ZEP Advisory Council 49

14th December 2016

Agenda Item 8: Network Policy and Economics update

8.a. Network Policy and Economics update

Appended to this paper is an update for the ZEP Network Policy and Economics.

8.b. Market Economics report

A final draft version of the report: Delivering the Paris agreement- Modelling the cost of meeting European energy and climate objectives, is appended to this paper.

Members of the Advisory Council are invited to approve this report.

8.c. ZEP Policy Brief: Reuse of unspent NER300 funds

The draft policy brief is appended to this paper for ratification by the Advisory Council.

8.d. ZEP Policy Brief: CCU in the EU ETS

The draft policy brief is appended to this paper for ratification the Advisory Council.

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8.a. ZEP Network Policy and Economics Progress Update: December 2016

NWPE co-chairs: Tim Bertels (Shell), Lamberto Eldering (Statoil), Jonas Helseth (Bellona)

The Network Policy and Economics (NWPE) most-recently met on Thursday 3rd November in Brussels to discuss progress under each of the Working Groups and future areas of work. Alongside the chairs of the various TWGs, the Network heard from Gassnova about Norwegian CCS plans, DG Energy on the future of the ROAD project and progress with the CO_2 thematic group, and DG Grow on on-going work on CCU.

Discussions at the meeting, which was attended by 17 people, were productive and largely positive. The emerging importance of the Temporary Working Group on CCS under the SET Plan was highlighted as was the Commission's Winter Package, which was published on 30th November and included a range of relevant legislative proposals.

The Network plans to next meet in February 2016.

Temporary Working Group – Market Economics 5 (ME5)

Chair: Charles Soothill (GE)

The TWG ME5 has now completed its draft final report, which has been submitted to the Advisory Council for discussion.

The report can be found appended to this paper. The Advisory Council is requested to approve the report.

Temporary Working Group – Policy and Funding (P&F)

Co-chairs: Jonas Helseth (Bellona), Theo Mitchell (CCSA)

The TWG has undertaken two main tasks since the AC last met in September. Attached to this update are two policy briefings, which have been approved by the Advisory Council Executive Committee but are being presented to the Advisory Council for ratification:

1. **CCU in the EU ETS** (appended to this paper). This paper was produced following a discussion at the NWPE, which identified a need for ZEP to take a position on whether CCU should be recognised as climate change mitigation under the ETS Directive. Currently, only geological storage and CO_2-EOR are eligible, whereas CCU technologies such as "power-to-gas", use of CO_2 in food, drink and chemicals, and mineralisation are not. ZEP has concluded that there is a need for detailed life-cycle analysis of CO_2 emissions associated with different forms of CCU ahead of any amendment to the EU ETS Directive.

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2. **Reuse of the NER300 unspent funds** (appended to this paper). It has become apparent that Member States and EU institutions are currently considering options for the redistribution of unspent funds from the NER300 programme. In total, it is estimated that the amount of funding available could be in excess of €1 billion by 2018. The ZEP position paper suggests that a proportion of this funding is set aside to support CCS projects under development, without the constraints that come with the NER300. To achieve this, funding would need to be reallocated to other financing initiatives (e.g. H2020 or EFSI) but this could run the risk of UK projects being excluded.

Temporary Working Group – CCU Policy

Chair: Rob van der Meer (Heidelberg Cement)

This new TWG has been established upon request from the NWPE, NWT and the ACEC to consider the topic of CCU in the Renewable Energy Directive.

Similarly to the issues discussed in the ETS paper, this discussion was initiated in the context of the Commission's Winter Package, which included a legislative proposal for a revision to the Renewable Energy Directive. As part of the proposal the Commission recognised CO_2-derived "alternative fuels", i.e. fuels produced by combining fossil-derived CO_2 with hydrogen, as an eligible unit of compliance towards renewable targets.

Beyond its existing position on CCU in the ETS, ZEP does not have a position on the appropriate policy instruments for supporting CCU deployment and this TWG will consider how this may be most effectively achieved.

The TWG is expected to have held its first teleconference ahead of the Advisory Council meeting and a draft Terms of Reference is being presented at the meeting for approval (appended to this paper).

Temporary Working Group – Projects of Common Interest (PCI)

Co-Chairs: Lamberto Eldering (Statoil), Owain Tucker (Shell)

The CO_2 Thematic Area under the TEN-E Regulation has met twice in recent months, on both the 14th October and 30th November.

At the most recent meeting, consultants appointed by DG Energy presented their latest thinking on the methodology for assessing CO_2 transport PCI bids and further detail on what bidders will need to demonstrate as part of the Cost Benefit Analysis (CBA). There was also an opportunity for stakeholders to present their views on these areas and the TWG was represented in this regard by the ZEP secretariat (Theo Mitchell). A representative from the UK Government also provided an update on the development of a North Sea CO_2 infrastructure plan being put together by the North Sea Basin Taskforce, including representatives from the UK, Netherlands, Norway and Germany. The Plan is currently being signed off by Ministers from the respective countries involved and is expected to be submitted to DG Energy (and made publicly-available) in January/February 2017.

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Following the 30th November meeting of the Thematic Area, ZEP was requested to provide written feedback to DG Energy on the draft methodology and proposed detail required for the CBA by Friday 16th December.

The Advisory Council is invited to provide feedback on the proposed input and approve the submission, noting the short window of opportunity to submit a response imposed by the Commission.

Temporary Working Group – Brexit

Co-Chairs: tbc

At the September meeting of the Advisory Council, ZEP members concluded that Brexit – although significant – should not be an immediate priority work area for the Network. The NWPE agreed with this and, noting resource constraints, suggested that other policy areas remain the priority in the short term. It was agreed that CCSA would maintain a watching brief from the UK perspective and update the Network and Advisory Council accordingly.

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Zep
Zero emissions platform

Delivering the Paris agreement

Modelling the cost of meeting European energy and climate objectives

December 2016

European Zero Emission Technology and Innovation Platform

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This document has been prepared on behalf of the Advisory Council of the European Technology and Innovation Platform Zero Emission Plant (ETIP ZEP). ZEP exists to advise the European Commission on Carbon Capture Utilisation and Storage Technologies and associated policies. The information and views contained in this document are the collective view of the Advisory Council and not of individual members, or of the European Commission. Neither the Advisory Council, the European Commission, nor any person acting on their behalf, is responsible for the use that might be made of the information contained in this publication.

Key conclusions

- A 2050 emission reduction target of 80-95% for Europe is achievable, but 9 of the countries modelled can only achieve this level of emissions reductions with a mix of technologies that includes CCS.

- Across the whole energy system, CCS is expected to have a value to the EU in excess of €1 trillion by 2050 alone. In the longer term, as European countries move towards net zero emissions, the value of CCS is expected to further increase.

- With CCS available, total energy system costs are up to 23% lower than comparable scenarios without CCS, despite the fact that many of the scenarios with no CCS do not achieve an 80% reduction in emissions. For the 10 countries modeled, including CCS is expected to save approximately €50 billion per annum by 2050.

- Combined Heat and Power/District Heating is a low hanging fruit and is the first and fastest way to increase supply side energy efficiency in Europe. It is selected most in northern and eastern countries where the climate and social traditions make CHP appropriate. In the longer term, there is economic and climatic value in combining CHP with CCS to yield significant emissions reductions.

- Increased electrification can avoid distributed emissions and plays a vital role in emissions reduction from transport and heating and cooling. In certain circumstances, hydrogen also has the potential to be a key low carbon energy vector for reducing emissions in these sectors. In either scenario, CCS has been shown to have an important role to play.

- The future of energy intensive industries including cement, steel and oil and gas in a CO_2 emissions constrained world is dependent on CCS. For these sectors and many more, CCS is critical to retaining high-skilled jobs and boosting economic activity across EU Member States.

- The modelling demonstrates the high value add that can be achieved by shifting spending on energy away from imported fuels to investments in infrastructure, renewables and local indigenous fuels. This can have important co-benefits for energy security objectives, employment and sustainable industrial activity.

- Infrastructure investments are needed now to achieve the lowest emissions and lowest costs out to 2050. CCS infrastructure can unlock emissions reductions across the whole energy system with significant potential for cost reductions through cross-border initiatives and sharing of infrastructure.

- The countries studied are different and the model shows that local solutions and indigenous fuels, as well as weather patterns, should be taken into account when countries develop their Integrated National Energy and Climate Plans.

- CCS facilitates the integration of renewables with near zero CO_2 backup power. Across the various scenarios, EU targets for renewables deployment (20% in 2020 and 27% by 2030) are expected to be achieved if ambient heat for heat pumps is included as one of the renewable sources. By 2050 renewables are expected to represent more than 50% of the energy system on an energy usage basis for cases both with and without CCS.

- Biomass is modelled to be an important component of the future European energy system because heat is twice as important as electricity in terms of energy use and associated emissions. Biomass as a renewable energy is modelled to contribute the largest energy content of the total energy system, approximately equal to ambient heat. Sustainable use of Biomass/Biofuels combined with CCS is needed for negative CO_2 emissions, which are essential to realise the “well below 2 degrees” vision of the Paris Agreement.

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1 Taking a local view

ZEP builds on previous pan European modelling of power and Industry

European nations and regions have taken positions at the Paris Conference of Parties (COP) to reduce CO_2 emissions substantially. The EU Intended Nationally Determined Contribution (INDC) is in the process of being converted to commitments by country and provides the high level framework for the EU 2030 Framework for Climate and Energy Policies.

EU Members States are in the process of agreeing the share of the EU commitment that each MS should adopt. The ZEP wishes to support this process and has undertaken detailed modelling - employing the expertise and data from its members and partners - to identify potential portfolios of CO_2 reduction technologies and their evolution to 2050 that can deliver on climate objectives at the least cost to European citizens. The lowest cost solution varies significantly by country and has been modelled.

Together with renewables, Carbon Capture and Storage (CCS) will play a critical role in achieving Europe's energy, climate and societal goals. It is an indispensable component of national and global decarbonisation pathways drawn up by the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA) and the European Commission. Indeed, the EU 2050 Energy Roadmap relies heavily on CCS to meet EU-wide decarbonisation targets.

A new energy systems model, developed specifically for this work, was designed to select the lowest-cost investment pathways to meet expected energy demand, while replacing assets that exceed a defined lifetime – country by country. The novelty compared to previous reports is the inclusion of the complete energy sector, namely electricity, space heating, industrial heat and transportation. It is based on yearly simulations, 8760 hours, considering real consumption and renewable generation data. It models the true integration costs of renewables and the opportunities that comes with a stronger link between the energy sectors, i.e. higher energy efficiency by combined heat and power (CHP) or the electrification of heating and transport via heat pumps and e-mobility.

The report is the latest installment in a long-line of landmark publications from the ZEP:

1. 2012 CO2 Capture and Storage: Creating a secure environment for investment in Europe.

2. 2013: "CO2 Capture and Storage: *Recommendation for transitional measures to drive deployment in Europe*"[1] confirmed the critical role of CCS in meeting EU decarbonisation targets and the need for transitional measures, including grants for early movers and feed-in premia to provide security of income. This led directly to the inclusion of CCS in the 2030 EU Energy and Climate Policy Framework.

3. 2014: "*CCS and the electricity market: modelling the lowest-cost route to decarbonising European power*"[1] modelled much lower future costs of renewable energy sources (RES) – mainly photovoltaics and onshore wind – at the request of the European Commission. Using a generic electricity storage model, this showed that a combination of CCS and RES leads to 20-50% lower electricity generation costs in 2050, compared to a RES-only path.

4. 2015: " CCS for Industry: Modelling the lowest cost route to decarbonising Europe highlighted the role of CCS in reducing emissions from Cement, Steel and Refining and the importance of specific measures to avoid that emissions reductions are translated as a loss of local industry to regions without the same emissions targets. Not only is CCS the *only* option for substantially reducing CO_2 emissions in these industries, but the costs of CO_2 transport and storage – 10-30% of the total CCS costs – can be significantly reduced by clustering power and industrial emitters.

[1] www.zeroemissionsplatform.eu/library/publication/253-zepccsinelectricity.html

A contribution to understanding how to achieve European and National targets.

Following the COP21 meeting in Paris in 2015 the ZEP decided to focus the next phase of its effort on system modelling at the member state level to assess the most cost effective technologies to meet the EU's INDC that was submitted to the Paris meeting, and later ratified by the European Parliament. Each Member State will be responsible for developing a plan and implementing the actions required to meet the climate targets, while the EU, through the proposed governance system of the Energy Union, will perform integrated strategic planning and foster coordination across EU. This report is therefore an important contribution to the forthcoming work, both within each member country and the Energy Union. [2]

Energy Intensive Industries

Cement, steel and refining sectors are represented in the model and were the focus of ZEP's previous market economics report, to the extent that these industries exist in the member states today. For some countries such as Germany this represents a significant component of potential emissions reductions. For some such as Switzerland this component is small. Overall, the model chooses to apply CCS to these industries at the point in the time sequence when CCS on these industrial processes becomes the next cost effective step.

The risk of exporting industrial production and jobs outside Europe is very real. The allocation of free ETS allowances to industries is a temporary measure and is intended to be phased out in the timescale of the modelling in this report. Unless CCS is deployed in a manner that allows these industries to connect their CO_2 sources quickly and at reasonable cost, these industries may shut down production in Europe and other regions where CO_2 emissions are constrained.

Many energy intensive industries in Europe produce highly-commoditized products and operate in global markets. Industrial companies operating in sectors such as steel and cement often have difficulty in accessing private finance as a result of poor credit ratings and short investment horizons. This makes the notion of investing in full-chain CCS a challenging proposition for European industry. In order to address these barriers to investment, ZEP has demonstrated how a system of "Market Makers" for CCS can unlock CO_2 infrastructure and enable low-cost access to climate mitigation solutions for energy intensive industries.

The modelling work contained in this report demonstrates that availability of CCS significantly lowers the cost of decarbonisation and can create new opportunities for sustainable industrial activity in Europe. Realising these benefits however will require collaboration between the public and private sectors, with a key role for both Member States and EU institutions.

Heating and transportation included in the model at local Member State level.

This, the fifth iteration of ZEP's market economics analysis, has been based on a newly-designed and improved energy systems model to accommodate the wider total energy system of Europe at a Member State level. In order to incorporate the emissions from heating and cooling sectors and as well transport, a revised model was adopted at Member State level. The model is similar to the one used in previous years and still incorporates a two-level economic optimiser: one for investment and the second for operation.

The transport system is modelled as short distance and long distance transport. Technology options include gasoline and diesel vehicles, electric vehicles and hydrogen fuel cell vehicles. The deployment of electric vehicles is accompanied by additional costs for vehicle charging infrastructure and the investment optimiser is free to make this decision when this becomes the next most cost effective step for CO_2 emission reduction. The model is constrained in the investment timescale by the typical replacement of the stock of vehicles.

[2] See http://www.consilium.europa.eu/en/press/press-releases/2015/11/26-conclusions-energy-union-governance/

Import and Export Assumptions

The model makes the same technology cost and evolution assumptions for all countries, including fuel costs. In general the model is based on the assumption of free trade of all sources of energy that are transportable. The Gas (methane) price in the model came originally from GCAM450ppm and was considered to represent the real cost of the fuel which is lower than the actual prices present in Europe. In line with previous reports, ZEP conducted sensitivity analysis to the gas price, including analysis of the impact of a gas price twice that from the GCAM scenario. (TO BE INCLUDED!!!)

The model assumes that current industry structure is maintained (steel, cement etc.), and that these commodities are not simply imported from another region of the world that does not set for itself emissions reductions at the same level or at all. The model assumes that these industries are incentivised to deploy the range of technologies available to them to reduce CO_2 emissions but are protected from imports that imply carbon leakage.

For this latest report, the model assumes that all energy production is undertaken within the relative Member State. There are especially no electrical interconnections modelled between the member states, which is recognized to be a substantial simplification.. This decision was taken to balance model complexity: previous versions which contained electrical connections modelled only a few days within a year. The present model considers 8760 hours and the complete energy system.

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2 Modelling the whole energy system to find lowest cost

Member State level Energy System Model

The new model builds on ZEP's previous experience and considers energy **sources** from fossil fuels, nuclear, renewables, as well as ambient heat. The model considers **use** of energy for electric power, industrial processes, space heating/cooling for domestic and industry, transport and chemical process conversion. The model includes **conversion** technologies to turn fuel into electricity, fuel into hydrogen, ambient heat for heating and sun and wind into electricity. The model also includes electricity storage (pumped hydro and batteries) and hydrogen stored as gas. As per previous reports, CO_2 transport and long-term storage is included as a cost per tonne based on previous ZEP reports but it is important to note that CO_2 transport and storage costs are expected to reduce significantly if planned strategically (e.g. to accommodate CO_2 from multiple emitters) and with economies of scale.

The previous ZEP Market Economics reports have highlighted the importance of the lead time to develop and construct CO_2 transport and storage infrastructure. ZEP has also proposed that CO_2 emissions 'clusters' and CO_2 storage 'hubs' are funded and constructed as European infrastructure projects as the best way to ensure that each CCS project is incrementally viable. Learnings from recent NER300 projects show that cross-chain risks (i.e. the risk to an emitter that a store may not be available and *vice* versa) make end-to - end CCS projects difficult to reach financial closure in the same way that investing in a trucking industry would be difficult if the road network were not planned and funded by the Member States of the EU.

The model calculates the lowest cost for the chosen Member State in each of a set of 5 year intervals from 2010 to 2050 to achieve the progressively tightening CO_2 emission target that would meet the NDC target (National Plan) for 2030 and 2050.

The new model includes heating and cooling as well as transport, energy intensive industry and the power sector. The effect of this change in the model is to recognise that the interaction between the different components of the energy system can be very important. Examples include Combined Heat and Power (CHP) that helps to deliver the European Energy Efficiency targets at low cost, and technologies such as Heat Pumps, which profoundly impact the demand for electricity and maintain centralisation of energy conversion, facilitating CCS at scale. The model predicts cost savings for the modelled countries, in the case of deployment of CHP plants and electric vehicles, while also delivering first emissions reductions.

The critical role of Heat

The heating sector is (i) regional because of the climatic differences between countries, (ii) seasonal due to the latitude of Europe (approx. 35-65 °N) and (iii) local in its emissions since most heating is provided by local heating using combustion of fuel: methane, oil and coal.

Since heating and cooling represent some 50% of total European energy-related CO_2 emissions this is a very important sector. There are regions that question the realism of converting heating to electric heat pumps (UK), especially for cities, and others that take it for granted (CH). This depends on the Coefficient of Performance to be achieved by the heat pump, which in turn depends on the capital investment in the heat pump and the level of building insulation.

Heating is fundamentally distributed. One way to make at least part of it centralised is through CHP. CHP is widely applied in cold north eastern European countries. By applying CCS to CHP it becomes possible to greatly-reduce CO_2 emissions from heat either by CHP (with CCS) as the heat source or by heating and cooling via Heat Pumps where the power comes from low carbon sources, such as fossil fuel or biomass power stations with CCS or from renewables. The new model allows for the selection of these options and sets limits for the proportion of heating that could be converted to CHP by country. The assumption is that only cities (and towns) could implement CHP cost-effectively. The model allows selection of CCS-ready CHP to gain a short term efficiency and CO_2 emissions improvement but also the fitting of CCS as part of a cluster concept as the CO_2 targets bite.

Since CHP is predicted by the model to reduce the overall cost of power, industry and heat production for the countries studied it is both an attractive option short term provided that, in the longer term, it is retrofitted with or replaced by new facilities with CCS. It also delivers on EU and National targets for Efficiency as well as CO_2 reduction.

There are other models for addressing heating and cooling demand, as ZEP has demonstrated through its recent report on Clean Hydrogen. In the UK, for example, the Committee on Climate Change (the UK's statutory body on climate change) has shown that hydrogen could play a major role in reducing emissions from UK heat production. A recent study by Northern Gas Networks – Leeds City Gate H21 – for example, has shown that Steam Methane Reformers (SMRs) with CCS can be used to create hydrogen to be piped in existing methane pipelines to domestic and industrial users. A relatively low cost of conversion from methane to hydrogen use at the consumer appliance is demonstrated by the project with CO_2 capture centralised at SMR facilities located as part of a CCS cluster.

The Leeds H21 project has shown that, for areas with high quality gas distribution infrastructure and a high concentration of gas domestic boilers and other appliances, the economic case for converting the gas distribution system to zero carbon hydrogen is extremely favorable compared to conversion to electric heat pumps. For areas with limited gas distribution infrastructure and low population density other options for decarbonising heat are likely to be preferable. Hydrogen for heating has been added to the model for the UK based on data provided by the Leeds H21 project and tested to see the uptake by the optimizer. ZEP's model chooses a combination of hydrogen heating and heat pumps for the UK, which shows that these two technology options (hydrogen and heat pumps) maybe selected by different regions and countries of Europe.

Energy Intensive Industries are so defined because they use process heat or process chemistry in their production. Considering process heat in the model makes the inclusion of Energy Intensive Industries more realistic. Using hydrogen to deliver process heat is currently not modelled but can be considered for future extension.

Transport is another energy use that is highly distributed. In the model ZEP has made both Electric Vehicles and Hydrogen Fuel Cell Vehicles available. The first is expected to primarily represent passenger cars whilst the latter is most applicable to longer distance haulage; this is due to the differing functionalities of these technologies. For both Electric Vehicles and Hydrogen Fuel Cell vehicles, CCS allows for centralized, cost-effective removal of CO_2 emissions in the production of the energy vector (be it hydrogen or electricity) and is therefore shown to be a valuable component of decarbonisation of the transport sector. The aviation sector has not been considered in the model.

Clusters will drive down the costs of CO_2 transport and storage

In previous reports ZEP has developed the concept of 'clusters' to centralise CO_2 transport and storage infrastructure around areas of high fuel use and industrial production. The purpose is to separate the investment decision for the transport and storage from the investment decision for the specific industrial production plant.

By developing transport and storage in advance of each plant decision the uncertainty is reduced and the decisions are smaller in magnitude than for an end–to-end system decision. By collocating Power, Energy Intensive Industry, CHP, Hydrogen Production for heat and Hydrogen and Power for Electric Vehicles the economies of scale can be large and therefore the financial hurdles to investment reduced. In an outcome where the production of electricity in a country would be a factor of 2 larger to meet its share of the EU NDC targets (via its integrated National Climate and Energy Plan) the substantial investment could be located and implemented to optimise and support CCS clusters.

Deployment Time Scales Matter

The deployment time for the necessary society-wide investments in infrastructure has substantial impact on the outcome of the modelling exercise. Electric Vehicles, Heat pumps, Combined Heat and Power (CHP) with CCS and CO_2 transport and storage infrastructure all require decades to implement. Regulation and policy and market structures must take CO_2 emission reduction targets into account, on a technology neutral

basis if investment is to be made in the necessary infrastructure. This will include heat distribution and housing stock adaptation, power transmission, CO_2 transmission, Methane and Hydrogen transmission, CO_2 storage and vehicle charging networks. It will also necessarily include industrial, small-scale and domestic installations of wind and solar, CHP, district heating plants, power plants with CO_2 capture, distributed generation, electric vehicles battery and thermal storage and heat pumps.

The Role of EU and Member state regulation and policy on investment decisions

The previous ZEP reports concluded that the current electricity and emissions trading markets do not incentivise the deployment of low carbon technologies. The current merit order dispatch system has been effective in optimising the electricity system as it existed in the past but presents challenges as Europe transitions to low carbon power. The EU ETS encourages reductions in emissions but has shown itself to be only a weak incentive for investment to actually reduce existing CO_2 emissions, e.g. through application of CCS.

Additional policy options, such as Feed-in Tariffs with Contracts for Difference (CfDs), can be an effective tool to deploy low carbon technologies where the ETS price alone is insufficient to drive investment decisions. The experience of the recent NER300 projects has shown that full chain end-to-end CO_2 capture transport and storage projects are difficult to finance. This is because there is not sufficient incentive to reduce emissions while we have seen effective support for other low carbon technologies. The merit order dispatch system discourages investment in CCS because any investment to reduce emissions that adds to marginal cost would reduce operating hours. Additionally, full–chain CCS projects are difficult to finance due to the previously discussed cross-chain counter party risks that exist between the different parts of the CCS system.

The ZEP report: “An executable plan for Europe” proposes that EU infrastructure funds be used to build a number of CCS hubs around which a cluster of capture projects could develop. The time scale to develop and build these hubs could be up to 10 years in some scenarios and the model shows that these infrastructure decisions should be made upstream of specific industry investment decisions to help enable private sector investments in emissions reductions. The model shows a ramp-up in the deployment of CCS in 2025 therefore the importance of pre-investment and development of CCS ‘clusters’ and CO_2 storage ‘hubs’ cannot be overstated.

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3 Key features of the model

Any modelling is a simplification of reality and increasing model complexity is not a guarantee for a higher quality of the results. In this report, ZEP chose to develop a simple model of the energy system of a country or a region that consists of the main final consumption forms (electricity, low and high grade heat, transportation), the main primary inputs (fuels, renewable electricity, ambient and solar heat), and the most important assets that convert a primary input into a final consumption form (power plants, heat pumps, etc.). The model also considers storage assets for electricity (e.g. batteries), thermal energy (hot and cold), hydrogen, biomass and lakes for regulated hydro.

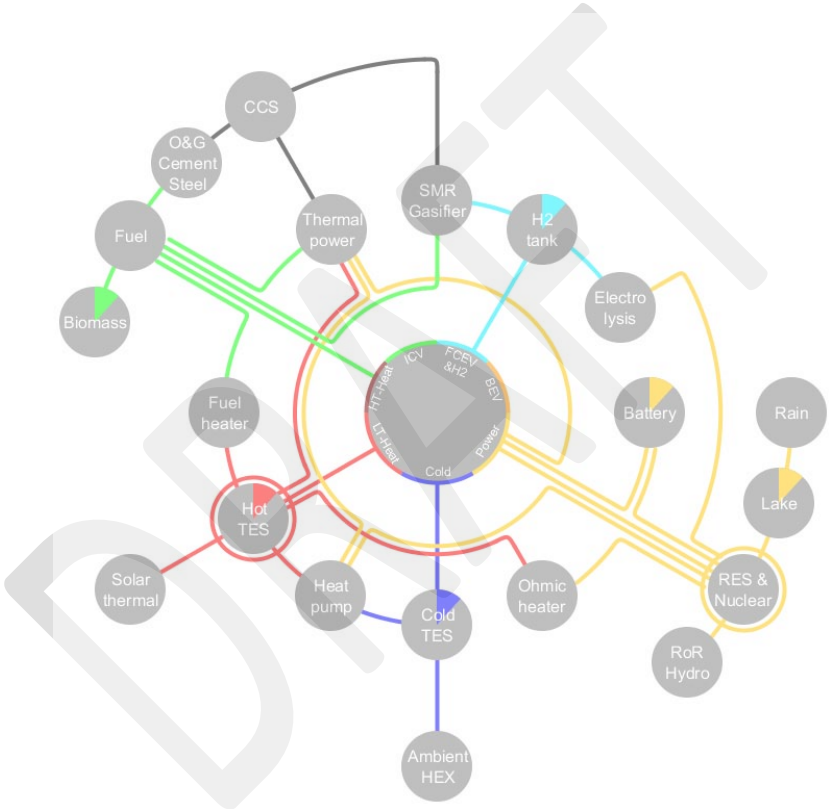

Figure 1: Model of the energy sector.

As shown in Figure 1 all afore mentioned elements are connected via energy flows, having the identical physical dimensions but different meanings: yellow – electricity, red – heat, green – fuel, dark blue – cold, light blue – hydrogen. The model is strictly local, i.e. it does not consider any limitations in the transmission or distribution of any energy flow, although these factors clearly should also be considered by policy makers. The model also neglects the complexity of the electrical grid with its various voltage levels. A cost for the additional grid and distribution infrastructure is applied in the model in proportion to the increase in the peak use of electricity in the overall energy system. This cost has been based on credible assumptions, further detail of which can be found below.

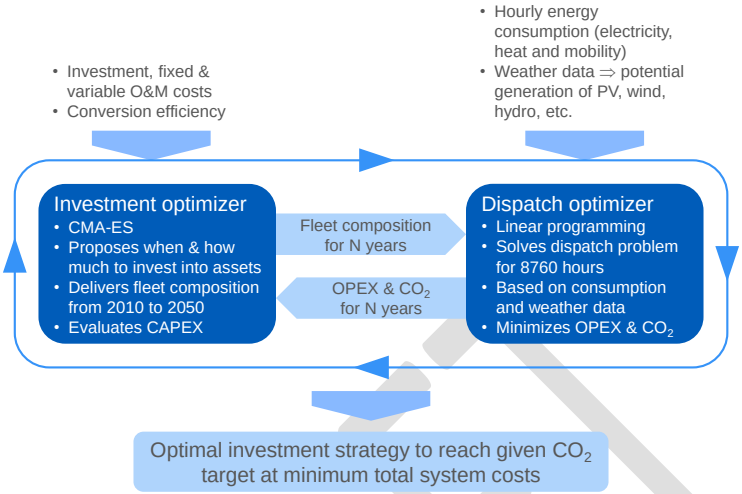

Figure 2: Structure of optimization approach.

Optimization approach

The objective of the model is to propose a cost-optimal investment strategy to achieve a given CO2 reduction target. This implies two distinct but interlinked types of optimization: (1) an investment optimization that proposes when and how much to invest in certain assets, and (2) a dispatch optimization that takes a given configuration of assets and runs through a full calendar year, minimizing operation expenses and CO2 emissions (see Figure 2).

The model can in principle be applied to any entity, e.g. a building, a city or a whole country. The only condition set by the specific approach is that no energy forms are exchanged with the exterior of the entity (except fuels). When applied to countries this limitation means that electricity transport between countries is not included in the model.

Investment optimization

The investment optimization spans across a certain time frame within this paper, from 2010 to 2050. For each asset three choices have to be made: (1) in which year to start installation; (2) how many years this installation should last; and (3) what total volume shall be reached (see Figure 3a). The latter can also be expressed in terms of installed capacity per year. Each asset has a given lifetime. Consequently, it is decommissioned later in the time horizon.

The actual installed capacity for each asset follows from simple integration in time (see Figure 3b). Asset 1 ramps up, stays at a plateau and then ramps down again, whereas Asset 2 has a life time beyond the considered time horizon and stays flat after the installation period has finished. Within the investment optimization there are three design variables for each asset. Those are controlled by an evolutionary optimizer, more specifically a Covariance Matrix Adaptation[3].

Note that the model is forced to satisfy demand at all times. Therefore it must install the appropriate amount of dispatchable generation to balance fluctuations in PV & wind generation.

[3] Hansen N, Ostermeier A. Completely derandomized self-adaptation in evolution strategies. Evolutionary Computation, 9(2):159–195, 2001.

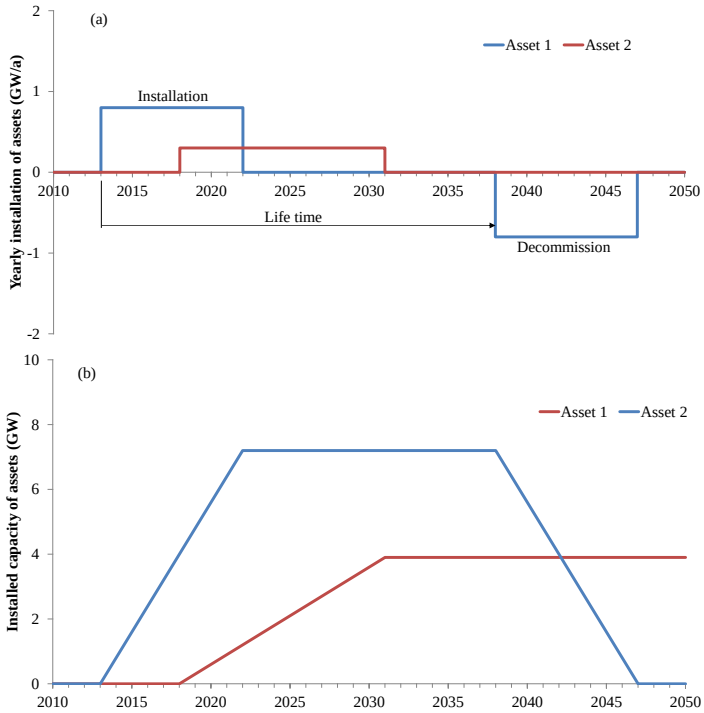

Figure 3: Investment optimization: (a) yearly installation of assets, (b) installed capacity.

Dispatch optimization

The investment optimizer proposes a large number of actual realizations of the energy systems, i.e. a certain configuration of assets and their installed capacity over the time horizon from 2010 to 2050. In order to assess how these realizations perform, a dispatch optimization is carried out for each 5th year within the time horizon.

The dispatch optimization aims at minimizing operation costs within a given year. A Linear Programming solver optimizes the energy flows as shown in Figure 1 for each of the 8760 hours of a year. No knowledge of the future is implied, i.e. the optimizer only reacts to the demand and renewable input within a given hour. It finds the optimal arrangement of energy flows that minimize the operation expenses, i.e. mainly the consumption of fuels. The presence of storage assets requires special attention. Since the optimizer does not see the future, ZEP has added an additional incentive to load the storage whenever there is more renewable energy available than required.

Overall objective function

The objective function for the investment optimizer consists of three major elements: (1) the capital expenses (CAPEX) within each 5th year that follows from the investment decision; (2) the operational expenses (OPEX) within each 5th year which follow from the dispatch optimization; and, (3) the CO_2 emissions within each time period which follow again from the dispatch optimization. The capital expenses are calculated using an annuity factor with the individual life time of the asset and a weighted average cost of capital (WACC) of of 5%.

Comment [MWPG1]: Clarify whether the investment/operations of the individual plants can be recouped from the product prices& utilisation in the market or whether a "perfect" market is assumed which installes and operates from a "total system costs". A paragraph on market models which would realise this lowest cost pathways can add insights.

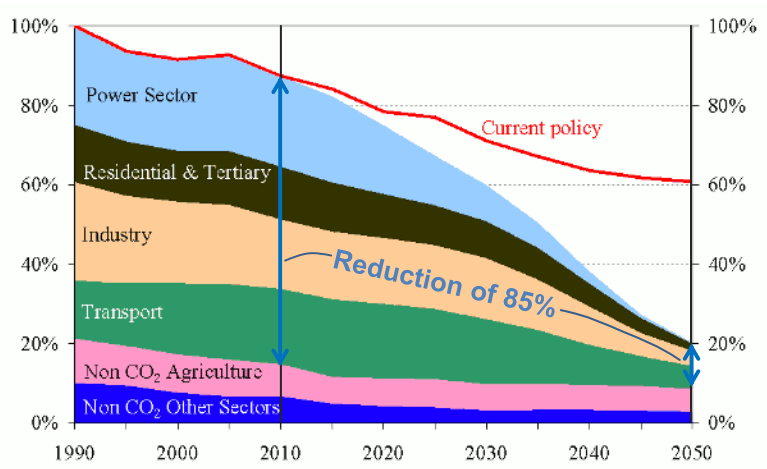

Figure 4: Target for CO_2 reduction from energy sector.

The objective function can be written down explicitly as follows:

$$OF = \sum_{i=0}^{N} (CAPEX_i + OPEX_i) + a \max(0, CO2_N - 0.15\ CO2_0)$$

With the first term, the optimizer aims at reducing the overall costs of years 0 to N (2010 to 2050). Figure 4 shows a possible reduction pathway for 80% GHG emissions from 1990 to 2050 for the EU[4]. Limiting the time horizon from 2010 to 2050 and the scope to the energy sector (power, residential, tertiary, industry, transportation) leads to a target of 85%. Therefore a second term is added to the objective function that penalizes any emission above 15% of the CO2 emissions in 2010.

Assumptions and inputs

Any model is as good or bad as the underlying assumptions and inputs. The main ones are listed in this section.

Consumption data

Four types of final energy consumption are considered, namely electricity, low-grade heat for room heating and warm water, high grade heat for industrial processes, and transportation. The hourly electricity consumption for European countries was collected for previous modelling work and is used again here[5]. The low grade heat consumption is deduced from the ambient temperature in Typical Meteorological Years (TMY)[6]. We selected 5 representative locations for each modelled country. The ambient temperature is related to a heating consumption[7]. Figure 5. shows typical distributions normalized to an average of 1.

Since the consumption of high grade heat is related to industrial processes that normally operate at a high utilization rate, the simple assumption is made that the demand is flat throughout the year.

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[4] See http://ec.europa.eu/clima/policies/strategies/2050/index_en.htm
[5] ENTSO-E, Statistical database, Available from https://www.entsoe.eu/resources/data-portal/; 2012.
[6] EnergyPlus, Available from https://energyplus.net/weather/; 2016.
[7] Hellwig, M. Entwicklung und Anwendung parametrisierter Standard-Lastprofile. Technische Universität München, Germany; 2003.

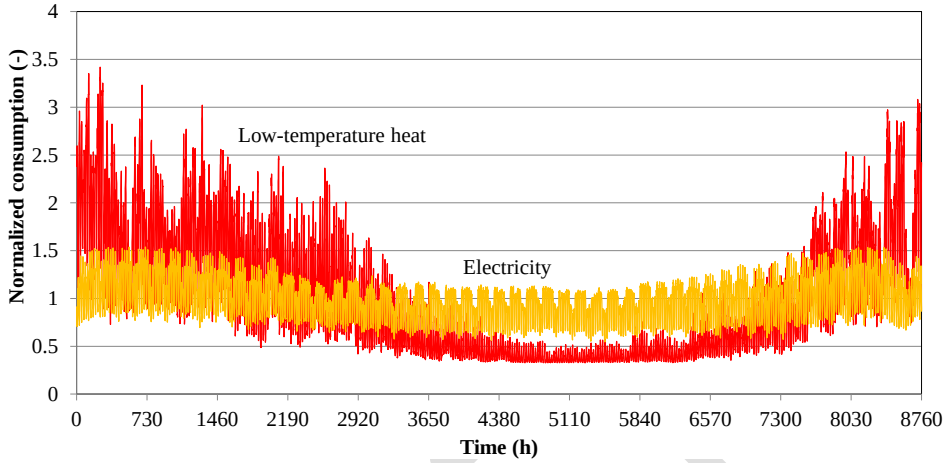


Figure 5: Normalized consumption of electricity and low-temperature heat.

ZEP uses only a simple model for the transportation sector. Taking the overall consumption of fuels which is known for each country, it is assumed that the average efficiency of internal combustion vehicles is 20%. Hence a consumption of 100 TWh of fuel heating value corresponds to 25 TWh of mechanical energy. If all fuel vehicles would be replaced by battery electric vehicles (BEV), this would require 31.25 TWh of additional electrical energy assuming a 65% efficiency of battery and electrical motor. Without a knowledge about real charging patterns in future E-mobility scenarios, we assume again a constant power offtake.

The overall yearly consumption of electricity, low & high grade heat, and transportation fuel is taken from the IEA[8]. Practically, these numbers are multiplied with the normalized distributions from Figure 5 to give the actual consumption pattern for every hour of the year. It is assumed that all consumption data remain unchanged throughout the whole time horizon.

Renewable generation data

The generation profile of renewables assets like wind and solar PV is estimated based again on meteorological data from Typical Meteorological Years (TMY) (5 locations for each country). Wind speed is converted to generation assuming typical wind turbine power curves. PV generation is modelled using measured Direct Normal Irradiation and Global Horizontal Irradiation, which is converted to a Global Tilted Irradiation that is set proportional to the PV output. Both quantities are again made non-dimensional.

Cost data, efficiency

Each asset that is available to the investment optimizer is characterized by a set of cost data, and by conversion efficiency. The latter is defined as useful output divided by required input. Cost data are capital investment costs (€/kW), fixed Operation & Maintenance (O&M) costs (€/kW/a), and variable O&M costs (€/kWh). Cost data and efficiency have been compiled within previous reports from the Market Economics group of the Zero Emission Platform (ZEP) and are re-used within this report. Some changes have been made which are described below:

- Coal and lignite plants have very similar characteristics. It was therefore decided to merge them into one technology. The specific fuel mix can be set individually for each country.

[8] International Energy Agency, Available from https://www.iea.org/Sankey/; 2016.

- CHP versions of coal and lignite plants were not considered in previous modelling work. Investment costs are increased by 200 €/kW to account for changes in the plant and a distribution network. In addition a 4 %pt efficiency reduction is assumed.
- Biomass was previously only considered as co-firing. Here it is assumed that a 100% biomass plant has a 50 €/kW higher investment cost and 2%pt lower efficiency.
- The same simple rules were used to define a biomass CCS plant and combined CCS & CHP plants.
- Gas turbine combined cycles with CHP were defined by adding again 200 €/kW investment costs and by subtracting 3 %pt efficiency.
- The total CHP efficiency ((electricity + heat) / fuel input) was set to 80%.

All cost and efficiency assumptions for the power generation equipment are summarized in Table 1. The original numbers from previous ZEP reports are marked in red.

Table 1: Cost data for power generation equipment.

	Investment costs (€/kW)			Fixed O&M (€/kW/y)			Variable O&M (€/MWh)			Efficiency (-)			Lifetime (y)
Technology	2010	2030	2050	2010	2030	2050	2010	2030	2050	2010	2030	2050	
Lignite	1600	1600	1600	32.4	32.4	32.4	0.48	0.48	0.48	0.43	0.46	0.49	40
Coal	1500	1500	1500	31.05	31.05	31.05	0.46	0.46	0.46	0.45	0.47	0.49	40
Coal/Lignite	1550	1550	1550	31.725	31.725	31.725	0.47	0.47	0.47	0.44	0.465	0.49	40
Lignite CCS	2810	2530	2250	55.35	50.04	44.73	3.28	3.28	3.28	0.34	0.385	0.43	40
Coal CCS	2710	2430	2150	50.31	45.85	41.39	2.46	2.46	2.46	0.35	0.395	0.43	40
Coal/Lignite CCS	2760	2480	2200	52.83	47.945	43.06	2.87	2.87	2.87	0.35	0.39	0.43	40
Coal/Lignite CHP	1750	1750	1750	31.725	31.725	31.725	0.47	0.47	0.47	0.4	0.425	0.45	40
Coal/Lignite CCS CHP	2960	2680	2400	52.83	47.945	43.06	2.87	2.87	2.87	0.31	0.35	0.39	40
Biomass	1600	1600	1600	31.725	31.725	31.725	0.47	0.47	0.47	0.42	0.445	0.47	40
Biomass CCS	2810	2530	2250	52.83	47.945	43.06	2.87	2.87	2.87	0.33	0.37	0.41	40
Biomass CHP	1800	1800	1800	31.725	31.725	31.725	0.47	0.47	0.47	0.38	0.405	0.43	40
Biomass CCS CHP	3010	2730	2450	52.83	47.945	43.06	2.87	2.87	2.87	0.29	0.33	0.37	40
GTSC	400	400	400	19.5	19.5	19.5	0.45	0.47	0.55	0.4	0.41	0.42	30
GTCC	650	680	800	30.38	30.51	54	0.45	0.52	0.8	0.601	0.613	0.66	30
GTCC CCS	1410	1330	1250	36.17	50.45	64.73	1.64	1.92	2.2	0.476	0.538	0.6	30
GTCC CHP	850	880	1000	30.38	30.51	54	0.45	0.52	0.8	0.571	0.583	0.63	30
GTCC CCS CHP	1610	1530	1450	36.17	50.45	64.73	1.64	1.92	2.2	0.446	0.508	0.57	30
Recip CHP	800	750	700	50	50	50	2	2	2	0.48	0.49	0.5	25
Nuclear	3000	2350	1700	134	120	1700	2	2	1	0.361	0.365	0.370	60
Regulated Hydro		3000			125			0			1		60
ROR Hydro		4000			125			0			1		60
PV	1900	1050	200		19.5			0			1		25
Wind	1200	1150	1100	54.4	50.85	47.03		0			1		25

Costs for heating and hydrogen generation equipment were compiled from available sources. They are summarized in Table 2.

Table 2: Cost data for heating and hydrogen generation equipment.

	Investment costs (€/kW)			Fixed O&M (€/kW/y)			Variable O&M (€/MWh)			Efficiency (-)			Lifetime (y)
Technology	2010	2030	2050	2010	2030	2050	2010	2030	2050	2010	2030	2050	
Electric heater		300			0			0		0.9			20
Fuel heater		500			0			0		0.8			20
Hydrogen heater		500			0			0		0.8			20
Biomass heater		500			0			0		0.8			20
Heat pump		2000			0			0		3.5	3.75	4	20
SMR		400			21			4		0.75			45
SMR CCS		527			21			4		0.7			45
Electrolyser		1000			0			0		0.7	0.725	0.75	20

Table 3 shows the assumptions on fuel costs and CO_2 intensity.

Table 3: Assumptions on fuel costs and CO_2 intensity. SENSITIVITY!!!

Fuel	Price (€/MWh)	CO2 intensity	Comment
Lignite	8	370	
Coal	15	340	
Oil	40	260	Equiv. 60 $/barrel
Gas	30	200	7-8 $/MMBtu
Nuclear	1	0	
Biomass	30	390	Emission compensated by extraction from atmosphere

Constraints

Each asset that is available to the investment optimizer can in principle be constrained in its maximum installed capacity. In practice, this limit is rarely hit by most assets with the exception of solar PV and wind. Here we make the optimistic assumption that wind power can be deployed up to a level of installed capacity that is equal to the average electrical load. For solar PV ZEP assumes three times this level as upper limit. Whereas the deployment of wind turbines will normally be limited by practical considerations such as the available land area, such limit is not relevant for solar PV. The real limitation will be in the grid infrastructure that is needed, although this is not considered in this modelling exercise. Note that the energy flow model considers the option to curtail an excess of PV and wind generation.

A further possible constraint is the starting point of installation of a certain asset. ZEP uses this, for instance, to allow for the installation of nuclear power in Poland only from 2030 onwards. In addition we assume that a deployment of e-mobility and CCS will only start in 2020. An additional constraint concerns the rate of deployment of a new technology. We make the general assumption that any installation from 0 to the maximum allowable level will take at least 3 periods, i.e. 15 years.

Simplifications and further assumptions

As mentioned before, the model does not consider the details of electrical infrastructure. This would not be an issue if the electricity consumption would not change during the modelled time horizon. However, one of the measures to drive down CO2 emissions is actually an electrification of heating and transport sector via heat pumps (or hydrogen heating) and electric vehicles, respectively. This leads naturally to both a higher electricity consumption and a higher peak power from the production to the consumer side.

The electricity consumption in Europe is roughly split 60% / 40% between households and commercial & industrial consumers, respectively. The average electricity price for households is 140 €/MWh, 45% of this being network costs. For the second group the average price is 90 €/MWh with 30% network costs[9]. In total ZEP estimates that electricity in Europe costs 50 €/MWh of network costs to bring it from the producer to the consumer. Multiplying this with the electricity consumption gives the yearly costs for electrical infrastructure, which will in detail consist of capital and operation expenses.

Two quantities can be extracted from the model for each 5 year period within the time horizon: (1) the total amount of electricity consumed ("traditional" use for lighting, motors, etc. and additional use for heat pumps and electric vehicles), and (2) the peak flow of electricity from the production to the consumption side. Assuming that grid infrastructure costs scale mainly with the power, and not with the energy, that is transported, ZEP uses the second quantity to simply scale up the yearly network costs.

One could argue that this estimate is too low since distributed solar PV generation with its strong peaks at midday requires additional grid reinforcement to let the electricity flow up to higher voltage levels. However,

[9] http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics

on a similar basis, the local use of electricity for heat pumps and electric vehicles (and batteries) will grow, hence reducing the need for stronger grids at local level. For the purposes of this exercise, ZEP therefore decided to use the simple assumption that grid infrastructure costs scale linearly with the peak electrical consumption.

For the transport sector, ZEP makes the assumption that electric vehicles (both hydrogen and battery based) will reach similar cost levels like todays fuel cars by 2025. The required charging infrastructure is not modelled explicitly but considered as an additional operation expense for battery cars. Based on estimates of xxx we take this as 100 €/kWh of mechanical power.

Comment [tm2]: Reference

The maximum amount of non-fuel mobility in 2050 is set to 75%, except in the case of Norway where government policy includes prohibition of fuel vehicles. Furthermore a fixed split of 75%/25% for battery electric vehicles and fuel cell vehicles has been defined.

The investment optimization has to start from a pre-defined fleet of assets. This is taken from a variety of sources for the different countries that were modelled, mostly IEA reports[10]. The simple assumption is made that those initial assets are decommissioned linearly over time, i.e. they completely disappear after the lifetime of the asset, if they are not replaced by new installations.

DRAFT

[10] See http://www.iea.org/publications/countryreviews/

4 The results for selected countries

Data sets have been created for several European countries including Poland, UK, Germany, Switzerland, Netherlands, Italy, France, Greece, Spain and Norway. This selection is motivated by the diversity of the respective energy systems and climatic conditions. Table 4 gives an overview of some indicators for the selected countries. The numbers are extracted from the energy flow diagrams published by IEA[11]. An apparent difference is the ratio of energy requirement for low grade heat (space heating and warm water) and electricity, which diminishes from north to south, in contrast to the solar PV potential. The investment optimization was performed for two basic scenarios: (1) assumes that CCS is available as a technical option, (2) that CCS is not available.

Table 4: Assumptions on fuel costs and CO_2 intensity.

	Consumption (TWh)			
Country	**Electricity**	**Low-grade heat**	**High-grade heat**	**Transportation**
United Kingdom	345	485	173	85
Poland	133	299	119	34
Germany	557	808	417	120
Netherlands	115	198	108	25
Switzerland	62	79	25	13
France	471	529	214	95
Italy	304	455	189	76
Spain	251	170	164	58
Greece	53	35	22	11
Norway	109	23	24	8
Sum	**2399**	**3080**	**1456**	**526**

Poland can increase competiveness, independence and use local resources

The Polish energy system is strongly based on indigenous coal and lignite, both for power generation and for space heating. There is a well-developed district heating system that is fed either by coal & lignite Combined Heat and Power plants or by heat-only-boilers. Being in the northern half of Europe, solar PV resources are limited and the ratio of energy for space heating to electricity is the highest of the countries considered here. Poland has plans to build up a nuclear generation capacity starting from 2030 onwards.

Figure 7 shows the installed capacity (GW) and the generation (TWh) both for electricity and for low-grade heat. The left column is the CCS scenario, the right the non-CCS scenario. In both cases one can distinguish two phases in the development which are characteristic also for most other countries. From 2010 to 2030 the traditional fossil technologies – coal & lignite power plants and heat only boilers – disappear both in terms of installed capacity and generation. They are replaced by a growing share of CHP plants and by heat pumps, biomass and CHP in the heating sector.

After 2030 the two scenarios follow different paths: if CCS is available, it appears from 2020 onwards both with and without CHP. The dominant fuel is coal, followed later in time by gas and biomass. If CCS is not available there is a stronger growth of other near-zero-CO2 technologies, mainly wind and solar PV.

[11] See https://www.iea.org/Sankey/

Biomass is used in all variants, with and without CHP as well as a heating fuel. Nuclear is introduced from 2030 onwards. In both scenarios there is a switch from fuel-fired road vehicles to battery-electric- and fuel-cell-vehicles in the timeframe from 2035 to 2050 (see Figure 8).

Coal & lignite is an important asset to guarantee a secure energy supply for the country. Figure 8 shows the primary energy input. It is obvious that having CCS in the mix allows to better utilise the fossil resources that Poland has available. Biomass is an important primary energy input in both scenarios. While an excellent solution in itself the management of truly sustainable biomass sources requires careful regulation.

The modelling shows that renewable technologies such as wind and solar PV have only a small share in terms of their primary energy input. While physically correct, the graph in Figure 8 does not show the different natures of the primary input, namely electricity and fuel heating value. The third row in Figure 8 shows the final energy use, again split into the various primary inputs. This takes into account the conversion efficiency from fuel input to electrical or thermal output. Here the share of electrical renewables is clearly larger.

The last row of Figure 8 shows the CO_2 balance for the two scenarios. The sum of all categories is the amount of CO_2 that is effectively generated by combustion. Two categories have to be subtracted: (1) CO_2 extracted from the atmosphere by biomass growth and (2) CO_2 that is captured and stored using CCS. The red line marks the amount that is actually added to the atmosphere. It is clearly visible that a stronger reduction can be achieved if CCS is available.

Figure 6 summarizes the results for Poland by showing total system costs vs. CO_2 emissions. The various years from 2010 to 2050 appear here as dots along the curve (the reader should note that the emission axis is reversed). With CCS available, Poland can achieve the EU emission reduction target while maintaining the use of indigenous coal & lignite as a primary energy resource.

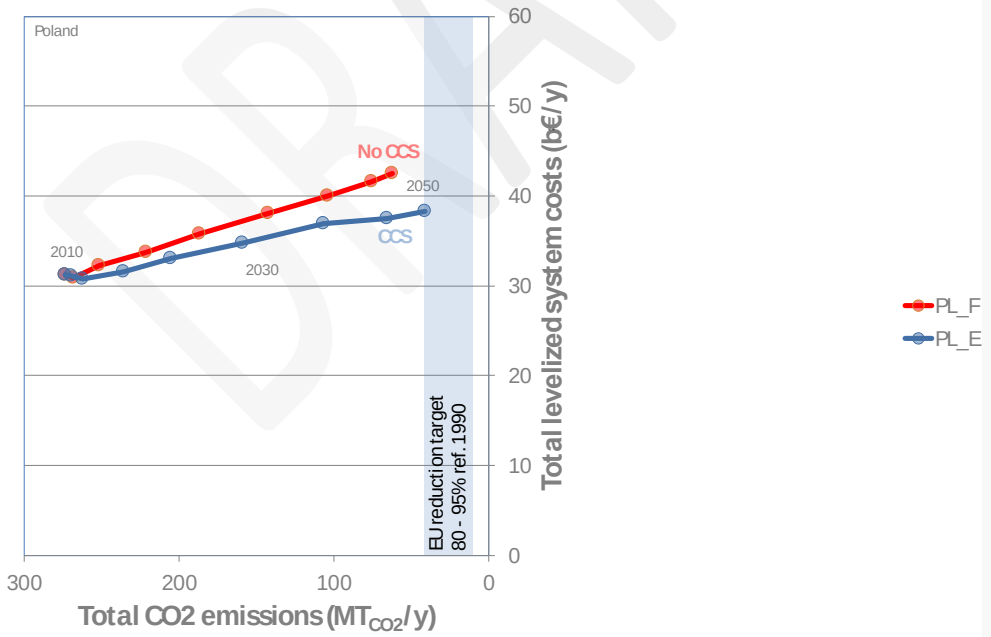


Figure 6: Costs vs. CO_2 emissions for Poland (with CCS, without CCS).

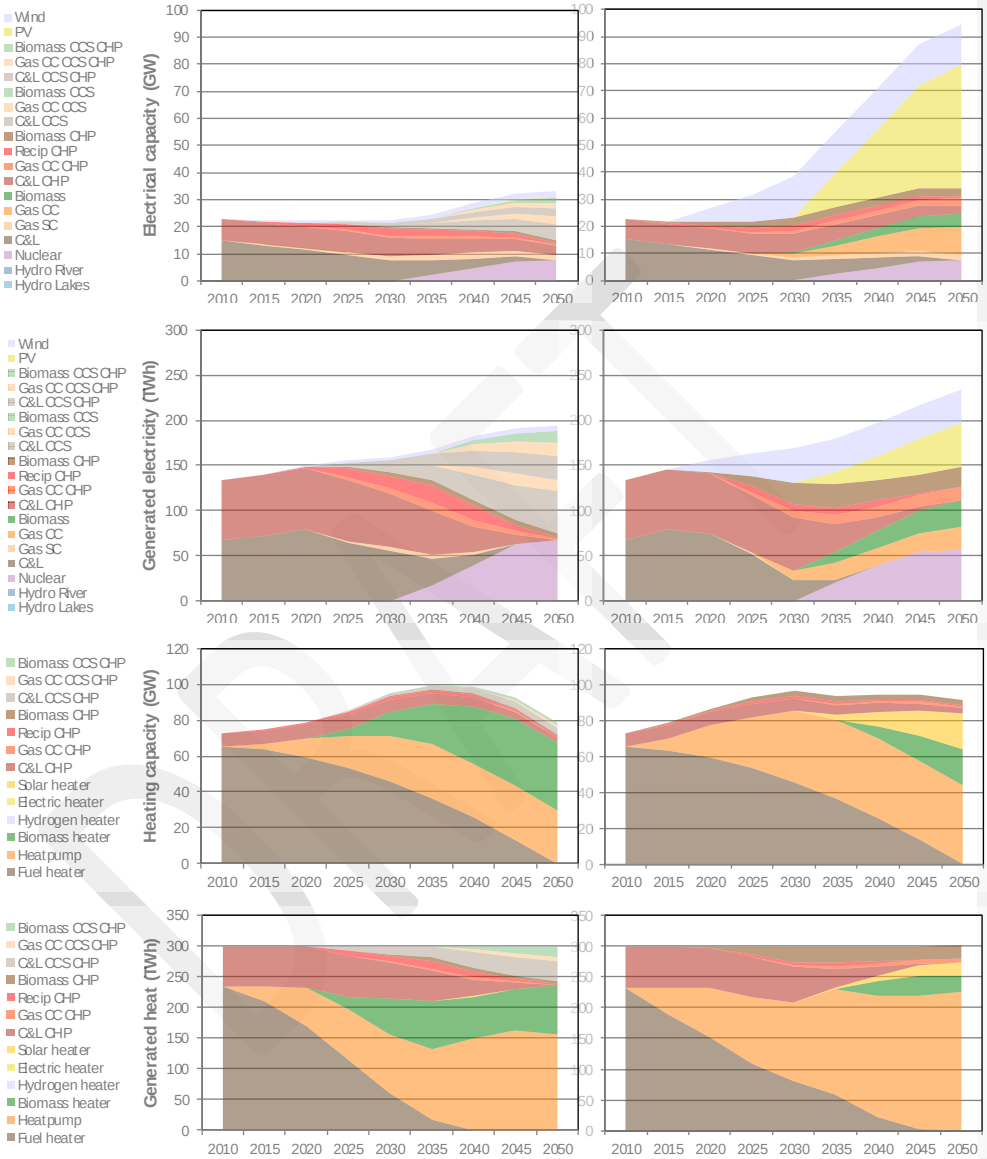


Figure 7: Results for Poland; CCS is available (left), CCS is not available (right).

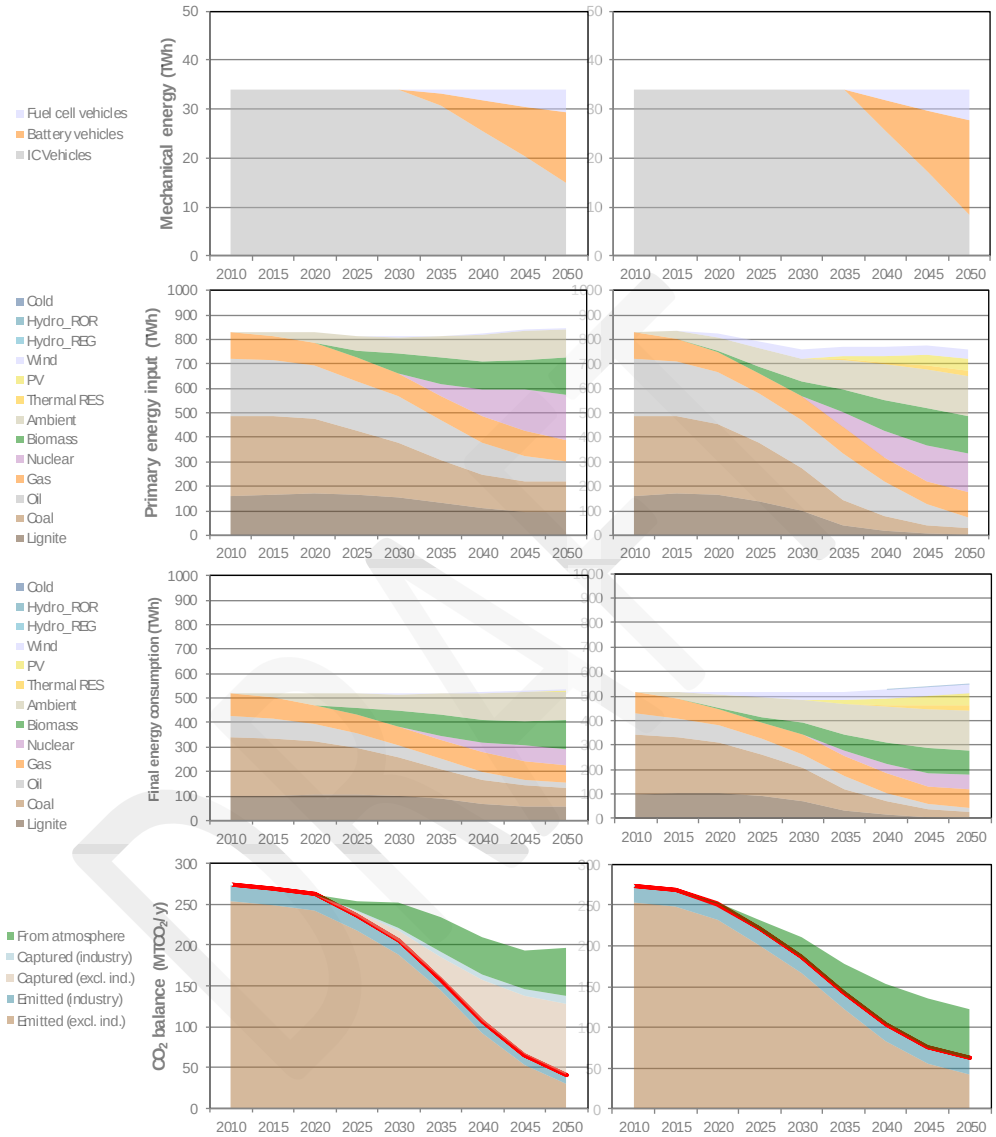
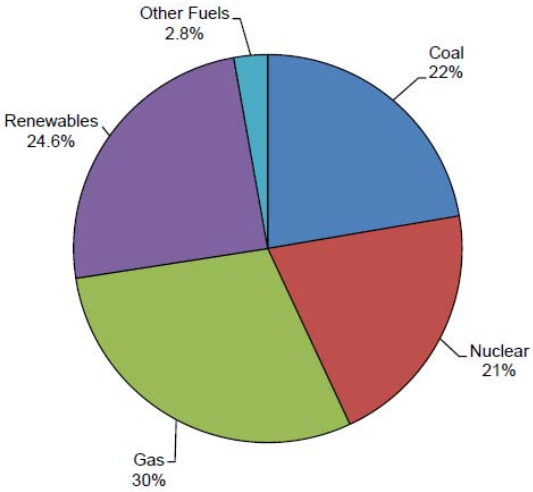


Figure 8: Results for Poland; CCS is available (left), CCS is not available (right).

The United Kingdom cannot meet its legally-binding emissions reduction target without CCS

The UK energy system is a technology mix: North Sea natural gas is most-commonly used for space heating and electricity generation, liquid oil is the dominant fuel for transport, coal still provides a notable share of electricity alongside an ageing nuclear and natural gas fleet and an increasing installed base of renewables.



2015 UK shares of electricity generation, by fuel
(Department for Business, Energy and Industrial Strategy,UK, 2016)

The UK has a flagship policy to 'phase out' the use of unabated coal by 2025 and is currently consulting on the policy instruments and regulatory changes that could help achieve this. Being in the northern half of Europe, solar PV resources are relatively poor but, being on the Atlantic Sea Board, the wind resources are some of the best in Europe, on and off shore. There is also potential for tidal and wave energy around the UK coasts although the economics of such projects are currently not well-understood. There is some application of CHP and district heating although the Committee on Climate Change has concluded that, "*while [district heat networks] can provide an important contribution to decarbonising new and existing buildings, this is limited to around 20% of total building heat demand to 2050 even if deployment challenges can be overcome*"[12]. There are areas of concentrated energy intensive industry in regions such as Humber and Teesside that are close to the North Sea oil and gas fields and infrastructure and have been identified as well-suited for CCS by multiple parties, including regional bodies and trade unions.

The UK has a well-developed natural gas distribution network that can is currently undergoing a major upgrade that makes it well-suited for potential conversion to hydrogen. ZEP considers here an alternative decarbonisation strategy for heating, namely the use of steam-methane reforming with CCS, coupled with domestic hydrogen heaters.

Figure 10 shows again electrical / heating capacity and generation, with and without CCS. The use of primary fuels for pure electricity generation and heating is reducing quickly. Unabated gas combined cycles (CCGT) remain important for electricity generation in the near term although many local commentators, including the CCC and the UK Energy Research Centre, have questioned the future compatibility of unabated gas use with climate commitments. CHP on various fuels grows in both scenarios as does the deployment of solar PV. With CCS available to the model, it is deployed from the early 2020s onwards.

[12] https://www.theccc.org.uk/publication/next-steps-for-uk-heat-policy/

In the heating sector the model chooses a mix of heat pumps, CHP, biomass and hydrogen. However, the latter is relatively small in terms of generated heat. In order to challenge the model, a second set of scenarios was computed where heat pumps are explicitly excluded. Figure 11 shows that, in this scenario, there is a switch of gas use from electricity generation to steam methane reforming for hydrogen heating. In this scenario, biomass is also used extensively used for heating, raising the question of whether sufficient amounts of sustainable biomass can be sourced to meet demand.

If CCS is not available, solid and liquid fuel heaters need to be kept in the system to guarantee supply; this increases the challenge of meeting CO_2 reduction targets. Comparing Figures 12 & 13 shows the differences due to the availability of heat pumps. Without heat pumps, more gas and biomass is needed. If CCS is not available, the model cannot achieve the UK's legally-binding 80% reduction in greenhouse gas emissions by 2050, even with significant deployment of other low carbon technologies.

Figure 9 summarizes total system costs *versus* CO_2 emissions. Again the reduction targets can only be met with CCS. This conclusion remains constant in either scenario, with and without heat pumps available to the model. The latter case shows only slightly higher energy systems costs in 2050, however ZEP considers this to be a result of the limitations of the model and a major underestimate of the expected electricity grid extension costs that are required for heat pumps.

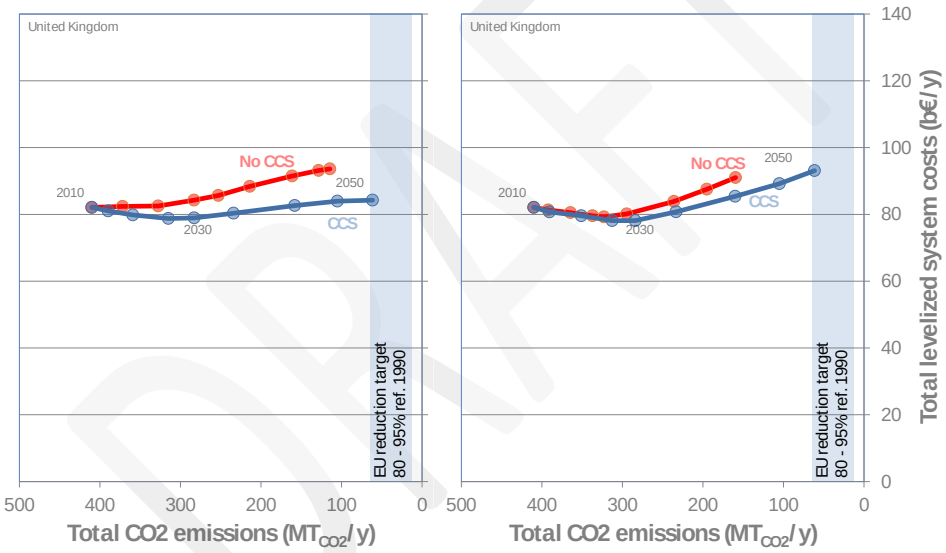


Figure 9: Costs vs. CO_2 emissions for United Kingdom (with CCS, without CCS). Left: Heat pumps are available; right: heat pumps are not available.

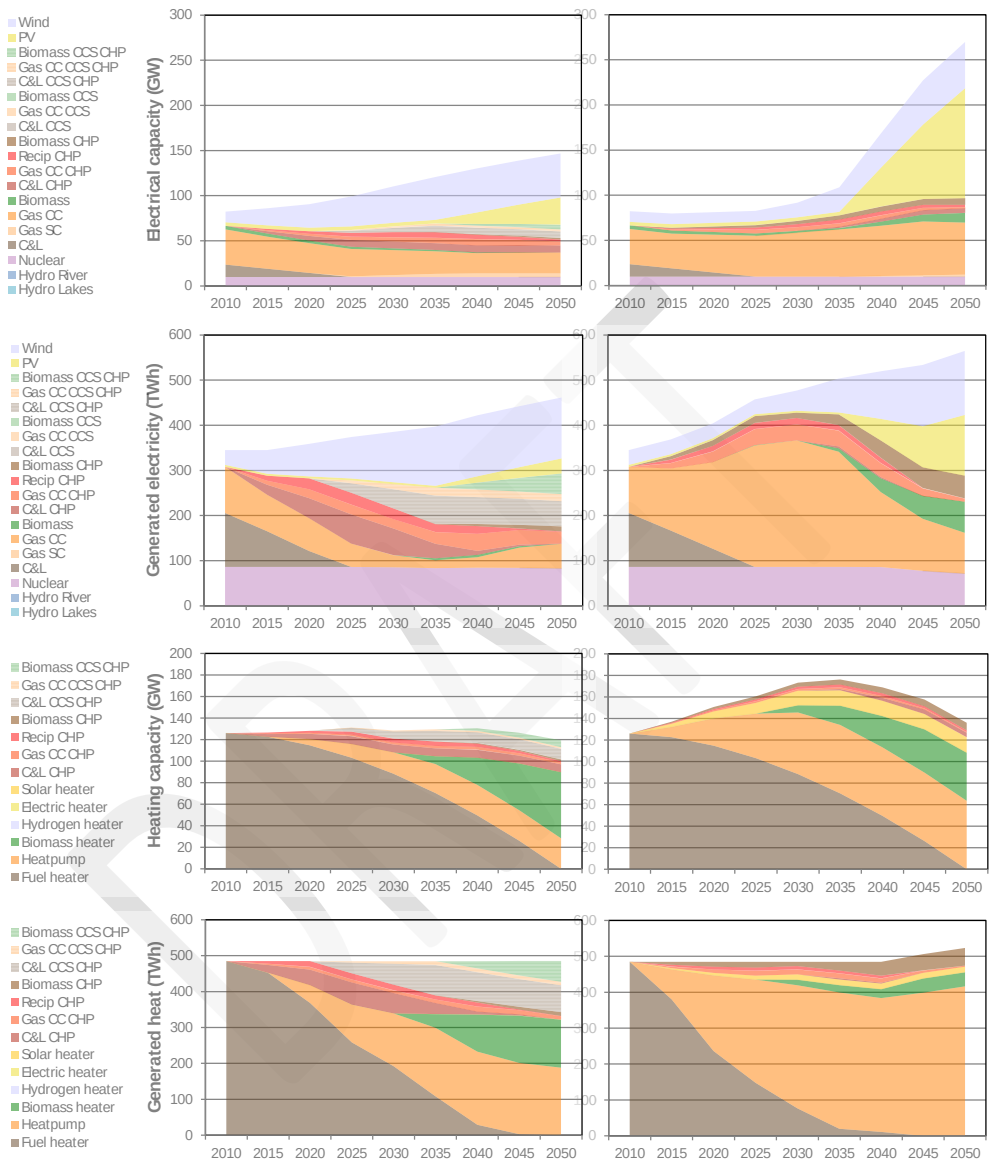


Figure 10: Results for UK; CCS is available (left), CCS is not available (right).Heat pumps are included in the technology mix.

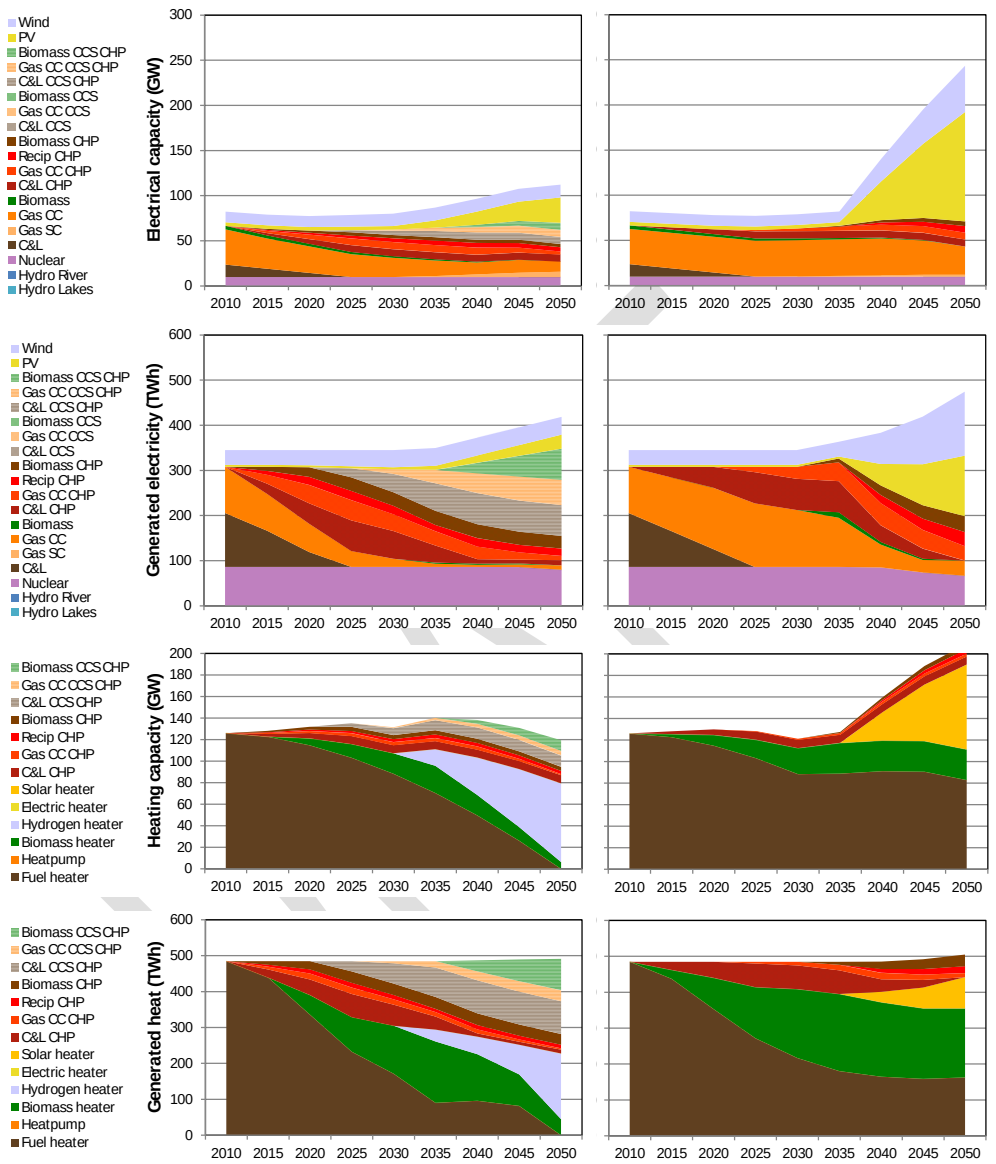


Figure 11: Results for UK; CCS is available (left), CCS is not available (right). Heat pumps are not included in the technology mix.

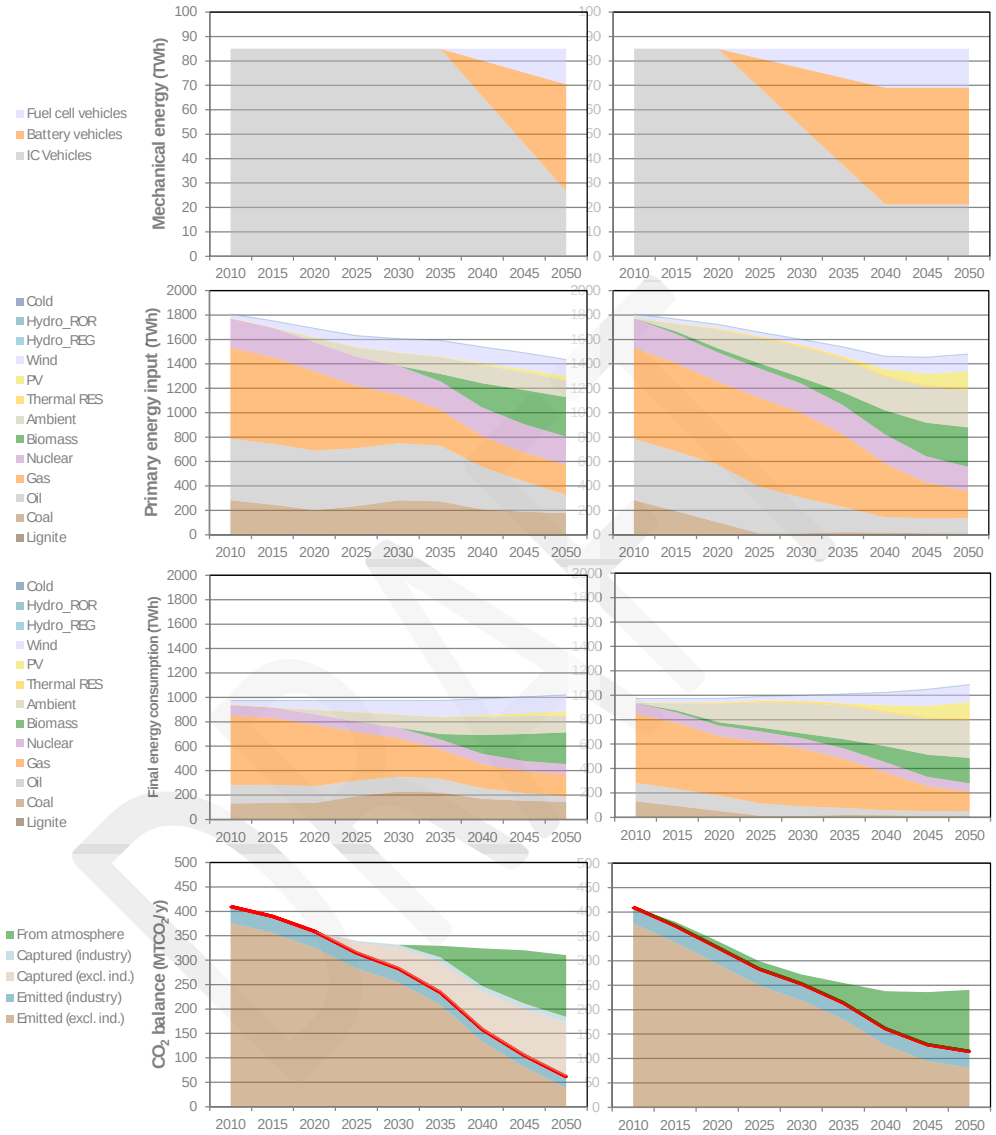


Figure 12: Results for UK; CCS is available (left), CCS is not available (right). Heat pumps are included in the technology mix.

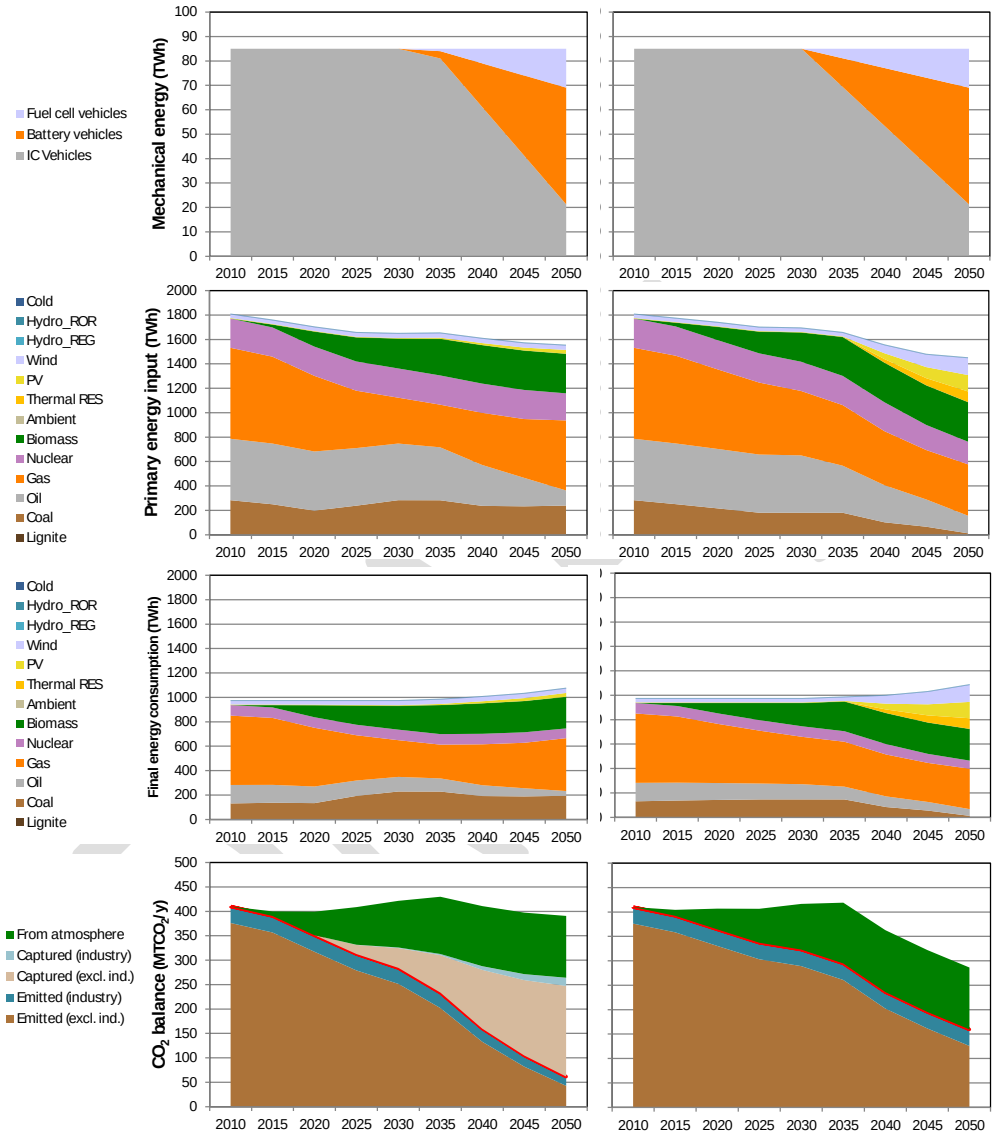


Figure 13: Results for UK; CCS is available (left), CCS is not available (right). Heat pumps are not included in the technology mix.

Netherlands can be the hub of Europe and lead the way on CCS

The Netherlands energy system is a technology mix with a strong reliance on natural gas for space heating and electricity generation, liquid oil for transport, some coal for electricity but no nuclear. Unabated coal is modelled to gradually reduce although the current political debate in the Netherlands may see coal phased-out sooner than expected. Being in the northern half of Europe, solar PV resources are poor but being on the Atlantic sea board the wind resources are good, on and off shore. There are areas of concentrated energy intensive industry that are also close to the North Sea oil and gas fields and infrastructure, in particular at the Port of Rotterdam.

Figures 15 and 16 show the installed electrical and thermal capacity for the two scenarios, with and without CCS. In both cases there is a continuous reduction in the use of primary fuels for purely electricity or heating. This is clearest with methane gas, which, in the Netherlands, is widely used for domestic heating and for electricity in combined cycle plants (CCGT). A growth of CHP and District heating is modelled and methane space heating is also replaced by Heat Pumps and biomass over time.

After 2030 the two scenarios follow different paths: if CCS is available it is deployed on CCGT, for electricity and for CHP. If CCS is not available there is a stronger growth of solar and the total installed capacity for power generation needs to increase around 400% relative to 2010 capacity in order to meet demand. Unabated gas power plants remain in the mix at 2050 and are available to balance fluctuations in solar PV and wind generation. In both scenarios there is large deployment of wind power and solar PV required to meet emissions reduction targets and to support the roll-out of battery-electric and fuel-cell-vehicles in the timeframe from 2025 to 2040.

As Fig 14. shows, there is a difference between the CCS scenario (left) and the non-CCS scenario (right). In both cases a mix of technologies is retained. When no CCS is available a larger installed base of PV is deployed and some solar thermal. The main difference is that, without CCS, the emission in 2050 are higher, meaning that annual emissions are not reduced below 50 $MTCO_2$ per annum and therefore emissions reduction objectives cannot be achieved. In the no CCS scenario, costs to consumers are also increased relative to a technology mix that includes CCS.

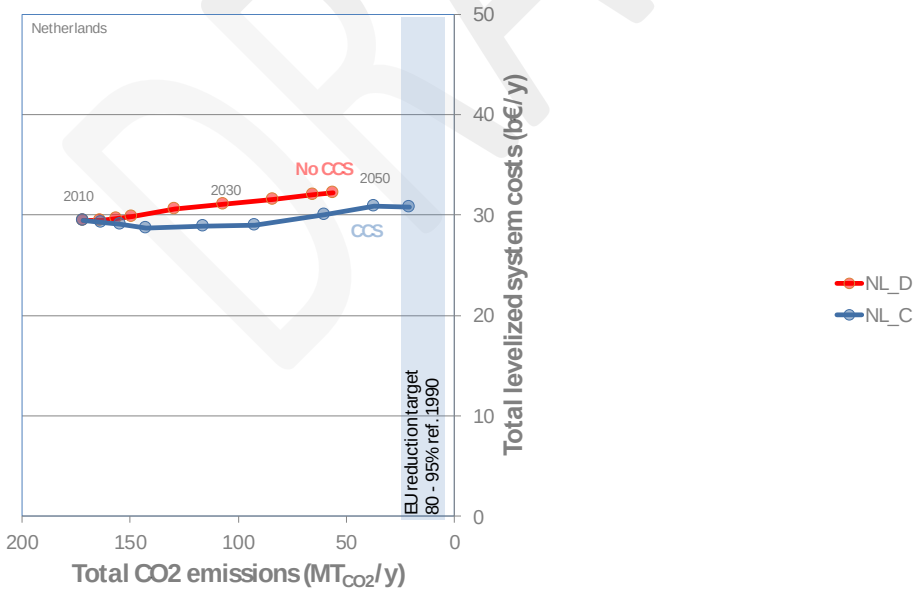


Figure 14: Costs vs. CO_2 emissions for the Netherlands (with CCS, without CCS).

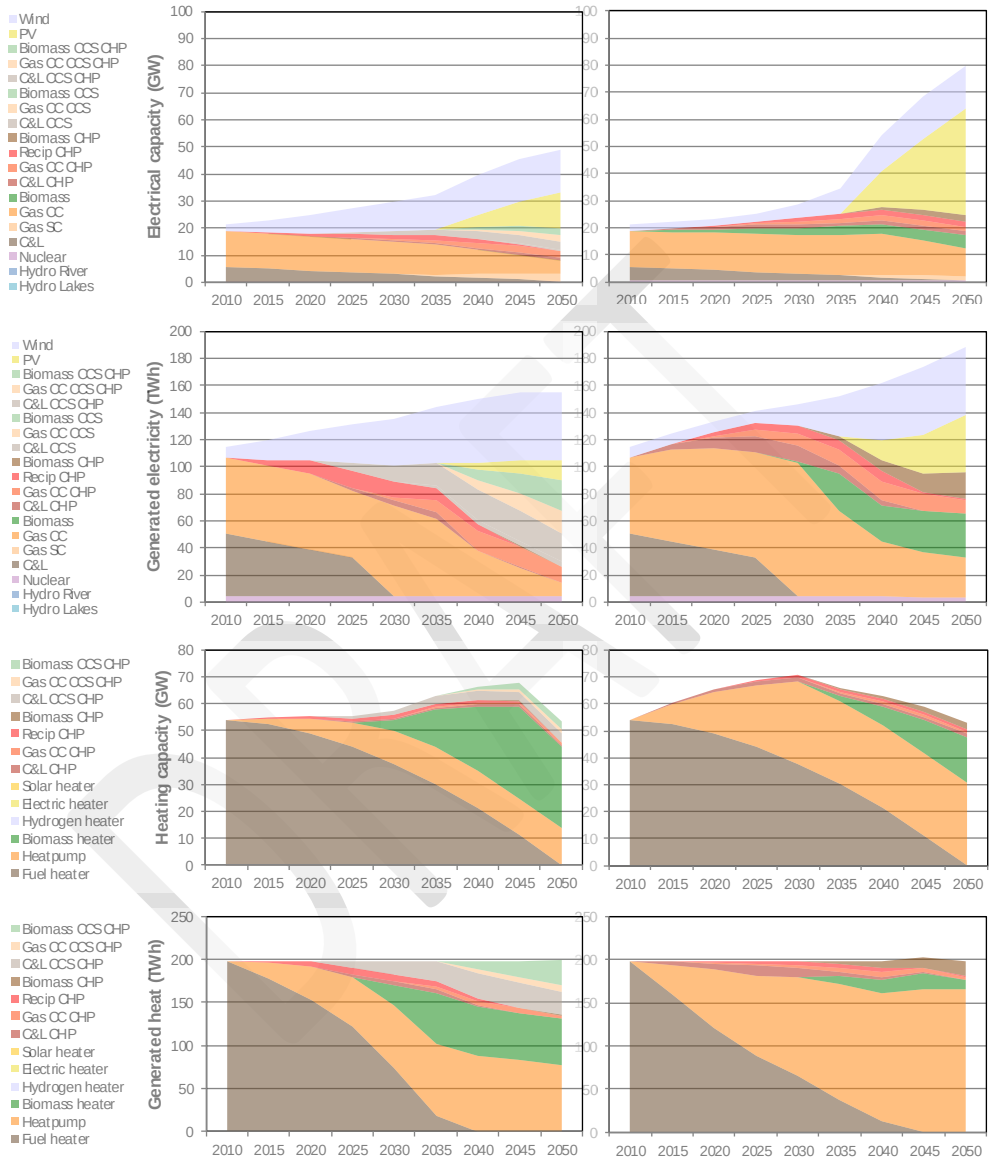


Figure 15: Results for the Netherlands; CCS is available (left), CCS is not available (right).

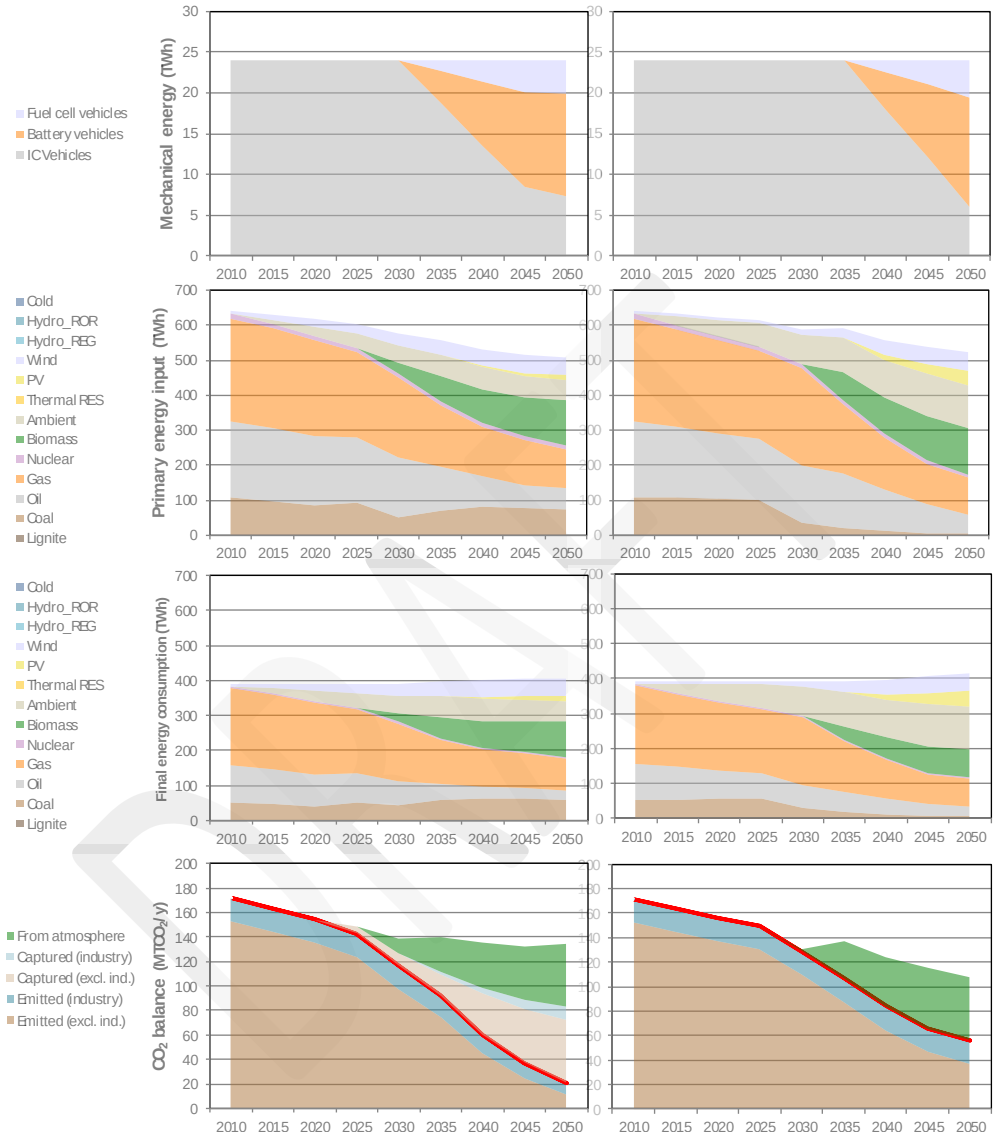


Figure 16: Results for the Netherlands; CCS is available (left), CCS is not available (right).

Spain has great renewable resources – but CCS remains essential

Spain is characterized by very good solar and wind resources. The ratio of heat to electricity consumption is obviously lower than the more Nordic countries Poland and Switzerland. It uses already today gas power to a large extent. We consider again two scenarios, with and without CCS available. The proposed investment strategy shows the common two phases: until 2030 there is a switch from gas combined cycles to gas fired CHP plants; gas and oil fired heating systems are replaced by biomass, CHP and heat pumps, with the first clearly dominating for Spain. After 2030 there is a growth of gas fired CCS plants both with and without CHP.

Due to the strong adoption of CCS, wind, solar and biomass in the Spain case the adoption of electric vehicles is slightly later than in other countries. The reduction of CO2 emissions for transport in Spain takes place after 2030.

The Energy Intensive industries are modelled to adopt CCS (in the cases where CCS is turned on). The impact of this can be seen in the CO2 balance curves.

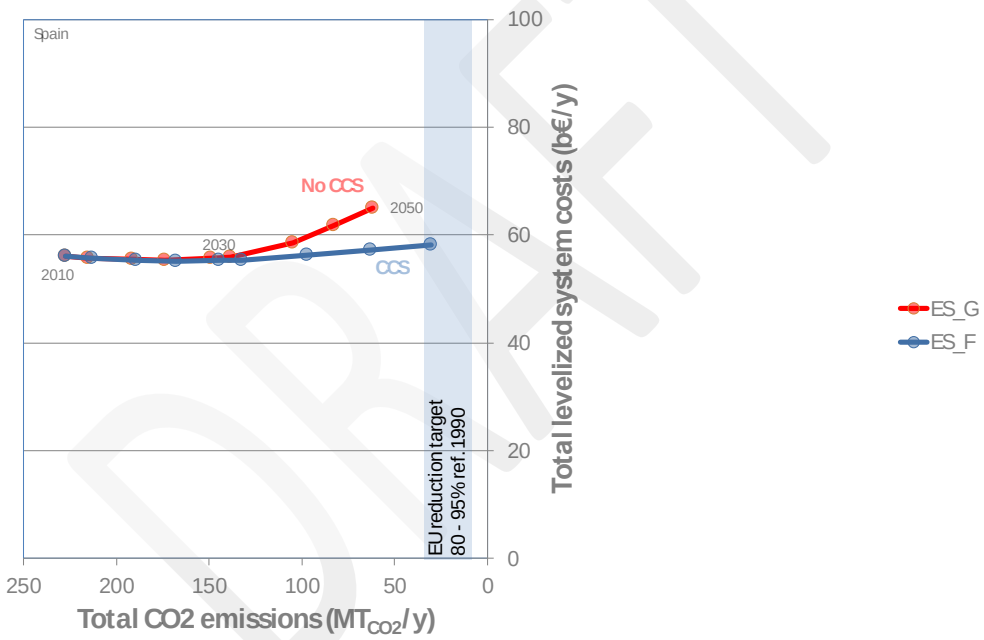


Figure 17: Costs vs. CO_2 emissions for Spain (with CCS, without CCS).

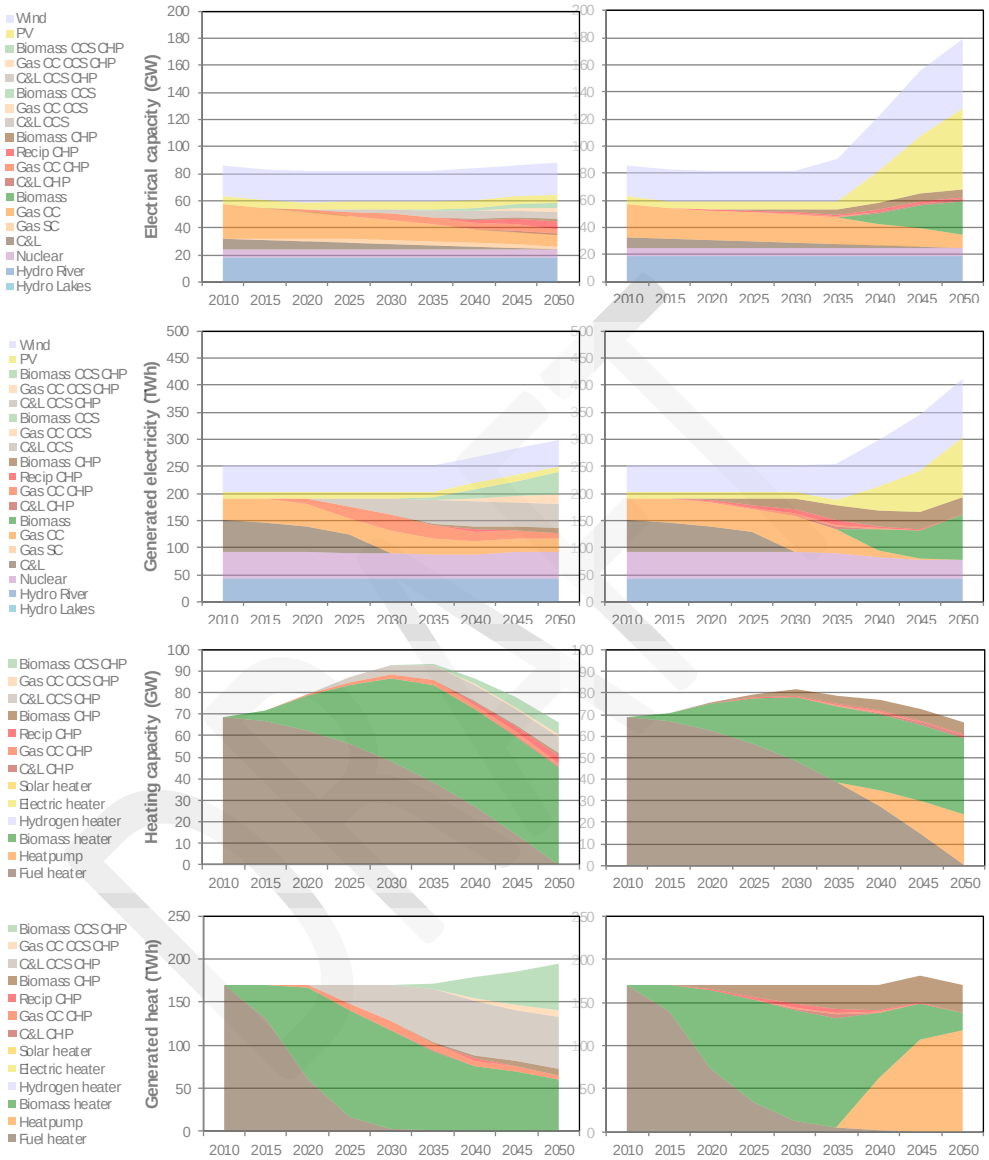


Figure 18: Results for Spain; CCS is available (left), CCS is not available (right).

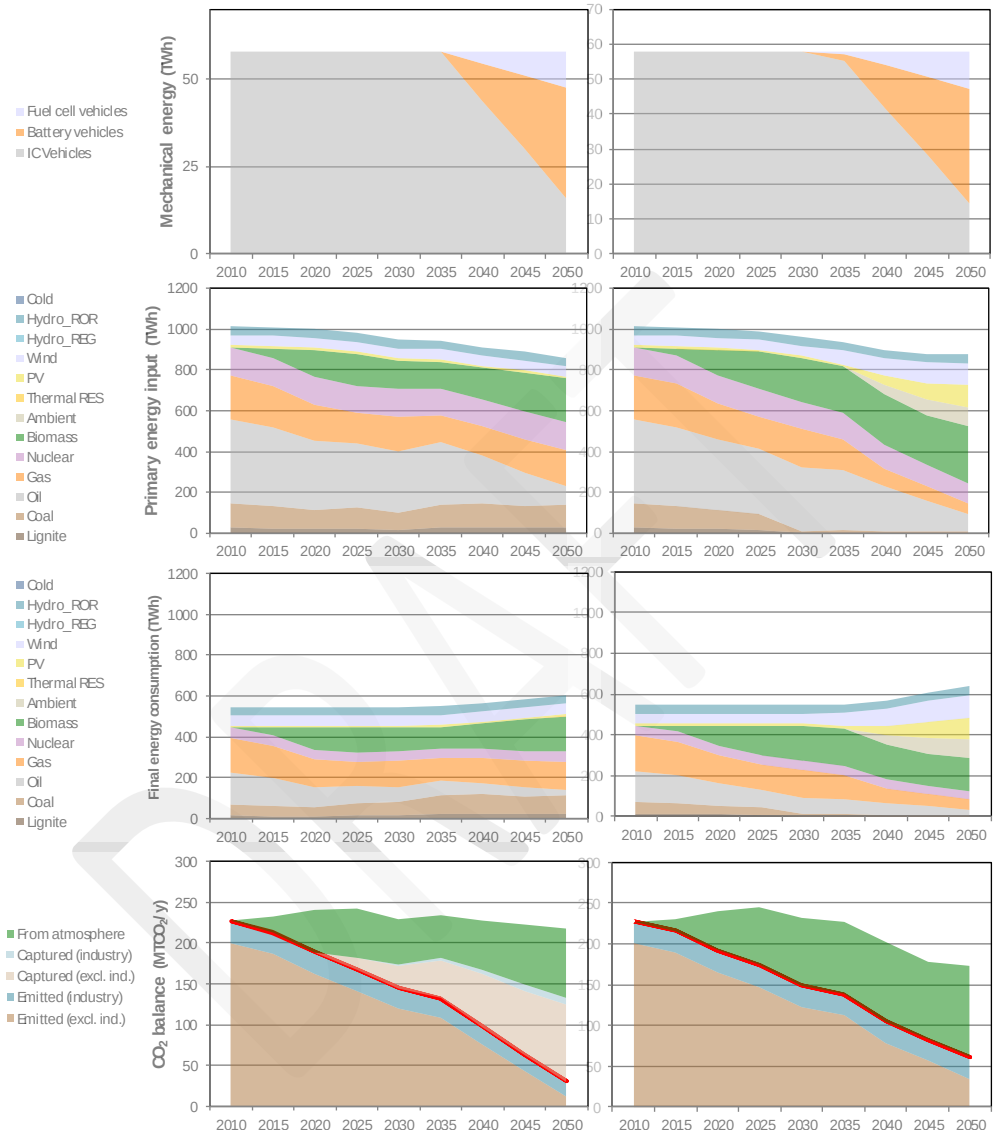


Figure 19: Results for Spain; CCS is available (left), CCS is not available (right).

Switzerland

The Swiss electricity system is currently based on two pillars, hydro power and nuclear which account for 60% and 40% of the electricity generation, respectively. Notwithstanding this zero-CO2 power generation, the Swiss energy sector emits approx. 45 Mt_{CO2} per year, mostly from burning oil and gas for space heating, road transportation and to a smaller extent industrial processes. The government of Switzerland has decided to discontinue nuclear power within the next 10-20 years. In addition there is an intense discussion on the so-named Energiestrategie 2050, which aims at reductions of CO2 emissions down to approx. one t_{CO2} per person and year.

The special challenge of the energy transition in Switzerland is to replace CO2-free nuclear power by other sources, while reducing at the same time the overall emissions from the energy sector. We show the mix of installed electrical and thermal generation capacity for the two scenarios: (1) CCS is available; (2) CCS is not available (see Fig. 21 and 22). We can clearly see the strong growth of gas fired combined cycle power plants in both scenarios. From 2030 onwards there is a bifurcation: combined cycles with CCS are deployed when available; if not, there is a strong growth of solar PV and wind. The heating sector shows a similar trend as for the other countries, i.e. a replacement of gas & oil-fired burners by heat pumps, CHP and biomass. Due to the low wind resources and the strong hydro and solar resources, renewable in Switzerland focus on hydro, solar and biomass.

The cost vs. CO2 emission curve shows that Switzerland can reach the target with CCS but not without. This is due to the high share of hydro power together with a relatively small industrial sector. The conversion from oil to heat pumps for space heating provide early cost and emissions benefits when CCS permits the electricity supply to be dependable and near CO2 free and in the absence of nuclear. The conversion of the private transport system occurs from 2030 and also reduces oil use, cost and emissions. Bio CCS is an important piece of the picture providing CO2 negative emissions. Switzerland is modelled to meet the 1tonCO2 per capita budget by 2050 in the CCS case but not without CCS.

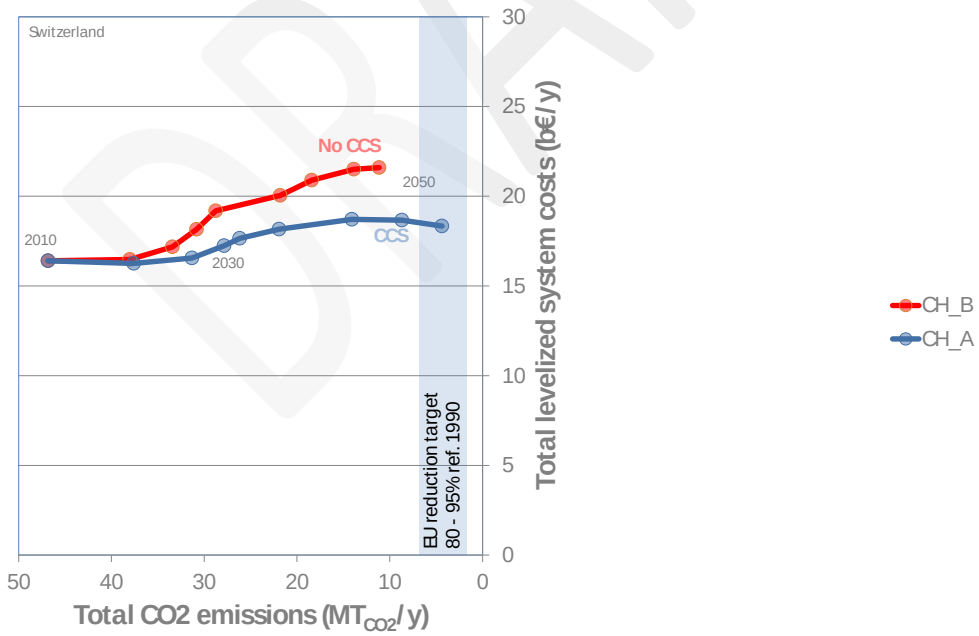


Figure 20: Costs vs. CO_2 emissions for Switzerland (with CCS, without CCS).

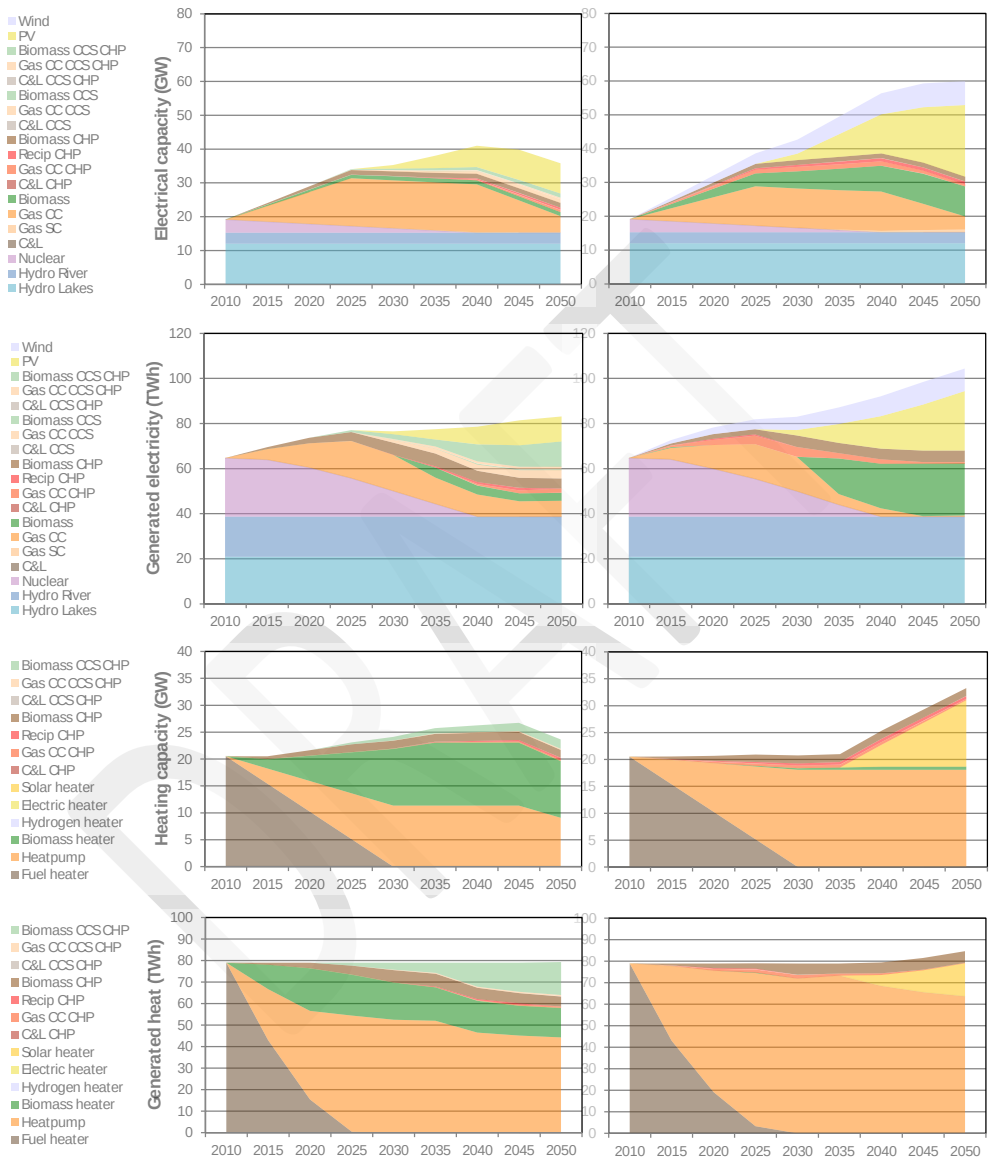


Figure 21: Results for Switzerland; CCS is available (left), CCS is not available (right).

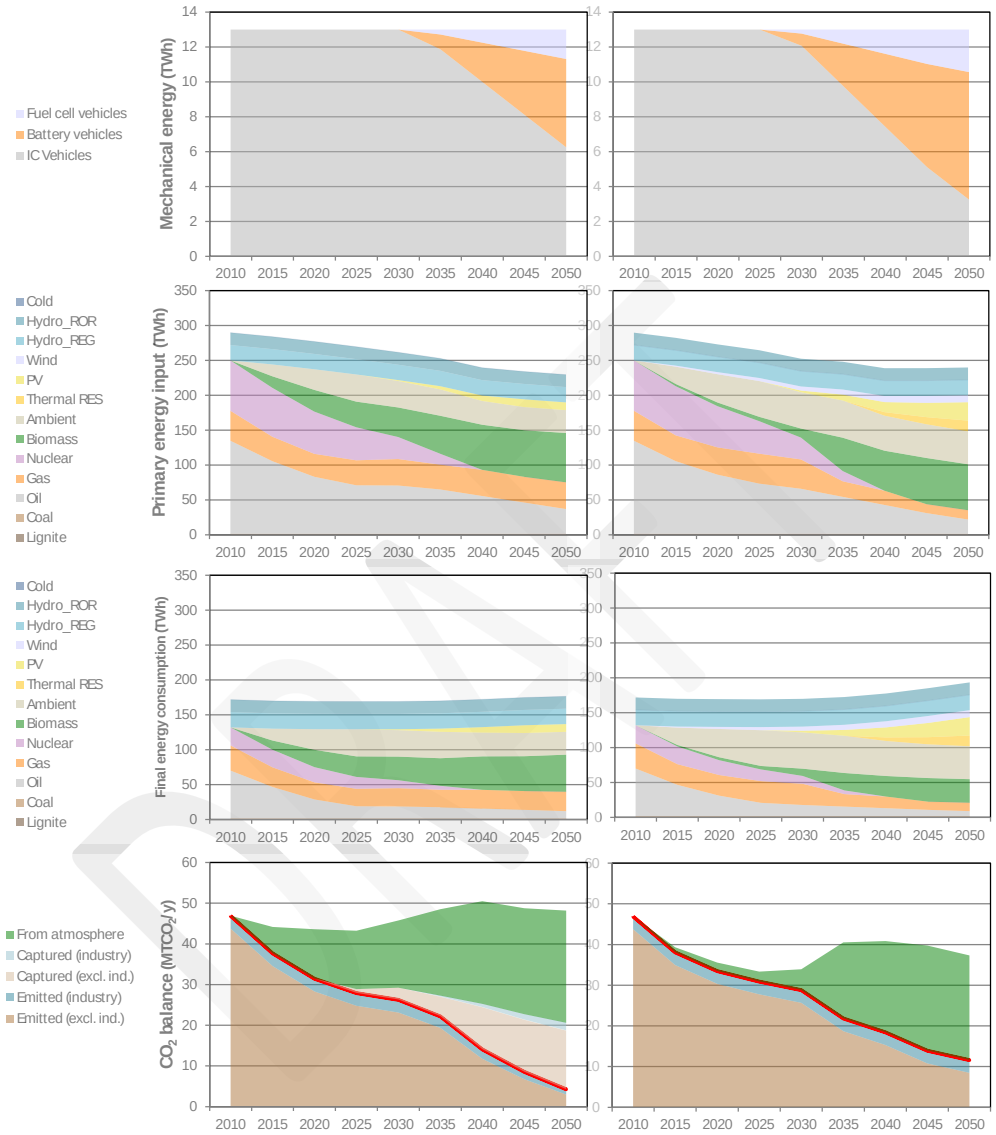


Figure 22: Results for Switzerland; CCS is available (left), CCS is not available (right).

Greece

The Greek electricity system was traditionally based on coal as primary fuel. There has been a switch to gas in the past years. The proposed scenarios show a diversification of the energy mix from coal to gas, CHP, PV and wind. If CCS is available, it is deployed mostly on gas combined cycles. The heat generation is to a large extent CHP if CCS is available. If not heating is supplied by heat pumps.

Since the use of natural gas was very low for Greece at the beginning of the time horizon, it was decided to relieve the condition that the primary gas input shall not grow. As a consequence, gas replaces coal as primary fuel, a development that other countries like UK and Italy have made previously.

Figure 23 shows as usual that the 85% target can only be reached with CCS.

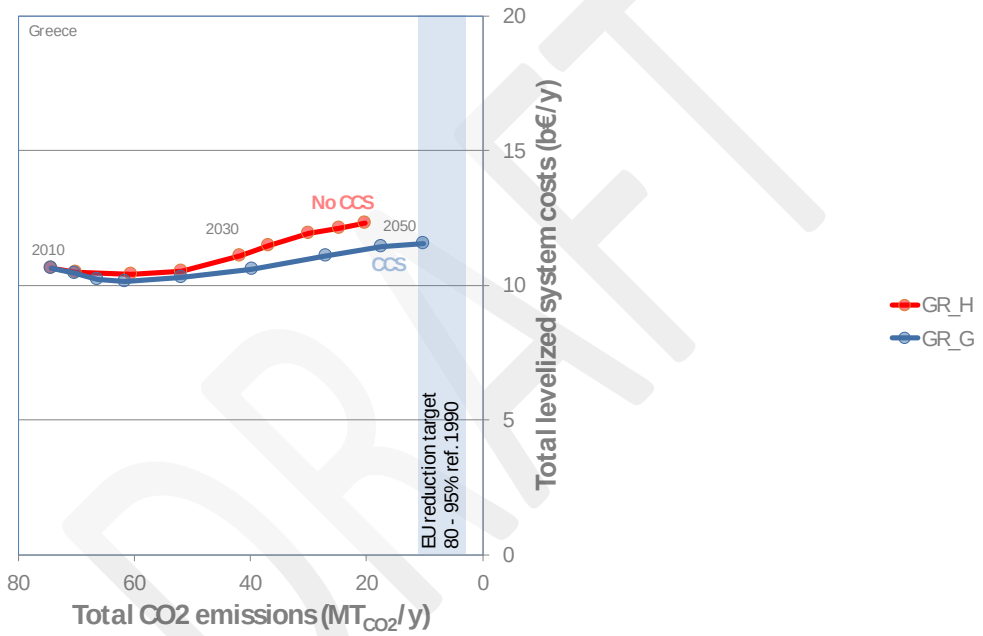


Figure 23: Costs vs. CO_2 emissions for Greece (with CCS, without CCS).

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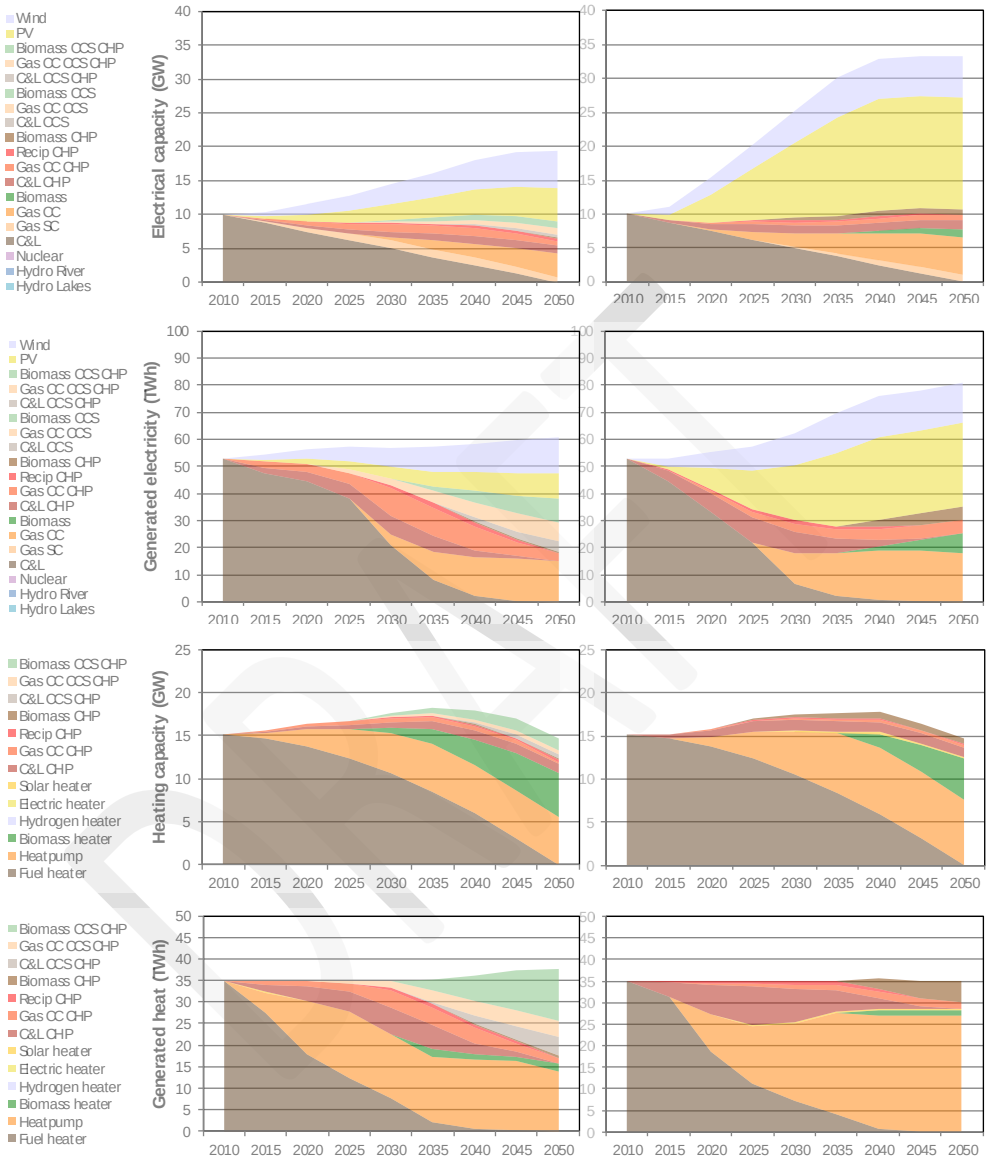

Figure 24: Results for Greece; CCS is available (left), CCS is not available (right).

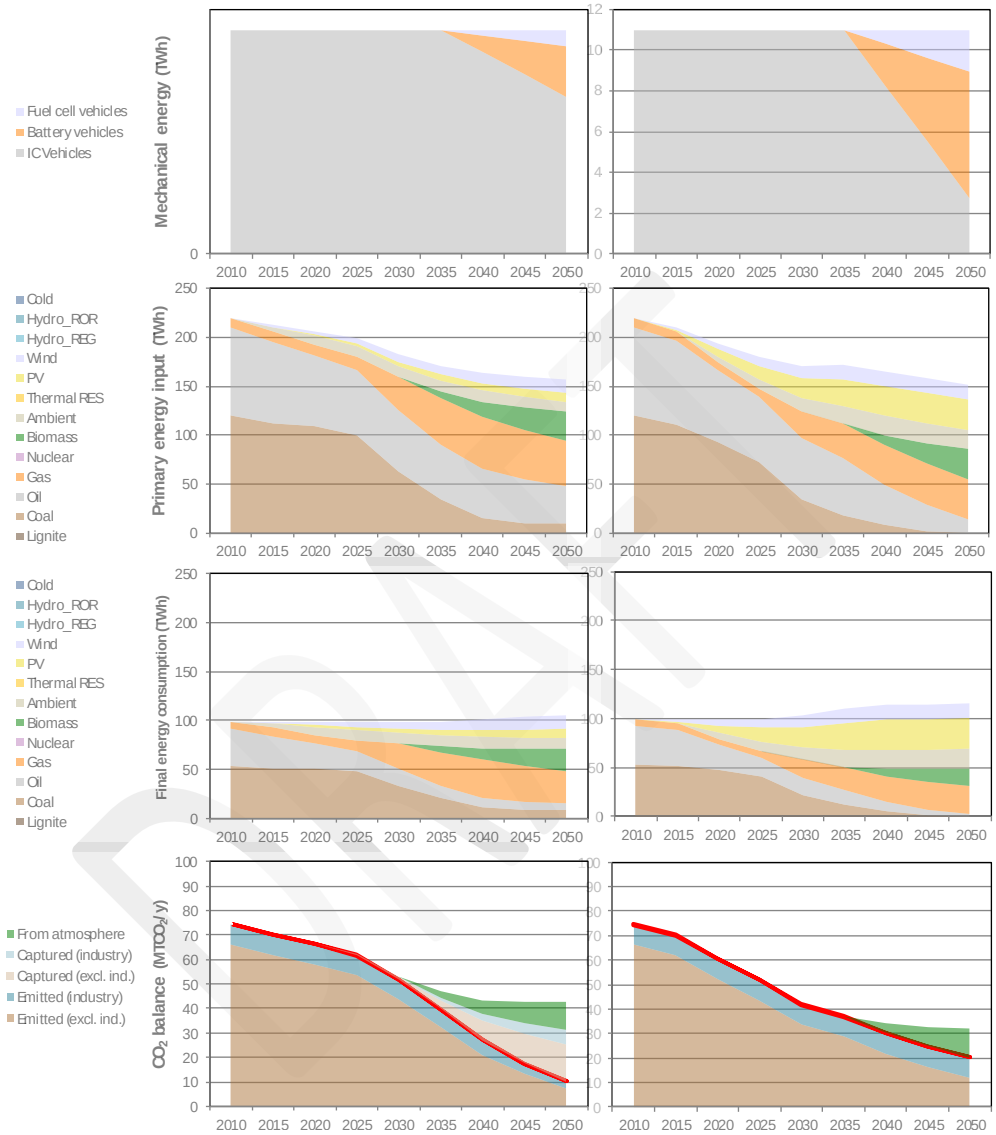

Figure 25: Results for Greece; CCS is available (left), CCS is not available (right).

Italy

Italy in the model follows a similar route to other southern European industrial countries. With good Solar resources this forms significant part of the mix in all cases along with existing Hydro and wind. Italy adopts biomass as a low CO2 fuel in all cases and uses the biomass for the lowest cost lowest CO2 emitting applications. In the cases with CCS the renewables are integrated more efficiently and half the volume of CO2 is emitted in 2050. The cost is also substantially lower in the CCS case. Without CCS Italy cannot meet its minimum goal for emissions reduction in 2050.

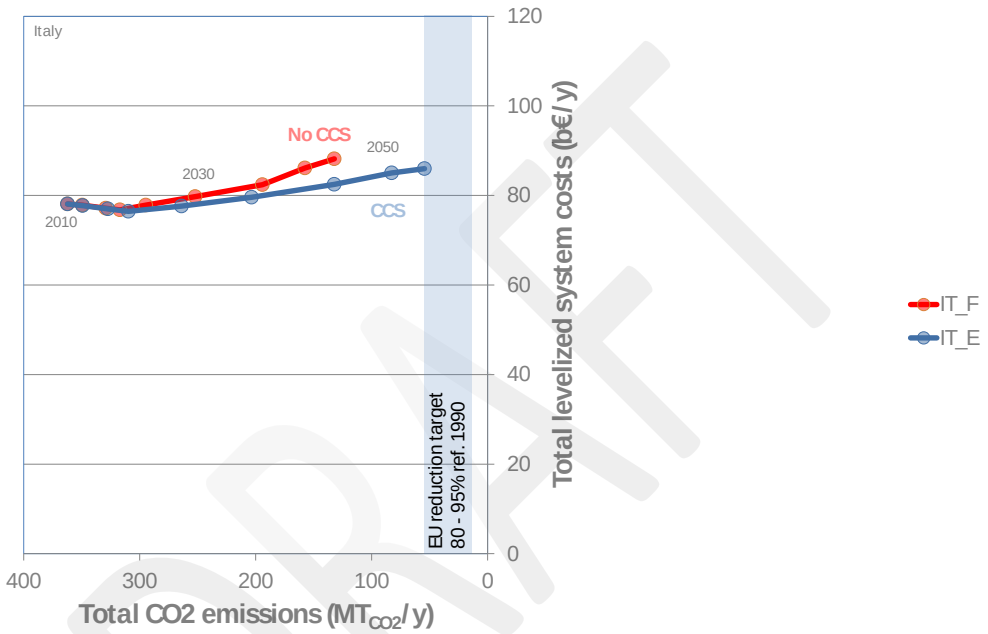

Figure 26: Costs vs. CO_2 emissions for Italy (with CCS, without CCS).

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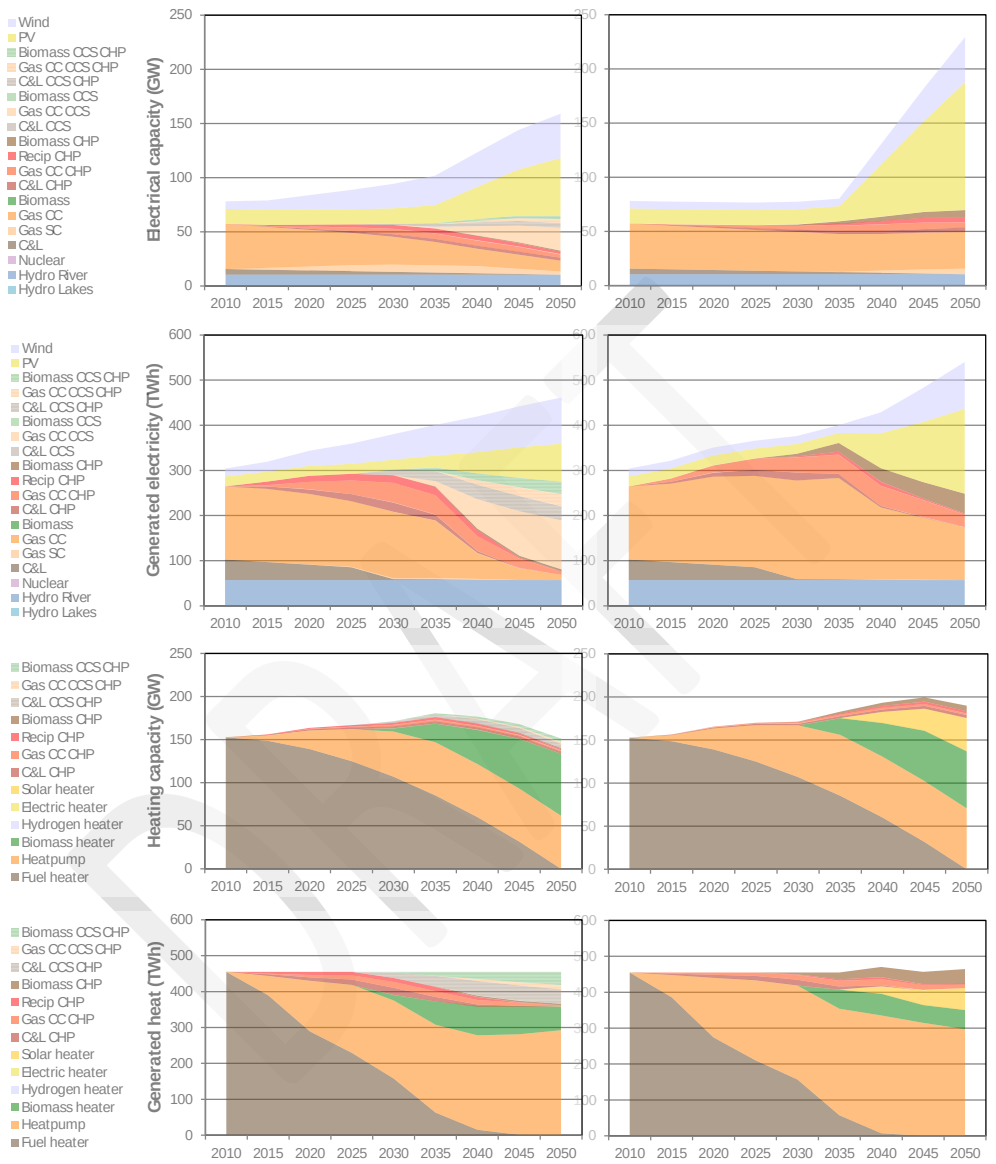

Figure 27: Results for Italy; CCS is available (left), CCS is not available (right).

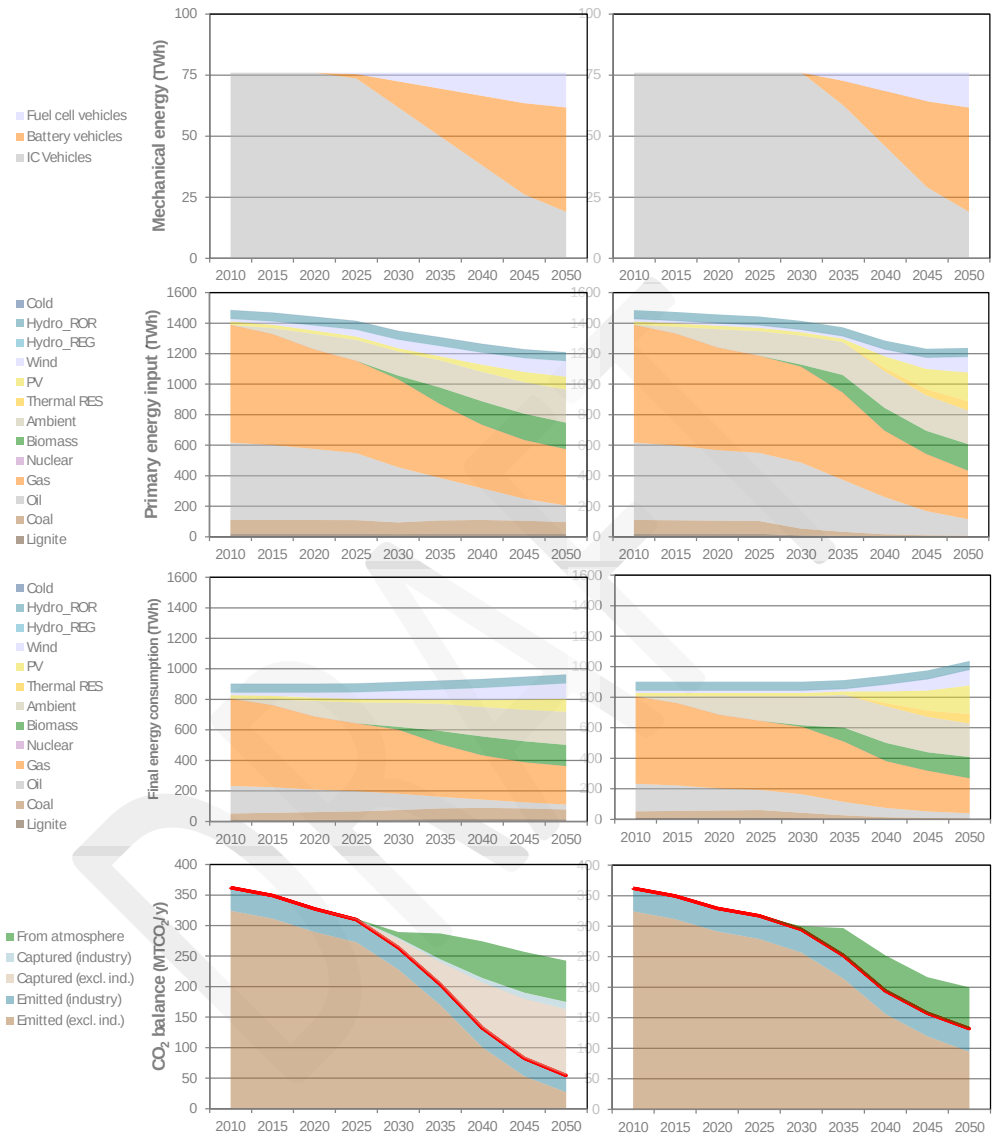

Figure 28: Results for Italy; CCS is available (left), CCS is not available (right).

France

The energy system of France is dominated by near CO2 free Nuclear and Hydro in electricity generation and combustion of gas and oil for space heating and industrial processes. The current CO2 emission per capita at 5tons per annum is about 60% of the average of the 10 countries.

The national policy to maintain the nuclear fleet drives the early adoption of electic vehicales from 2025. Excess capacity in the nuclear fleet is used to increase electricity production to allow electricification. With strong wind resources this becomes an important part of the fleet.Together with hydro capacity this mix gives France a strong base for CO2 emissiomns reduction using CCS on the industrial emsiions and CHP CCS plant and heat pumps and biomass for space heating.

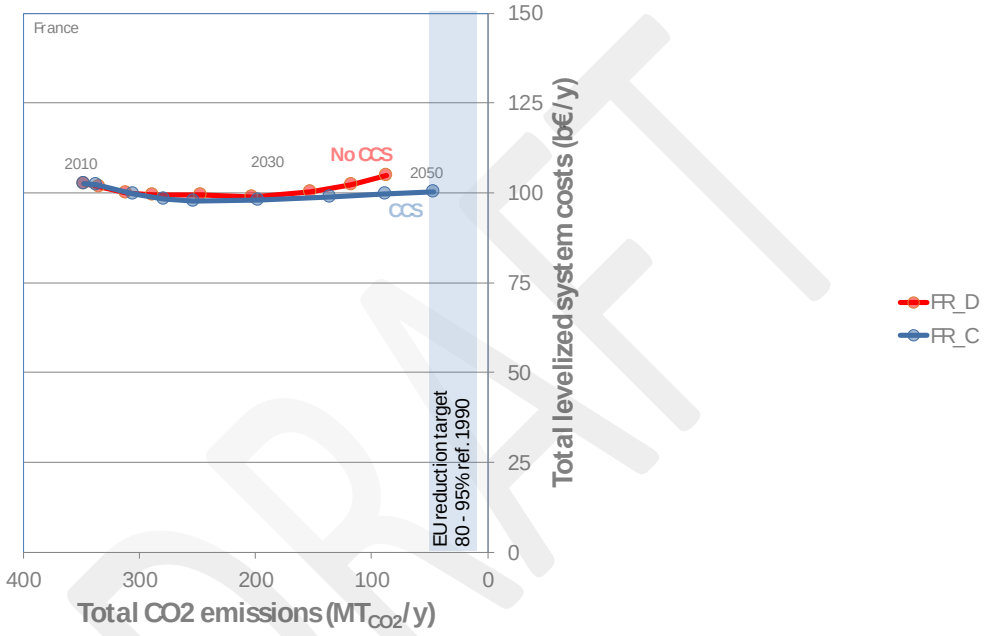

Figure 29: Costs vs. CO_2 emissions for France (with CCS, without CCS).

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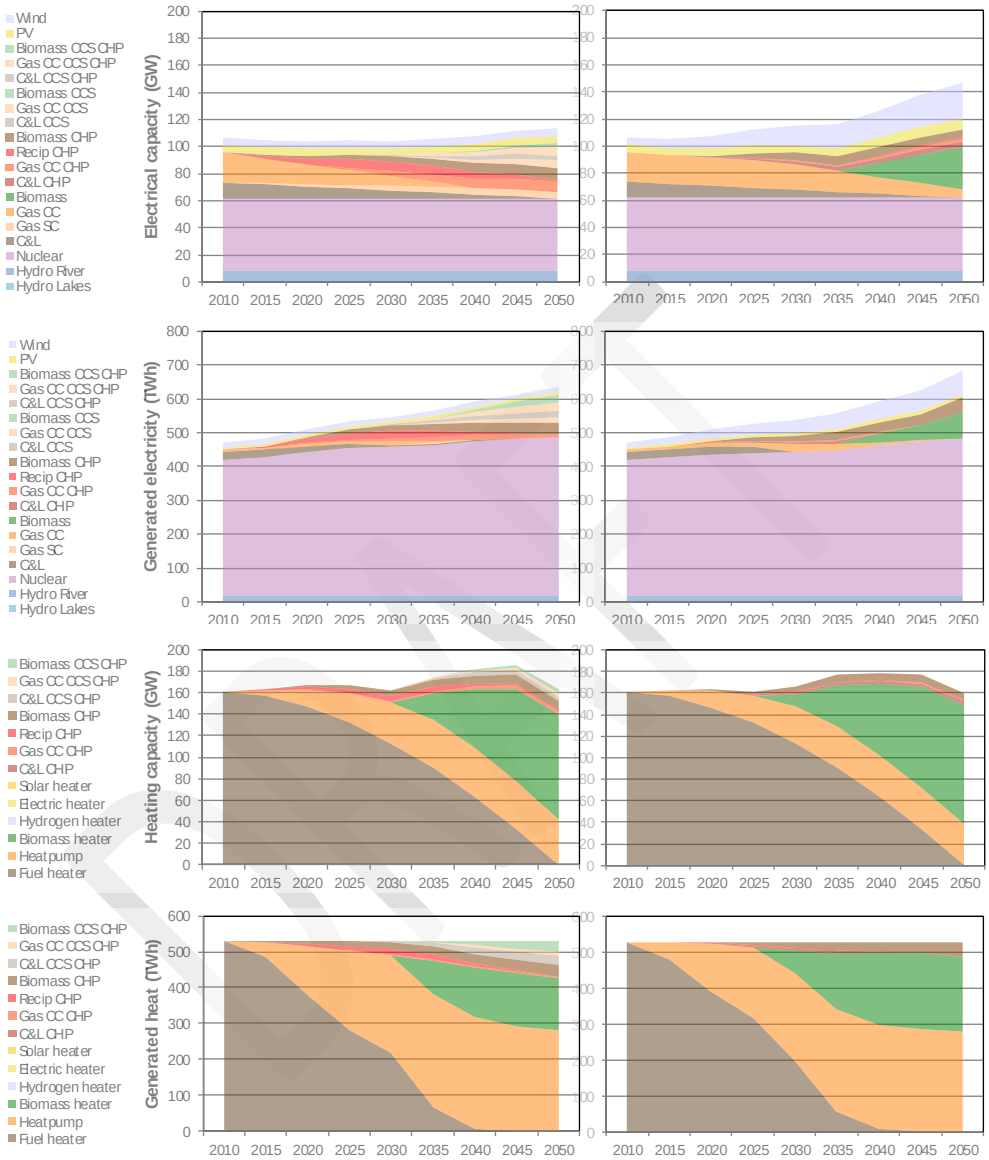

Figure 30: Results for France; CCS is available (left), CCS is not available (right).

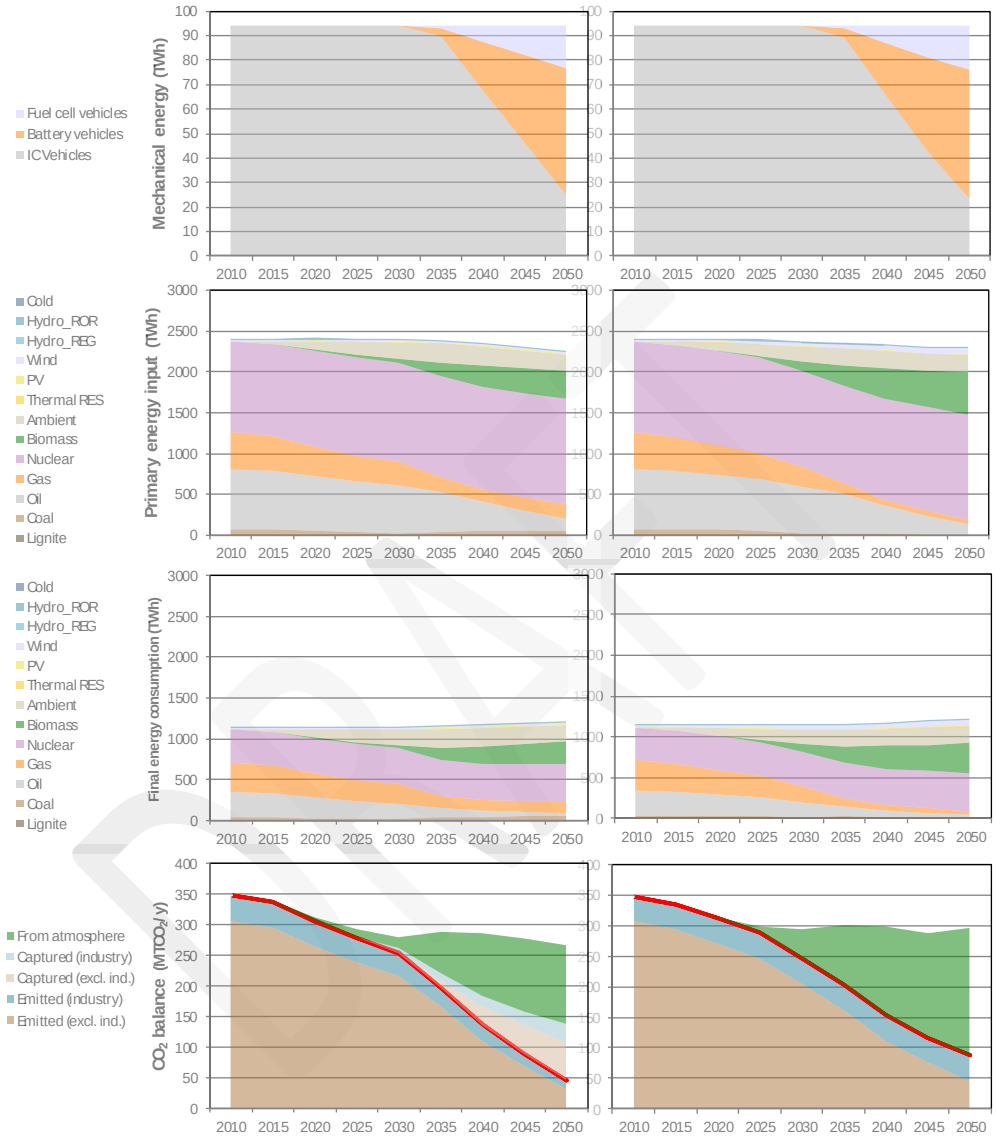

Figure 31: Results for France; CCS is available (left), CCS is not available (right).

Germany

Germany has a strong mix of technologies for electricity and heat, and also a large industrial emission base. The policy to discontinue the use of nuclear leads to a strong growth of wind and solar in both the CCS and non-CCS cases. The use of unabated coal and lignite gradually reduces and is replaced by coal and lignite CCS and Gas CCS in the CCS case. In the non CCS case it is replaced by further gas fired generation and biomass partly in CHP where possible.
For space heating heat pumps are widely adopted along with CHP and district heating schemes and biomass heaters.
For transport Germany is modelled to be an adopter of electric vehicles from 2030 on.
Since industrial emission are an important volume in Germany we see that for the CCS case a visible level of industrial CO2 emissions reduction applying CCS to industry and in 2050 the residual industrial CO2 emissions are shown as larger than the residual CO2 emissions from electricity and heating. There could well be scope to apply CCS more widely on these residual emissions than has so far been allowed in the model.
Again Germany is modelled to only meet its emission reduction target if CCS is part of the mix.

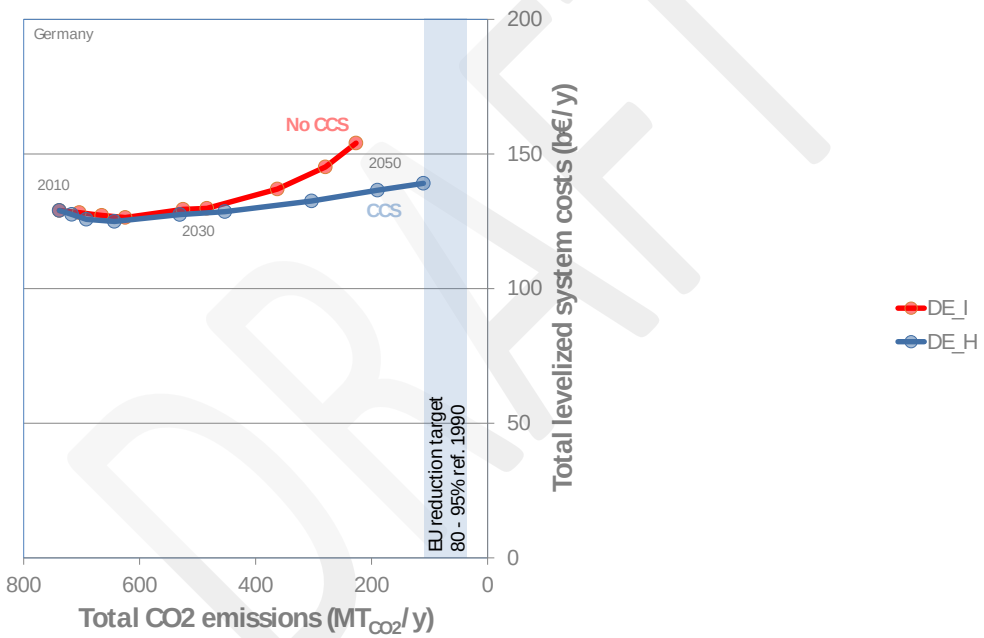

Figure 32: Costs vs. CO_2 emissions for Germany (with CCS, without CCS).

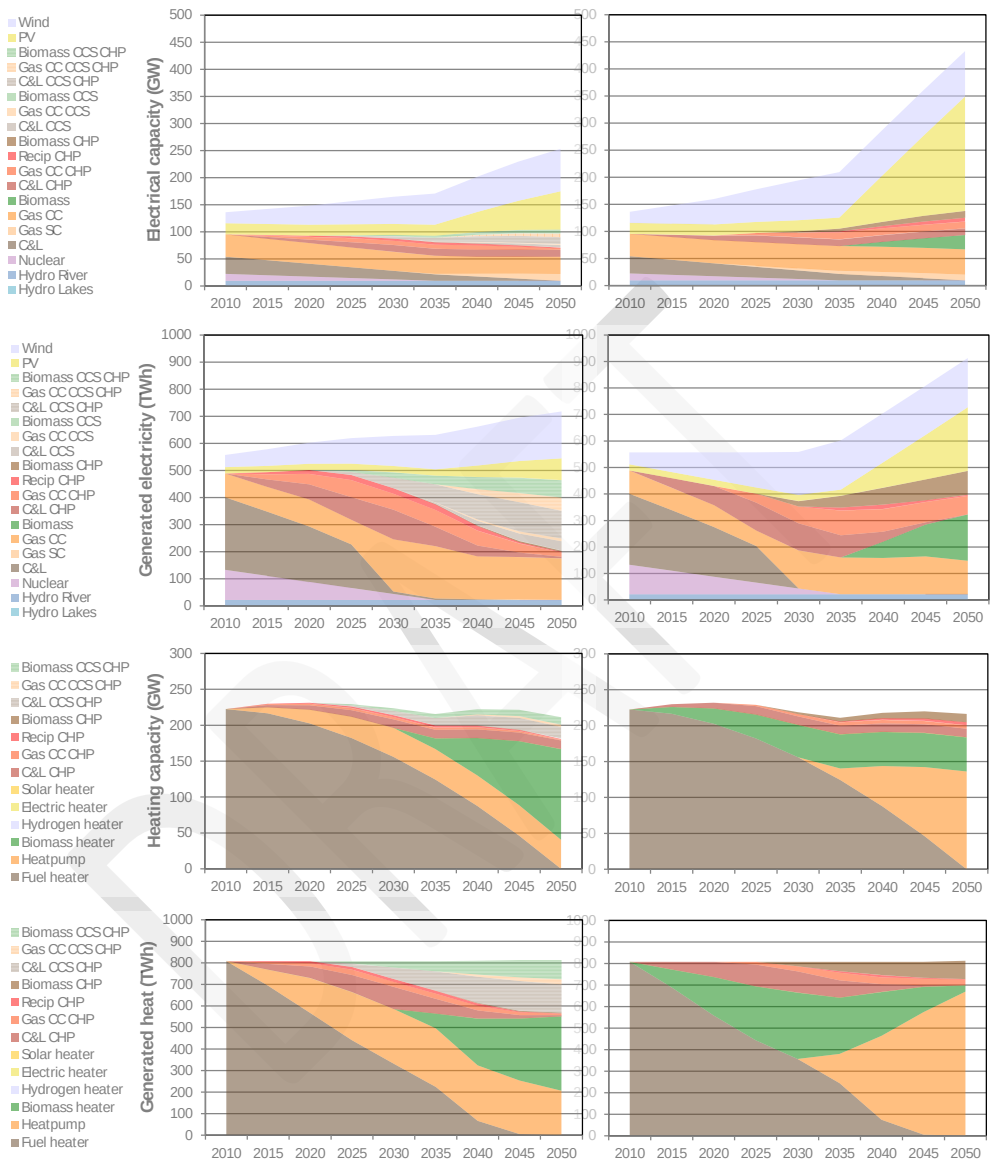

Figure 33: Results for Germany; CCS is available (left), CCS is not available (right).

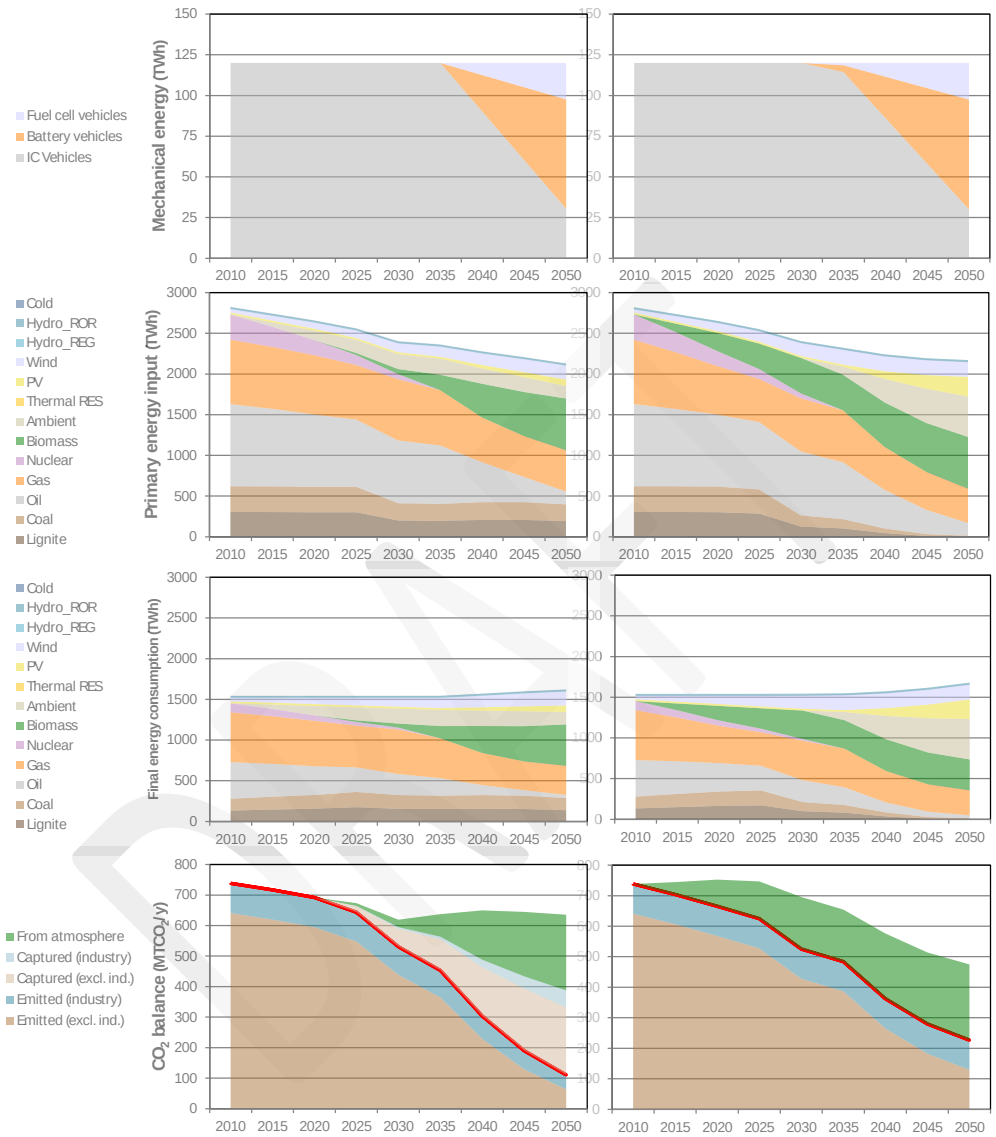

Figure 34: Results for Germany; CCS is available (left), CCS is not available (right).

Norway

Norway is an exceptional case in many respects. It is blessed with enormous hydro power resources that produce close to 100% of the electricity demand. With emissions free electricity being available also the heating sector is almost CO2 free. The dominant technology is the simple electrical heater followed by heat pumps and to a small extent oil and gas furnaces. Only the transport sector and the relatively large industrial sector emit CO2.

The obvious strategy for decarbonisation is therefore an electrification of transport. The model adopts electric vehicles from 2025 onwards. The required electricity can be obtained by increasing the energy efficiency of the heating sector, i.e. by replacing some electrical heaters by heat pumps. CCS plays only a role for the energy intensive industries, mostly oil & gas and cement.

The remaining CO2 emissions are related to other industrial sectors which cannot easily use CCS. A possible way to overcome this limit would be to use biomass as primary energy input, however, such substitution was not modelled within this work.

Figure 35 shows indeed that an 85% reduction is not possible when starting from an almost CO2-free electricity system.

The cost of applying CCS on Industry is uniquely shown in the Norway case. While the other countries of Europe see cost savings by avoiding imported fuels and by efficiency in the heating sector, the Norwegian industry sees the cost of reducing its emissions using CCS something that cannot be avoided if industry is to continue in a low CO2 emitting Europe.

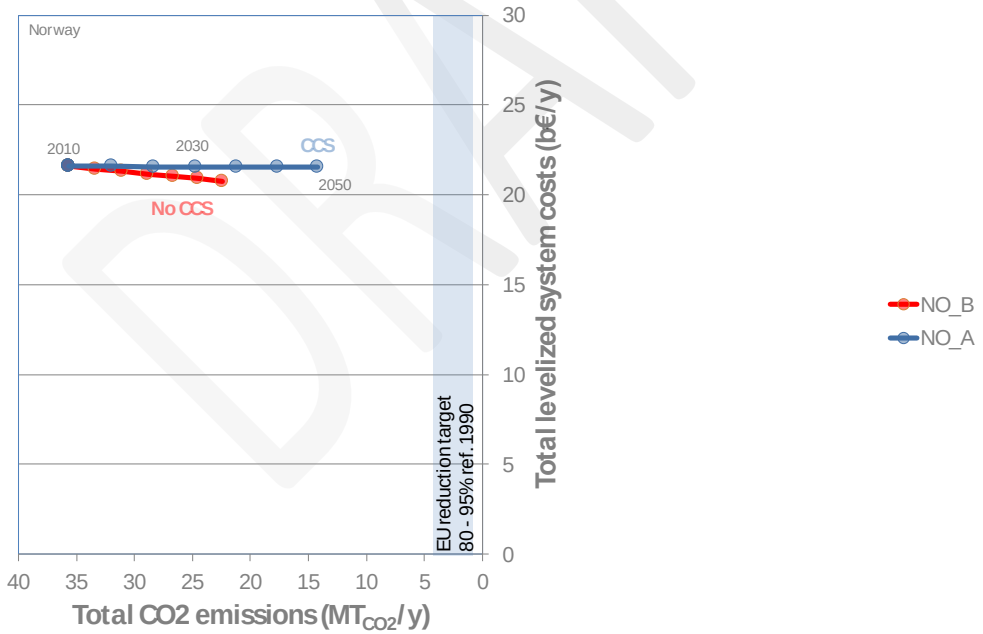

Figure 35: Costs vs. CO_2 emissions for Norway (with CCS, without CCS).

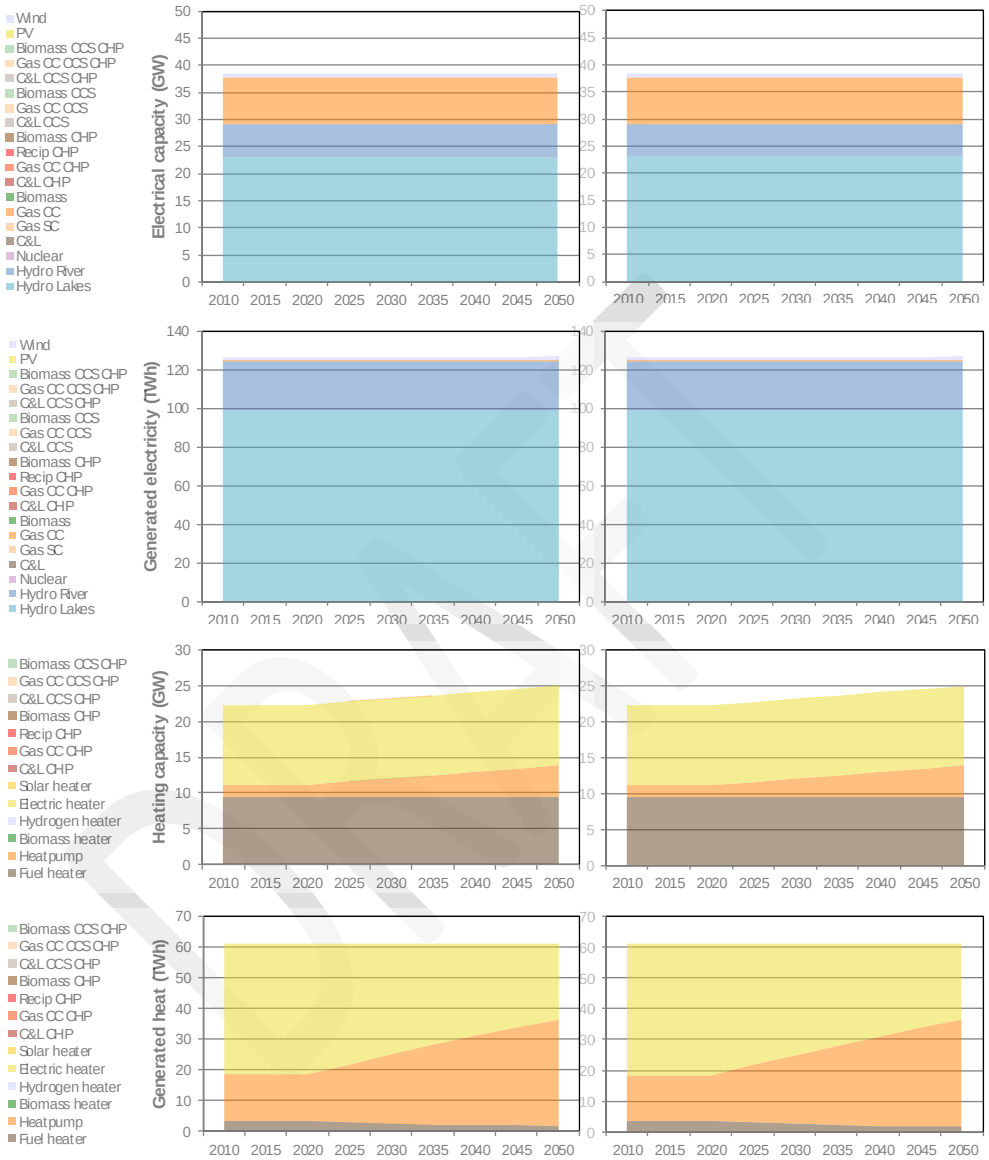

Figure 36: Results for Norway; CCS is available (left), CCS is not available (right).

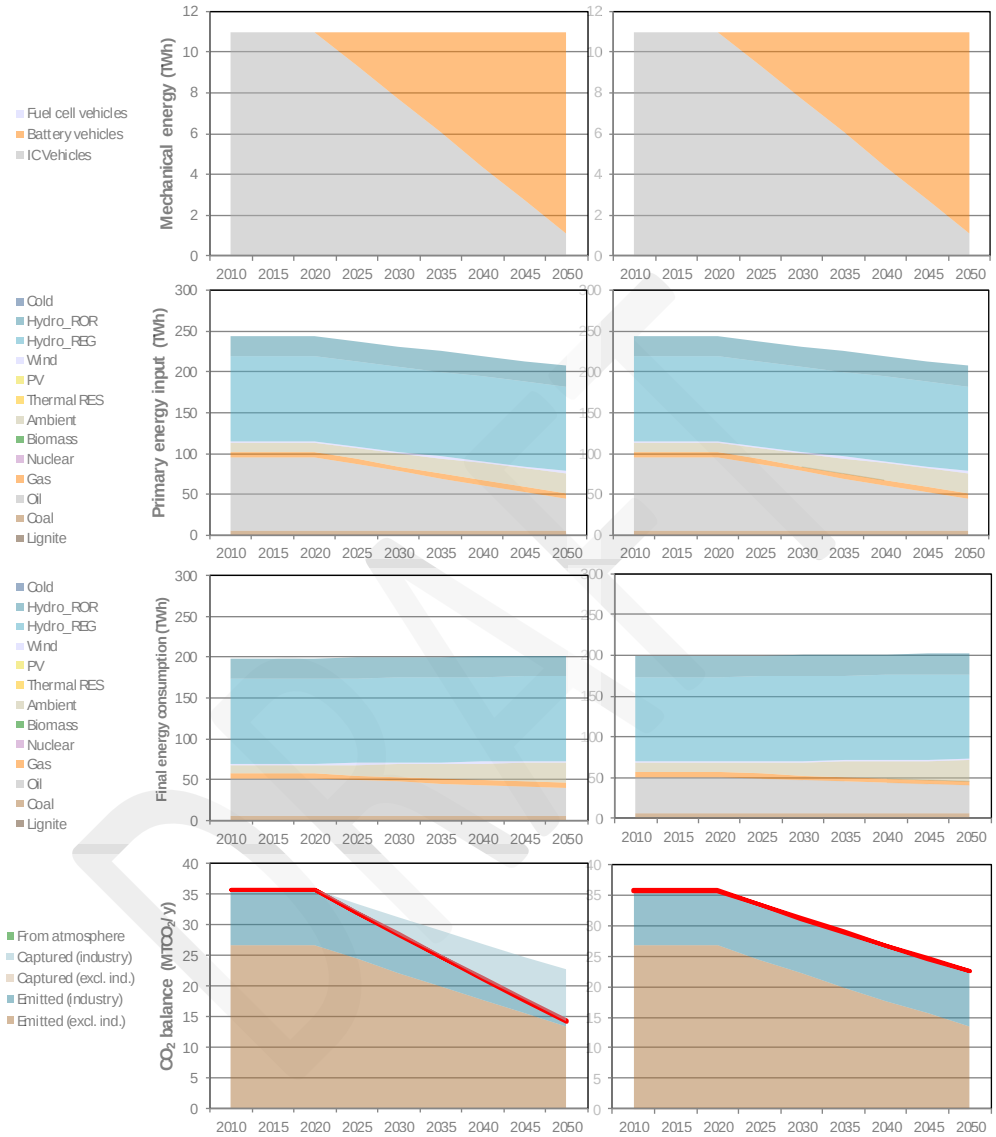

Figure 37: Results for Norway; CCS is available (left), CCS is not available (right).

5 Meetings the EU's NDC: Sum of all countries

The previous nation state level sections highlighted the diversity of solutions for the various countries. This section focuses on the general learning by looking at the sum of the 10 considered countries.

Electricity sector

Figure 38 shows the installed electrical capacity and the generated electricity for the two sets of cases with and without CCS available. Some observations can be made:

- The base load generation by hydro and nuclear stays roughly flat. The retirement of nuclear in Germany and Switzerland is partly compensated by a growing capacity in Poland.
- Unabated coal & lignite plants will disappear within the time horizon to 2050 as they are incompatible with the EU's longer term energy and climate objectives.
- Unabated gas CCGT remain important assets throughout the time horizon with slightly higher levels for the non-CCS case. However, generation from those plants peaks around 2030 and declines towards 2050. This reduction of utilization rates has been observed in previous ZEP reports.
- A new feature in this report is the growth of CHP (gas, coal & lignite, biomass). Unabated versions of these technologies appear from the beginning and remain until 2050 although the proportion of CHP technologies with CCS fitted necessarily increases over time.
- CCS appears as early as 2020 for all fuels (coal & lignite, gas and biomass), with and without CHP, with biomass combined with CCS (BECCS) potentially providing a greater role in the energy system according to the need for negative CO_2 emissions.
- Both scenarios see a strong increase of PV and wind. Naturally this growth is even stronger when CCS is not available but the reader should note that this will also come with higher system integration costs not comprehensively modelled in this exercise.
- The total electricity generation increases in both scenarios. Since the traditional use (lighting, motors, etc.) has been kept constant, the increase is due to the growth of heat pumps and e-mobility.
- Without CCS, total installed capacity across the modelled countries must increase to nearly 1600GW by 2050 – approximately a three-fold increase in capacity from 2010 levels.

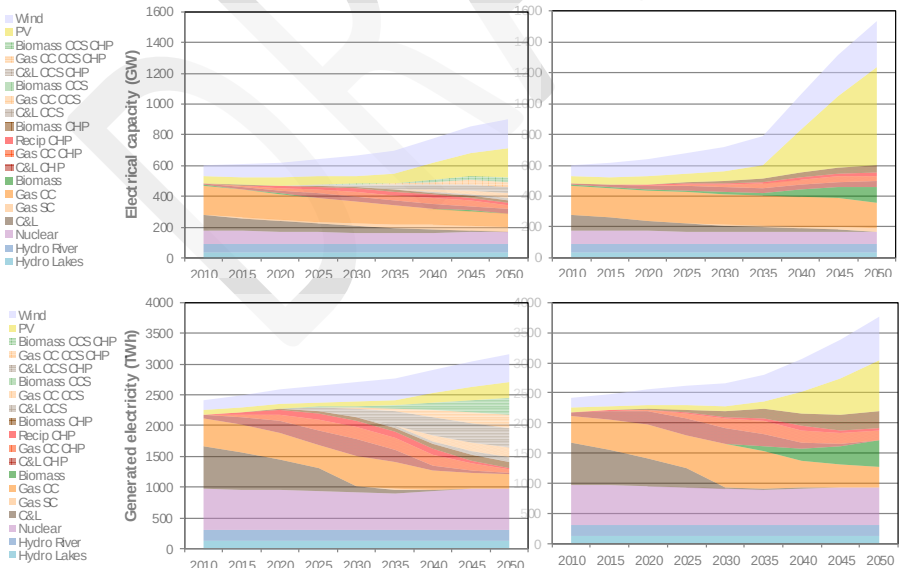

Figure 38: Electricity sector for the 10 selected countries; CCS is available (left), CCS is not available (right).

Heating sector

Figure 39 shows the installed heating capacity and the generated heat for the two cases with and without CCS available. Some observations can be made:

- The typical heating technology by gas and oil furnaces disappears and is replaced by heat pumps, biomass heaters and CHP.
- Heat pumps are the dominant technology, especially in the non-CCS case. This result needs critical evaluation especially in the context of the required electrical grid reinforcements.
- CHP has a strong share in the generated heat, especially when delivered by combined CCS&CHP plants. Without CCS the share of CHP is much smaller.
- Some solar heating appears in the non-CCS case.

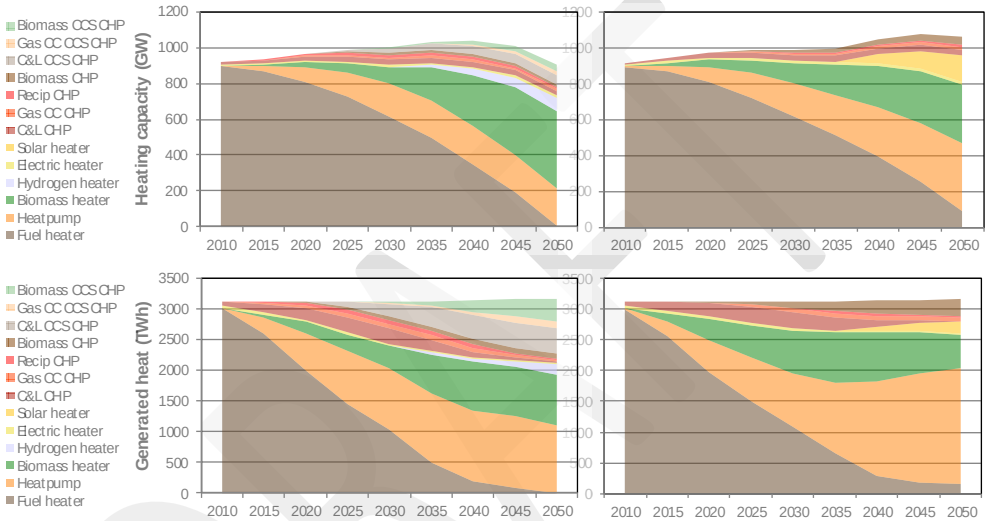

Figure 39: Heating sector for the 10 selected countries; CCS is available (left), CCS is not available (right).

Transport sector

Figure 40 shows the mechanical energy required to drive road vehicles, split into the three technologies internal combustion, battery and fuel cell vehicles. In both cases e-mobility starts to appear between 2020 and 2025, and it hits the imposed limit of maximum 75% non-fuel mobility. There are differences country to country but overall the rate of electrification of transport is similar for both CCS and non CCS cases. It is driven by cost and rate of turnover of vehicles.

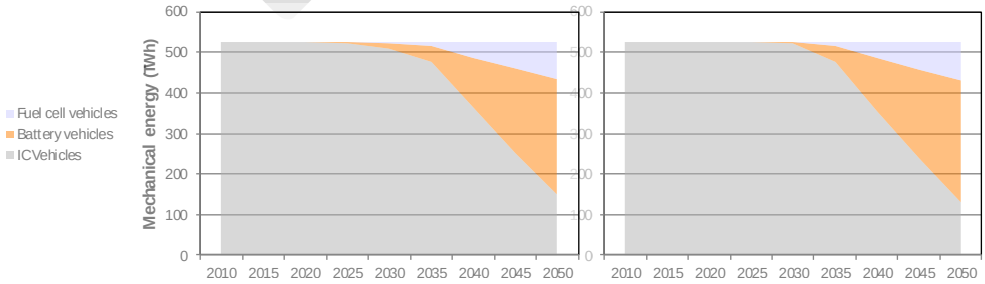

Figure 40: Transport sector for the 10 selected countries; CCS is available (left), CCS is not available (right).

Primary energy input and final energy consumption

Figure 41 (top) shows the primary energy input for the two cases with and without CCS available, separated by fuels. The bottom part shows the same split but for the final energy consumption. Some observations can be made:

- In both cases the primary energy input reduces towards 2050. This is due to a general increase of conversion efficiency, e.g. the replacement of oil and gas furnaces by CHP or heat pumps, the switch from internal combustion to battery and fuel cell vehicles, etc. It is again emphasized that no reduction of electricity (e.g. LED) or heating (better house insulation) consumption was assumed.
- All fossil energy sources reduce to a varying degree. Oil consumption is strongly reduced in both cases, mostly due to the retirement of oil furnaces and the switch to e-mobility. The use of gas declines to a lesser degree. In this case there is a switch from gas furnaces to gas power plants in all variants (with/without CCS/CHP).
- Two remarkable features of the results are the strong growth of ambient heat due to heat pumps and the growth of biomass. Especially biomass requires a critical review since it has to be sourced in a sustainable and CO_2-neutral way.
- While total renewables is approximately 40 – 50% of energy input in 2050 in both cases and zero CO2 from 60 – 75%. PV, wind and hydro power appear to be a small sliver in the primary energy input, however, it has to be stressed that these inputs come in the form of electrical energy, whereas all other inputs are either fuel heating value or heat. In order to better visualize this fact the bottom graph shows the same picture but without the transformation losses that can be attributed to the various fuels. This emphasizes the importance of electrical renewables for the energy mix.

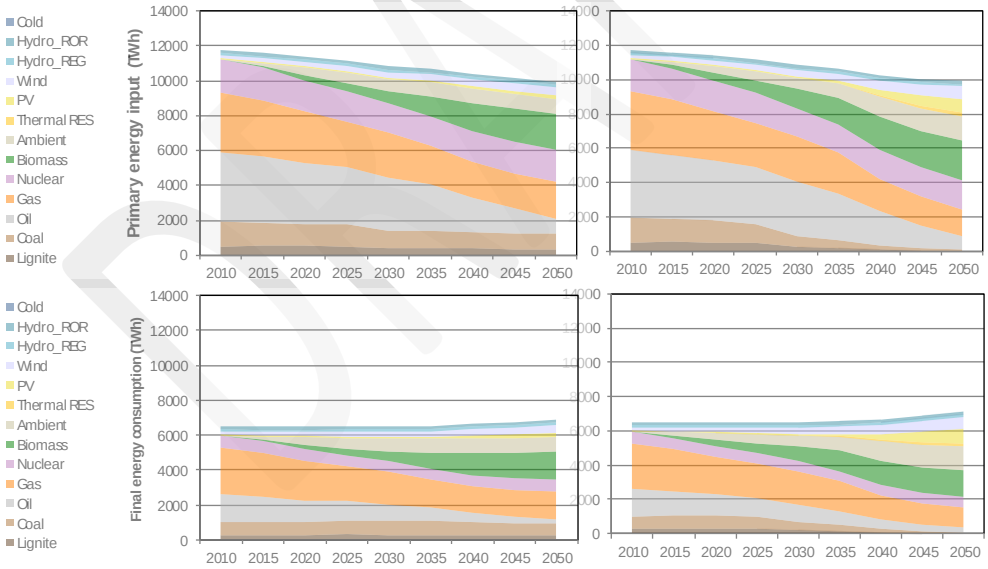

Figure 41: Primary energy input (top) and final energy consumption (bottom) for the 10 selected countries; CCS is available (left), CCS is not available (right).

CO_2 balance and required storage volume

Figure 42 shows the overall CO2 balance for the two cases with and without CCS available.

- The sum of all categories shows the CO2 that is generated by burning a carbon containing fuel. Two items have to be subtracted: (1) the CO2 that is extracted from the atmosphere by the growth of biomass, and (2) the CO2 that is captured and stored via CCS (at the capture rate emissions).
- The red line marks the actual balance, i.e. the effective emission into the atmosphere. Both the emitted and the captured CO2 are split into the industry part (steel, cement, oil & gas) and the rest (power, heating, transportation and other industry).
- **If CCS is available the effective emission reduction from 2010 to 2050 is 85% as required to reach an overall 80% GHG emission reduction (1990 to 2050, see section 3). If CCS is not available the reduction from 2010 to 2050 is only 70%. Therefore the overall GHG emission reduction from 1990 to 2010 is only 65% well below the 80-95% target.**

Comment [MWPG3]: Is it possible to show/quantify the Bio CCS negative emissions/offsetting

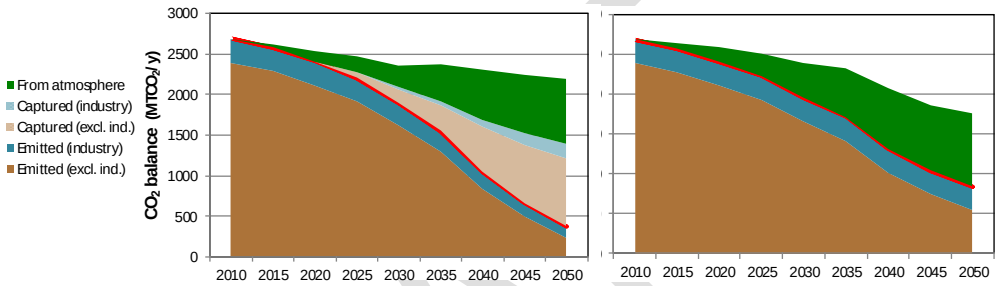

Figure 42: CO2 balance for the 10 selected countries; CCS is available (left), CCS is not available (right).

Figure 43 summarizes the emission reductions seen from 2010 to 2050 in scenarios with and without CCS. The model is optimized so that emissions reductions beyond the indicative 85% target are not pursued unless it is more cost-effective to do so. It should be noted by the reader that technology choices made in the period to 2050 will, however, have implications on the ability to achieve deeper emissions reductions in the period beyond 2050 on the pathway to net zero emissions.

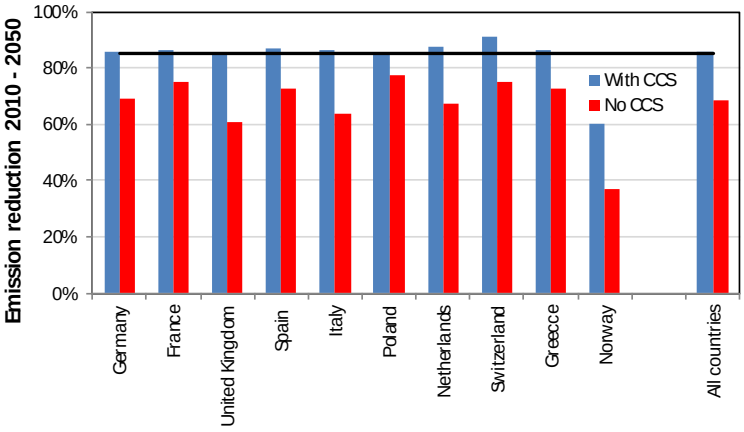

Figure 43: Achievable emission reductions from 2010 to 2050; target set to 85%.

Figure 44 shows the per capita emissions in 2010 and 2050. With CCS a level of one t_{CO2} per capita can be achieved, without CCS it will be double this amount.

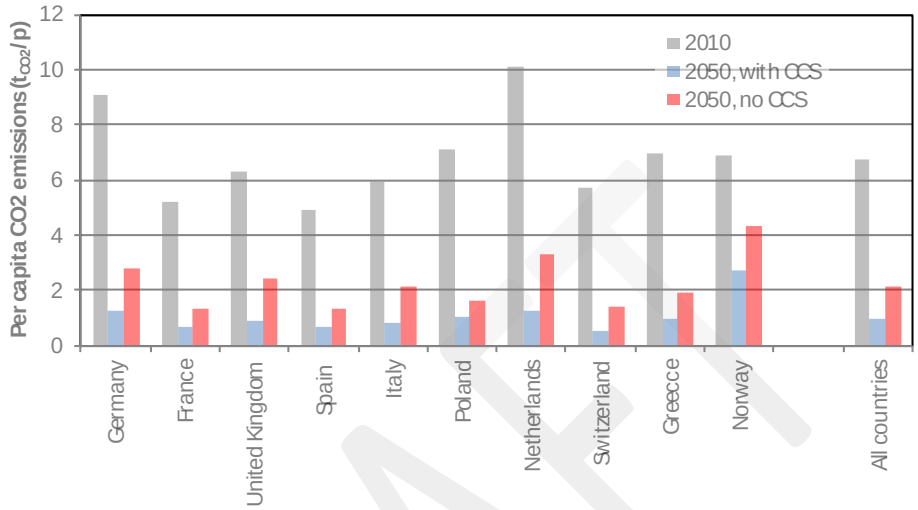

Figure 44: Per capita CO_2 emissions in 2010 and 2050.

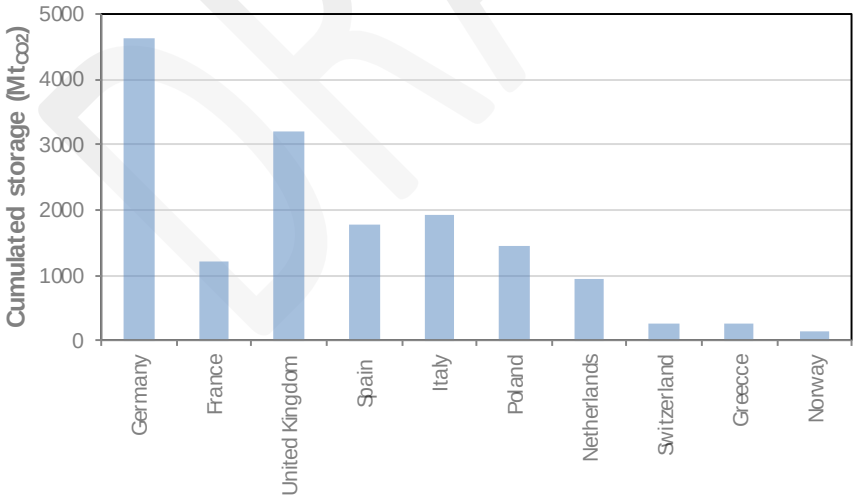

Figure 45: Cumulated stored CO_2 from 2010 to 2050.

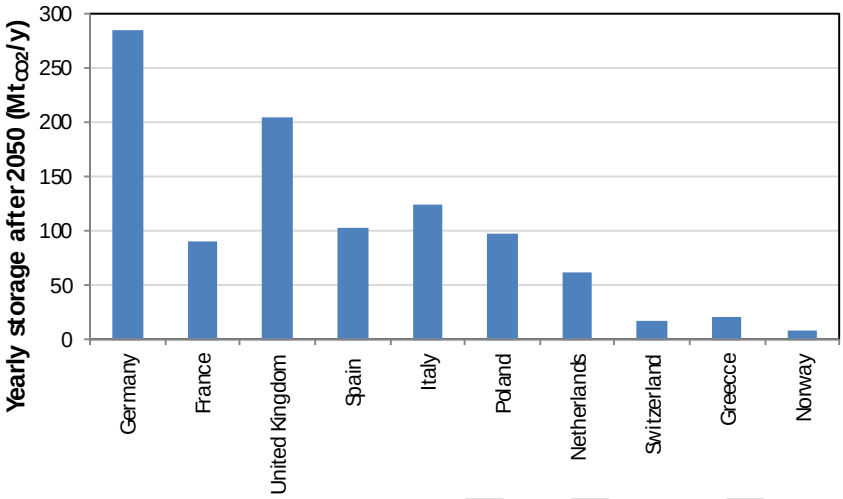

Figure 46: Yearly CO_2 storage after 2050.

Costs vs. CO_2 emissions

Figure 47 shows the total system costs versus the CO2 emission reduction. The end point of the two curves corresponds to the 85% and 70% emission reduction, with and without CCS, respectively.
A number of further conclusions can be drawn from Figure 47:

- The cumulative CO_2 emissions for the 10 countries are 77 Gt with CCS and 84 GT without CCS. Having CCS available saves 7 Gt within the timeframe from 2010 to 2050.
- The cumulated energy system costs (capital, operation and fuels) for the 10 countries are €25.3 trillion with CCS and €25.8 trillion without CCS but it should be emphasized that the latter scenario does not deliver on energy and climate objectives. Having CCS available saves approximately €500 billion within the timeframe from 2010 to 2050.
- The model can allow readers to deduce an implied social cost of CO_2 that is emitted to account for the damage of climate change. Estimates are in the order to 50 to 100 €/t_{CO2} (verify!!!)[13]. Taking the lower end leads to additional savings of 7 Gt x 60 €/t_{CO2} = €400 billion if CCS is available.
- **Considering that the selected countries represent approximately 70-75% of the EU28 emissions it can be concluded that the availability of CCS has a value in excess of €1 trillion for the time period of 2010 to 2050.**
- Following the same logic and assuming that the emission intensity and costs stay constant after 2050, one can derive a yearly value of CCS in excess of €60 billion per annum for the second half of the century. This corresponds roughly to 0.5% of the GDP.

[13] See https://www.whitehouse.gov/omb/oira/social-cost-of-carbon for an overview on methods and results.

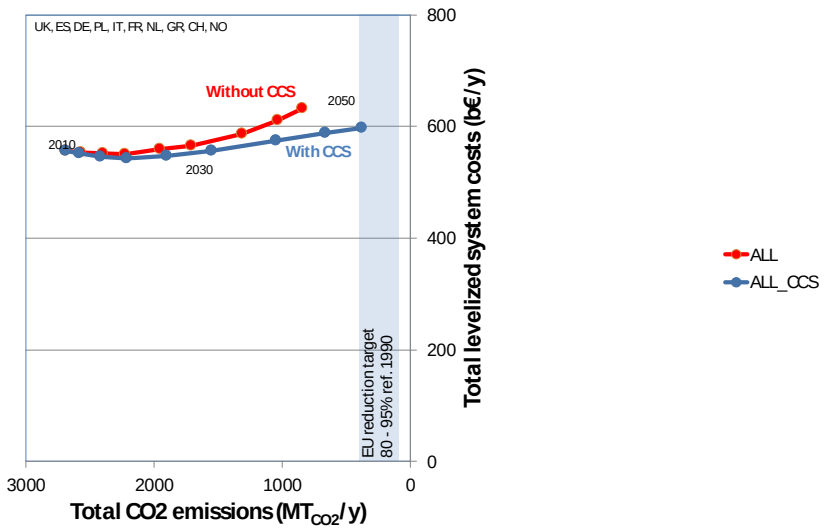

Figure 47: Costs vs. CO_2 emissions for the sum of the considered countries (with CCS, without CCS).

The total system cost has been calculated (2010 Euros, no tax, no subsidies, no inflation and no growth of population, economy or living standards) and presented for the cases with and without CCS. The model shows a saving in cost to 2050 of 500 trillion Euros even though the non-CCS case does not meet climate objectives. On top of this the value to society of the difference in emissions taking a conservative value for the external cost of CO_2 emissions is in excess of 400 billion Euros. In the non-CCS scenario, the main reason for not reaching the target is that the model reaches the realistic limit for wind and solar deployment per country on a land-use basis. As previously indicated however, there is also a theoretical limit to the deployment of intermittent renewables based on the required system integration and grid expansion costs – this has not been investigated by the model but provides further weight to the conclusions.

A key learning from these curves for the energy system of Europe is the cost saving potential of CHP and District Heating through the more efficient use of the fuel. The shift to electric vehicles is also shown to be deliver potential cost savings since the price of oil in the model is much higher than the price of methane, which replaces it as the main fossil fuel.

Comment [MWPG4]: Add that this may be a model simplification as gas has been indexed on oil prices in EU.

Clearly predicting commodity prices out to 2050 and even the relative prices of these fuels is not likely to be the actuality, however even though the magnitudes of the costs are very large, the impact of cost increase to Europe of the emission reduction is not modelled to be so great. The overall shift is away from burning fuel, particularly road fuel, to investing in infrastructure. This investment has the potential to improve countries and EU balance of payments if the infrastructure comes at least substantially from European industry. The remaining fossil fuels used particularly in the CCS cases are predominantly indigenous local fuels, which can help to safeguard jobs and protect energy security.

The indication of the results that total energy system costs could reduce to 2050, seen mostly in Norway but also in the early years in several of the other countries, should be taken in the context of the 'no growth' assumptions employed in the model and that the strong technology learning curve in the model. For instance, for solar PV, costs are modelled to reduce from €1950/KW installed 2010 to €200/KW in 2050. There are similar cost reductions for other technologies in the model which all together create a positive view of costs out to 2050.

Carbon Capture and Utilisation (CCU)

Carbon Capture and Utilisation is an important variant of CCS that has been addressed in recent ZEP reports[14]. To make use, where possible, of CO_2 captured from industrial installations can help to create a business case for carbon capture technologies. Urea production is one excellent such example. The CO_2 needed for Urea production is normally created by the burning of methane as part of the industrial set-up. To bring in and use CO_2 from another industrial process or a power plant can displace the direct use of fossil fuels and should therefore be encouraged and supported appropriately.

There may well be many such cases possible and they will be best identified and exploited by the industries engaged in such fields. An important aspect to keep clearly in mind is that the volumes of CO_2 emitted by industry, transport and electricity production that needs to be captured and stored, far exceeds what can be imagined that could be utilized by other industries. Although CCU is not explicitly included in the model, ZEP considers that CCU should be used where cost effective and of proven and demonstrable climate benefit. CCU may create applications for capture technologies, but should not be seen as an alternative to CCS as a real means to climate change mitigation.

System integration costs

Figure 48 helps to explain where the savings and the business case for CCS may come from in the power sector. In Europe's future energy mix, ZEP has modelled an excess of renewable capacity: Wind and Solar only operating between 10 and 40% of the year, supported by backup capacity that also will only operate for a part of the year. This is intrinsically more expensive than a system with a constant supply demand balance from fully dispatchable plants. Figure 48 shows a simplified image based on the Levelised Cost of Electricity (LCOE) metric. The system consists only of PV and CCGTs.

The brown line shows the LCOE for CCGTs which are required to guarantee supply at all times. As the installment of PV rises (towards the right of the graph), the utilization of CCGTs goes down, consequently the CAPEX portion of LCOE grows and the brown curve goes up. The LCOE of PV was modelled to be initially lower than the one of CCGTs. However, from a certain point onwards there is an overshoot of PV generation which has to be curtailed. Again, LCOE goes up as utilization goes down.

The black curve shows the average LCOE for the system that is composed of PV and CCGTs. It steadily grows with higher share of PV and reducing CO2 emissions. This can serve as a simple illustration of the true integration costs of fluctuating renewables.

It should be remembered that the model used here has available to it a number of storage technologies: batteries, pumped hydro, hydrogen, *et cetera*. In general, these technologies are short-term in their capacity and relatively expensive to install. The model finds that, with the integration of heat and transport, the optimum solution can be found with little use of electricity storage for either case, with or without CCS. Only in the non-CCS case does the installed capacity of PV and Wind grow to the level where it is substantially curtailed. In this case, the model still does not choose storage but allows the curtailed capacity to be under-utilised for part of the day and year so that it can play a part in emissions reduction for a very limited period. It is this system integration cost of intermittent generation that drives the business case for CCS on the backup capacity that will necessarily be required. Without CCS on this capacity the emission targets are more expensive and at a point unreachable.

[14] Carbon Capture and Utilisation (CCU), ZEP (April 2016)

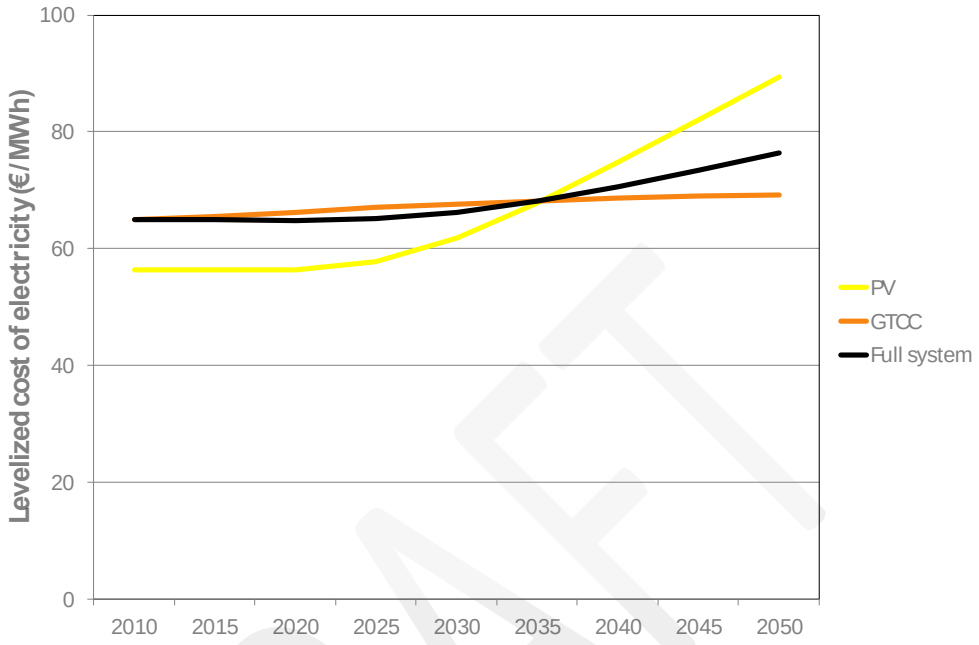

Figure 48: Illustration for system integration costs.

The Role of EU and Member state regulation and policy on investment decisions

We see from the results that while the trends are consistent across the countries, the specific outcome in the model depends on the local and regional variation: fuels, weather, security of supply concerns, and the mix of the current installed base. Whilst this means that the best solution by country will be each country's own responsibility in their National Plan to help meet the European objectives, there is clearly value to be derived from knowledge exchange and shared CCS infrastructure in particular regions of Europe, e.g. around the North Sea.

The ZEP is keen and ready to engage with the Member State representatives to discuss and compare these results with the work of others, including within the relevant national ministries and research communities of that country to help advise on policy that really takes account of local needs and interests.

As has been set out in the previous Market Economics reports, the ETS and the ongoing reforms to the European Electricity Market have not been sufficient to incentivise investment in technologies to substantially reduce CO_2 emissions. Investment decisions require a predictable financial return from the action alongside a known level of risk. While direct subsidies have successfully incentivized low CO_2 technologies in the power sector such as solar and wind, equivalent measures such as Feed in Tariffs and CfDs have only had limited application for CCS and some other local carbon technologies. In order for progress to be made in the commercial deployment of CCS, ZEP has therefore recommended a multi-faceted approach:

- Commercial separation of the different parts of the CCS chain (capture, transport and storage);
- Funding of regional CO_2 'Market Makers' to develop shared CCS infrastructure, accessible to the full range of CO_2 emitting industries; and,

- Complementary CO_2 capture incentives, designed and funded as appropriate by individual Member States.

In the UK, a similar approach has recently been produced by an independent Parliamentary Advisory Group on CCS, chaired by Lord Oxburgh. The report provides a clear example of how policies can be evolved to encourage investment in CCS over time, with appropriate rates of return and an exit strategy for governments.

ZEP's modelling here has shown the value and importance of wide-scale deployment of CCS from 2025 onwards across the modelled countries. For deployment on this scale to be realised, the infrastructure for CO_2 transport and storage needs to be put in place as soon as possible. This would allow sources of CO_2 to be connected to the infrastructure whether they are large or small continuous or intermittent, fossil or renewable based sources. In this way a Member State can plan for the future on its energy intensive industries - post the current exemptions - the electrification of heating and transport with a realistic expectation that any new sources of energy will be low emission but that the existing energy sources that are back bone of our systems such as methane can also be low emissions, ready from the 2020s. To make this happen, policies and leadership are needed now from both Member States and the EU institutions. In the absence of a credible, long-term approach to CCS, the private sector will not be able to make the necessary investments in deployment and innovation.

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6 Summary

Building on ZEP's previous Market Economics reports, the results here prove that the business case for CCS in the European energy system to meet energy and climate objectives is even stronger when the heating, cooling and transport sectors are added to energy intensive industries and electricity generation.

CCS has a vital role in the energy mix if many Member States and other European countries are to meet their proposed own national plans. Not only does the absence of CCS appear to preclude the achievement of emissions reductions targets, the cost savings seen when CCS is included as part of the energy system is substantial: in the order of €500 billion. The analysis has shown a value of CCS to the EU as a whole in excess of €1 trillion by 2050 alone, with the expectation that CCS has an even-greater value post-2050 as the EU moves towards a net zero economy and the importance of negative emissions technologies (such as BECCS) increases.

A key conclusion from the modelling exercise is that Europe needs to shift the balance of its expenditure away from fuel imports towards infrastructure development. Not only does help to achieve energy and climate objectives in terms of costs and emissions reductions, it could also help to create and retain sustainable jobs, increase security of supply and unlock opportunities for innovation and technology exports.

This report once again reinforces the essential role that CCS is expected to play in the decarbonisation of energy intensive industries across Europe, unlocking a long-term, low emission future for cornerstone industries such as steel, cement and chemicals. The analysis demonstrates the underlying economic rationale for investment in CCS to support these industries in their transition to a low-carbon economy; highlighting the important role for EU institutions and Member States in providing the framework to enable investment in the CO_2 transport and storage infrastructure that can, in turn, unlock investment and innovation in CO_2 capture and CO_2 utilisation.

The report highlights the large growth in electricity demand that can be expected to come with electrification of heat and transport, but shows that this can be accommodated with a portfolio mix of renewables, nuclear and indigenous fuels with CCS. Furthermore, the availability of CCS can greatly reduce the total installed capacity required to meet future demand, both directly and indirectly.

The tighter CO_2 limits discussed in Paris require not just strong reductions in CO_2 emissions; they necessitate negative emissions from the use of Biomass with CCS to remove CO_2 from the atmosphere. ZEP's analysis here shows the value of negative CO_2 emissions to achieving the EU's 2050 energy and climate goals; a role expected to increase in importance over time, both environmentally and economically. But any application of CCS – be it to power, industry, transport or heat sectors; be it direct or indirect; whether it is for negative emissions or not – first requires the availability of CO_2 transport and storage infrastructure.

Following on from this report, ZEP recommends that polices and incentives should be designed at the nation state level to suit the local situation, and effectively facilitate regulated infrastructure for transport and storage of CO_2. A collaborative approach to infrastructure development – as suggested in ZEP's business case for storage report and further elaborated upon in its work on an Executable Plan for CCS for Europe – can help to unlock industrial investment decisions to reduce the emissions of CO_2 from existing industrial sources and help to encourage inward investment in flagship, low-carbon regions.

Annex I: Glossary

a	Annum
b	Billion
BASE	Base power plant with CO_2 capture
BAU	Business-as-usual
BF	Blast Furnace
Bio	Biomass
BOF	Basic Oxygen Furnace
Capex	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
CCS	CO_2 Capture and Storage
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DRI	Directly Reduce Iron
EAF	Electric Arc Furnace
E-storage	Electricity Storage
ETS	Emissions Trading Scheme
EU	European Union
EUA	Emission Unit Allowance
FCC	Fluid Catalytic Cracker
GCAM	GCAM
Geo	Geothermal Energy
GHG	Greenhouse Gas
GJ	Giga Joule
GT	Gas Turbine
hr	Hour
HRC	Hot Rolled Coil
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
km	Kilometre
kWh	Kilowatt Hour
kW	Kilowatt
LCOE	Levelised Cost of Electricity
M	Million

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Mt	Mega (million) Tonnes
MWe	Megawatt (electric)
MWh	Megawatt Hour
NER300	New Entrant Reserve (300)
OCGT	Open Cycle Gas Turbine
OPTI	Optimised power plant with CO_2 capture
O&M	Operation and Maintenance
OBF	Oxy-blast Furnace
ppm	Parts Per Million
PV	Pholtovoltaic
RES	Renewable Energy Sources
Spec	Specific (emissions per unit produced)
t	Tonne
T&S	CO_2 Transport and Storage
UK	United Kingdom
ULCOS	Ultra-Low CO2 Steelmaking
US	United States
WACC	Weighted Average Cost of Capital
w/o	Without
yr	Year

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To be updated

Annex II: Members of the ZEP Temporary Working Group Market Economics

Name	Country	Organisation
Stale Aakenes	Norway	Gassnova
Gerdi Breembroek	Netherlands	RVO
Jonas Helseth	Belgium	Bellona Europa
Karl Buttiens	Luxembourg	ArcelorMittal
Alan Reid	Belgium	CONCAVE
Niall Mac Dowell	UK	Imperial College
Mark Downes	UK	Shell
John Gale	UK	IEAGHG
Ward Goldthorpe	UK	Crown Estate
Gianfranco Guidati	Switzerland	GE
R Bernat	Poland	ITC
Zoe Kapetaki	Belgium	Global CCS Institute
Nicolas Kraus	Belgium	EPPSA
Wilfried Maas	The Netherlands	Shell
George Day	UK	Energy Technologies Institute
Theo Mitchell	UK	CCSA
Harriet Howe	UK	CCSA
Dan Sadler	UK	Leeds H21
Tim Peeters	The Netherlands	Tata Steel
Ian Luciani	UK	BP
Tristan Stanley	UK	IEA
Christian Skar	Norway	Norwegian University of Science and Technology (NTNU)
Charles Soothill	Switzerland	GE
Katrin Stoetzl	Belgium	EUTurbines
Kazimierz Szynol	Poland	PKE S.A.
Asgeir Tomasgard	Norway	SINTEF
Robert van der Lande	The Netherlands	ZEP Secretariat
Rob van der Meer	The Netherlands	HeidelbergCement
Ralf Wezel	Belgium	EUTurbines
Keith Whiriskey	Belgium	Bellona Europa

To be updated

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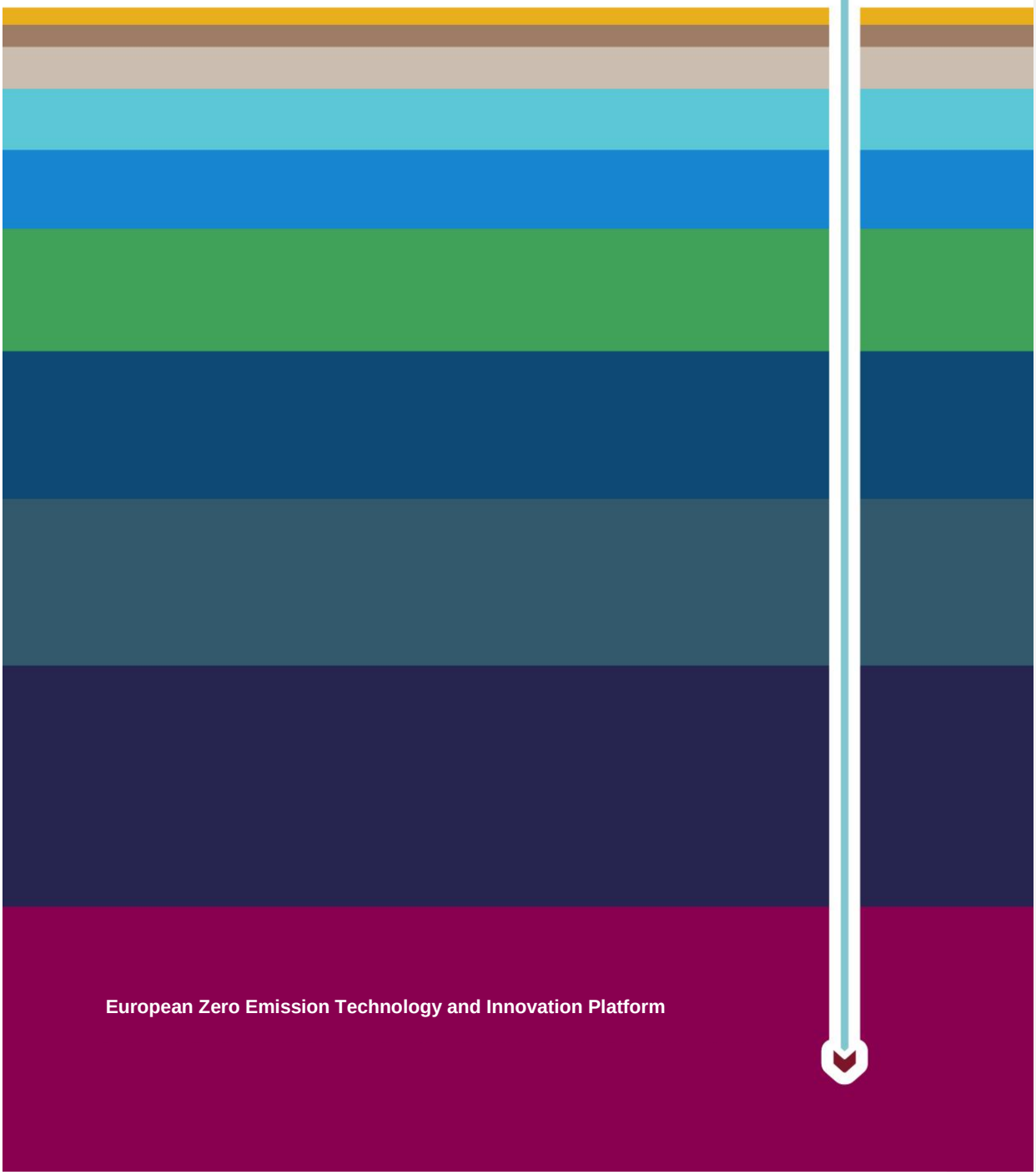
Zero emissions platform



European Zero Emission Technology and Innovation Platform

ZEP Advisory Council 49

8.c. Executive Summary of the ZEP Policy Brief: Reuse of unspent NER300 funds, November 2016

- An important opportunity has arisen to utilise unspent NER300 funds and deliver tangible progress on CCS in Europe. Used intelligently, these funds could make a major contribution towards achieving the targets recently agreed for CCS by the SET Plan Steering Group.

- Redistributing funds to existing NER300 projects or launching a third NER300 call would not deliver progress on CCS as these options would fail to address the underlying commercial barriers to CCS deployment identified by ZEP. Instead the Platform recommends that the unspent funds are allocated to alternative, existing financial instruments, which are able to disburse funds in a timely manner to a wide range of CCS initiatives.

- Within the framework of an alternative financial instrument, ZEP recommends establishing a dedicated CCS Development Fund made up of at least the €300 million of which should be derived from the unspent NER300 funding awarded to the White Rose CCS project.

- In order to achieve a balance in the use of unspent funds between CCS and innovative renewables, ZEP recommends that the CCS Development Fund should have a minimum endowment of €500 million and should seek to leverage private sector co-funding through initiatives like the £1 billion fund recently announced by the Oil and Gas Climate Initiative (OGCI).

Context

The NER300 programme was established under the EU ETS Directive to provide funding for innovative low carbon technologies needed to support the EU's transition to a low-carbon economy. The Directive sought to achieve a balance in funding to CCS projects and innovative renewables projects and aimed to fund at least 8 CCS projects to ensure technological diversity.

A total of 39 projects were awarded funding through two calls in 2012 and 2014 (38 renewable projects and 1 CCS project), only three of which are now operating. Of an estimated €2.1 billion awarded to projects, ZEP understands that only €65.7 million of that is allocated to the three operational projects and that €553 million from the first call could potentially become available by early 2017 as a result of projects either being cancelled or failing to take a final investment decision. In addition to this, it is expected that a significant amount of funding will become available in 2018 as a result of projects from the second call failing to progress, including up to €300 million awarded to the White Rose (UK) CCS project – the only CCS project to be awarded any funding under the scheme.

ZEP Secretariat, www.zeroemissionsplatform.eu
Carbon Capture and Storage Association
6th Floor, 10 Dean Farrar Street, London, UK

Unlike other EU funding schemes such as the EEPR, funding under NER300 is derived from the sale of emissions allowances under the EU ETS and, as a result, funding that has been disbursed but not spent could be made available for other similar initiatives.

Options for the reuse of funds

ZEP understands that EU institutions and Member States are currently considering options for the redistribution of unspent NER300 funds:

(1) Topping up the future Innovation Fund as proposed in the Commission's ETS revision proposal;
(2) Allocation of the funds to existing financial instruments, e.g. European Fund for Strategic Investment (EFSI), InnovFin Energy Demo Projects (InnovFin EDP) or Connecting Europe Facility (CEF);
(3) Increasing the support available to existing projects; and/or,
(4) Launching a third NER 300 call for proposals.

Of these four options, **ZEP recommends that funding should be allocated to alternative financial instruments, and that a significant proportion should be dedicated to supporting the development of CCS projects**.

Following on from its 2014 report on Business Models for Commercial Scale CO_2 Transport and Storage[1], in September 2015, ZEP published an Executable Plan for CCS in Europe[2], which highlighted the commercial challenges associated with deployment of CCS and recommended 'breaking the CCS chain' into its constituent parts – capture, transport, utilisation and storage. By separating the chain from a commercial and risk perspective and putting in place a framework for CCS infrastructure "Market Makers", ZEP demonstrated that the major barriers to investment could be overcome and that CCS could be delivered at a lower cost to society.

Building on this analysis, and the lessons derived from the UK CCS Commercialisation Programme[3], it is clear that options (3) and (4) being considered for the unspent funds are unlikely to deliver progress on CCS as they do not fundamentally address the barriers to private sector investment in CCS. Whilst option (1) offers a potential solution – assuming the modalities for the Innovation Fund are designed to meet the needs of potential CCS projects[4] - an interim fund is necessary to support the development of projects between now and 2020 in line with the adopted targets for CCS and CCU under the SET Plan[5].

Based on these conclusions, **ZEP recommends that a total of €500 million, including the funding allocated to White Rose, is set aside from the unspent NER300 funding and used to establish a CCS Development Fund under an existing financial instrument**.

[1] http://www.zeroemissionsplatform.eu/downloads/1523.html
[2] http://www.zeroemissionsplatform.eu/downloads/1545.html
[3] http://www.ccsassociation.org/index.php/download_file/view/1023/503/
[4] http://www.zeroemissionsplatform.eu/downloads/1598.html
[5] https://setis.ec.europa.eu/system/files/setplan_doi_ccus-final.pdf

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Candidate initiatives

The SET Plan Steering Group recently adopted 10 specific targets for CCS and CCU by 2020 and a Temporary Working Group on CCS has been established to develop an Implementation Plan. Although funding has yet to be allocated to each of the targets that were agreed, it is clear that unspent NER300 funds could play a major role in achieving the targets. As examples, the CCS Development Fund could potentially support a number of important CCS initiatives currently under development within Europe, including:

- **CCS in Norway** – The Norwegian Ministry for Petroleum and Energy has recently completed a feasibility study on a full-chain CCS project incorporating three industrial emitters (steel, energy from waste, ammonia), CO_2 via shipping and three potential storage options. The Ministry has provided further funding for FEED studies, with a view to having an operational full-chain project by 2022.

- **A Rotterdam CCS cluster** – The Port of Rotterdam is currently considering options for industrial CCU and CCS as part of a broader initiative to address sustainability in the region. Alongside this, the ROAD CCS project (NL) is hoping to begin operating in 2020 providing it takes a positive FID in the near future, which could provide the anchor load to justify investment in regional CO_2 infrastructure.

- **A CO_2 transport Project of Common Interest (PCI)** – potentially providing CO_2 transport solutions from industrial regions of Europe to offshore storage formations, e.g. in the North Sea

- **UK CCS cluster(s)** – The UK recently undertook a review on the role of CCS to UK decarbonisation via an independent Parliamentary Advisory Group on CCS, chaired by Lord Oxburgh. The final report concluded that the UK should proceed with full-chain CCS clusters combining industrial and heat emitters, and highlighted the important role of CCS in decarbonising the heating sector.

- **Storage pilots** – The CCS Declaration of Intent under the SET Plan includes a target for "at least 3 new CO2 storage pilots in preparation or operation in different settings" by 2020.

The advantages of a dedicated CCS Development Fund would include its flexibility to support a broad range of proposals; from R&D, feasibility studies and FEED studies right through to supporting capital investments or operational costs. A CCS Development Fund could also help to unlock CCS opportunities in parts of eastern and southern Europe where commercial interest in project development is less apparent.

Next steps

Joint efforts from Member States and the EU institutions to repurpose unspent NER300 funds represent an important opportunity to secure further EU funding for CCS and achieve the agreed 2020 targets for CCS and CCU under the SET Plan Declaration of Intent.

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Given certain operational constraints and inflexibility associated with the NER300 programme, and a lack of clarity on the future modalities of the Innovation Fund, ZEP recommends that allocating the funds to other financial instruments, and establishing a dedicated CCS Fund, would be the most appropriate use of the unspent funding for CCS. This Fund should focus on working towards commercial scale deployment and not fundamental R&D.

If the opportunity to establish a dedicated fund for CCS is not forthcoming, ZEP would recommend allocating remaining unspent funds to the new Innovation Fund and targeting further efforts at ensuring that the modalities for the Fund are fit-for-purpose for developers of CCS projects.

In order to further develop this concept, ZEP would welcome an ongoing dialogue between industry, Member States, the Commission and other stakeholders (particularly the SET Plan Temporary Working Group on CCS) to conceive how the CCS Development Fund could be established and made most effective.

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8.d. Executive Summary of the ZEP Policy Brief: CCU in the EU ETS, November 2016

In April 2016 the Zero Emission Platform (ZEP) published a report on Carbon Capture and Use/Utilization (CCU)[1] which highlighted the potentially important economic and climate impacts that different types of CCU could have in Europe.

The report concluded that whilst CCU could have a key role in terms of unlocking the business case for CO_2 capture and managing emissions in industrial regions poorly suited to CCS, the climatic value of different types of CCU needs to be better understood and carefully considered before incentives and policies are put in place to support delivery.

ZEP considers three main "types" of CCU in its report:

(1) Conversion of CO_2 as a feedstock for chemical processes;
(2) Conversion of CO_2 into fuels; and
(3) Non-conversion use, such as CO_2-Enhanced Oil Recovery (CO_2-EOR) or mineral carbonation.

ZEP's analysis has shown that, with the exception of mineralisation and CO_2-EOR (where EOR operations ensure a permanent storage requirement), a substantial number of CCU options will still result in CO_2 being released into the atmosphere.

In the case of a (hydrocarbon) fuel, such as those fuels that are produced by combining hydrogen with captured, fossil-derived CO_2 (often associated with 'power-to-fuels'), the emission of CO_2 to the atmosphere will happen relatively quickly. Similarly, if CO_2 is used for producing a polymer, the CO_2 will be released at the end of the lifetime of the final product (e.g., when the product is incinerated). This variety in terms of climate impact from the different types of CCU means that a one-size-fits-all approach to 'CCU' from a policy and regulatory perspective is not advisable.

ZEP's report concluded that the potential impact of "temporal storage" (or delayed emission) should be quantified in LCA methodologies relating to CCU. The report also noted that debate on the significance of temporal storage in terms of climate change is still on-going and that robust conclusions are yet to be drafted.

CCU in the context of the EU Emissions Trading System (ETS)

From a policy perspective, ZEP has welcomed the proposed inclusion of CCS within the Innovation Fund and shown through our analysis that allowing so-called "part-chain" projects, i.e. projects that cover the capture, transport, use or storage of CO_2, but not necessarily the full-chain, to access EU funds could help to remove some of the economic hurdles for CCS and reduce the costs of both CCS and CCU.

[1] http://www.zeroemissionsplatform.eu/news/news/1660-ccu.html

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Beyond this, however, ZEP believes that only those forms of CCU that lead to permanent, direct abatement of CO_2 – e.g. mineralisation and CO_2-EOR with permanent CO_2 storage – have a place within the EU ETS reporting framework.

To ensure an economically and environmentally robust ETS, it is essential that credit for CO_2 abatement is not awarded to emitters if they cannot demonstrate that their CO_2 emissions have either been permanently stored or otherwise abated.

If, as an example, power-to-fuels was recognised under the ETS and an industrial emitter was able to deliver its CO_2 'over the fence' to another entity that produced alternative fuels, and subsequently claim climate benefit, the regulatory driver for investing in CO_2 mitigation and process efficiency technologies could be removed. This would have the effect of removing emissions from traded ETS sectors (such as steel, cement and chemicals) and locking-in emissions from distributed sources and harder to abate sectors outside the ETS such as transport.

Furthermore, discussions on the potential for CCU often make highly optimistic assumptions about the potential growth in global markets for CO_2. According to ZEP's analysis, a realistic assessment of the potential global market for CO_2 in 2040 could be in the order of 400 million tonnes of CO_2 per annum. Even if all CO_2 used equated to permanent abatement, which the above example shows not to be the case, 400 million tonnes per annum would offer only a very small contribution to the total emissions reductions required[2].

Whilst CCU has clear high-value economic potential, ZEP believes that it is vital that policy makers understand the limitations of CCU from a climate perspective before making major policy and regulatory adjustments.

CCU has an important role to play in Europe – and ZEP stands ready to support EU institutions in realising the potential of different types of CCU – but this potential does not currently justify recognising CCU technologies and processes as climate mitigation technologies under the ETS Directive or other similar climate policy tools. In the view of the Platform, doing so could undermine the EU's aspirations to be a global leader on climate change, destabilize efforts on other CO_2 mitigation and low carbon energy technologies such as renewables and CCS, and put at risk delivery of the Paris Agreement.

In recognition of the above, ZEP is making the following recommendations:

1. DG Climate Action should conduct a robust, independent review of the lifecycle analysis of different types of CCU (including external circumstances that might impact their LCA) and determine which processes have the highest economic and environmental value;

2. EU institutions should continue to support innovation in CCU technologies and processes, particularly those where permanent direct abatement of CO_2 emissions can be achieved;

[2] In 2015 global emissions were estimated in the order of 37.6 billion tonnes of CO_2. The Paris Agreement will require emissions to be reduced to net zero by the second half of this century.

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3. EU institutions should retain the current approach to CCS and CCU in the EU ETS, recognising permanent abatement from CCS and CO_2-EOR, and committing to a further review the regulatory framework for CCU technologies and processes ahead of Phase V of the ETS.

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