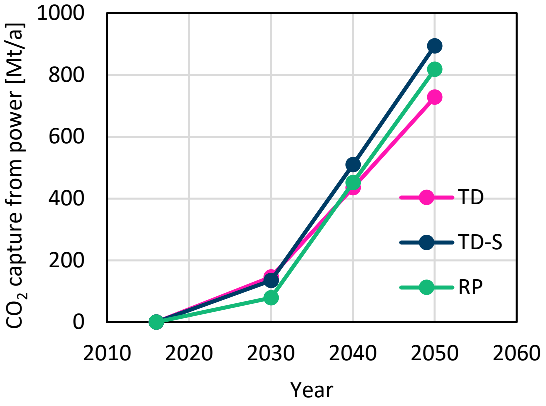

Figure 6: Captured CO_2 in the power sector.

Figure 7 illustrates the captured CO_2 from carbon dioxide removal technologies *via* CDR deemed necessary to compensate emissions on hard-to-abate sectors. This includes both CO_2 captured from biomass in the power sector and in hydrogen production. As we can see in this figure, CO_2 captured from CDR is comparable in both main scenarios in 2040 and 2050, while the unconstrained CO_2 injection rate sensitivity has significantly more CO_2 captured in 2040 and 2050 using CDR.

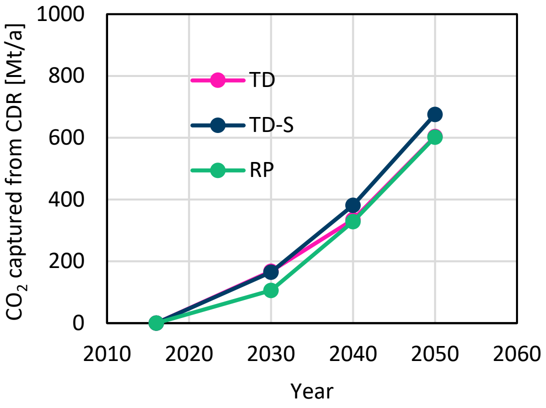

Figure 7: Captured CO_2 from CDR technologies.

This increase is mostly due to an increased usage of DAC. The total CO_2 captured from biomass is similar in all scenarios, although the distribution between hydrogen production and power generation differs. Seen together with the level of DACS, it can be concluded that the carbon removal technologies are required in all scenarios for achieving a zero-emission energy system. However, the total system costs may be affected by the chosen CO_2 injection rate and renewable energy constraints, as *TD-S* captured significantly more CO_2 from DAC compared to the two main scenarios. Hence, it may be beneficial to continue using oil and compensate the emissions with DAC.

Figure 8 highlights the captured CO_2 from hydrogen production. Compared to the other sectors, we can directly see that the amount of captured CO_2 varies significantly between the scenarios. While the captured CO_2 is similar in 2030 in both the *TD* scenario and its sensitivity, it is already significantly higher than in the *RP* scenario. This corresponds to 50 % of the CO_2 injection rate difference in Figure 2. The picture is even more pronounced in 2040 and 2050 where CO_2 captured from hydrogen production differs significantly between all scenarios. The small value in the *RP* scenario can be explained by the high share of renewables in the gross energy consumption. The difference between the *TD* scenario and its sensitivity *TD-S* is affected by the CO_2 injection as it corresponds to 37 % and 39 % of the increase in the CO_2 injection rate in 2040 and 2050, respectively.

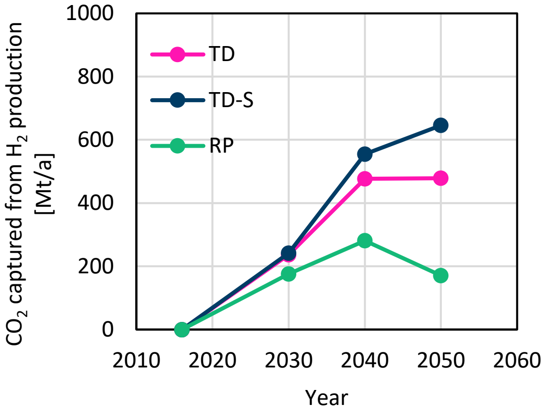

Figure 8: Captured CO_2 from hydrogen production.

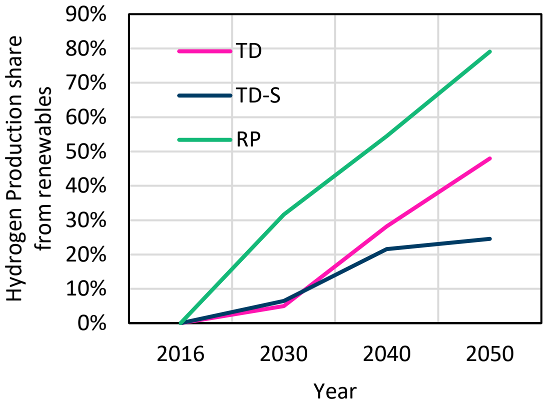

Figure 9: Share of hydrogen produced from renewable sources (wind, solar, biomass *via* electrolysers and gasification of biomass).

The total hydrogen production is however similar in all scenarios, as shown in Figure 4. Correspondingly, the share of hydrogen produced from electrolyser and renewable power is increased especially in the *RP* scenario, as shown in Figure 9. Note that this increase correlates with the increased share of renewable energy in the gross final energy consumption.

CCU was also implemented in the models. The e-Fuels are then mostly used for decarbonizing the aviation sector. However, the difference in CO_2 used for power-to-liquid is rather small (31 Mt) between *TD-S* and *RP*. Hence, CCU does not affect the hydrogen market significantly in terms of production routes.

6. Conclusion

The pace at which CO_2 injection rates unfold has a major impact on the deployment of carbon capture in particular and on the decarbonization pathways in general. The implications are however very different across sectors. The industry sector is almost not affected by this due to the lack of alternatives for decarbonisation. The differences in the power sector are more pronounced, although it is surprising that the *Renewable Push* scenario with the lowest overall CO_2 injection rate captures more CO_2 from the power sector. The major difference occurs in the breakdown of hydrogen production technologies. A limit in the CO_2 injection rates significantly disfavour hydrogen production *via* reforming with integrated CCS.

In the case of the *RP* scenario, the required CO_2 injection rate is lower than for the other scenarios since CO_2 abatement is achieved through the use of renewables which is brought about by the requirement for renewable energy in the gross final energy demand.

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