CCS and Europe's Contribution to the Paris agreement

Modelling least-cost CO_2 reduction pathways

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European Zero Emission Technology and Innovation Platform

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Executive Summary

For this, the fifth iteration of ZEP's Market Economics analysis, a new energy systems model was developed to encompass the whole energy system, including the heat, power, industrial and transport sectors. A total of 10 countries were modelled and results were drawn for both the individual countries and the 10 countries combined. The following conclusions can be drawn;

- Across the European energy system, ZEP's modeling shows that the value CCS to the EU could be in excess of €1 trillion by 2050 alone.

- In the longer term, and as European countries move towards net zero emissions, the value of CCS is expected to further increase to more than €50 billion per annum.

- When CCS was not available to the model, total emissions in 2050 from the 10 countries modelled were found to be 3 to 4 times higher.

- Combined Heat and Power/District Heating is a low hanging fruit 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 further 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 is highly 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 in an increasingly carbon-constrained world.

- 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 under the proposed EU Energy Union governance arrangements.

- 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 and, 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 shown to be an important component of the future European system because of its potential role in reducing CO_2 emissions from the heating sector. 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 21) to reduce CO_2 emissions substantially, with an ambition to limit global temperature increases to 'well below 2 degrees Celsius'. The EU target of reducing greenhouse gas emissions by 80-95% from 1990 to 2050 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.

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 most cost efficient mix of technologies to be chosen will depend on national opportunities, and different elements in the final mix of technologies will develop at different pace and with different lead-times. It is therefore important to make long-term analysis for each individual country based on their actual installed base, current opportunities for low carbon energies and estimate what type of choices and infrastructural investments that could be required for each country to reach indicative emissions reduction objectives by 2050. Such analysis may reduce the risk of expensive detours on the least-cost pathway to net zero emissions.

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 CO_2 Capture and Storage: Creating a secure environment for investment in Europe.

2. 2013: "CO_2 Capture and Storage: *Recommendation for transitional measures to drive deployment in Europe*"[1] confirmed the critical role of CCS in meeting EU greenhouse gas reduction 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.

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[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 national level to assess the most cost effective technologies, which could, collectively, help the EU to deliver on the 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 EU 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 reaching a near-zero CO_2 emission energy system 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 national governments and EU institutions. .

Heating and transportation included in the model at the national level.

This, the fifth iteration of ZEP's market economics analysis, has been based on an 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.

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 selected countries, 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.

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 climate targets (National Plan) for 2030 (40% reduction of GHG) and 2050 (80-95% reduction vs 1990 level).

By extending the model to include all energy consumption, the interaction between the different components of the energy system is recognized to 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 hydrogen heating over heat pumps for the UK, which shows that these two technology options (hydrogen versus 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 model presented in this report does not take into account any regulations, taxes or subsidies. The model is purely based on finding the cost optimal solution for achieving the CO_2 reduction targets for each country, while maintaining the supply of energy to the market.

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 longer term investment in technologies required to reduce 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 chain.

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 understated.

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.

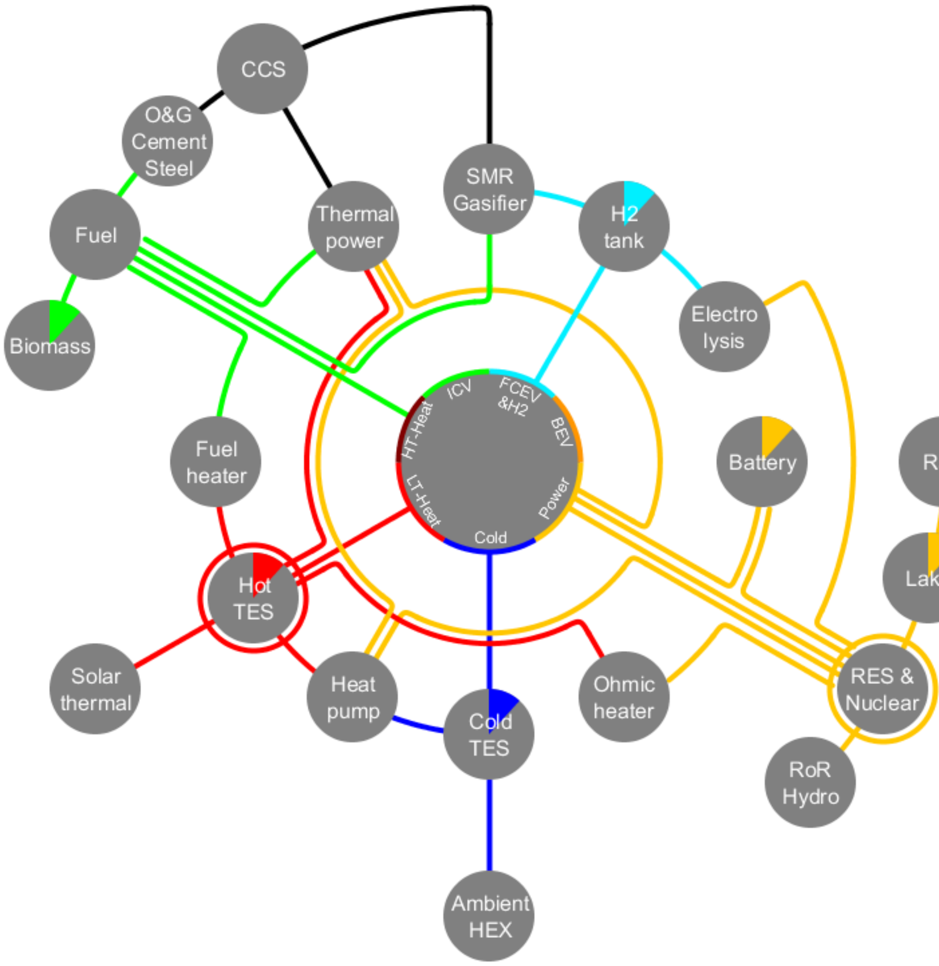

Figure 1: Model of the energy sector.

As shown in Figure 1 all aforementioned 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.

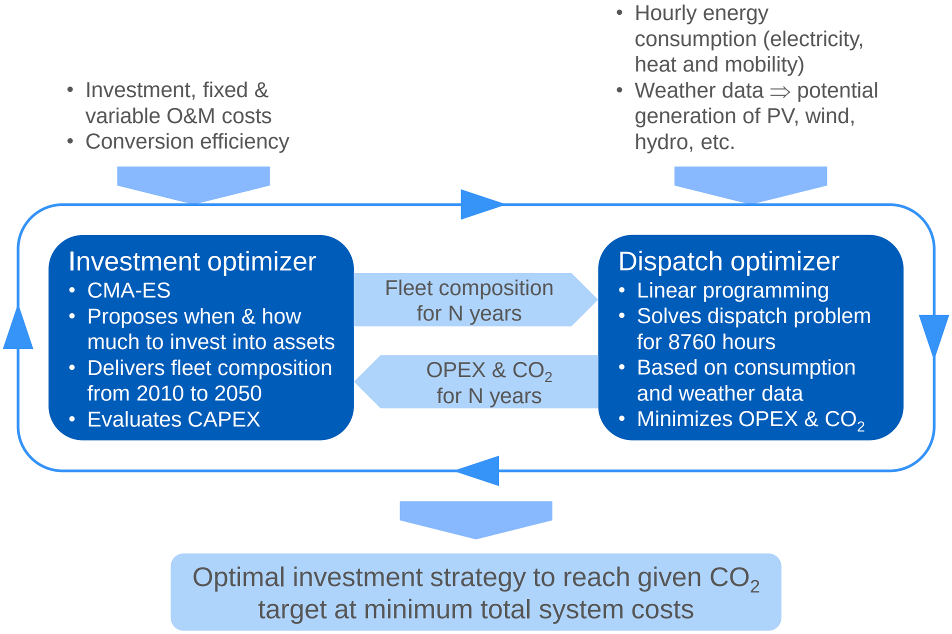

Figure 2: Structure of optimization approach.

Optimization approach

The objective of the model is to propose a cost-optimal investment strategy to achieve a given CO_2 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 CO_2 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 variable 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.

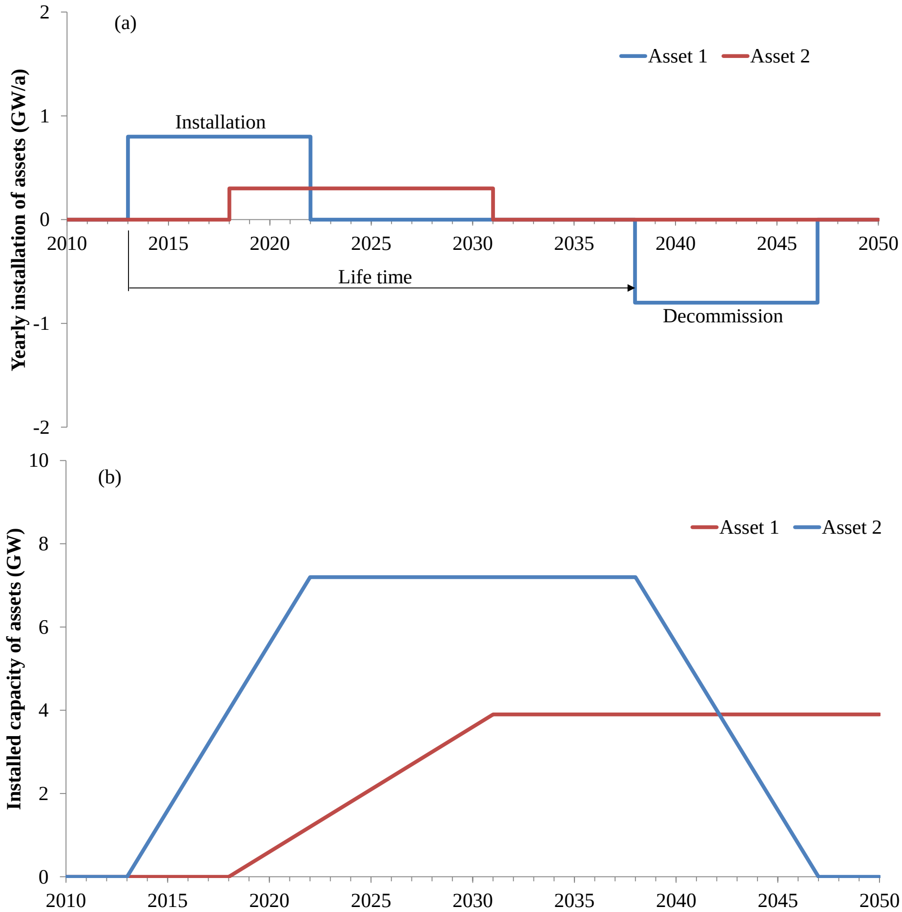

Figure 3: Investment optimization: (a) yearly installation of assets, (b) installed capacity.

The optimizer is based on perfect information for all coming 5-year periods until 2050, and is therefore able to select the lowest cost solution, not only for each 5-year period individually, but for the entire period up to 2050. The cost development forecasted by the model must therefore be considered to be rather optimistic compared to real life. On the other hand, the assumption underlines an important message of the report, that long term analysis and choices are important to select the lowest possible cost route for achieving the climate goals.

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 5%. This choice is a compromise between a social WACC that is usually set to 2-3% and a company WACC that is closer to 8-10%. The model assumes a 'perfect market', which installs and operates on the basis of total system costs.

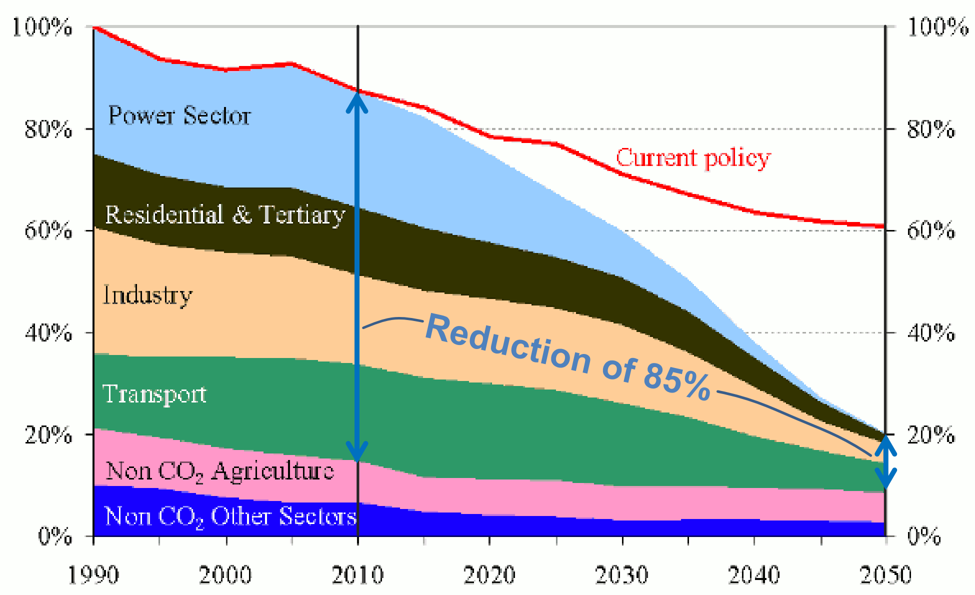

Figure 4: Target for CO_2 reduction from energy sector.

The objective function can be written down explicitly as follows:

$$OF = \sum_{i=0}^{N}(CAPEX_i + OPEX_i) + a\max(0, CO2_N - 0.05\ CO2_0)$$

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% for the energy sector alone. However, since the overall goal of Europe is 80-95% CO_2 reduction (ref 1990) we set the more ambitious goal of 95% reduction in the energy sector. Therefore, a second term is added to the objective function that penalizes any emission above 5% of the CO_2 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

[4] See http://ec.europa.eu/clima/policies/strategies/2050/index_en.htm

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 utilisation rate, the simple assumption is made that the demand is flat throughout the year.

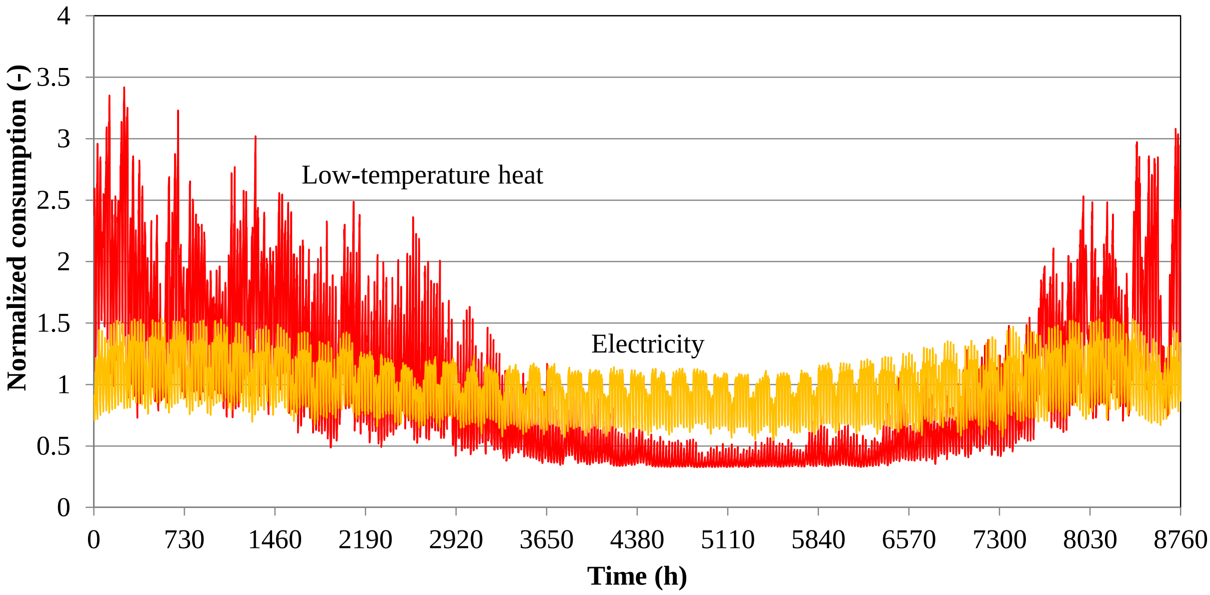

Figure 5: Normalized consumption of electricity and low-temperature heat.

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.

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

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.
- 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.

	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	0.36	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

Table 1: Cost data for power generation equipment.

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

	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 2: Cost data for heating and hydrogen generation equipment.

Fuel	Price (€/MWh)	CO2 intensity (kg_{CO2}/MWh)	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

Table 3: Assumptions on fuel costs and CO_2 intensity.

Biomass potential

Biomass has a critical role in all future energy scenarios. It offers the unique combination of being (in principle) CO_2 neutral and allowing for on-demand energy conversion, both for electricity generation and for supply of low or high-grade heat. Estimations of biomass potential show generally a wide scatter. A few are listed here for EU27.

- The University in Hohenheim suggests a potential in 2050 of 1500 TWh for energy crops only[9].
- The EU-funded Biomass Futures project gives a sustainable potential of 4100 TWH in 2030[10]
- A Swedish study gives a total potential of 1500 TWh [11]
- The EU-funded EUbionet3 project arrives at a potential of 1800 TWh/y[12]
- Another study gives the total potential between 2000-7000 TWh/y[13].
- A study by IINAS gives the potential of 800-1600 TWh/y for woody biomass only[14].
- The European Environment Agency (EEA) published a report that suggests an environmentally compatible potential of 3400 TWh/y by 2030[15].
- The FP7 project Biomass Energy Europe (BEE) summarized a variety of other studies. The potential estimates range from 1000-3000 TWh/y[16].

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[9] https://www.uni-hohenheim.de/i410b/download/publikationen/Globale%20Biomassepotenziale%20_%20FNR%2022003911%20Zwischenbericht%202012.pdf
[10] http://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/biomass_futures_atlas_of_technical_and_economic_biomass_potential_en.pdf
[11] http://www.ieabioenergy.com/wp-content/uploads/2013/10/ExCo58-P8-Biomass-Potential-in-Europe.pdf
[12] file:///C:/Users/gguidati/Downloads/EUBIONETIII_IEE_07_777_SI_499477_slides_final.pdf
[13] Marc de Wit, André Faaij. European biomass resource potential and costs. Biomass and Bioenergy Volume 34, Issue 2, February 2010, Pages 188–202
[14] http://iinas.org/tl_files/iinas/downloads/bio/IINAS_EFI_JR-2014-Forest_biomass_for_energy_in_the_EU.pdf
[15] http://www.eea.europa.eu/publications/eea_report_2006_7

The 10 selected countries represent 70-80% of the EU population, energy consumption and CO_2 emissions. The total amount of biomass primary energy input within this study was limited to 2400 TWh/y, an ambitious but realistic goal given the aforementioned potential estimates (see breakdown in Table 4 below).

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. Potential maximum installation numbers vary just as much as in the case of biomass (see studies by various institutes[17],[18],[19],[20]). Here we use a similar argument as in a previous ZEP publication, namely to scale the maximum capacity on the available land area. Following roughly the numbers from the previously mentioned studies a limit of 6% land coverage is assumed for wind energy, 0.5% for photovoltaics and 0.2% for solar thermal collectors. A typical power density that can be achieved with the various technology leads to maximum capacities for each country (see Table 4 below). It is again emphasized that the real limitation for renewable installation may be the required grid infrastructure, which 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 CO_2 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[21]. 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.

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[16] http://www.eu-bee.eu/
[17] https://www.ise.fraunhofer.de/de/veroeffentlichungen/veroeffentlichungen-pdf-dateien/studien-und-konzeptpapiere/studie-100-erneuerbare-energien-in-deutschland.pdf
[18] http://www.dewi.de/dewi_res/fileadmin/pdf/publications/Magazin_43/05.pdf
[19] http://www.greenpeace.org/espana/Global/espana/report/other/renewables-2050-a-report-on-t.pdf
[20] https://www.energy.eu/publications/a07.pdf
[21] http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics

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, 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 today's fuel cars by 2025. The required charging infrastructure is not modelled explicitly but considered as an additional operation expense for battery cars. The model takes this as 100 €/kWh of mechanical power.

The maximum amount of non-fuel mobility in 2050 is set to 75% to reflect the consensus view of the ZEP working group. Some stakeholders have questioned whether this is a realistic assumption to apply but, on balance, the group agreed that a 75% limit felt appropriate for this analysis. 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[22]. 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.

[22] 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[23]. 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 shows also the upper limits for biomass, wind, PV and solar thermal (see previous chapter).

	UK	PL	DE	NL	CH	FR	IT	ES	GR	NO	Sum
Surface (mio km^2)	248.0	312.0	357.0	41.5	41.0	632.0	302.0	506.0	132.0	385.0	2957
Population (mio)	65.1	38.5	81.5	17.0	8.2	66.5	61.0	46.4	10.7	5.2	400
Electricity (TWh/y)	344.7	133.0	557.0	114.9	61.8	470.9	304.3	250.6	53.4	75.0	2366
Low-grade heat (TWh/y)	484.7	299.1	808.3	198.1	79.1	528.9	454.7	169.7	34.6	61.0	3118
High-grade heat (TWh/y)	173.3	119.4	417.2	108.1	25.0	214.2	188.9	163.9	21.6	42.0	1474
Transportation (TWh/y)	85.1	34.3	119.9	24.5	13.1	94.6	76.4	58.4	11.2	11.0	529
Biomass potential (TWh/y)											
Biomass Futures, reference	255.9	430.3	674.5	81.4	81.4	756.0	360.5	372.2	97.1	531.0	3640
Stricter sutainibility criteria	104.7	407.1	616.4	81.4	81.4	674.5	290.8	302.4	78.9	502.3	3140
Other studies	96 - 500		330 - 500								
Used within this study	250.0	400.0	600.0	80.0	80.0	700.0	300.0	300.0	80.0	500.0	3290
PV, 0.5% of surface (GW)	186.0	234.0	267.8	31.1	30.8	474.0	226.5	379.5	99.0	288.8	2217
Solar thermal, 0.2% of surface (GW)	198.4	249.6	285.6	33.2	32.8	505.6	241.6	404.8	105.6	308.0	2365
Wind, 6% of surface (GW)	89.3	112.3	128.5	14.9	14.8	227.5	108.7	182.2	47.5	138.6	1064

Table 4: Input data and constraints for the 10 countries.

The item electricity contains all energy that is consumed for the typical uses such as lighting, motors, etc. The use of electricity for space heating (resistance heaters or heat pumps) or transportation (e-mobility) is not included in the item electricity but in the respective categories low-grade heat and transportation. This was done to account for alternative options such as biomass for space heating. For most countries this has little impact, only Norway is an exception because most of the space heating is done using electricity. The effective electricity consumption in Norway is therefore close to the sum of electricity and space heating in Table 4.

Note that the industrial high grade heat consumption is actually split between the energy intensive industries (steel, cement and refineries), and the rest (chemical, pulp & paper, food and many more). Within this model the rest is not tackled in terms of its CO_2 emissions, it is merely considered in the overall balance. The energy intensive industries have only CCS as a decarbonization option, using all assumptions on costs and reduction level that were summarized in a previous ZEP report. The use of biomass would be an option but is not modelled here.

The next sections present results for the 10 countries. Each section contains a graph which displays the total levelized systems costs vs. the emitted CO_2 for the two scenarios. This allows a direct evaluation which level of emission reduction can be achieved and how much more the consumer will have to pay. These graphs contain a vertical line that represents the minimum CO_2 emission that can be reached by totally de-carbonizing the electricity & heating sector, and 75% of the transport sector. This sets a floor to the non-CCS scenario consisting of 25% of the transport emissions plus all industrial emissions.

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

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-CO_2 technologies, mainly wind and solar PV. 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.

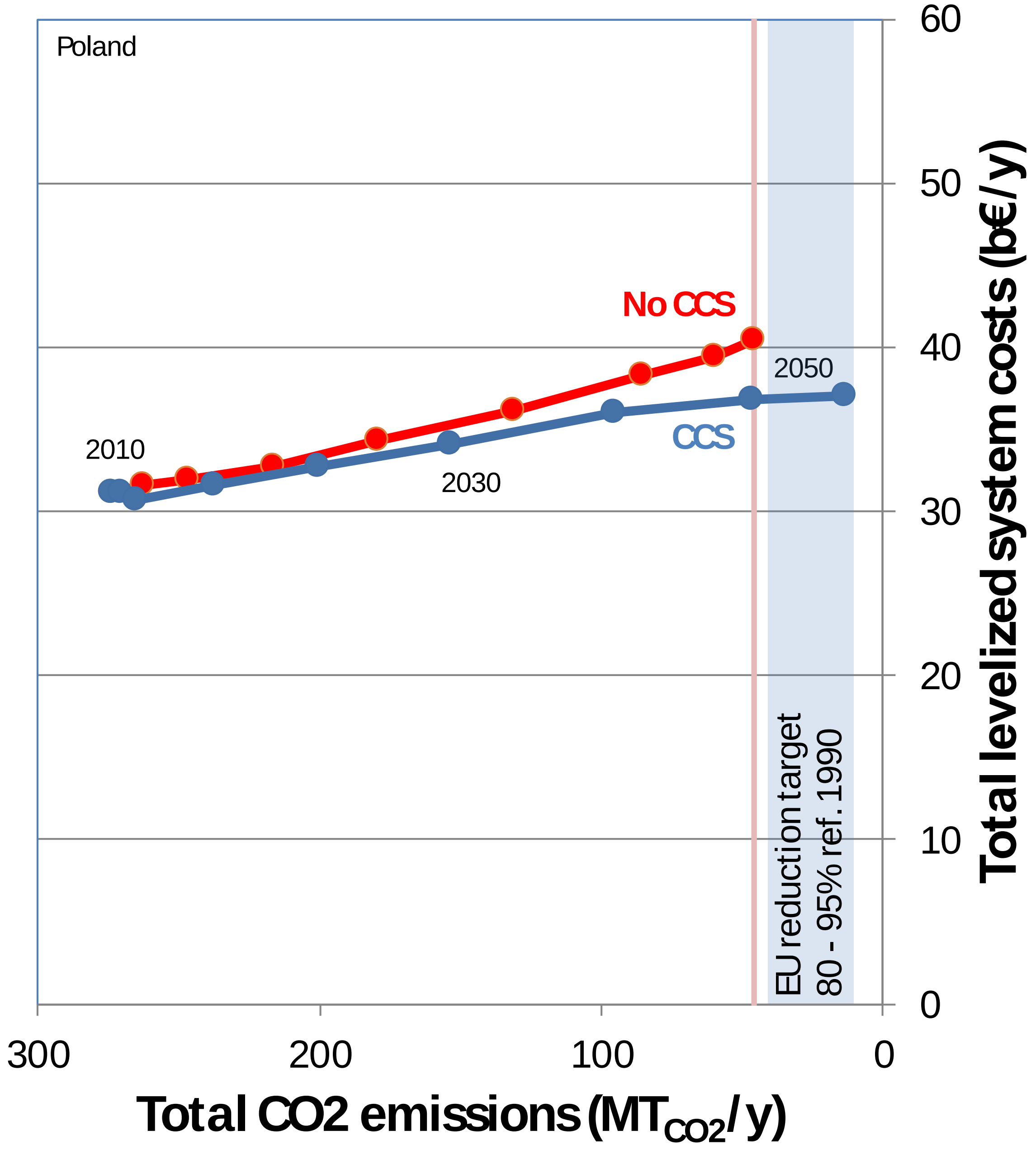


Figure 6: Costs vs. CO_2 emissions for Poland (with CCS, without CCS).

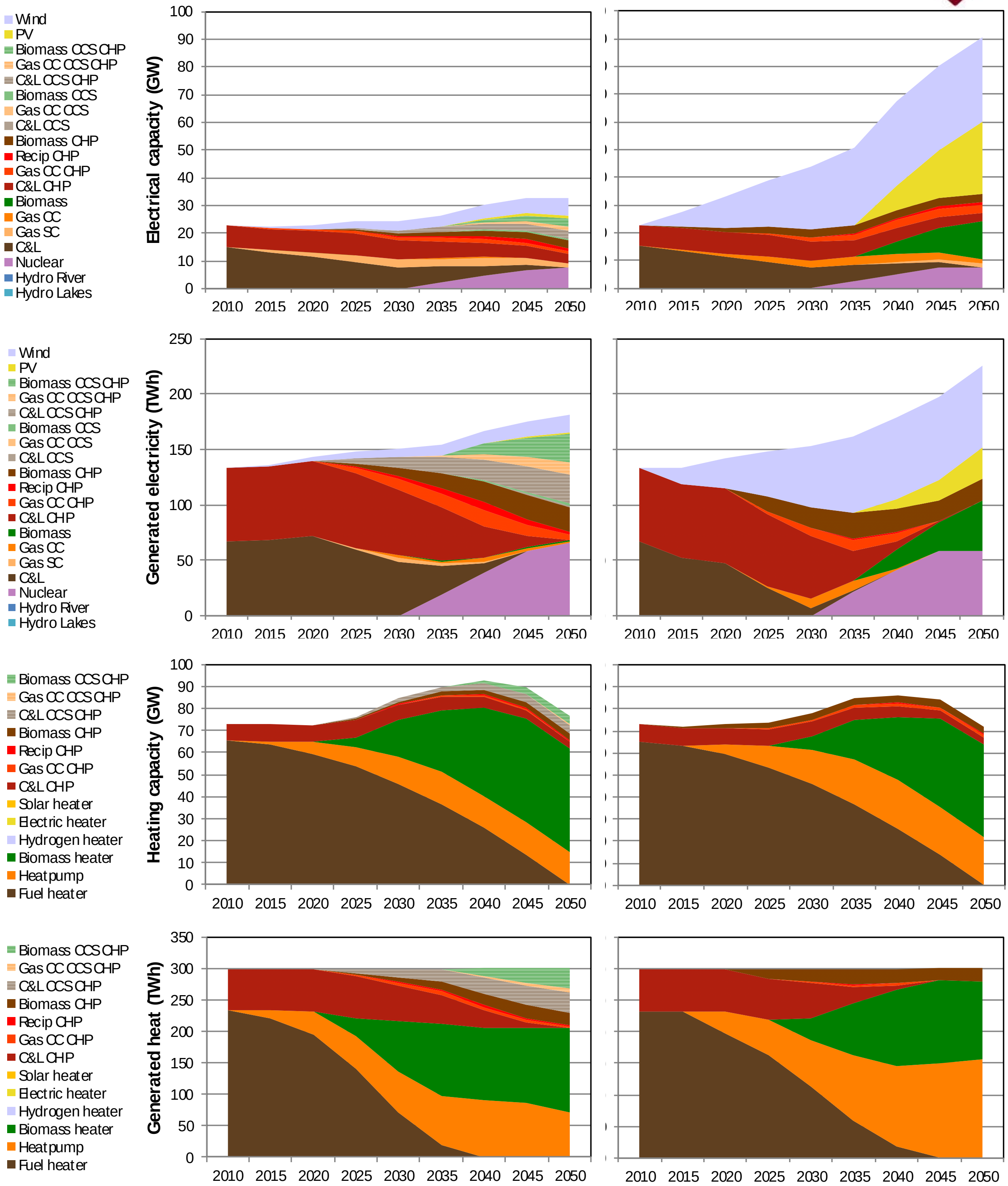


Figure 7: Results for Poland; CCS is available (left), CCS is not available (right).

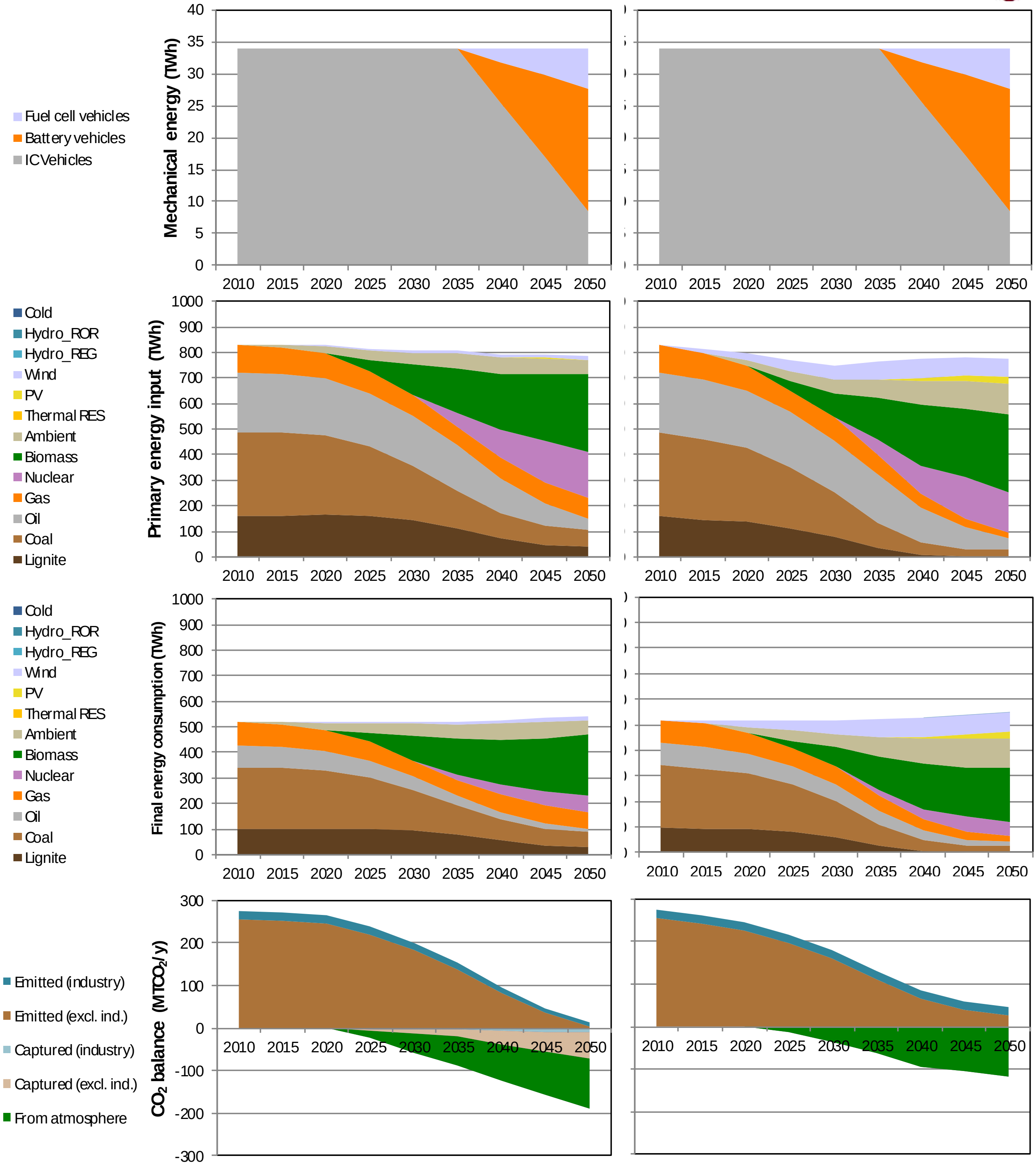
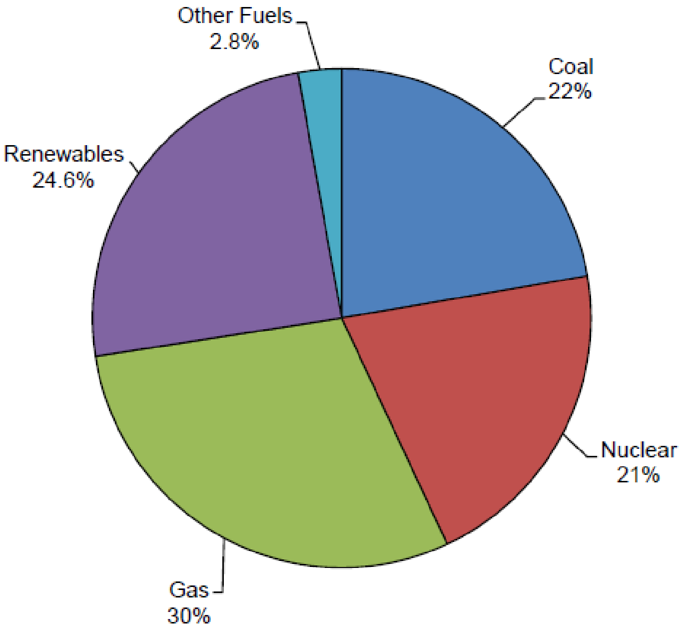


Figure 8: Results for Poland; CCS is available (left), CCS is not available (right).

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*"[24]. 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.

[24] 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.

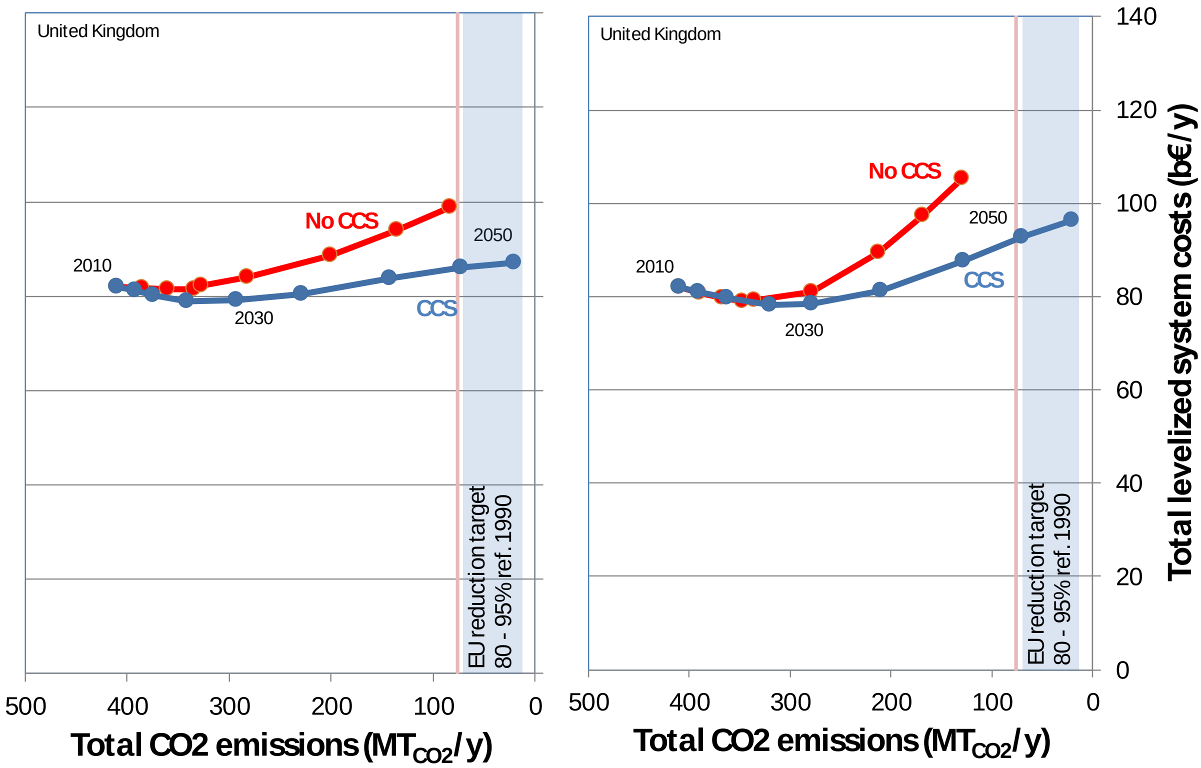


Figure 9: Costs vs. CO_2 emissions for United Kingdom (with CCS, without CCS). Left: Heat pumps are available; right: heat pumps are not available.

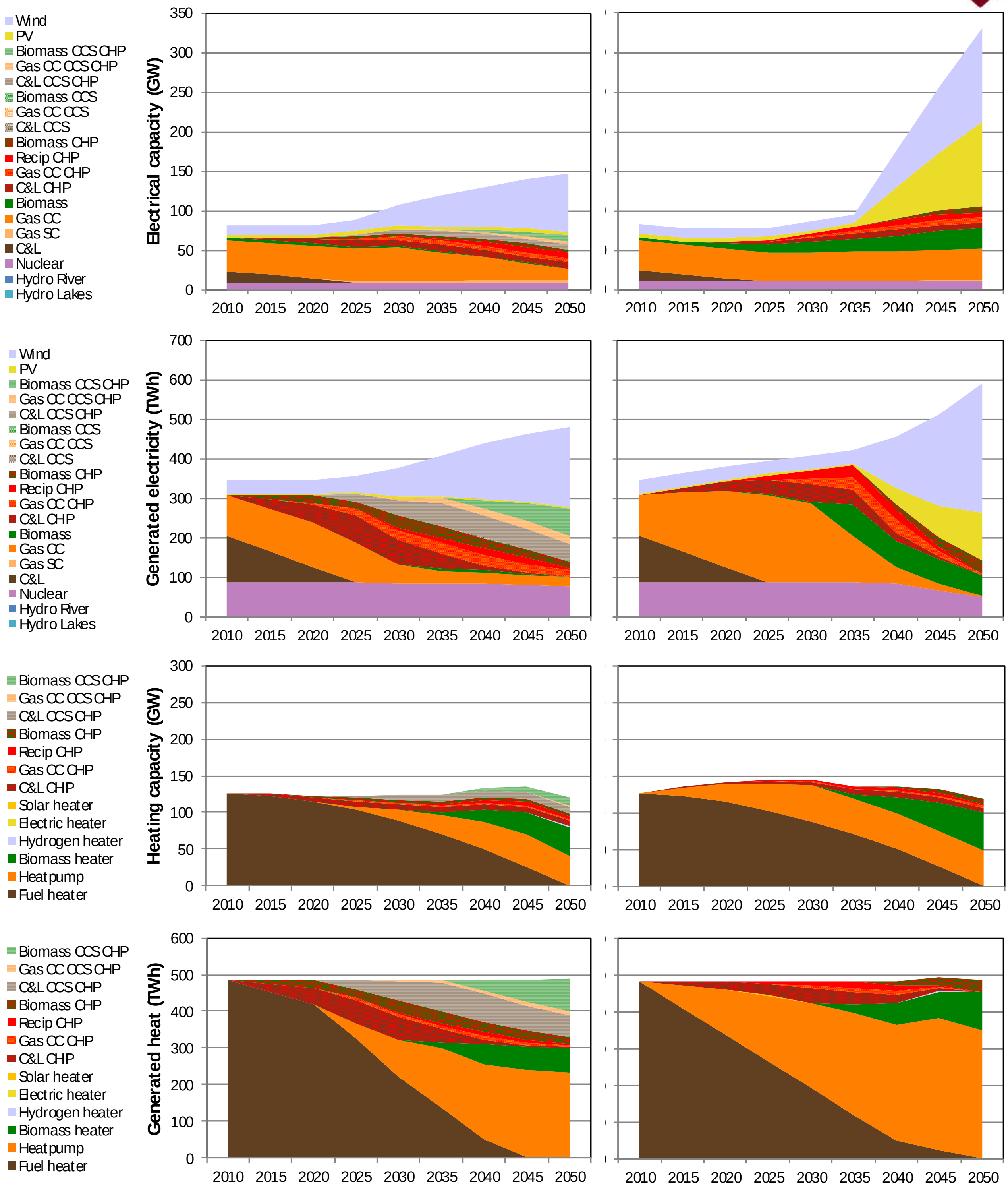


Figure 10: Results for UK; CCS is available (left), CCS is not available (right).Heat pumps are included in the technology mix.

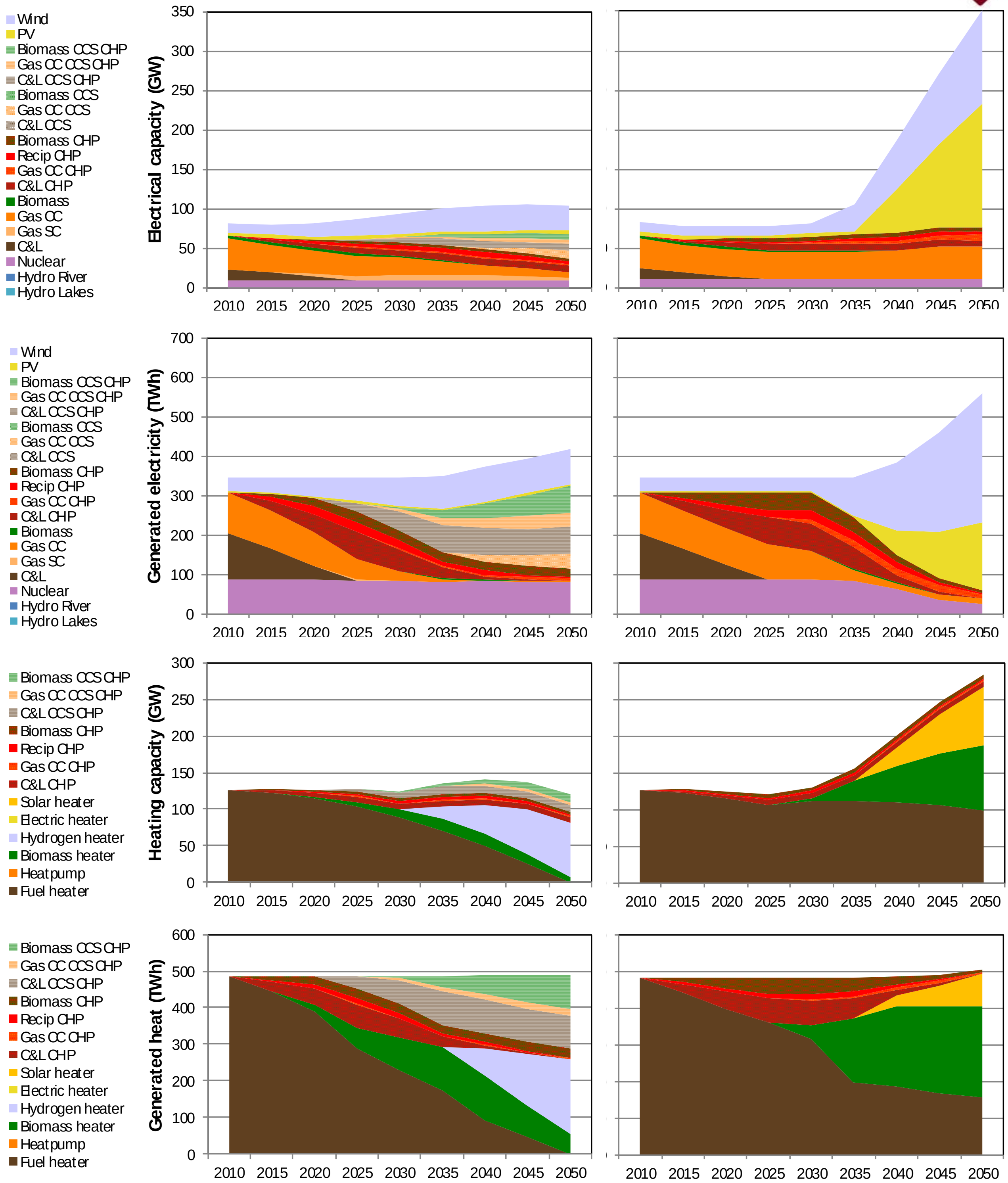


Figure 11: Results for UK; CCS is available (left), CCS is not available (right). Heat pumps are <u>not</u> included in the technology mix.

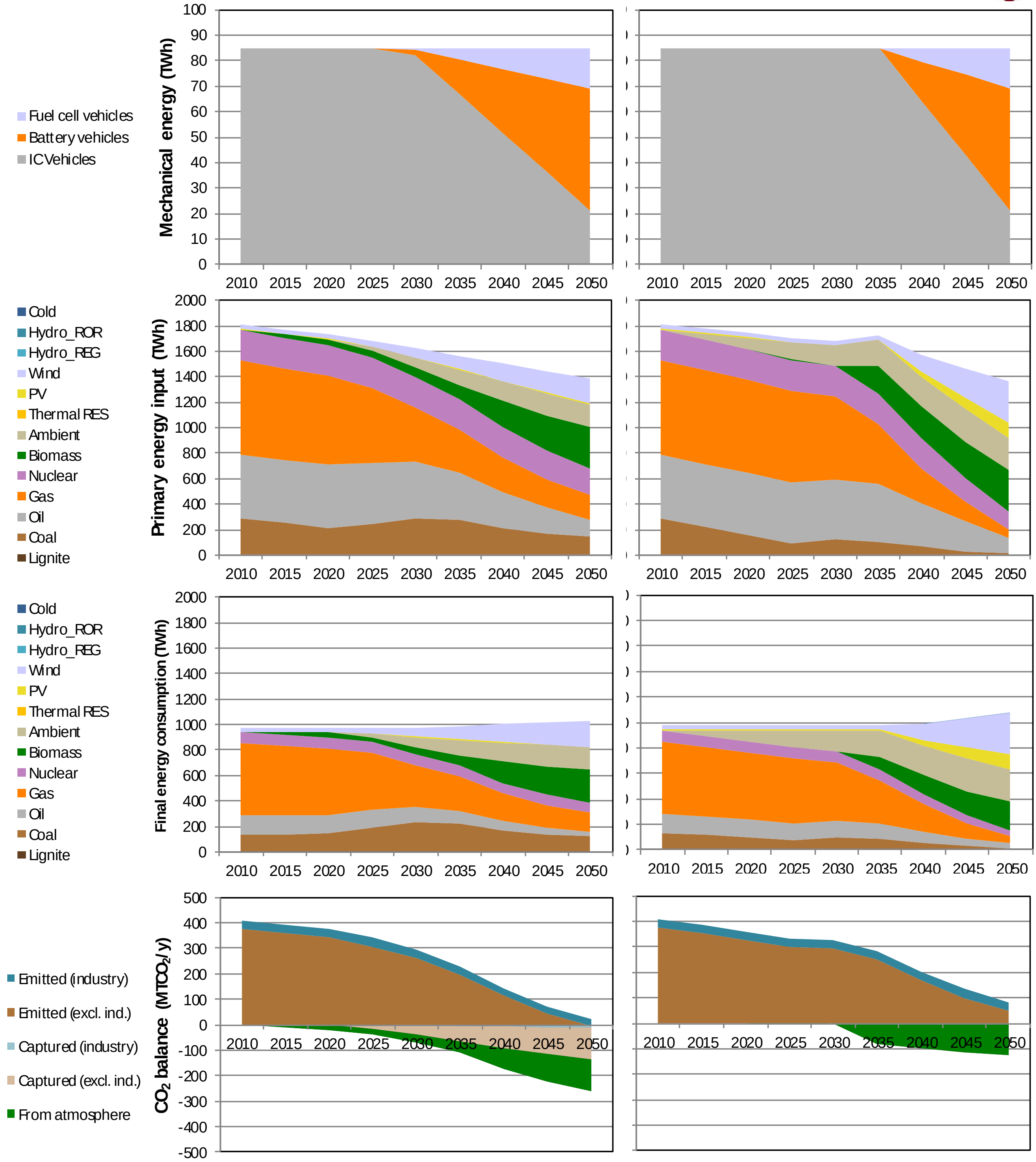


Figure 12: Results for UK; CCS is available (left), CCS is not available (right). Heat pumps are included in the technology mix.

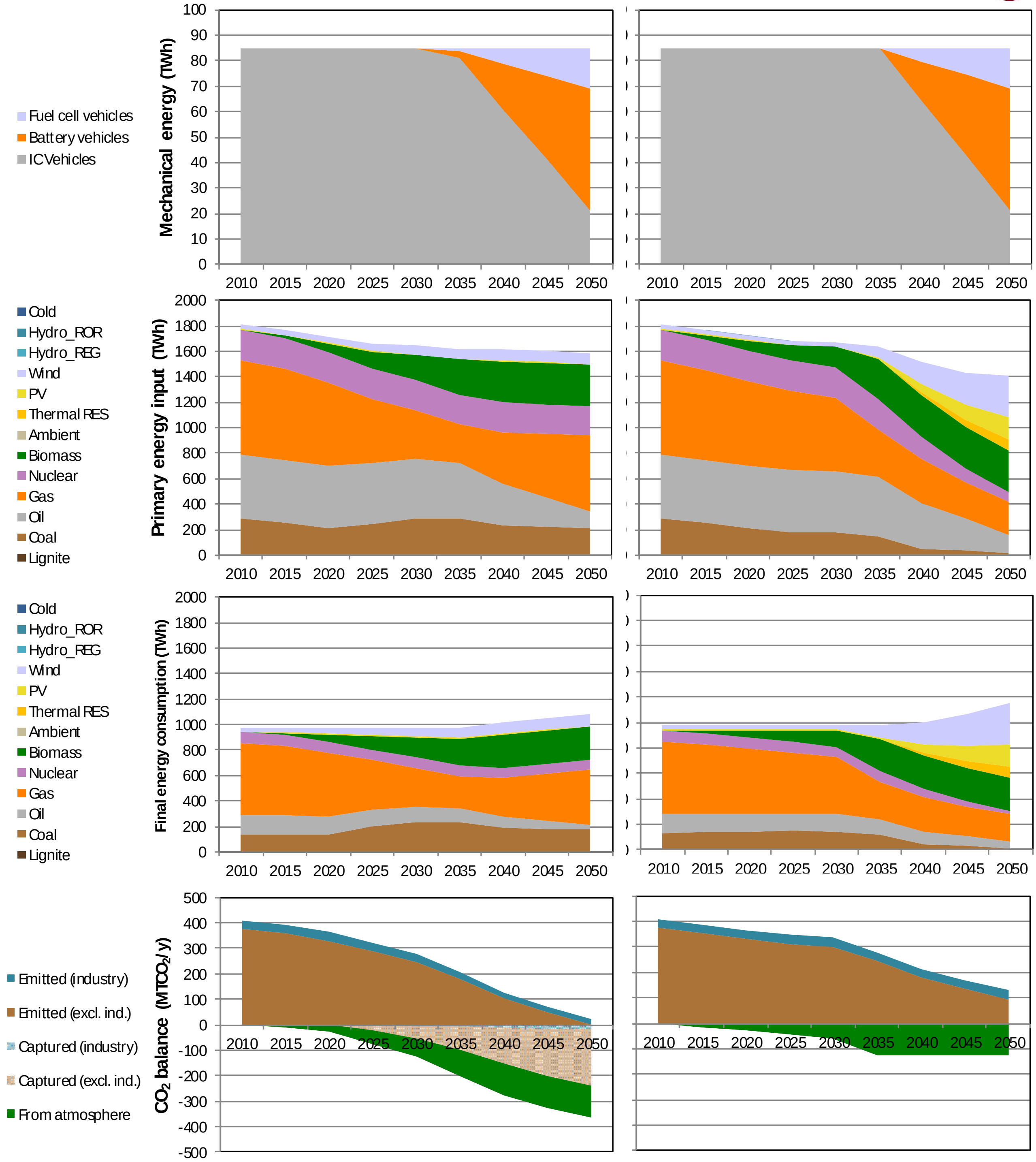


Figure 13: Results for UK; CCS is available (left), CCS is not available (right). Heat pumps are <u>not</u> included in the technology mix.

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.

The Netherlands has relatively easy access to storage locations offshore. There is currently no political support for onshore storage in the Netherlands. Once the ROAD project starts, CO_2 storage will start close to the Rotterdam harbour. Once started, there will probably be much benefit in attaching new storage locations and improving the flexibility of the network. The Dutch government will update its transport and storage plan in 2017, setting out potential further developments. The Dutch storage locations could be the first candidates for captured CO_2 from neighbouring countries as well. If there were a market for storage, the Netherlands could benefit from making available storage capacity.

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.

While the model logically uses its options to decarbonise low temperature heat production, the Netherlands is also considering different options for this challenge. The Energy Report, which was early 2016, sets out the expectations of the Dutch Government on low-temperature heating, as well as on the other energy functions (high-temperature heat, electricity and lighting, and transportation). Considering low-temperature heat, the strategies include direct use of solar heat; a growth of district heating systems using geothermal heat, biomass-fired CHP, and waste heat from industry or municipal waste incinerators; heat production from electricity through heat pumps, and from renewable gaseous sources such as ‘green gas’ or hydrogen.

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.

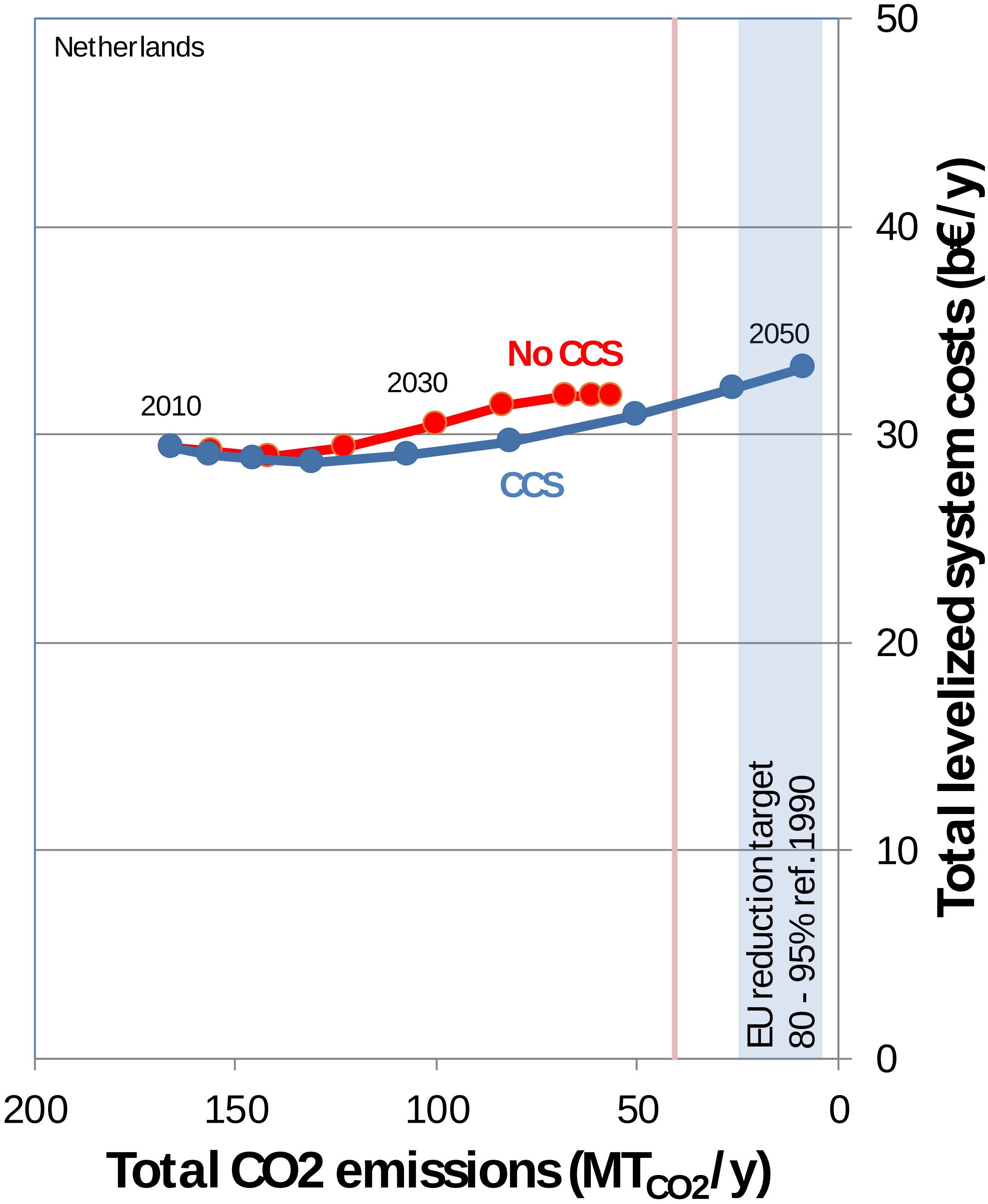


Figure 14: Costs vs. CO_2 emissions for the Netherlands (with CCS, without CCS).

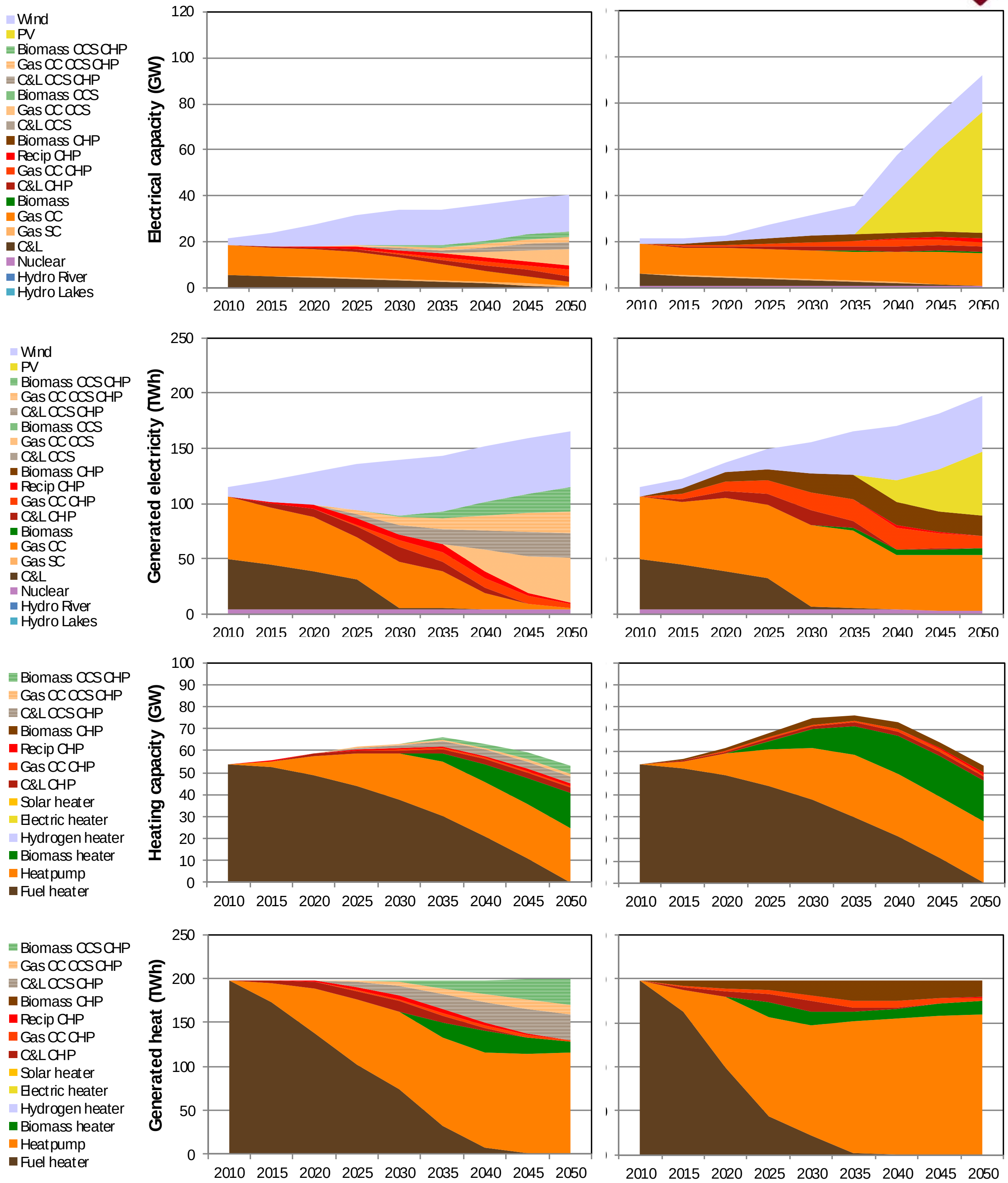


Figure 15: Results for the Netherlands; CCS is available (left), CCS is not available (right).

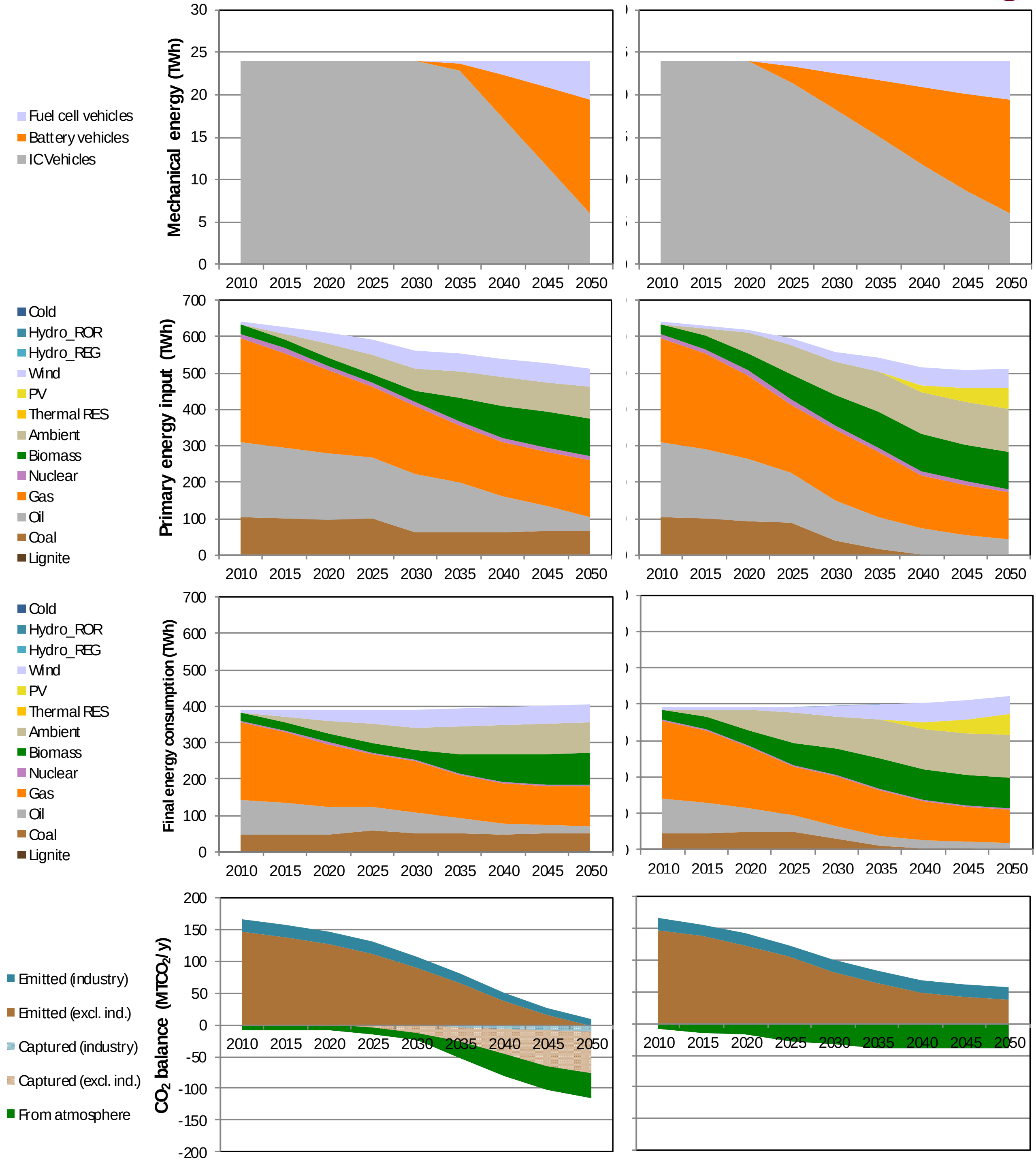


Figure 16: Results for the Netherlands; CCS is available (left), CCS is not available (right).

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 CO_2 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 CO_2 balance curves.

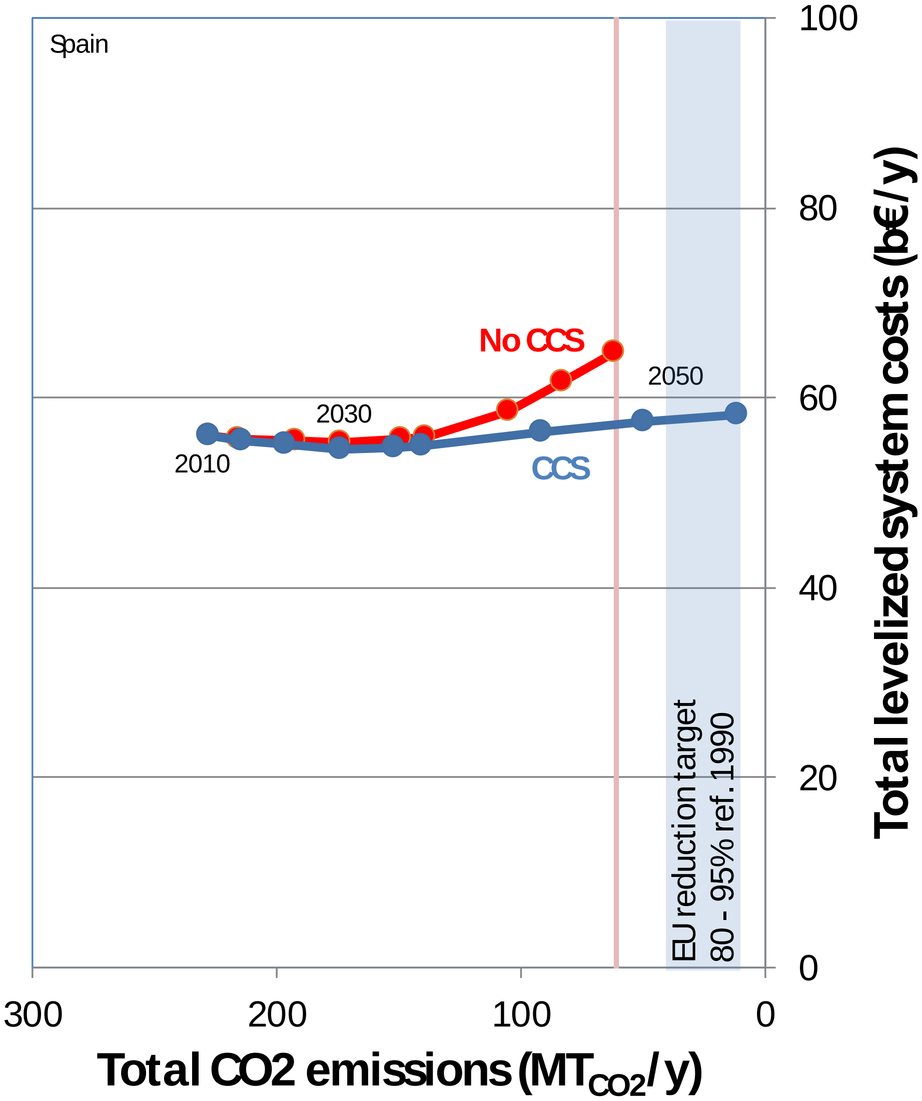


Figure 17: Costs vs. CO_2 emissions for Spain (with CCS, without CCS).

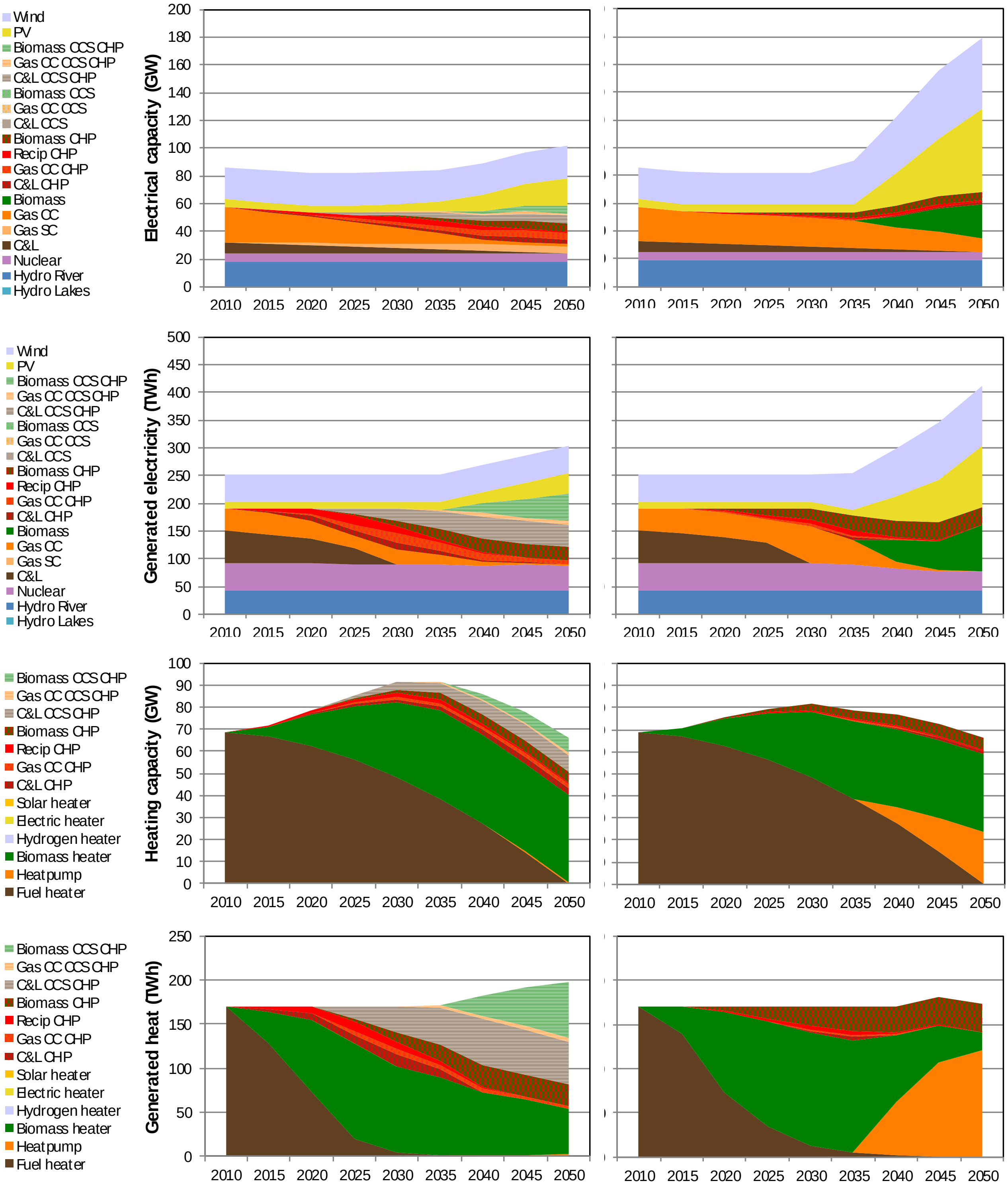


Figure 18: Results for Spain; CCS is available (left), CCS is not available (right).

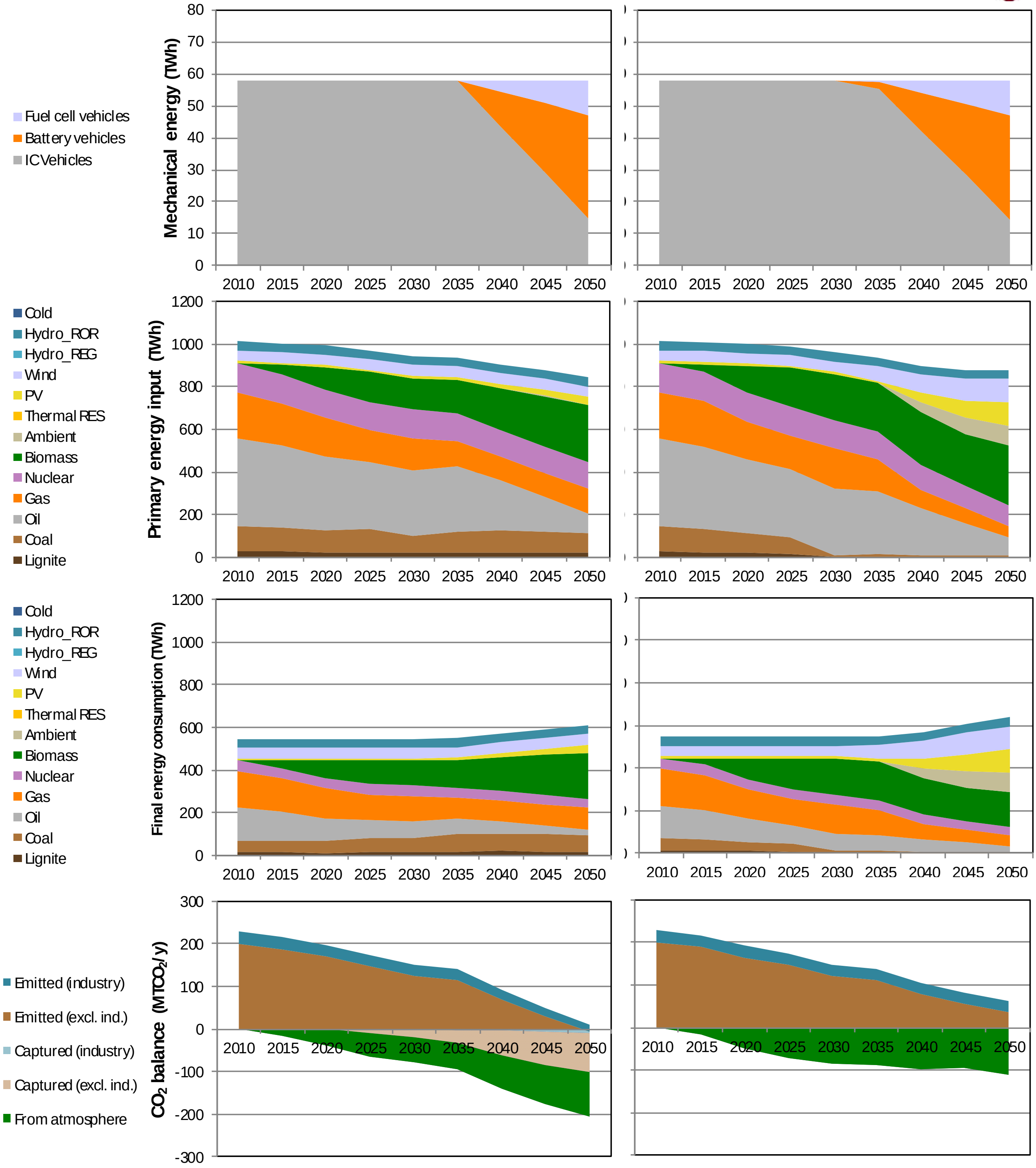


Figure 19: Results for Spain; CCS is available (left), CCS is not available (right).

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-CO_2 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 CO_2 emissions down to approx. one t_{CO2} per person and year.

The special challenge of the energy transition in Switzerland is to replace CO_2-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. CO_2 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 CO_2 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 CO_2 negative emissions. Switzerland is modelled to meet the 1tonCO_2 per capita budget by 2050 in the CCS case but not without CCS.

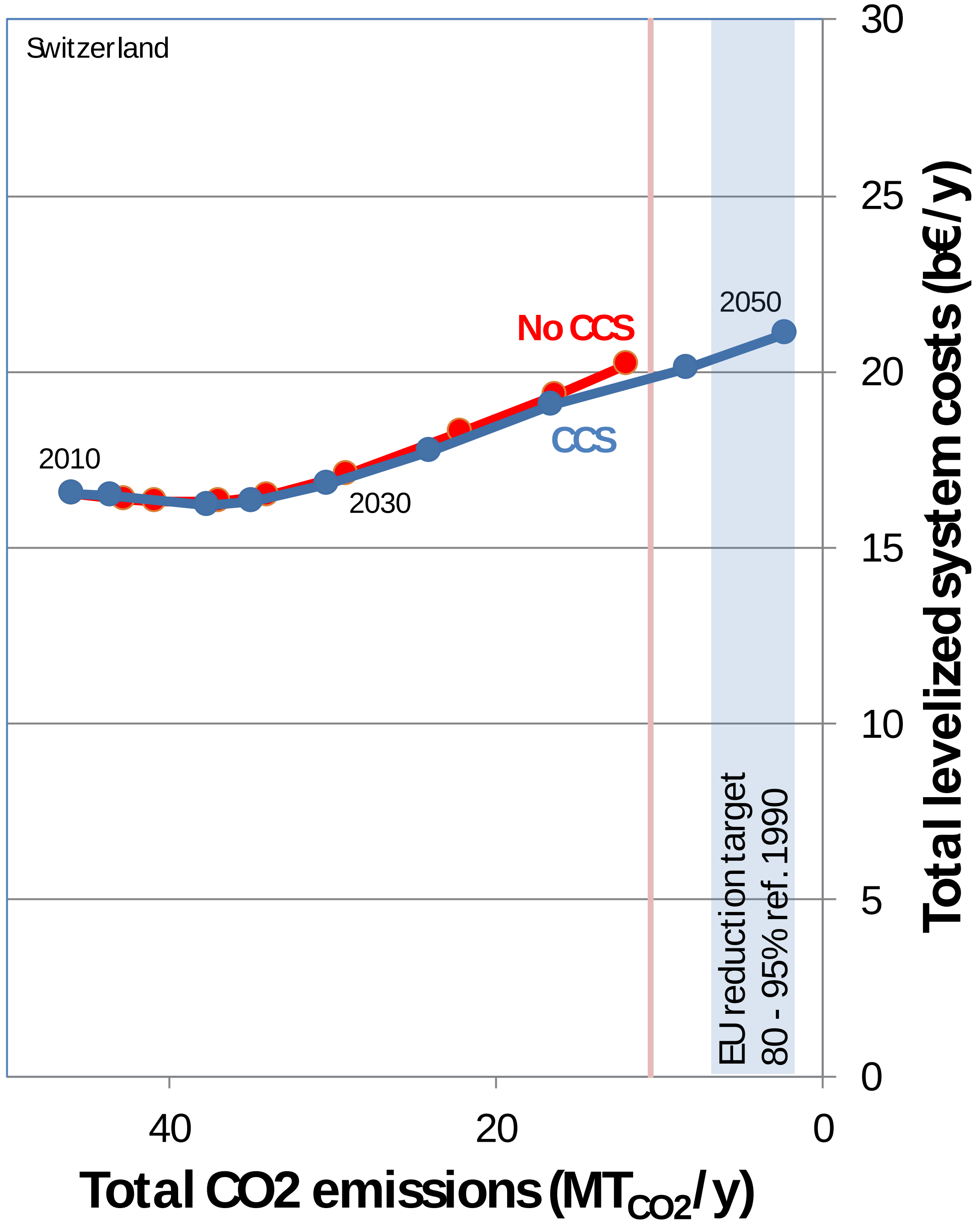


Figure 20: Costs vs. CO_2 emissions for Switzerland (with CCS, without CCS).

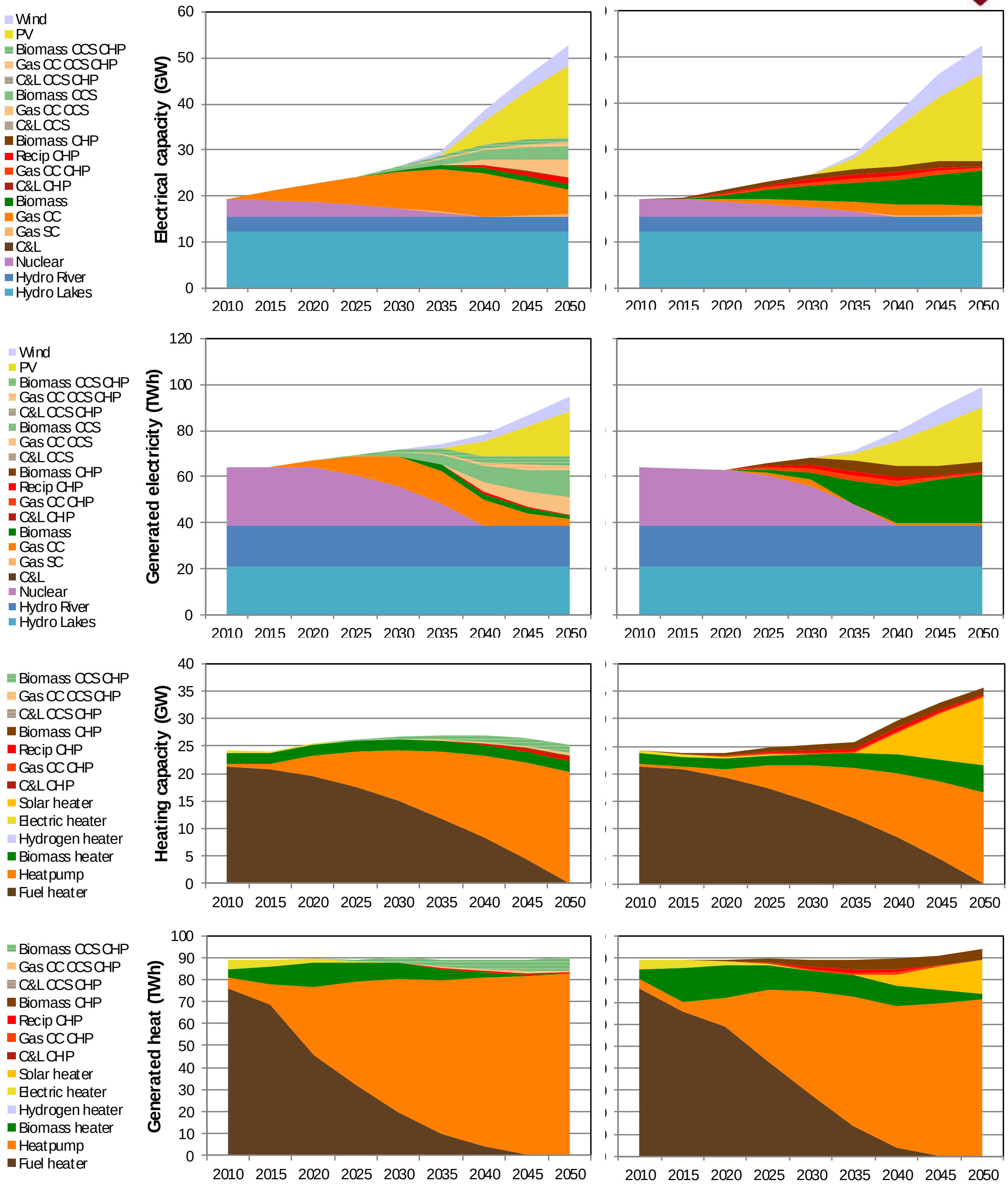


Figure 21: Results for Switzerland; CCS is available (left), CCS is not available (right).

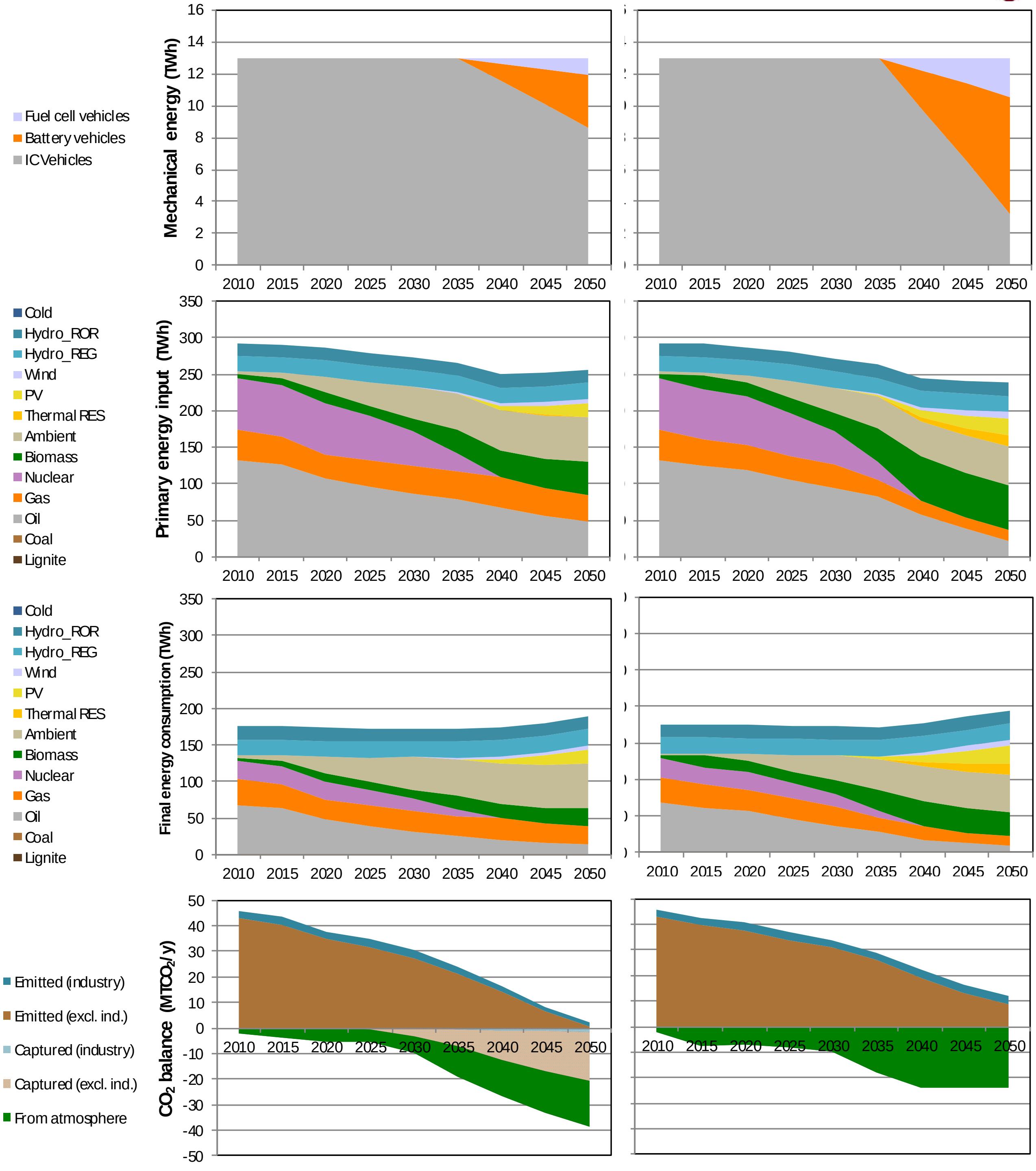


Figure 22: Results for Switzerland; CCS is available (left), CCS is not available (right).

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.

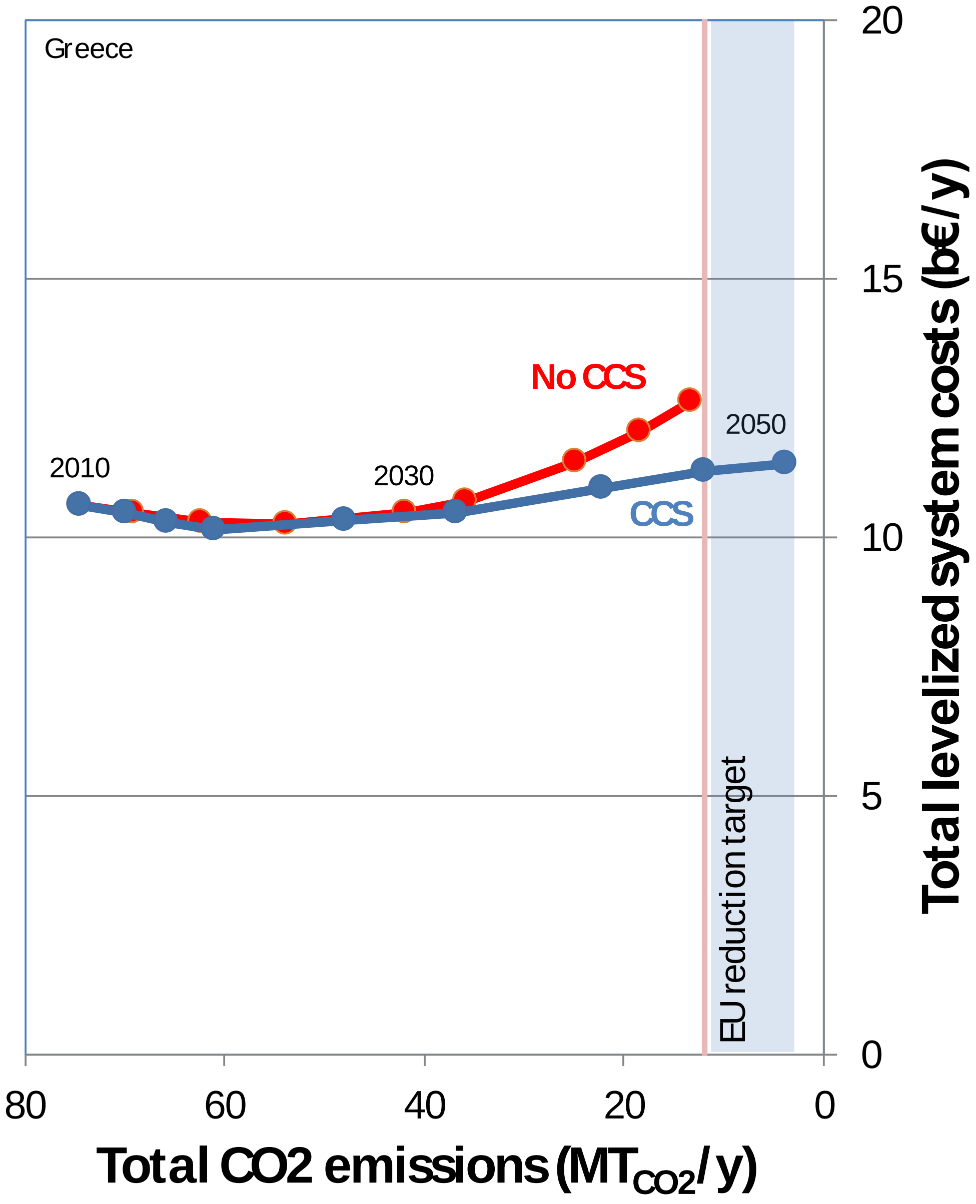


Figure 23: Costs vs. CO_2 emissions for Greece (with CCS, without CCS).

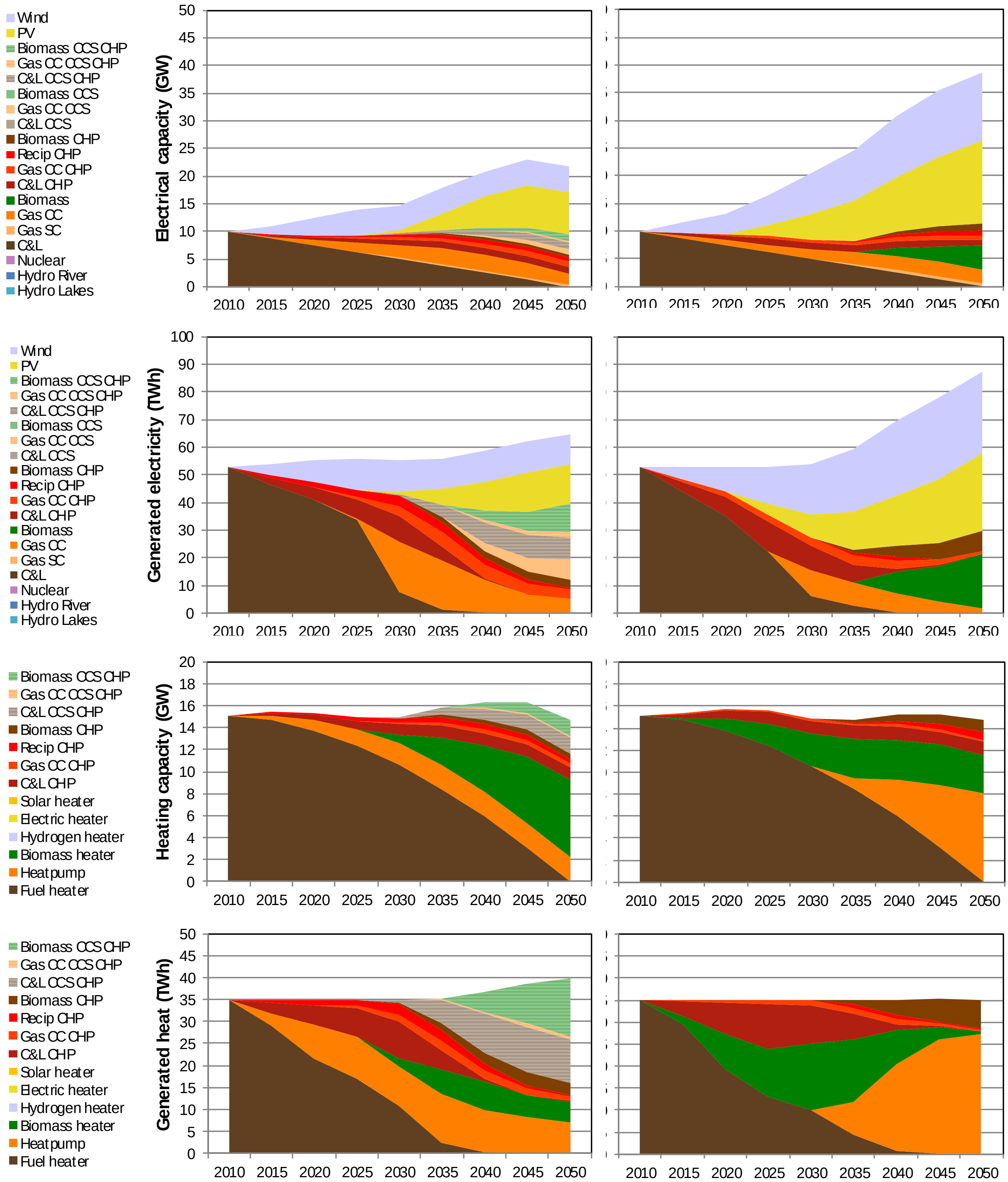


Figure 24: Results for Greece; CCS is available (left), CCS is not available (right).

Zero emissions platform

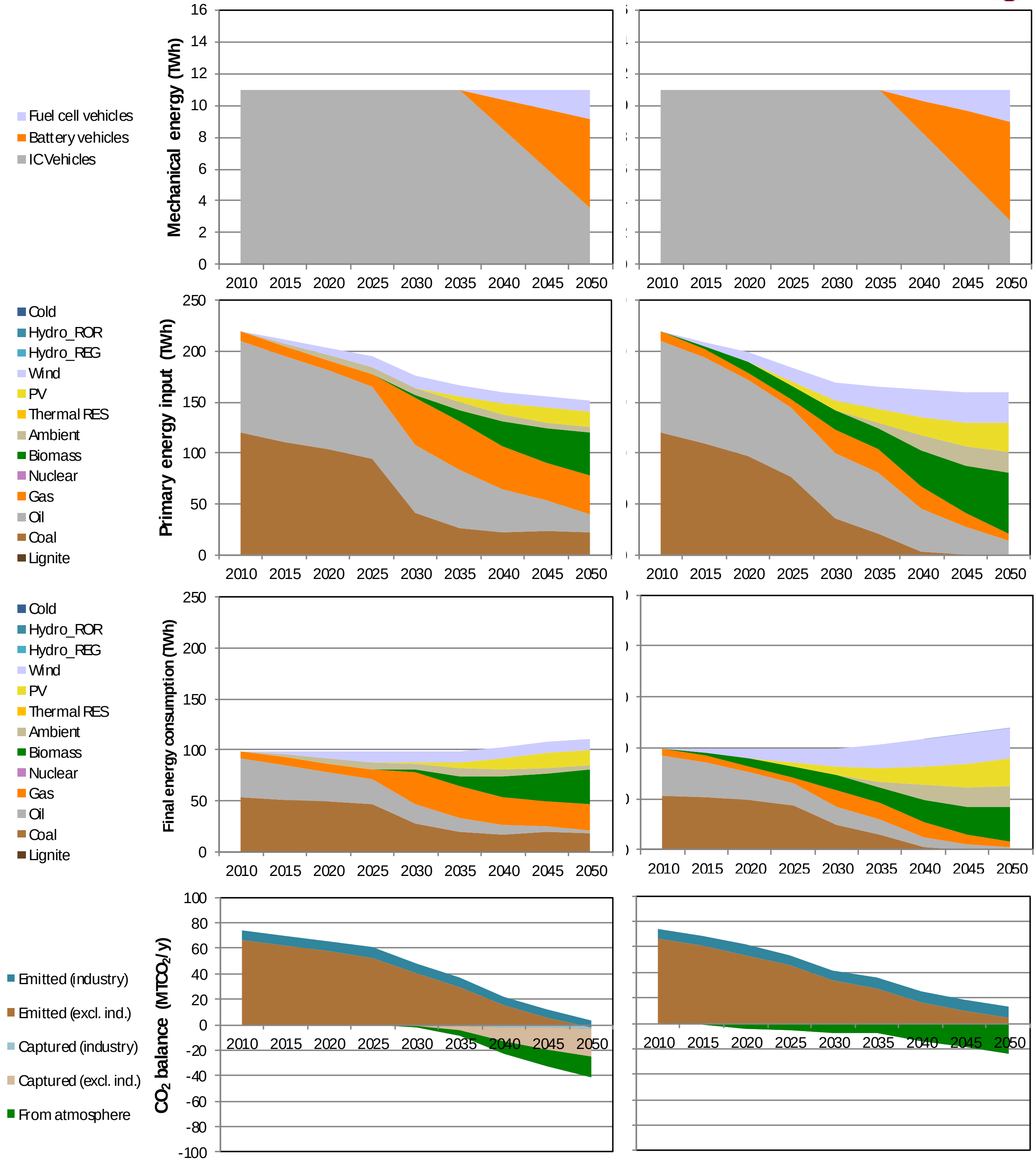


Figure 25: Results for Greece; CCS is available (left), CCS is not available (right).

Italy

The Italian electricity system shows a balanced portfolio of fossil fuels (mostly gas) and renewable generation. The installed capacity of solar PV and wind, in particular, has grown substantially over the past years. In both the CCS and no-CCS scenarios, high efficiency gas combined cycles remain the backbone of the electricity system into the future. If CCS is available, it starts being deployed from 2025 onwards, in parallel with further strong growth of wind and PV. If CCS is not available, the growth of renewable generation in terms of installed capacity is even more pronounced, however, with the negative consequence of higher curtailment.

CO_2 reductions in the heating sector are achieved primarily through a replacement of oil and gas furnaces by a mix of CHP, biomass heaters and heat pumps. Not having CCS available requires a considerably larger share of heat pumps to achieve emission reductions in 2050. Figure 26 shows that despite excellent solar and wind resources, the cost-optimal mix for the Italian energy system should contain CCS.

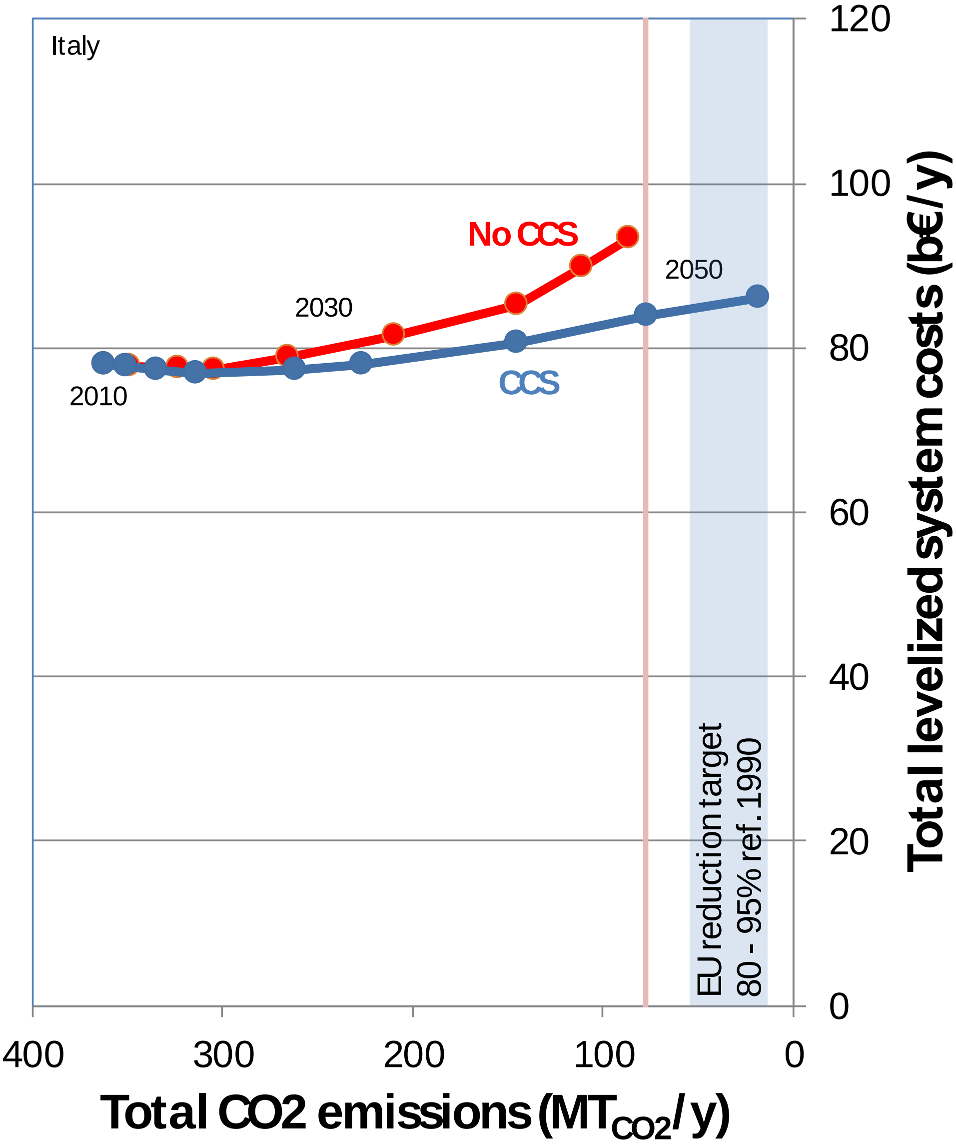


Figure 26: Costs vs. CO_2 emissions for Italy (with CCS, without CCS).

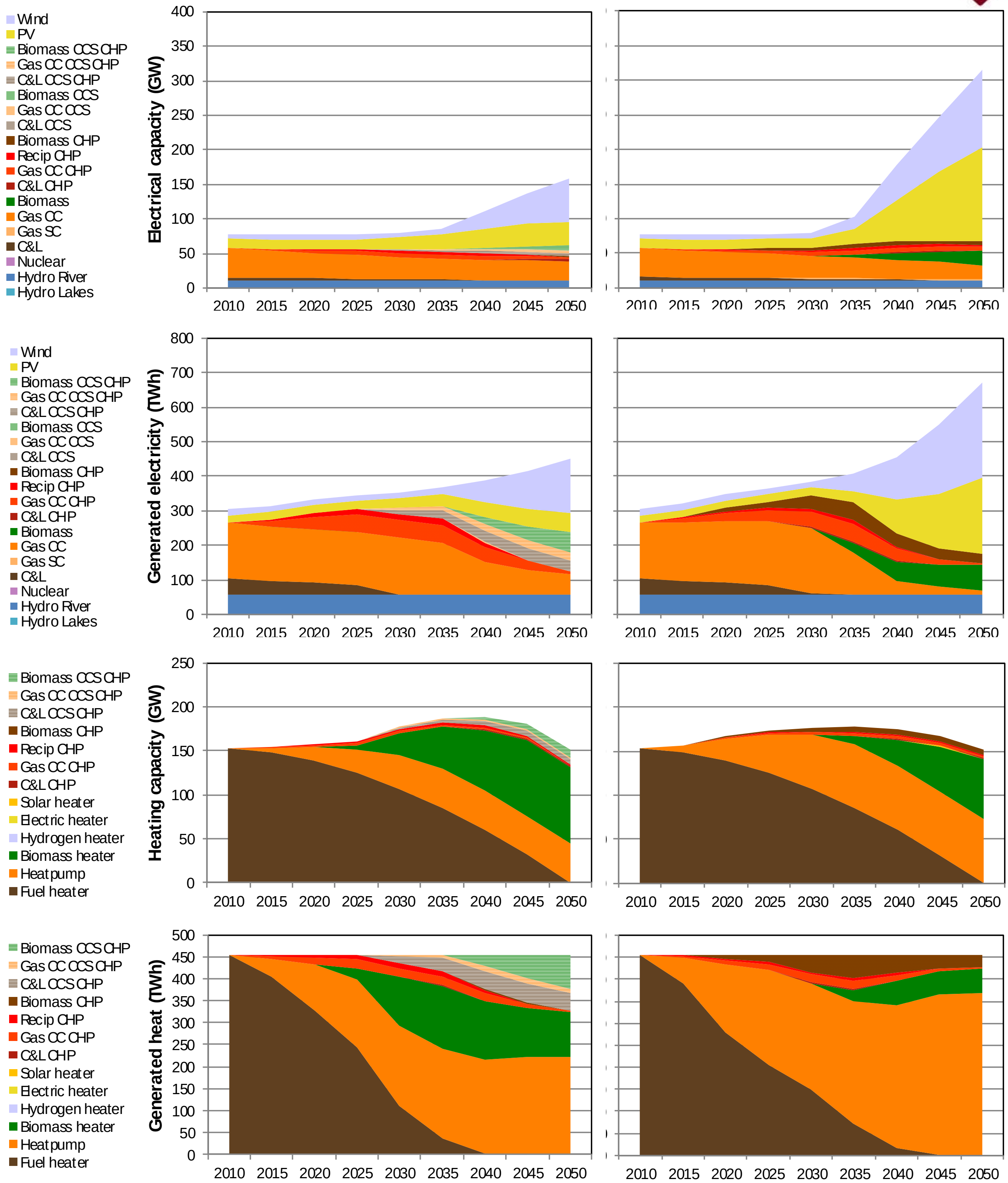


Figure 27: Results for Italy; CCS is available (left), CCS is not available (right).

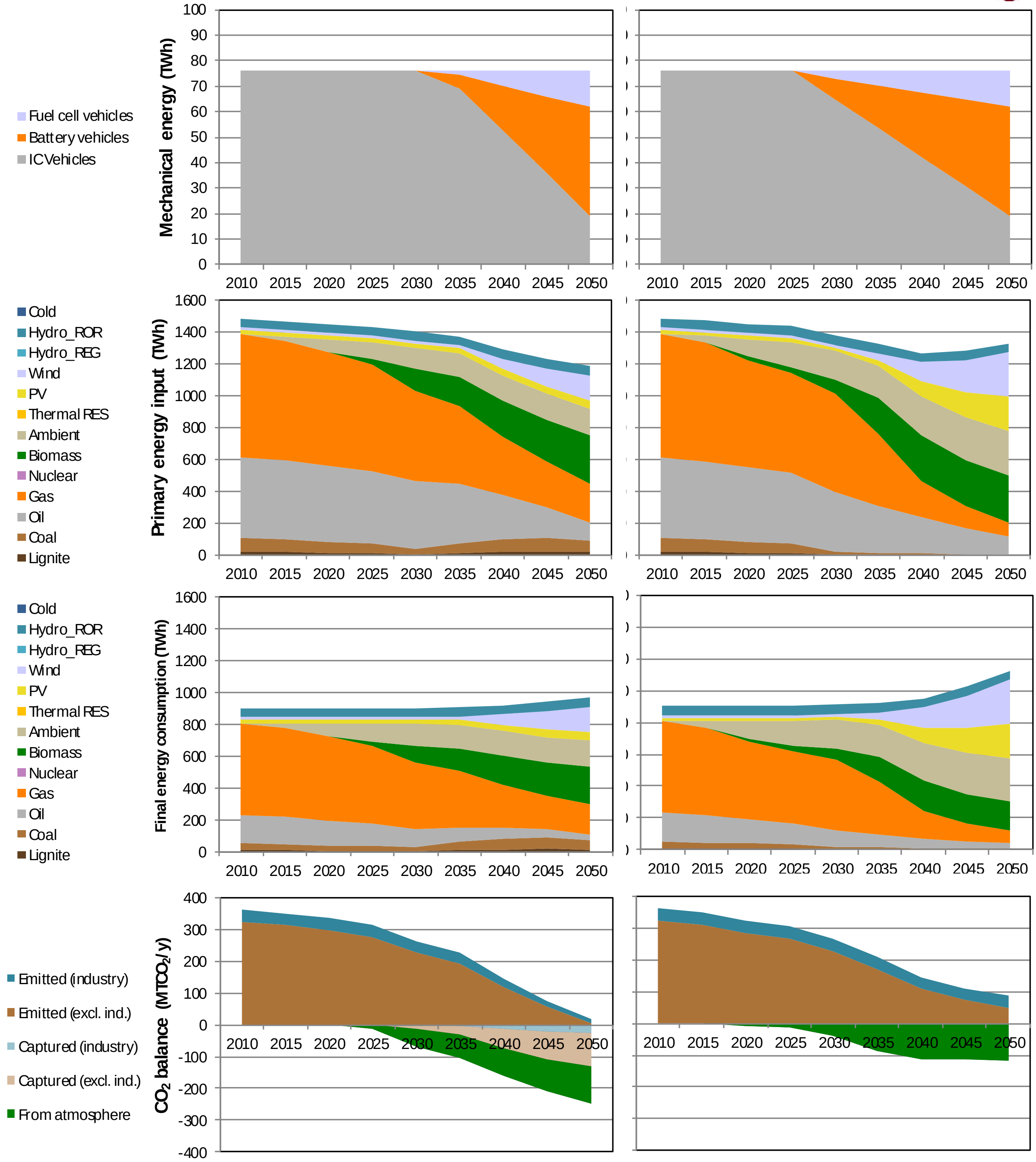


Figure 28: Results for Italy; CCS is available (left), CCS is not available (right).

France

The energy system of France is dominated by near CO_2 free Nuclear and Hydro in electricity generation and combustion of gas and oil for space heating and industrial processes. The current CO_2 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. With strong wind resources this becomes an important part of the fleet.Together with hydro capacity this mix gives France a strong base for CO_2 emissions reduction using CCS on the industrial emsiions and CHP CCS plant and heat pumps and biomass for space heating.

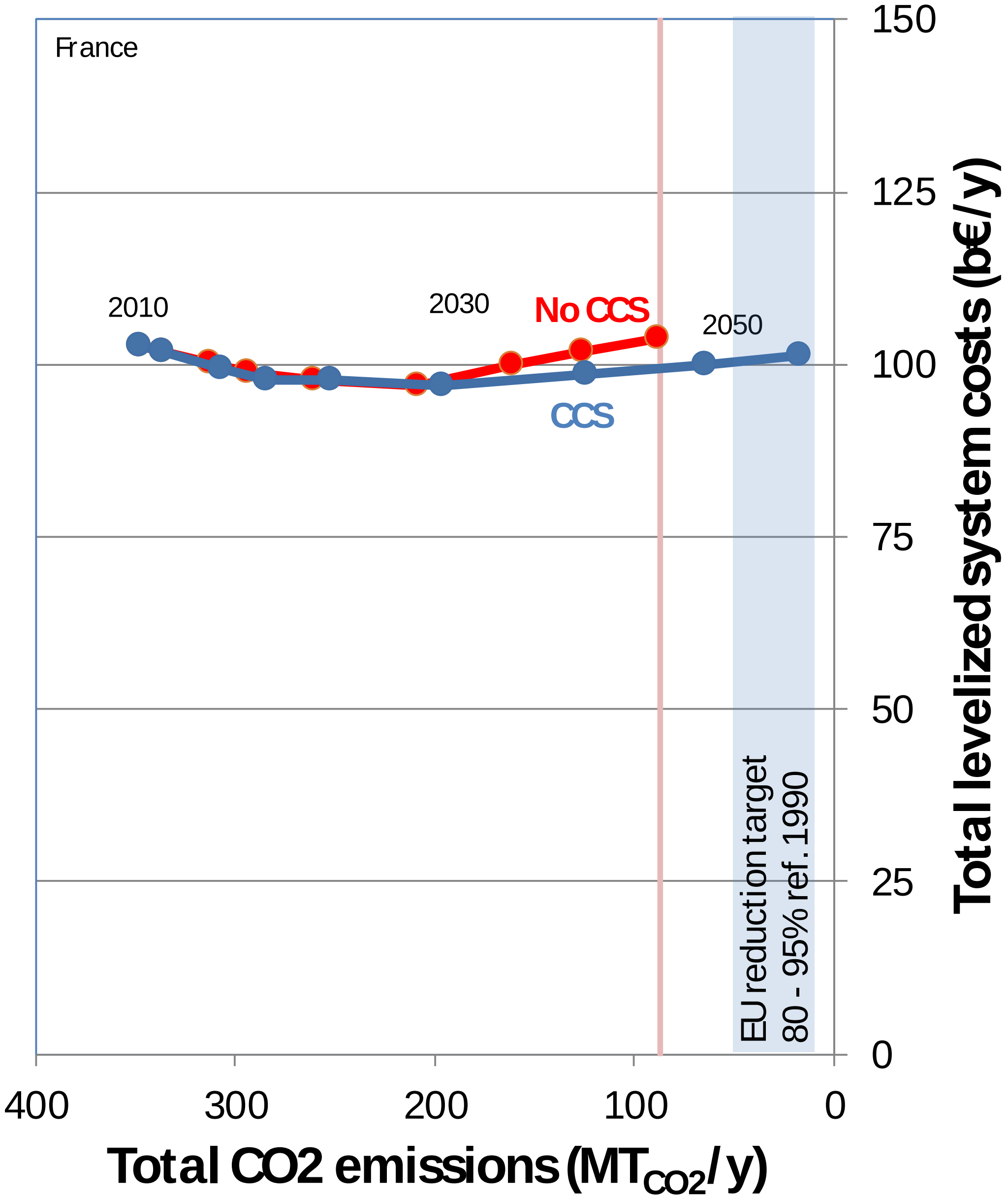


Figure 29: Costs vs. CO_2 emissions for France (with CCS, without CCS).

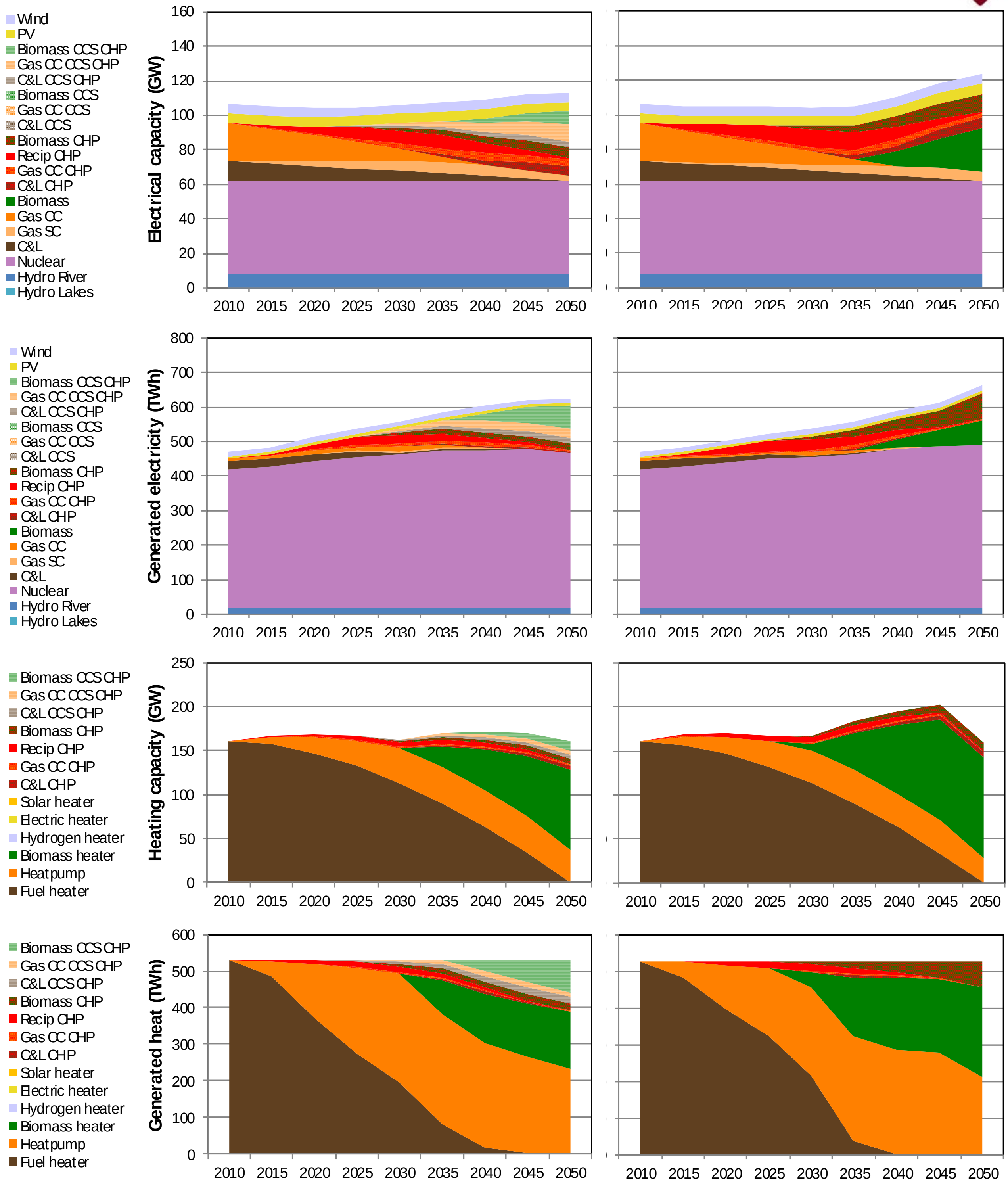


Figure 30: Results for France; CCS is available (left), CCS is not available (right).

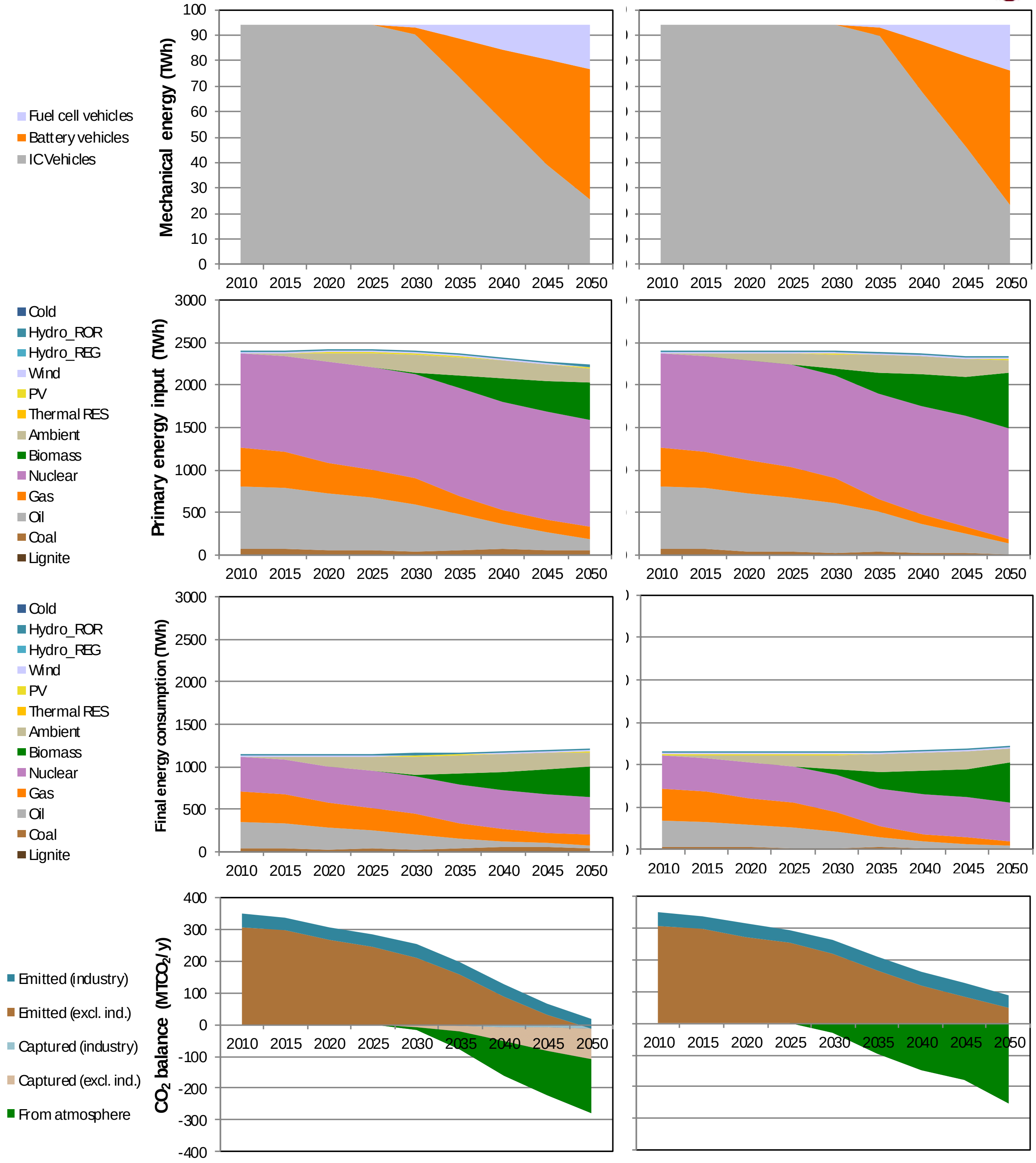


Figure 31: Results for France; CCS is available (left), CCS is not available (right).

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. The primary energy input by biomass is limited to 500 TWh[25, 26].

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 CO_2 emissions reduction applying CCS to industry and in 2050 the residual industrial CO_2 emissions are shown as larger than the residual CO_2 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.

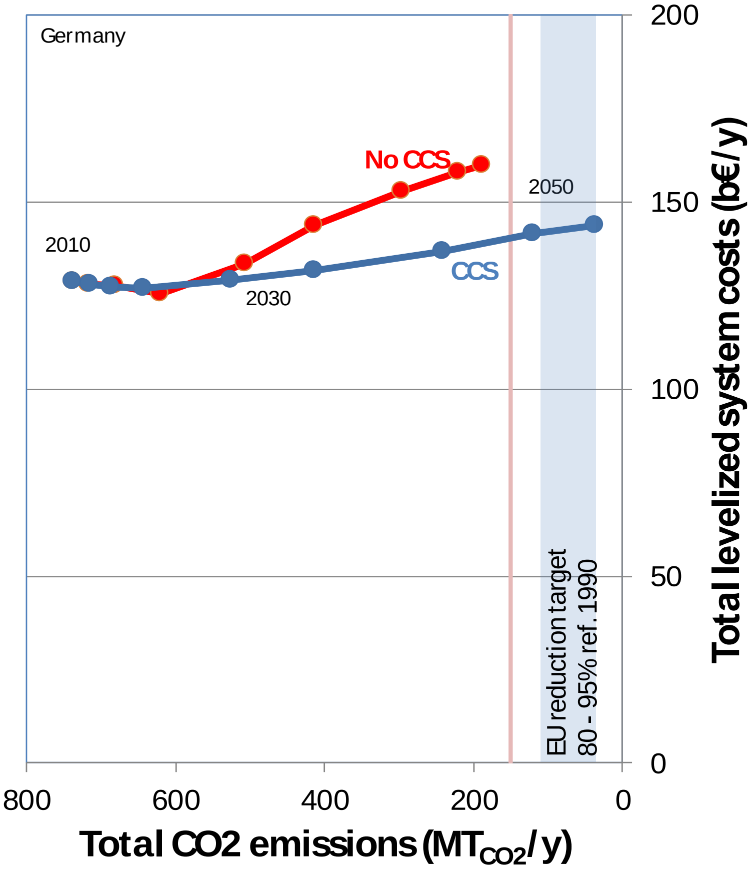


Figure 32: Costs vs. CO_2 emissions for Germany (with CCS, without CCS).

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[25] See http://bioenergie.fnr.de/bioenergie/biomasse/biomasse-potenziale/
[26] See http://www.bmvi.de/SharedDocs/EN/Documents/MKS/mks-short-study-biomass-potentials-and-competition-for-biomass-utilisation.pdf?__blob=publicationFile

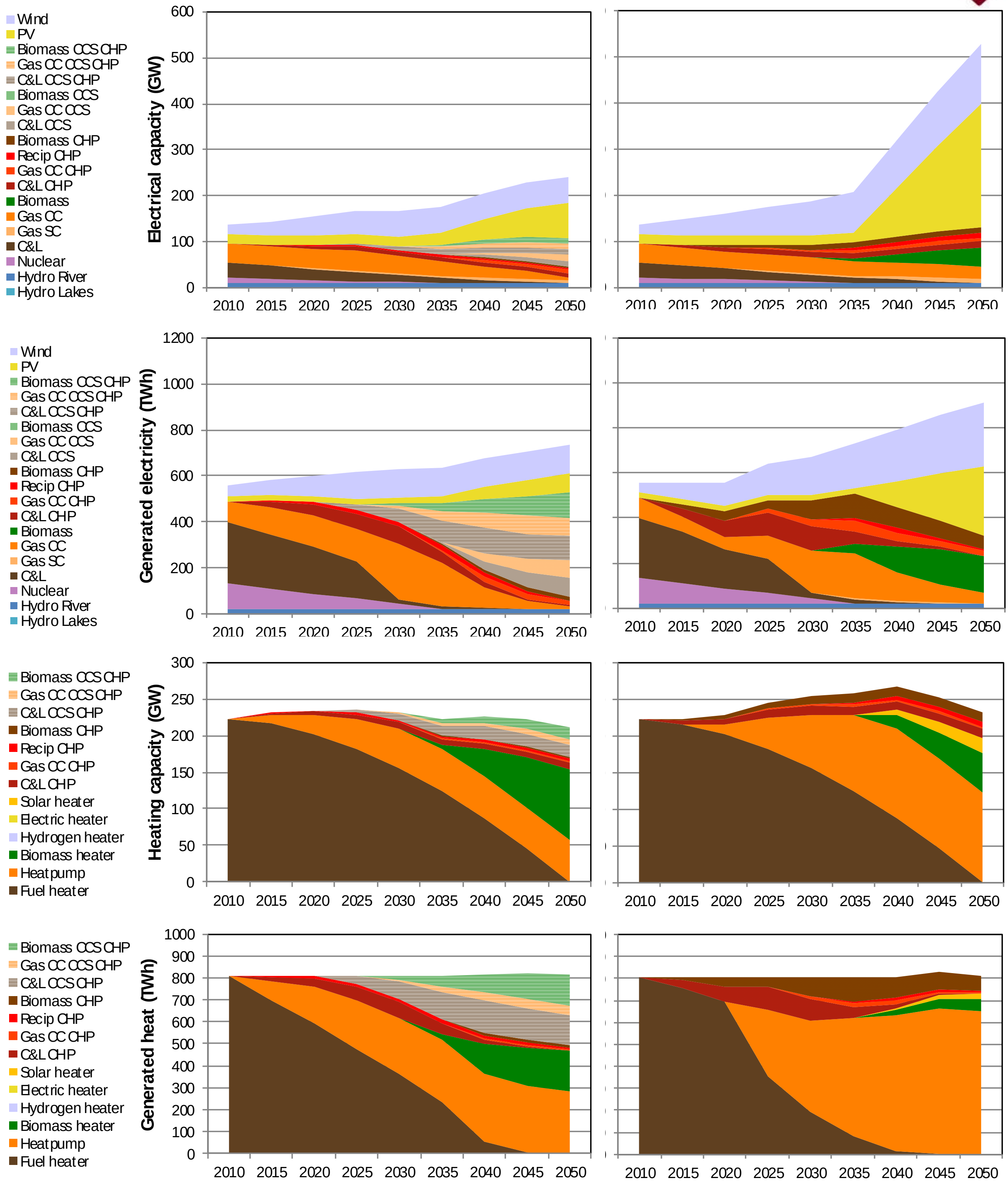

Figure 33: Results for Germany; CCS is available (left), CCS is not available (right).

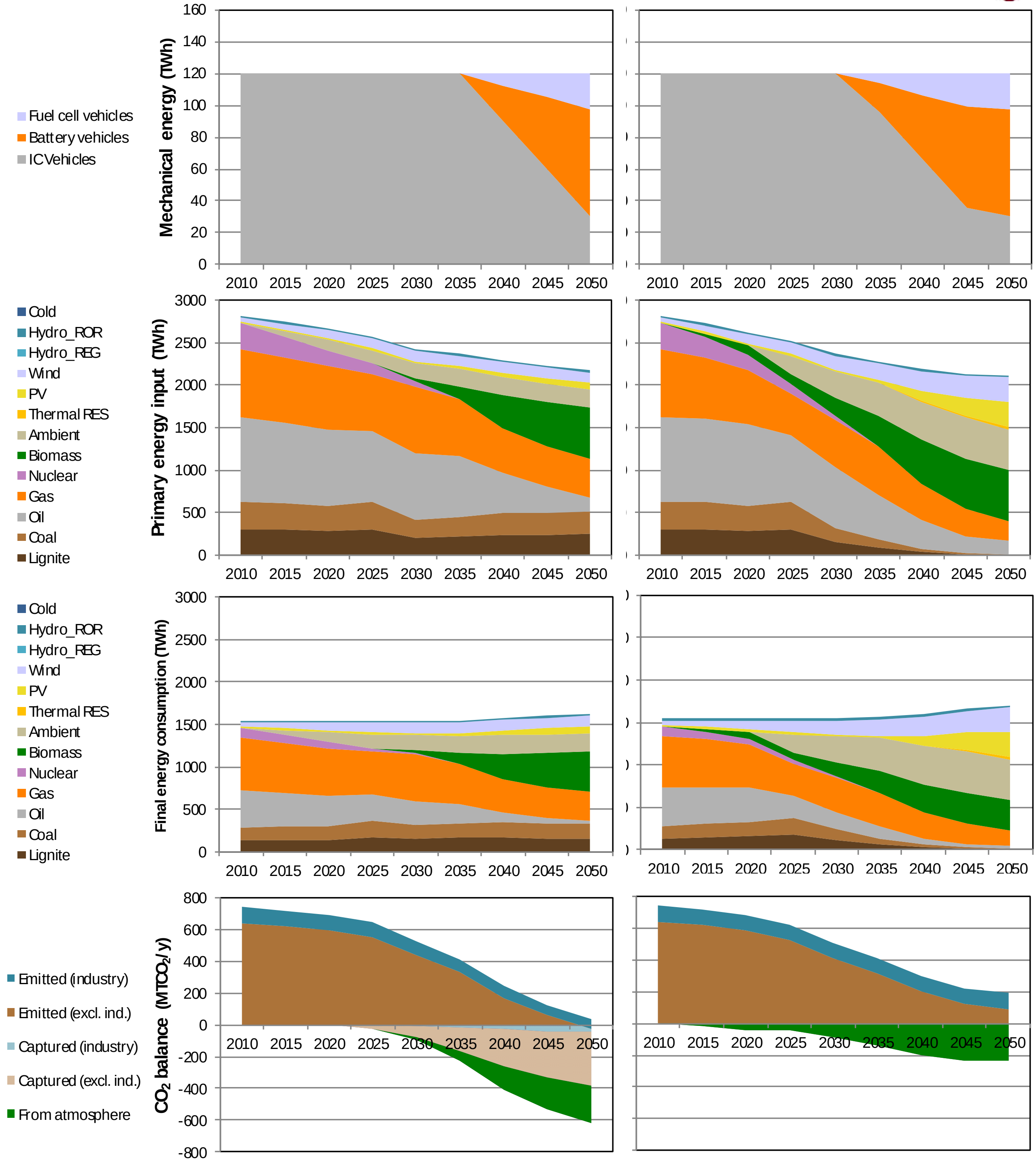

Figure 34: Results for Germany; CCS is available (left), CCS is not available (right).

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 emission free electricity being available also the heating sector is almost CO_2 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 CO_2.

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 CO_2 emissions are related to other industrial sectors which cannot easily use CCS and to Norway's offshore exploration of oil and gas. The first amounts to 10 MT_{CO2}/y, the latter amounts to 14 Mt_{CO2}/y. Around 12 of the 14 Mt are emitted from offshore installations, primarily related to energy production and flaring. The remaining 2 Mt are related to onshore oil- and gas activities.

Use of current CCS technology on offshore installations is very complicated and expensive mainly due to physical limitations on existing platforms (weight and size), relatively limited energy production and CO_2 emission on each installation, logistics and cost from closing the oil- and gas production for doing necessary rebuild or modifications of the platforms. For fields in operation, a local CO_2 capture solution would most likely require building of a new platform.

Implications of using hydrogen instead of natural gas to produce power on the platform have not been studied to the extend required to be specific on costs or challenges, but there are ongoing studies. The oil and gas companies operating in the north sea have put up targets to implement CO_2 reducing measures which adds up to 2,5 Mt per year by 2030. In this report, the oil & gas Norwegian production is kept flat, with a 1% annual decrease of CO_2 emissions and no use of CCS.

These special circumstances lead to a picture that looks very different from the other European countries (see Figure 35-37). There is a very high lower floor for CO_2 emissions which is composed of the aforementioned industrial sector and offshore exploration. The impact of CCS is limited since it is only applied to cement, steel and the onshore portion of the oil & gas industry.

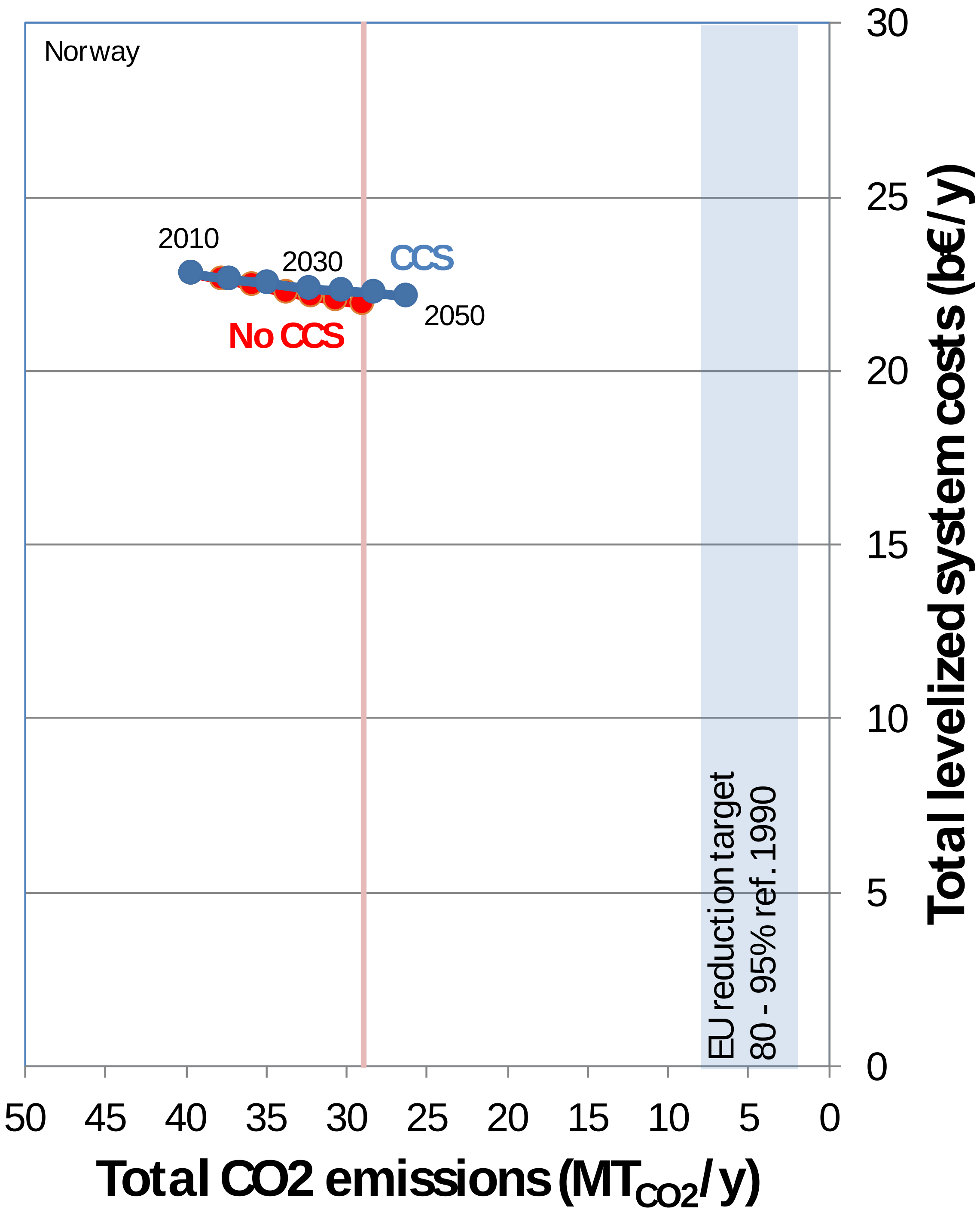

Figure 35: Costs vs. CO_2 emissions for Norway (with CCS, without CCS).

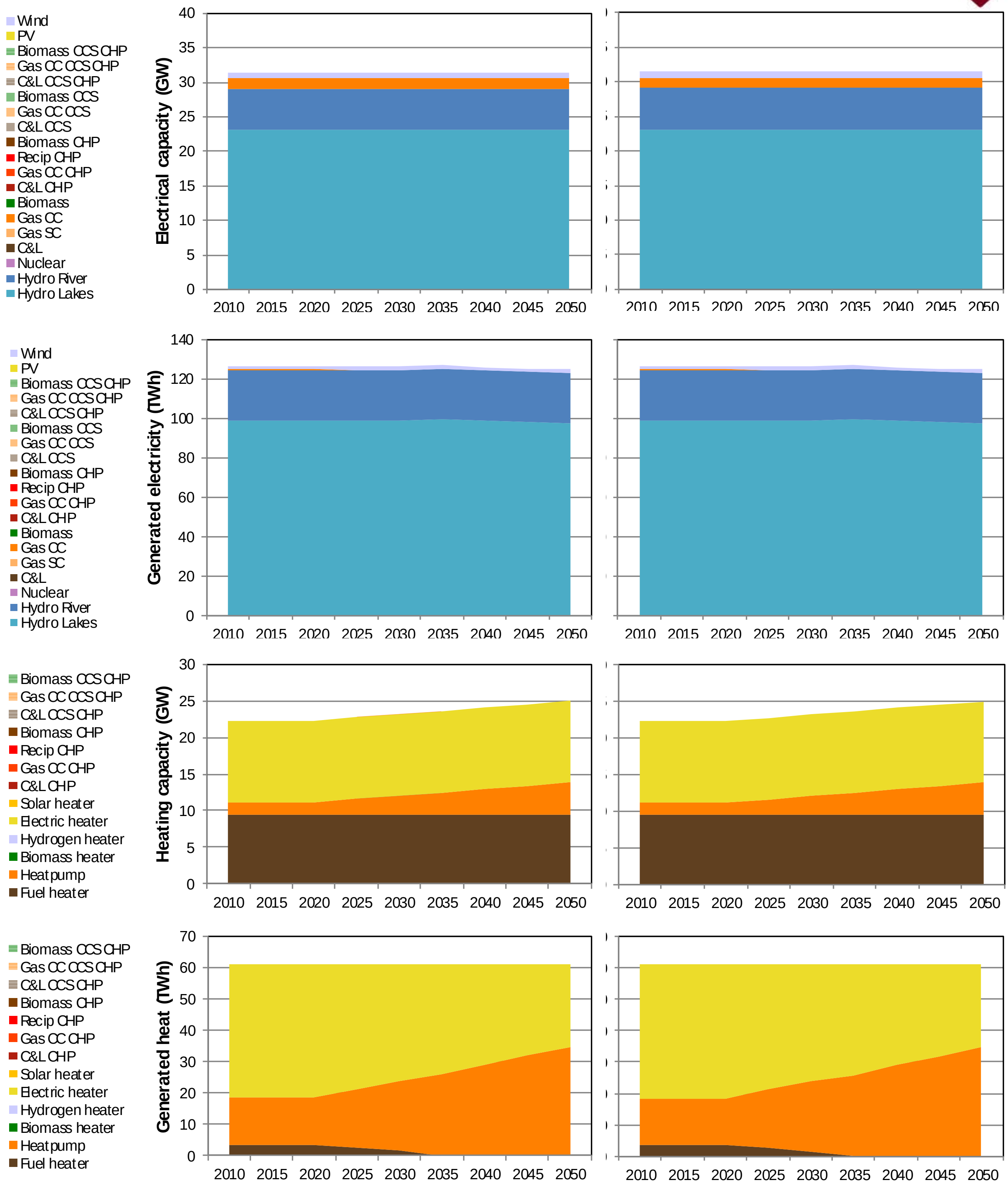

Figure 36: Results for Norway; CCS is available (left), CCS is not available (right).

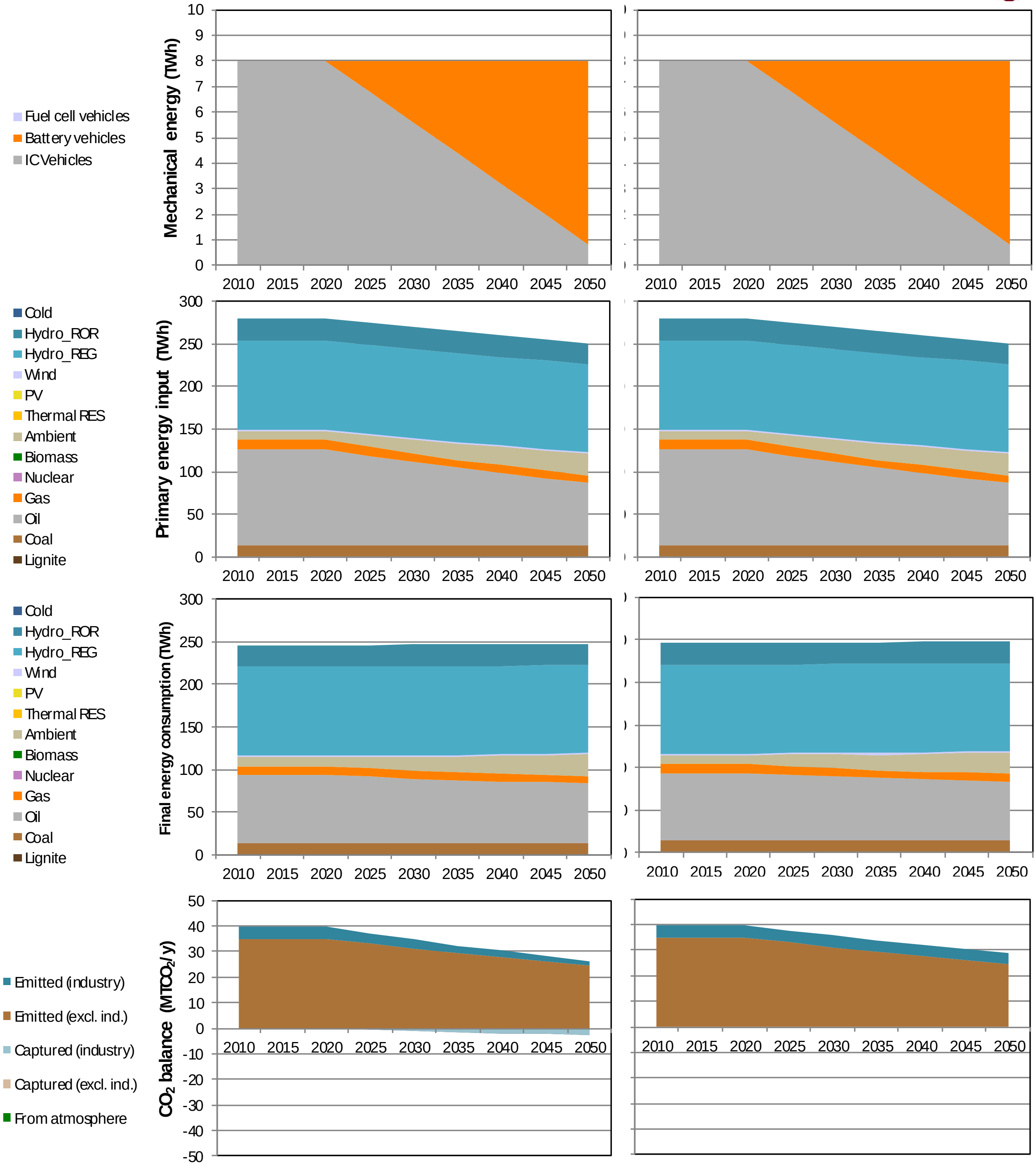

Figure 37: Results for Norway; CCS is available (left), CCS is not available (right).

5 Meeting 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 utilisation 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 1800GW by 2050 – approximately a three-fold increase in capacity from 2010 levels.

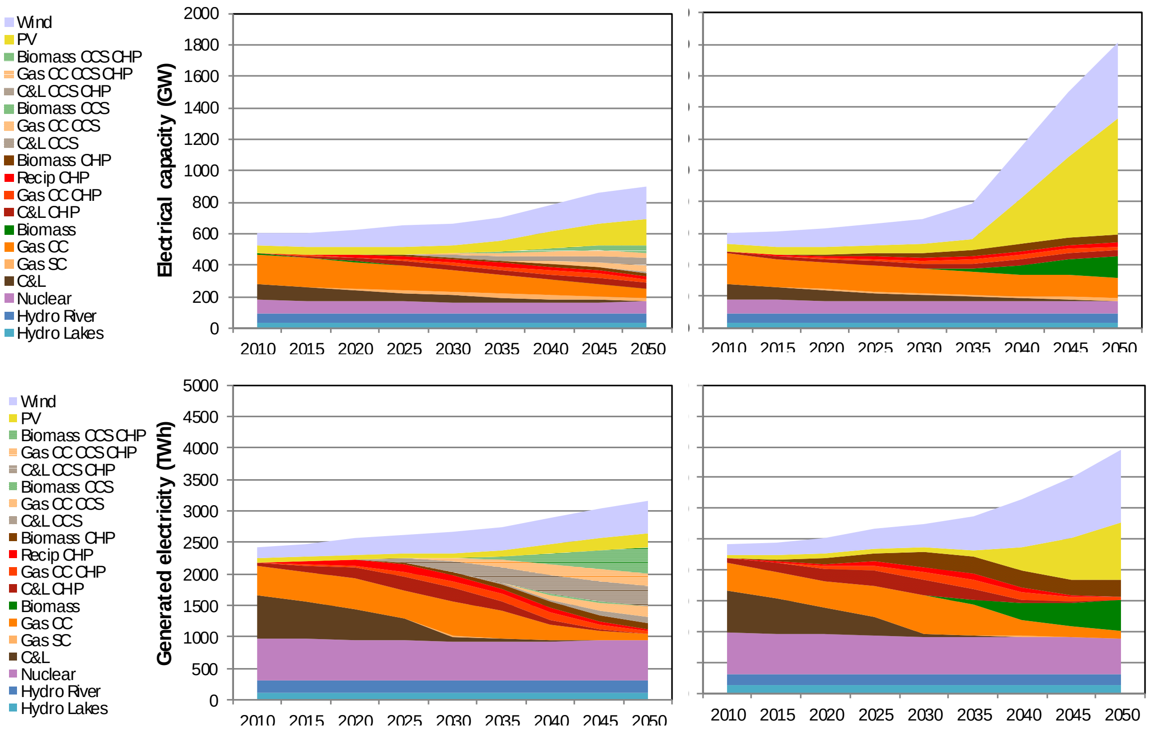

Figure 38: Electricity sector for the 10 selected countries; CCS is available (left), CCS is not available (right).

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.

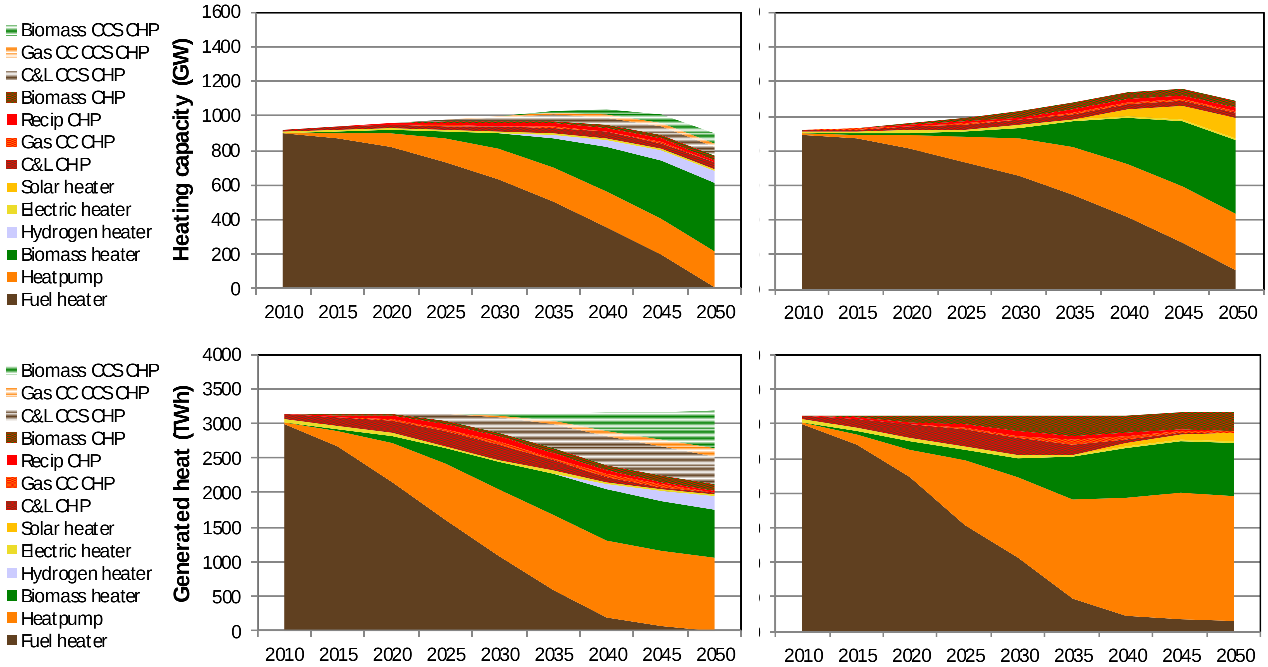

Figure 39: Heating sector for the 10 selected countries; CCS is available (left), CCS is not available (right).

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.

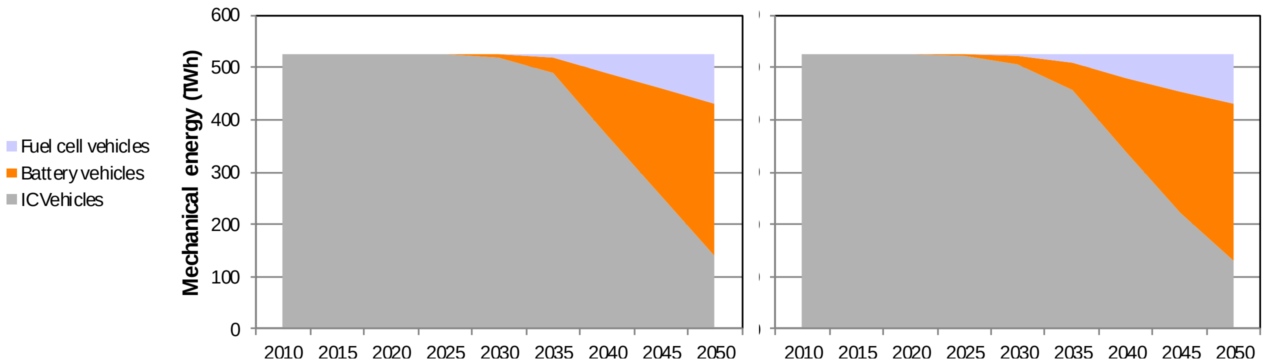

Figure 40: Transport sector for the 10 selected countries; CCS is available (left), CCS is not available (right).

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.
- 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.

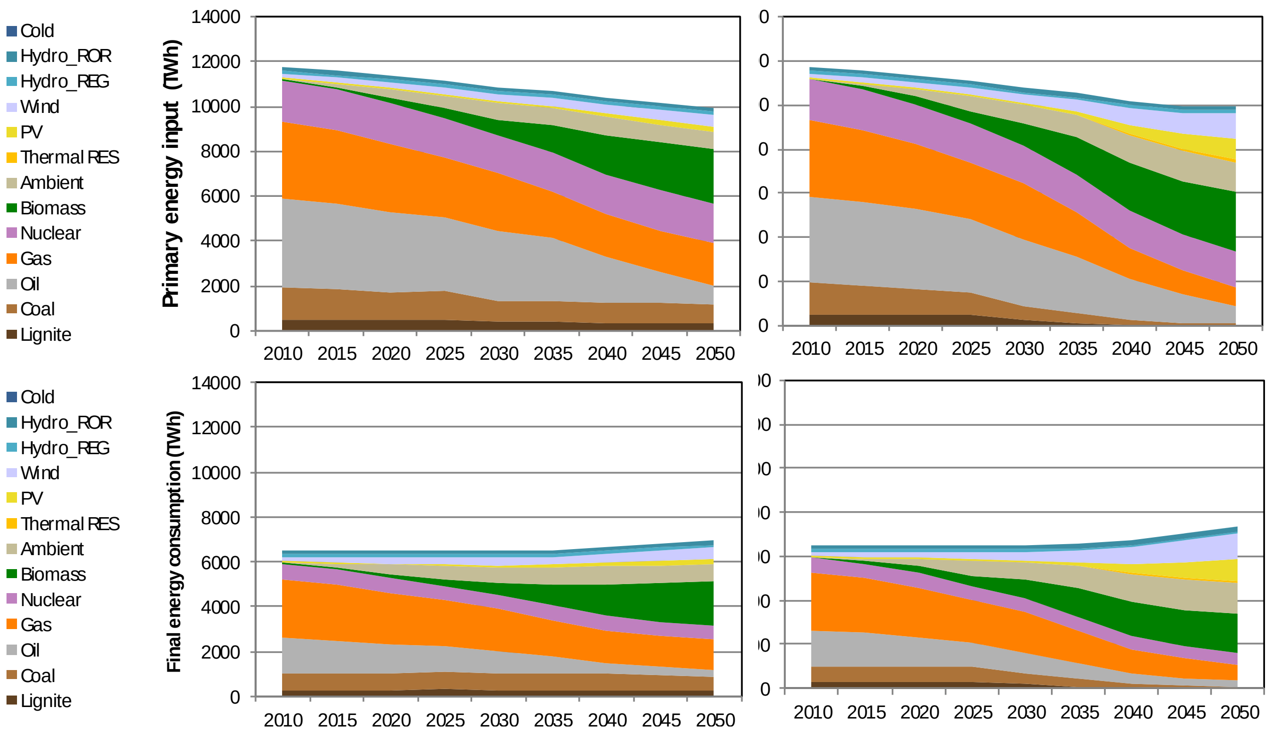

Figure 41: Primary energy input (top) and final energy consumption (bottom) for the 10 selected countries; CCS is available (left), CCS is not available (right).

CO_2 balance and required storage volume

Figure 42 shows the overall CO_2 balance for the two cases with and without CCS available.

- The sum of all categories shows the CO_2 that is generated by burning a carbon containing fuel. Two items have to be subtracted: (1) the CO_2 that is extracted from the atmosphere by the growth of biomass, and (2) the CO_2 that is captured and stored via CCS (at the capture rate emissions).
- The upper limit of the shaded areas marks the effective emission into the atmosphere. Both the emitted and the captured CO_2 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 95% as required to reach an overall 80-95% GHG emission reduction (1990 to 2050, see section 3). If CCS is not available the reduction from 2010 to 2050 is only 74%. Therefore the overall GHG emission reduction from 1990 to 2010 is only 68% well below the 80-95% target.**

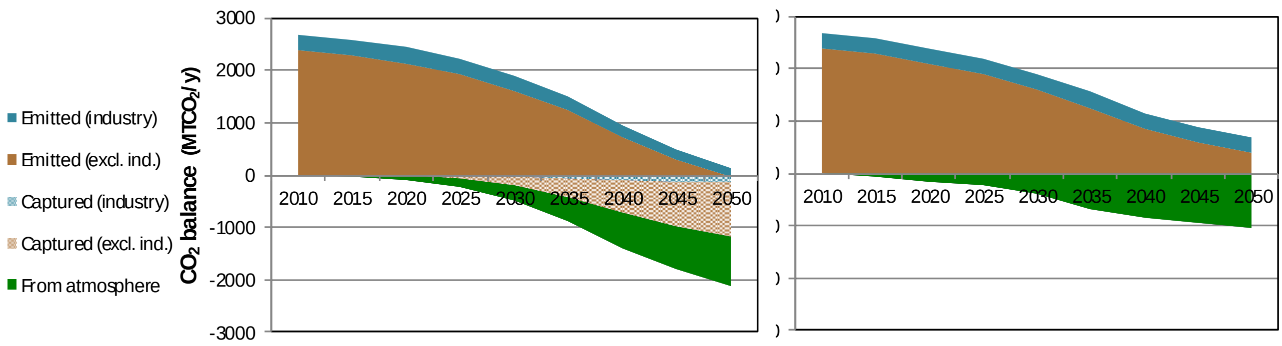

Figure 42: CO_2 balance for the 10 selected countries; CCS is available (left), CCS is not available (right).

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 95% 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. It is again noted that Norway is an exception since it starts with an effectively emission-free electricity and heating sector and a large industrial sector with limited options to avoid CO_2 emissions. The reduction seen in Figure 43 are mostly achieved by e-mobility.

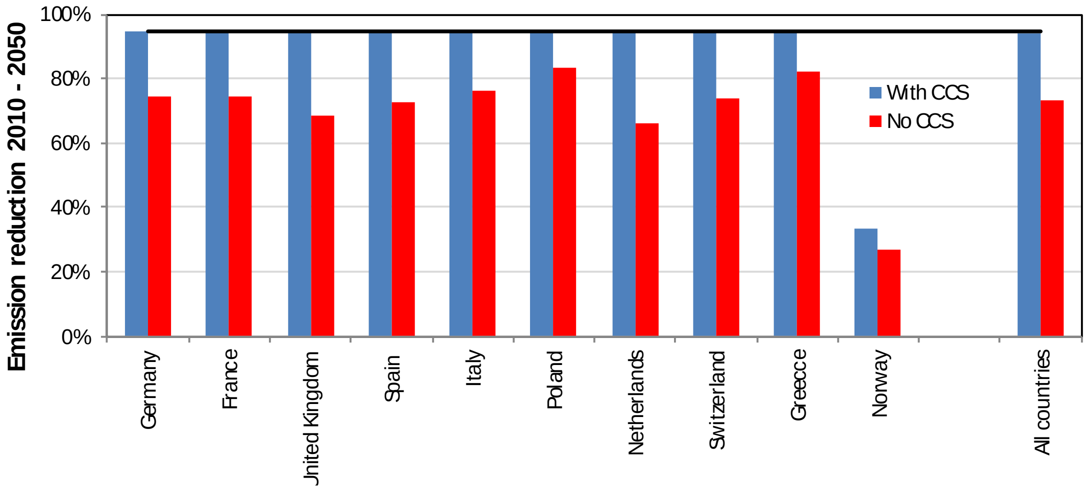

Figure 43: Achievable emission reductions from 2010 to 2050; target set to 95%.

Figure 44 shows the per capita emissions in 2010 and 2050. With CCS a level of less than one can be achieved, without CCS it will be two. Figures 45 and 46 illustrate the cumulated stored CO_2.

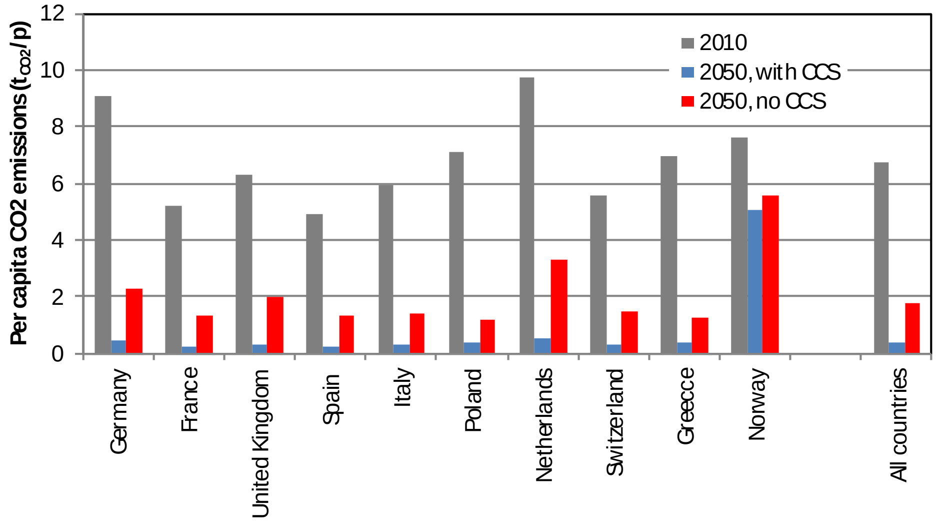

Figure 44: Per capita CO_2 emissions in 2010 and 2050.

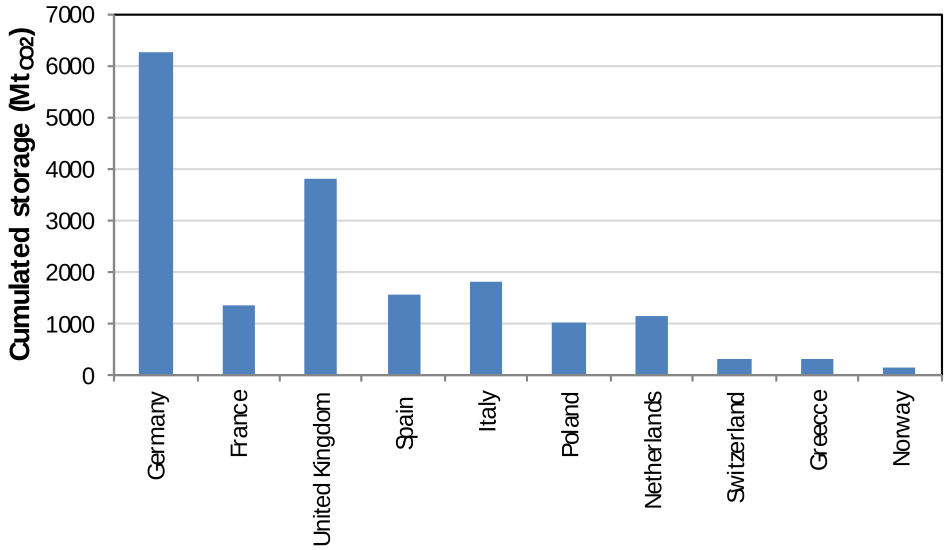

Figure 45: Cumulated stored CO_2 from 2010 to 2050.

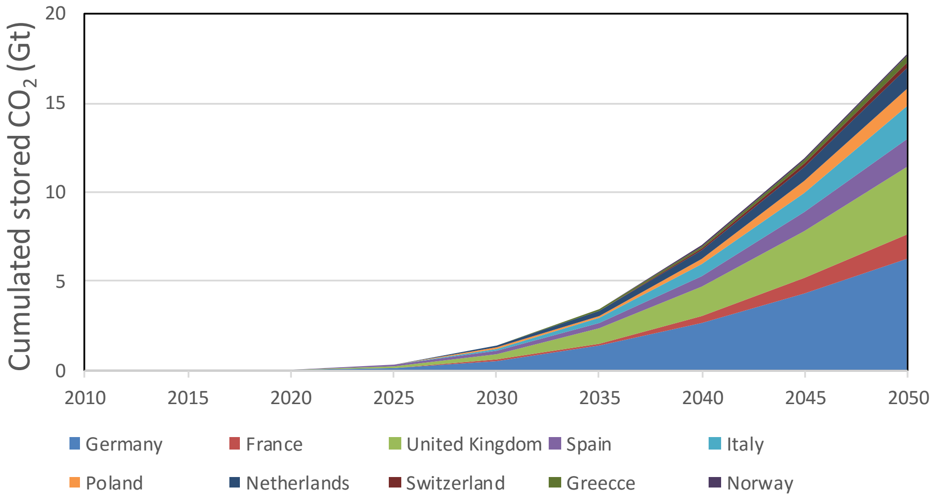

Figure 46: Temporal evolution of cumulated stored CO_2.

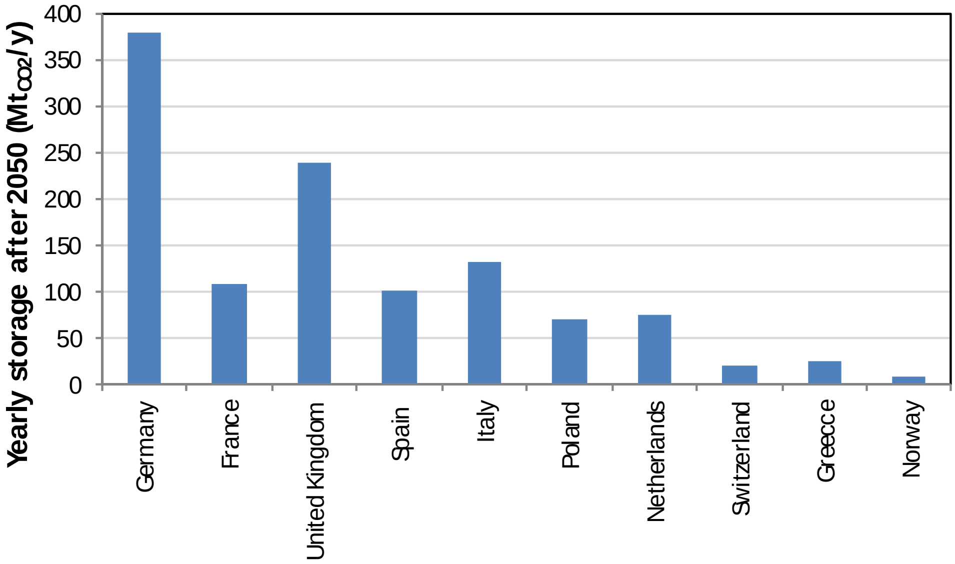

Figure 47: Yearly CO_2 storage after 2050.

Finally, Figure 47 shows the yearly stored CO_2 after 2050.

Costs vs. CO_2 emissions

Figure 48 shows the total system costs versus the CO_2 emission reduction. The end point of the two curves corresponds to the 95% and 74% emission reduction, with and without CCS, respectively.
A number of further conclusions can be drawn from Figure 48:

- The cumulative CO_2 emissions for the 10 countries are 74 Gt with CCS and 80 GT without CCS. Having CCS available saves 6 Gt within the timeframe from 2010 to 2050.
- The cumulated energy system costs (capital, operation and fuels) for the 10 countries are €25.5 trillion with CCS and €26.2 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 €700 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} [27]. Taking 60 €/t_{CO2} leads to additional savings of 6 Gt x 60 €/t_{CO2} = €360 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.

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

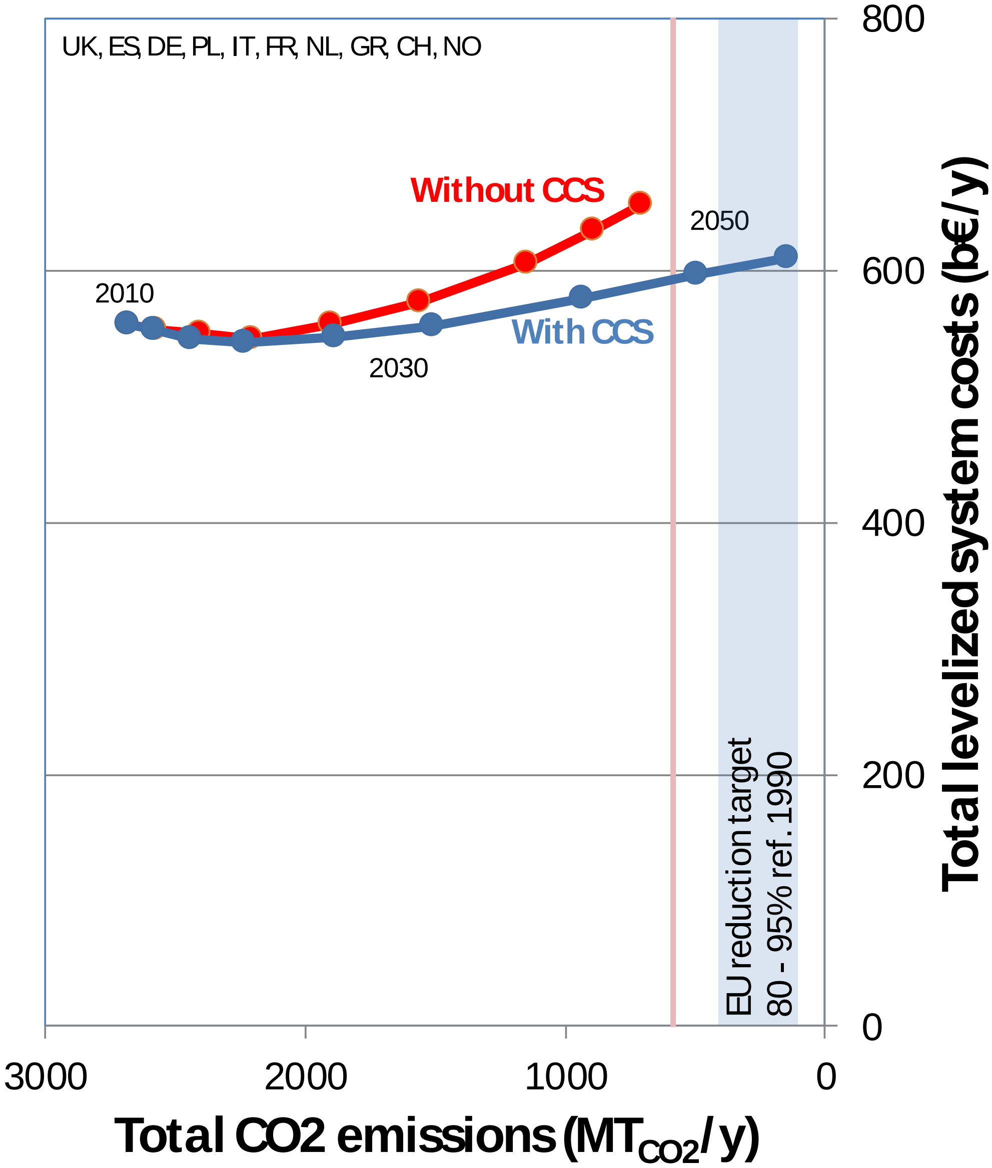

Figure 48: Costs vs. CO_2 emissions for the sum of the considered countries (with CCS, without CCS).

Figure 49 further highlights the cost saving with CCS. It can be seen that after 2025 the advantage of having CCS available rises steeply. Another way of visualizing costs and CO_2 emissions is by evaluating the CO_2 avoidance costs. The latter is defined as a difference in costs divided by a difference in emissions. Figure 50 shows the marginal CO_2 avoidance costs, i.e. the costs of further reducing CO_2 emissions going from one period to the next. This is equivalent to the gradient on the curves in Figure 48. Again the availability of CCS leads to lower costs.

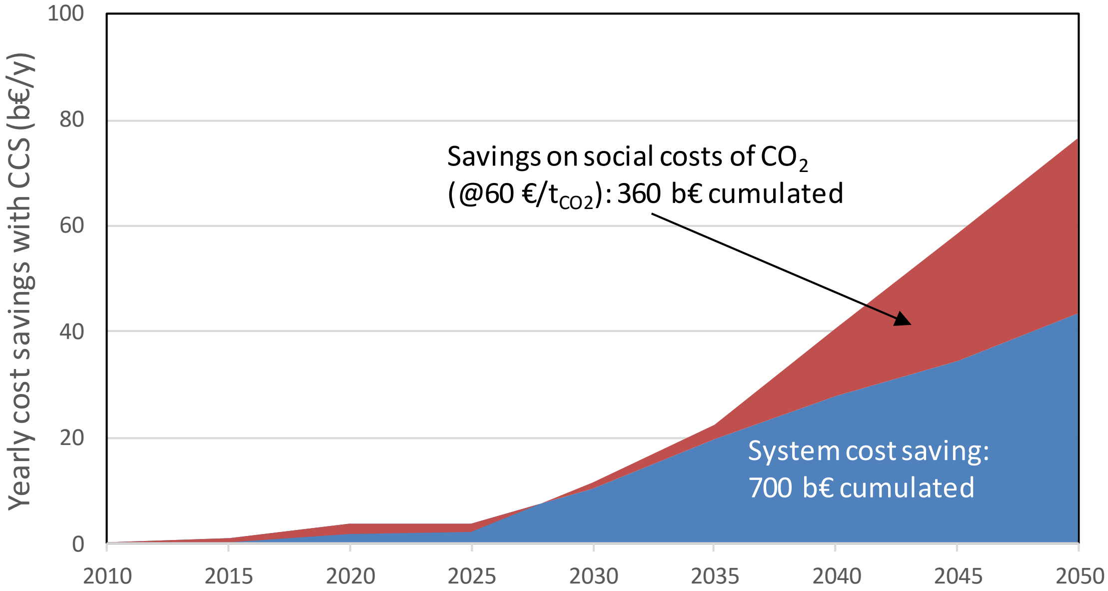

Figure 49: Yearly costs saving when CCS is available.

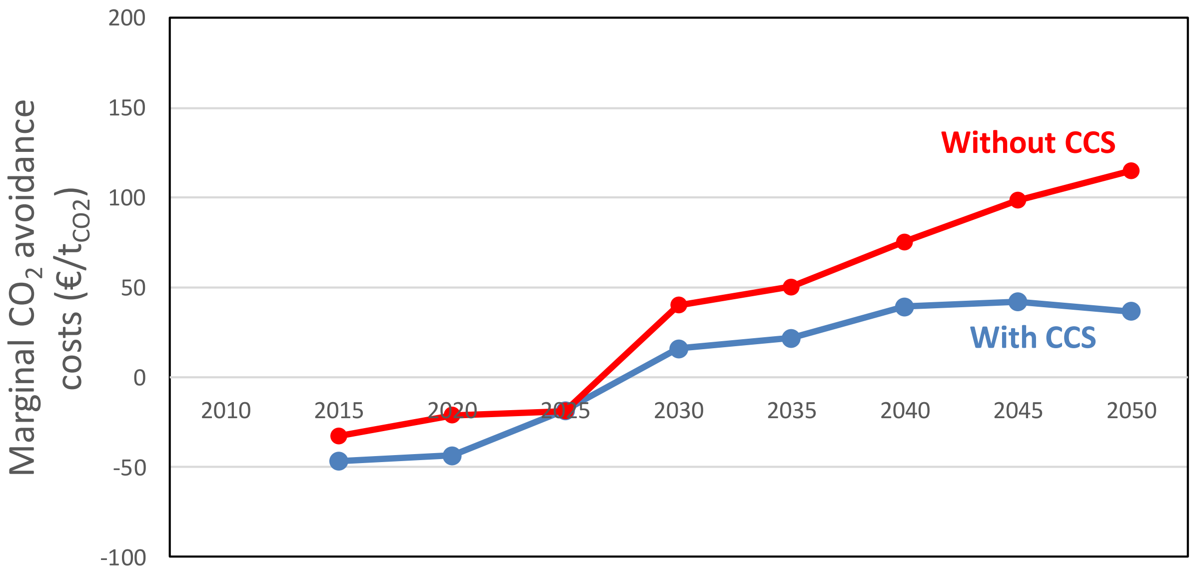

Figure 50: Marginal CO_2 avoidance costs.

Impact of limits on renewable technologies

As shown in previous sections an upper limit was assumed for the deployment of renewable technologies (PV, Wind) and biomass energy input. Figure 51 and 52 show that this limit is rarely reached for most countries. As expected, the deployment is higher for the non-CCS cases. In contrast to this, Figure 53 demonstrates that biomass is fully utilized as a resource in practically all cases. In fact it is mostly the availability of biomass that allows several countries to reach or come close to the theoretical lower limit of emissions without CCS (see vertical light red line in the various cost vs. CO_2 plots).

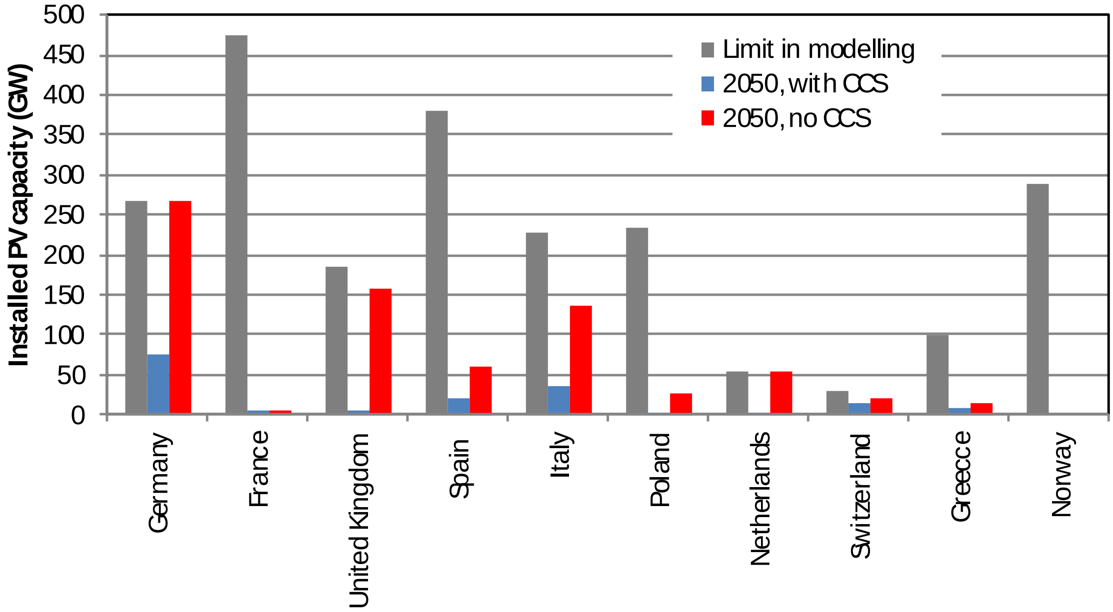

Figure 51: Limits and actual installation of PV in 2050.

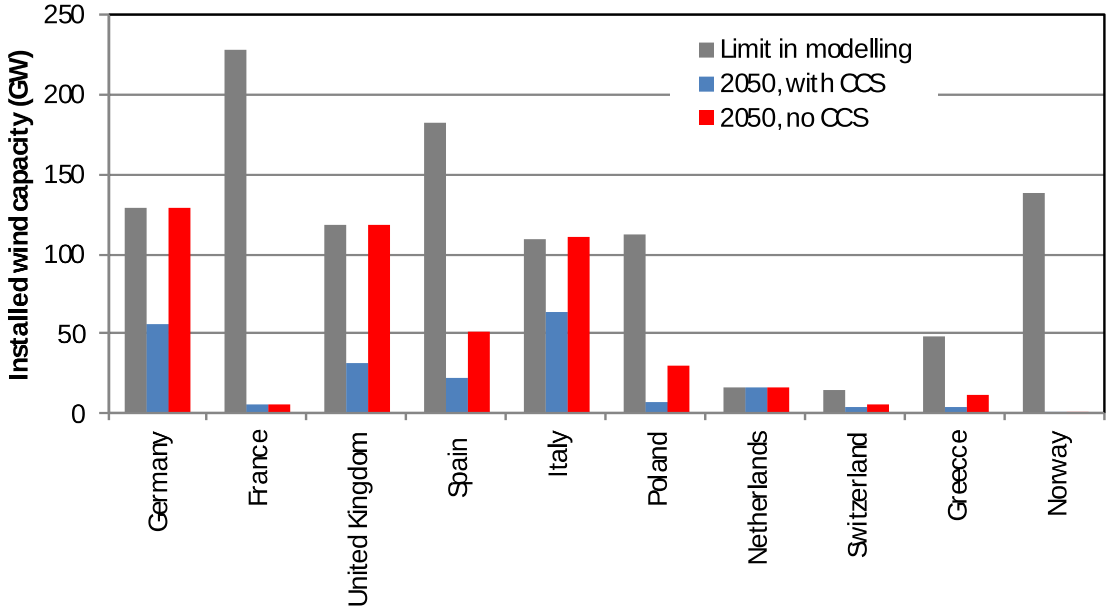

Figure 52: Limits and actual installation of wind in 2050.

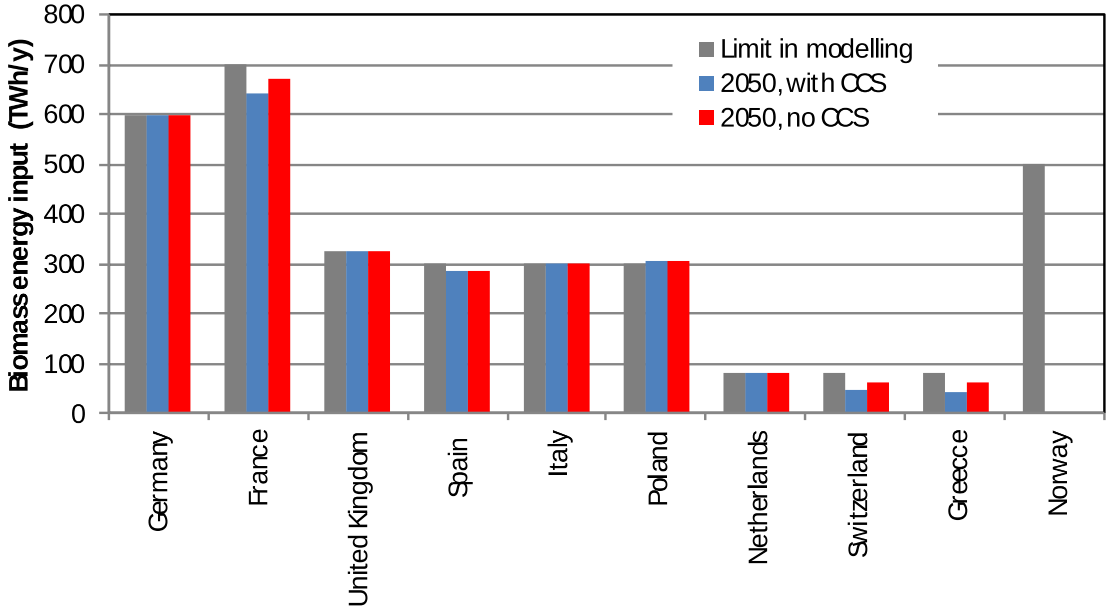

Figure 53: Limits and actual use of biomass primary energy input in 2050.

Figure 54 shows the curtailed PV & wind electricity from 2010 to 2050. In the early decades the curtailment is effectively zero. It starts rising after 2040, however, but at much lower level when CCS is available. This shows again that CCS and renewables are not in competition but complement each other. CCS helps to integrate renewables in to the system and maintain capacity factors for PV and Wind that would otherwise be reduced by curtailment.

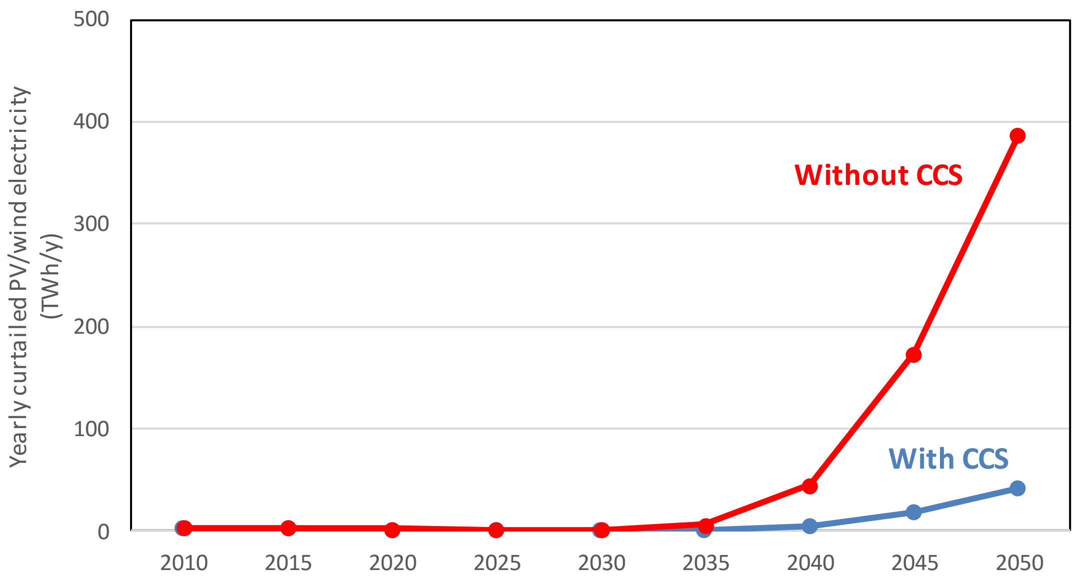

Figure 54: Curtailed PV & Wind electricity.

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 700 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 300 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. This result may be a result of oversimplification in the model, however, as the gas prices used in the model have been index-linked to oil prices.

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[28]. 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 55 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 55 shows a simplified image based on the Levelised Cost of Electricity (LCOE) metric. The system consists only of PV and CCGTs.

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

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 utilisation 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 utilisation 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 CO_2 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.

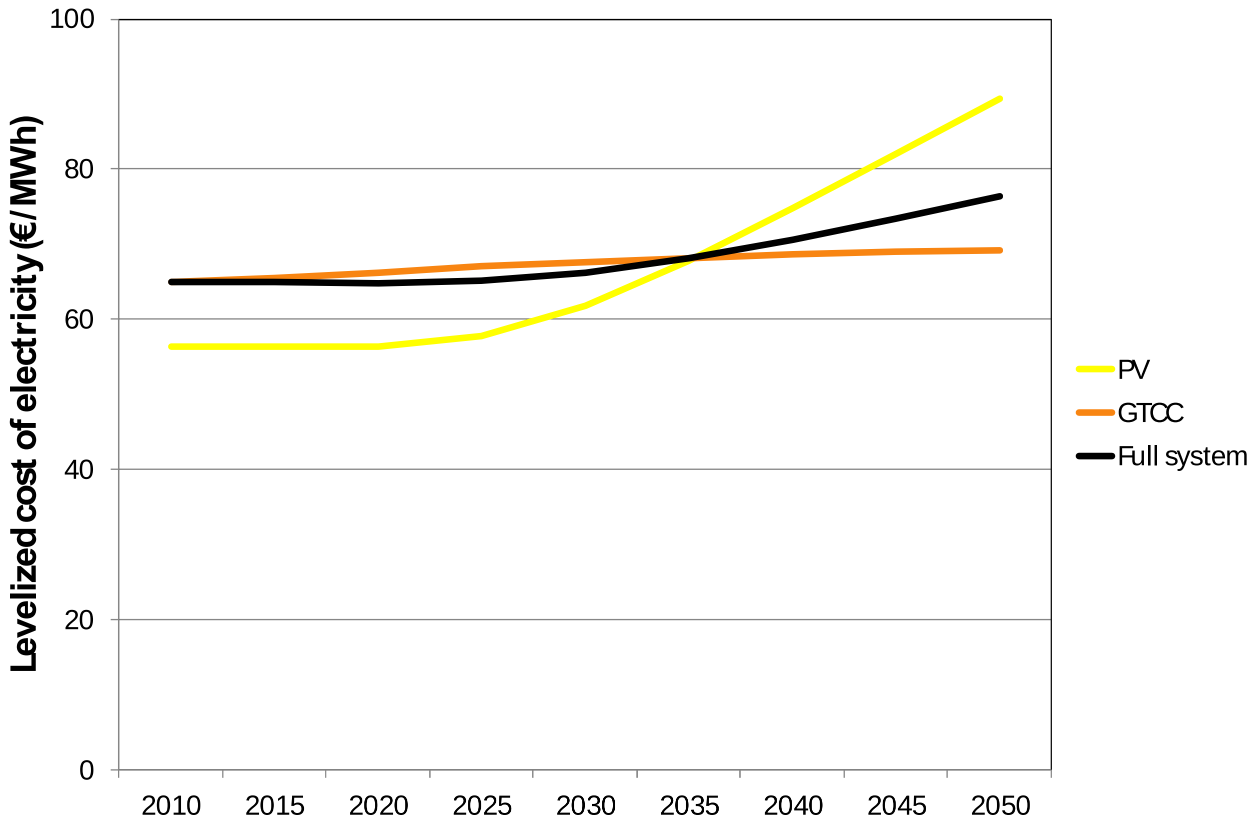

Figure 55: Illustration for system integration costs.

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[29]. 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.

[29] Lowest cost decarbonisation for the UK: The critical role of CCS (September 2016)

6 Conclusions

Building on ZEP's previous Market Economics reports, the results here show 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 analysis has shown a value of CCS to the EU as a whole of approximately €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. The modeling estimates the post-2050 value of CCS in excess of €50 billion per annum.

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 reducing CO_2 emissions from the 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 at the Paris COP 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	Global Change Assessment Model
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

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 CO_2 Steelmaking
US	United States
WACC	Weighted Average Cost of Capital
w/o	Without
yr	Year

Annex II: Contributors to the ZEP Temporary Working Group Market Economics

The authors of the report would like to thank the following people for their various contributions, inputs and guidance in completing this analysis and report:

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Zero emissions platform

March 2017

European Technology Platform for Zero Emission Fossil Fuel Power Plants