Zero emissions platform

CCS and the Electricity Market

Modelling the lowest-cost route to decarbonising European power

European Technology Platform for Zero Emission Fossil Fuel Power Plants

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Executive summary

- **ZEP's model shows the lowest-cost route to decarbonising European power**

In order to identify how low-carbon technologies can reduce European power emissions most cost-effectively in the horizon to 2050, the Zero Emissions Platform (ZEP) has developed a model based on an existing model from the Norwegian University of Science and Technology (NTNU) and linked it to the Global Change Assessment Model (GCAM).

ZEP's model is designed to select the lowest-cost investments to meet expected electricity demand, while replacing plants that exceed a defined lifetime – country by country. It is unique in that it not only takes into account optimised operating costs hour-by-hour, but also has a dispatch model for renewable power based on capacity factors and historic weather data.

- **Baseline modelling highlights the critical role of CCS as early as 2030**

Cases studied in the baseline modelling show that the wide and progressive use of lignite, coal, gas and biomass with CO_2 Capture and Storage (CCS) between 2030 and 2050 – combined with a large expansion in hydro, wind and solar – is the lowest-cost route to achieving an 80% absolute[1] reduction in emissions from power. This is documented in ZEP's report, "*CO_2 Capture and Storage (CCS) – Recommendations for transitional measures to drive deployment in Europe*", published in November 2013.[2]

- **CCS is needed to meet electricity demand *and* climate targets – cost-effectively**

Having such a powerful model available, ZEP decided to undertake further modelling in response to questions from the European Commission and other stakeholders:

1. *If CCS is excluded altogether, what is the impact on costs and emission reductions?*
   If CCS is not available to the model and limits[3] on onshore wind and solar photovoltaics (PV) from the original modelling are maintained, electricity demand is not met after 2045 because the model's 80% emission reduction target cannot be achieved without CCS. Blackouts are a possible consequence.

2. *What if the cost of solar in 2050 is also much lower than originally estimated?*
   If the cost of solar is drastically reduced from 1,000 to 200 €$_{(2010)}$/kW installed in 2050 – requiring a major technology breakthrough compared to today – demand is still not met after 2045 and the cost to Europe is 20-50% higher than with CCS.

3. *What if the limits on solar and wind are also relaxed?*
   To see if the above results were robust, limits on the amount of onshore wind and PV were also relaxed – including cases with no limits whatsoever. The latter results in 600 GW of PV and 1,000 GW of wind in 2050 with the original PV cost; up to 1,500 GW of PV and 640 GW of wind with the low PV cost. This represents up to 200,000 5 MW-class wind turbines and up to 10,000 km^2 of Europe's surface covered with PV. Even if this was practically possible, the cost is 35-45% higher than equivalent cases with CCS.

4. *What is the impact of electricity storage on costs?*
   If the model is allowed to select electricity storage to help integrate the renewables, this only has a limited effect (from 2040 onwards) and plays a small role in reducing costs.

- **Conclusion: without CCS, the cost of decarbonising European power is 20-50% higher by 2050**

Even when the limits on PV and wind are relaxed and the cost of PV is significantly reduced, CCS still plays a critical role in the generation mix, reducing the cumulative cost of European power by 20-50% by 2050. This represents some €2-4 trillion – a substantial amount compared to, for example, the ~€150 billion annual electricity expenses incurred by European industry.

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[1] i.e. relative to 2010 levels
[2] See www.zeroemissionsplatform.eu/library/publication/240-me2.html for full details of model equations, cost parameters and results
[3] A total of 250 GW of solar PV and 270 GW of onshore wind in Europe in 2050

1 Background

ZEP's model shows the lowest-cost route to decarbonising European power

In order to identify how low-carbon technologies can reduce European power emissions most cost-effectively in the horizon to 2050, ZEP has developed a model[2] based on an existing model from the NTNU and linked it to the GCAM. It is designed to select the lowest-cost investments to meet expected electricity demand, while replacing plants that exceed a defined lifetime – country by country. It is also unique in that it not only takes into account optimised operating costs hour-by-hour, but also has a dispatch model for renewable power based on capacity factors and historic weather data.

Baseline modelling highlights the critical role of CCS as early as 2030

Cases studied in the baseline modelling show that the wide and progressive use of lignite, coal, gas and biomass with CCS between 2030 and 2050 – combined with hydro, wind and solar – is the lowest-cost route to reducing emissions from electricity generation, driven by the EU ETS.

Given the assumptions made, the model suggests that a CO_2 price ramp rising from its current low levels through to 35-40 €(2010)/tonne in 2030 is sufficient for CCS to be deployed, taking into account cost learning curves. This means that the average emissions intensity for Europe will drop from 420 g CO_2/kWh to 60 g CO_2/kWh in 2050. When considering the increase in electricity consumption, this corresponds to an absolute reduction of ~80% in CO_2 emissions.

These results are fully documented in ZEP's 2013 report: "*CO_2 capture and Storage (CCS) – Recommendations for transitional measures to drive deployment in Europe*".[2]

ZEP undertakes further calculations in response to stakeholder requests

Having such a powerful model available, ZEP decided to carry out further simulations in response to requests from the European Commission and other key stakeholders:

- A number of scenarios were simulated where CCS was excluded in order to see the impact on both emissions and cost.
- Costs for solar PV were originally assumed to drop from 1,900 €/kW in 2010 to 1,000 €/kW in 2050. An extremely aggressive cost reduction to 200 €/kW (that cannot be anticipated with today's technology trends, requiring a new innovation leap) was also simulated to see the impact.
- Limits for onshore wind and PV in the original report were based on projections in the various European countries. These limits were also revised (see Chapter 2).
- Finally, an electricity storage model was added: although pumped hydro storage was present in the original simulations, possible new installation sites were limited. The storage model is described by three variables:

    1. The cost of power components (generator, hydro runner, compressor etc.) at 600 €/kW
    2. The cost of energy storage (caverns, thermal stores etc.) at 60 €/kWh
    3. A round-trip efficiency of 75%.

    The model is free to choose power and energy independently. It appears that a typical ratio of energy to power is 7 hours, which gives 1,000 €/kW for installation costs (600 €/kW + 7 h x 60 €/kWh), or 140 €/kWh for overall storage costs. The latter value is in line with long-term targets for batteries and is ~20% of today's cost level.

2 Testing a variety of assumptions

Relaxing the limits on onshore wind and solar PV

The model needs realistic limits for the deployment of each technology – especially those that require a substantial amount of land area due to their low energy density. However, it was observed that the limits in the original ZEP report[2] were very tight for some countries – in particular, those on PV installations appeared unequal across Europe.

In Germany, for example, a limit of 70 GW was assumed which, given a panel efficiency of 15%, corresponds to 0.15% of the country's total surface area. Considering that Germany has a comparably high population density, a similar coverage should be possible for other countries as well.

It was therefore decided to set the limit for PV at 0.15% of each country's surface area, which corresponds to a total of 1,000 GW for Europe (the limit in the original report was 250 GW). Figure 1 compares the original and revised limits.

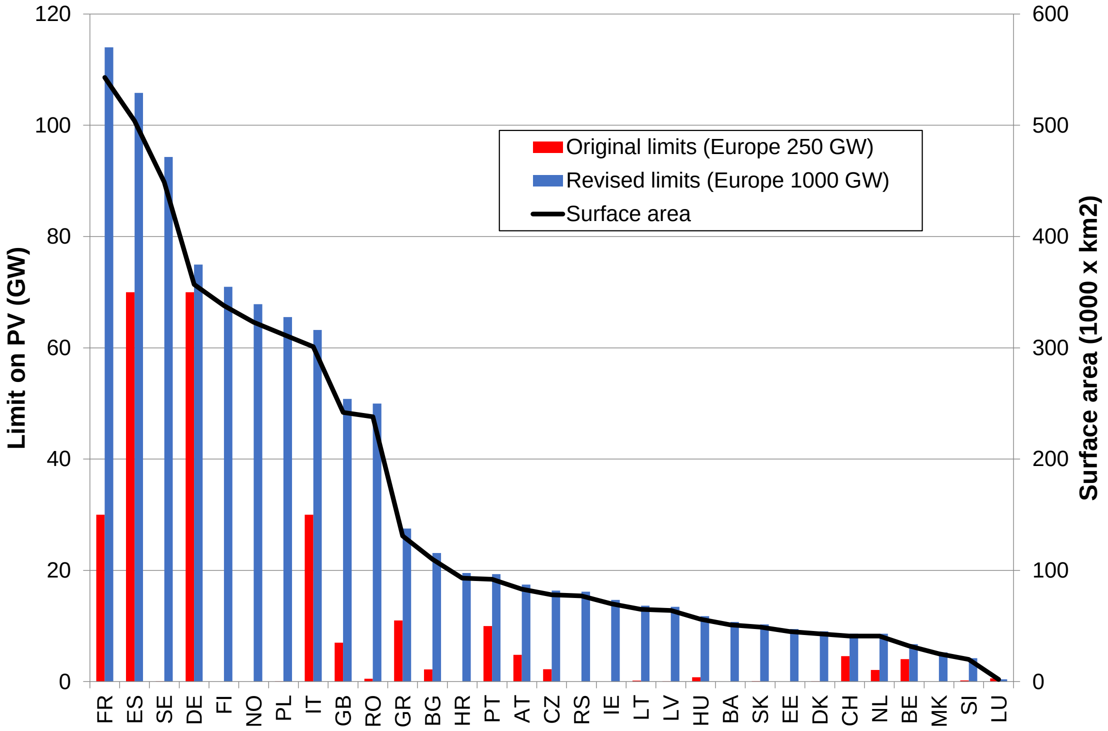

Figure 1: Original and revised limits on PV installations in European countries

A similar argument can be made for onshore wind: a modern 6 MW wind turbine occupies ~1 km^2 of land, in the sense that no housing or other turbines can be within this area. Taking again the example of Germany, the limit for onshore wind was set at 60 GW, which corresponds to 10,000 km^2 or 3% of the country's surface area. As before, the same coverage was therefore used for all European countries. Figure 2 below compares the original and revised limits.

It must be emphasised that these are only technical limits based on a simple argument of land usage. The model is free not to build onshore wind in eastern European countries with poor wind resources, or not to deploy PV in northern European countries with low solar irradiation.

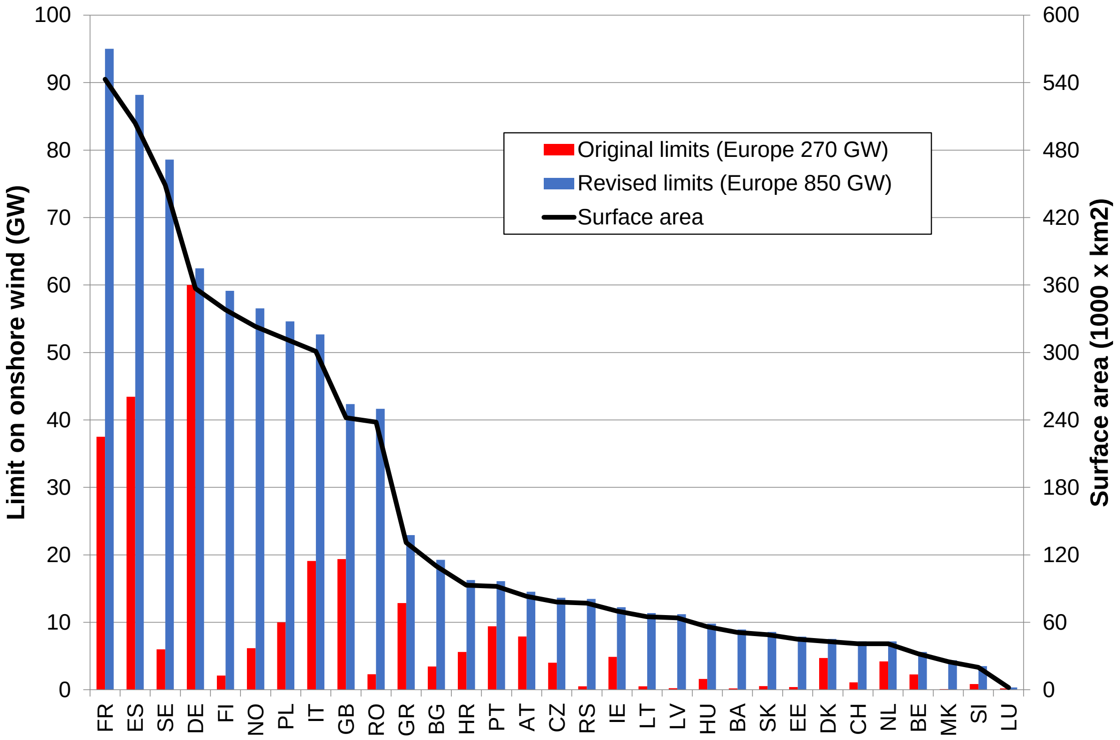

Figure 2: Original and revised limits on onshore wind installations in European countries

Assuming a significantly lower cost for solar PV in 2050

The simulations are based on cost assumptions for the period 2010 to 2050. Given the maturity that established technologies, such as thermal power plants and wind turbines, have reached following an organic growth from the early 1990s, the projection of costs should be reasonably accurate.

PV has paved the way for a more distributed generation. There has been a collapse in module prices that was greater than anticipated. Considering that PV belongs more to the world of semi-conductors than to that of steel and glass fibre, further substantial cost reductions can be expected. Of course this will only be true for the core modules; nevertheless one has to assume that roof-mounted PV, as we know it today, will be substituted by integrated PV, e.g. on windows or directly on walls.

The original ZEP report[2] assumed a cost reduction from 1,900 €/kW in 2010 to 1,000 €/kW in 2050. In order to challenge this assumption, simulations were performed assuming a reduction to 200 €/kW. Figures 3 and 4 summarise the most important cost elements, namely investment and fixed operating & maintenance costs. Figure 5 shows the assumptions for fuel and CO_2 prices from the original ZEP report.

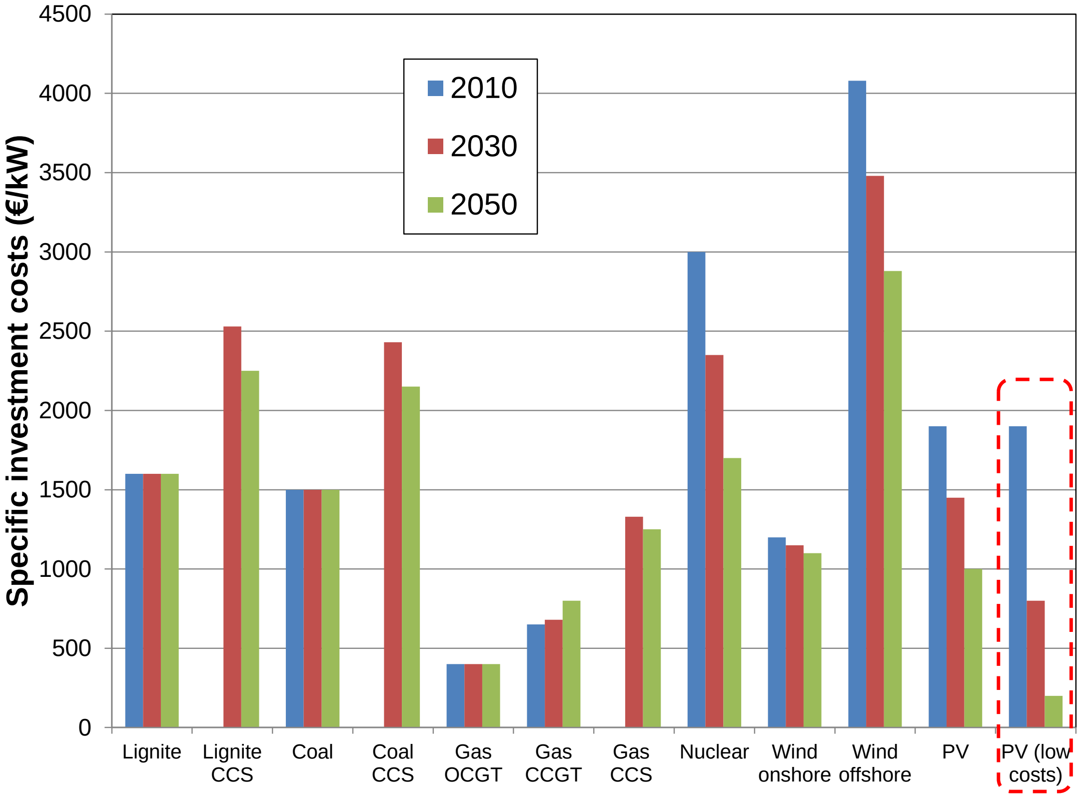

Figure 3: Cost assumptions for the main technologies, including low PV cost scenario

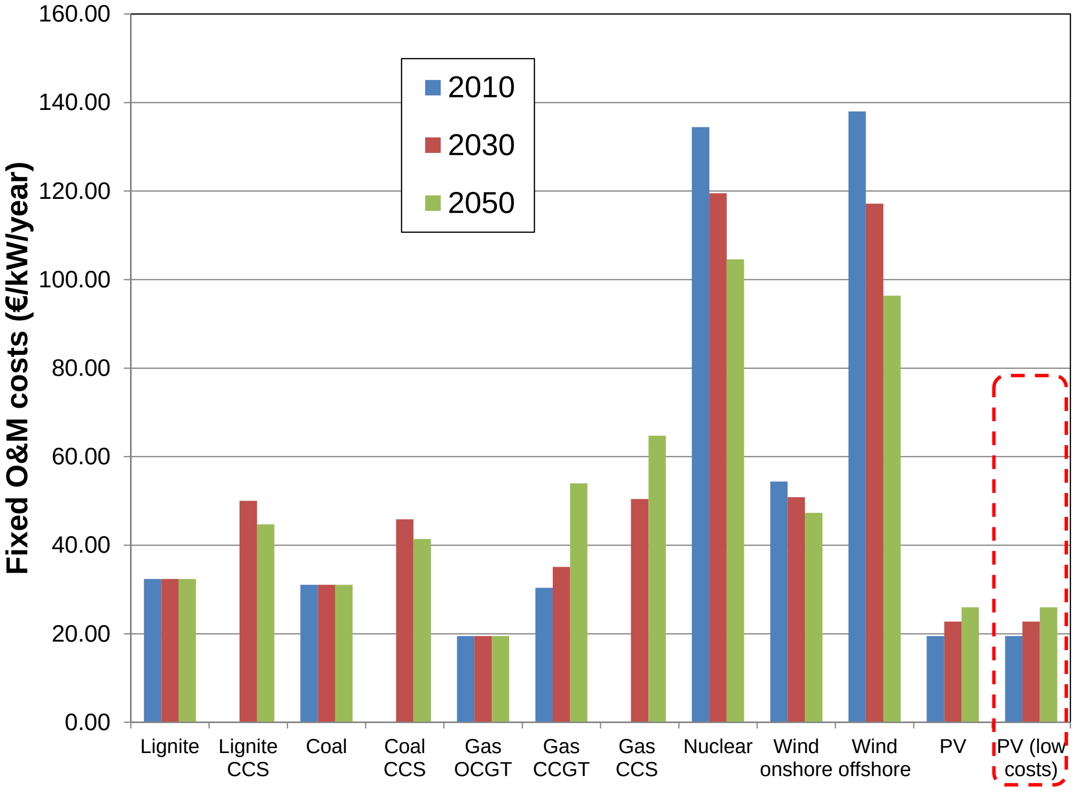

Figure 4: Cost assumptions for the main technologies, including low PV cost scenario

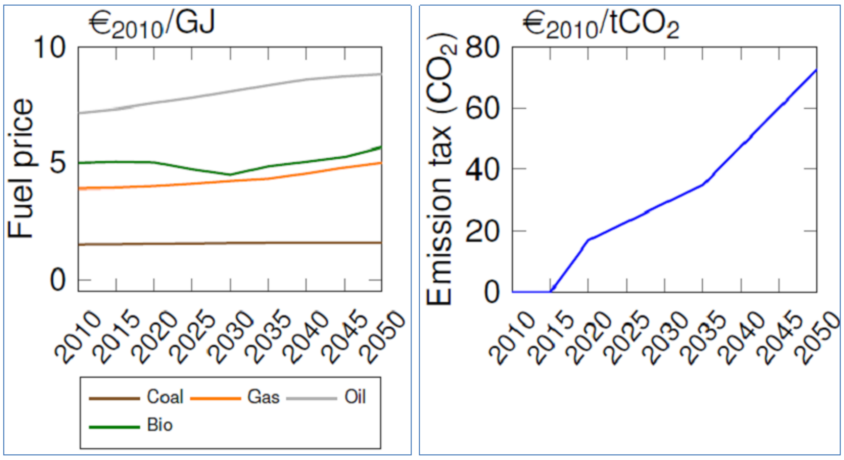

Figure 5: Fuel and CO_2 prices for the GCAM 450 ppm scenario

Modelling a range of scenarios, including electricity storage

Six different scenarios were built, resulting from a combination of different limits on PV and onshore wind, and different costs for PV. These were defined as follows:

- *High constrained*: limits on onshore wind as per the original report (270 GW in Europe). Limits on PV were revised to 1,000 GW (the original limit of 250 GW was considered too restrictive).
- *Weak constrained*: limits on onshore wind were revised to 850 GW in Europe. Limits on PV were revised to 1,000 GW.
- *No limits*: a hypothetical scenario to see the reaction of the model.

PV costs were:

- *High*: 1,000 €/kW in 2050
- *Low*: 200 €/kW in 2050

This gives scenarios 1 to 6:

	PV High	PV Low
High constrained	1	2
Weak constrained	3	4
No limits	5	6

Each scenario had the same three variants:

- Variant A – With CCS and electricity storage
- Variant B – No CCS, no electricity storage
- Variant C – No CCS, with electricity storage

A comparison of Variant A and Variants B and C highlights the impact the lack of support measures for CCS may have on future generation costs. The difference between Variant B and C shows the potential value of electricity storage.

All non-CCS variants were subject to an important constraint: as the deployment of CCS leads to a massive reduction in specific[4] CO_2 emissions, the model enforced the same Europe-wide reduction for cases *without* CCS. This enables the cost of different variants to be comparable based on an *equal* impact on climate change.

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[4] Specific emissions = emissions divided by demand

Ensuring a fair comparison of possible trajectories

Simulations were carried out in 5-year periods from 2010 to 2050. The model delivers various types of results, including for each period:

- Investment costs (€bn)
- Annual operation costs (€bn/y), consisting of variable and fixed operation & maintenance costs, fuel costs, emission unit allowances (EUAs) and CO_2 transport and storage
- Annual electricity demand and production (TWh/y)
- Amount of released and stored CO_2 (M tonnes/year).

The simulations offered a fair comparison of the different trajectories, i.e. mainly CCS-dominated vs. renewable-dominated. This was achieved on the basis of two types of charts:

1. A temporal trajectory of cumulated costs produced by totalling operation costs and investment costs. In order to account for the expected interest yield, investment costs were multiplied by a factor of 2.5 – see Figure 6. (The annuity factor for an expected interest rate of 9% and a typical lifetime of 25 years is 10%. Paying 10% of the investment for 25 years leads to a factor of 2.5.)
2. A temporal trajectory of the cost of electricity was determined with the aforementioned assumptions (interest rate 9%, 25 year lifetime, 10% annuity factor).

The other parameter is specific CO_2 emissions in kg_{CO2}/MWh – the figures in Chapter 3 plot cumulated costs and LCOE vs. specific CO_2 emissions.

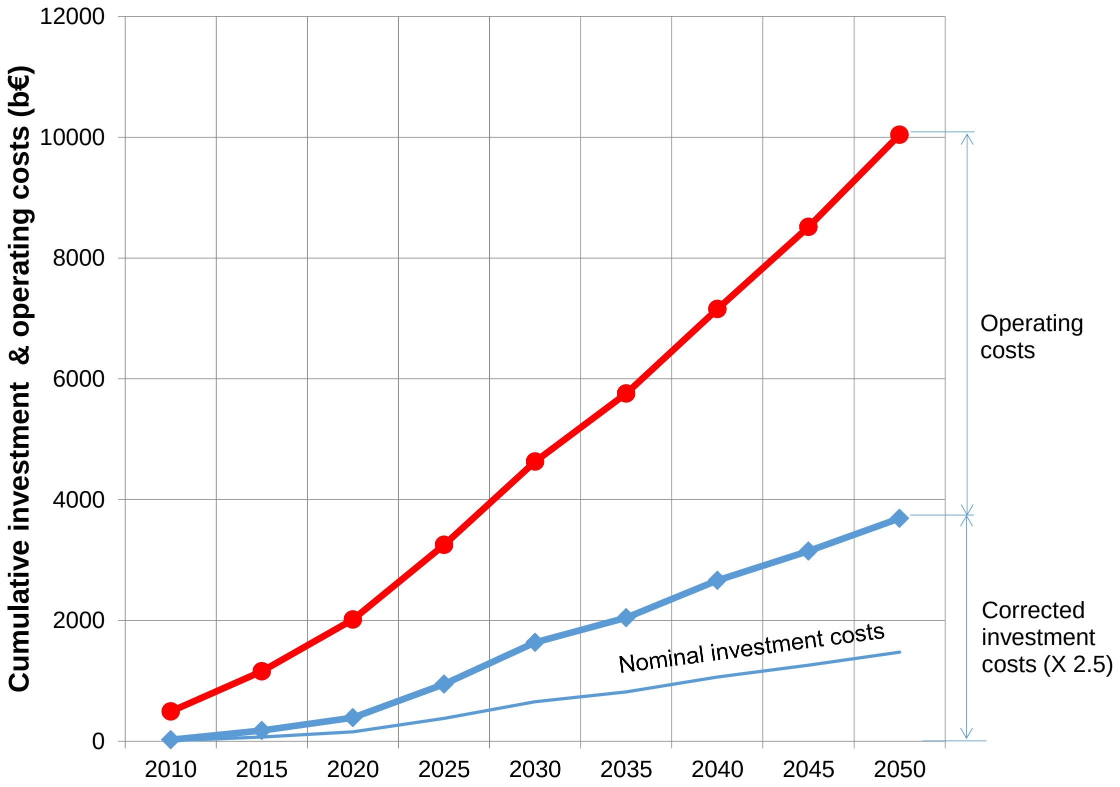

Figure 6: Trajectory of cumulative investment and operating costs for the period 2010 to 2050

3 The results

Without CCS, the cost of decarbonising European power is 20-50% higher by 2050

The following figures show the results of the six scenarios. These demonstrate that:

- All constrained scenarios without CCS (1-4) lead to crises where demand cannot be met in 2050. This is driven by the model's attempt to reach the same high level of emission reduction that can be achieved with CCS. In every case, renewable capacity is used up to its constrained level and blackouts are a possible consequence.
- For all scenarios, the CCS option clearly offers the lowest-cost route to reducing CO_2 emissions. Until 2030, the CCS and no-CCS cases are similar and emission reductions are mostly achieved by switching to highly efficient, gas-fired combined cycle power plants. After 2030, however, a massive investment in PV and wind capacity takes place for the no-CCS scenarios that leads to higher costs than investment in CCS. This can be seen in both the cumulative costs (top graphs) and in the relative LCOE (bottom graphs).
- Electricity storage only has a limited effect towards the end of the time horizon, i.e. from 2040 onwards. It is more present in cases where PV plays an important role. This is most likely an artefact related to the fact that the model considers only single days throughout a year, when the time scales of wind energy fluctuations go beyond one day. These require a longer-term storage that is beyond the scope of the model.

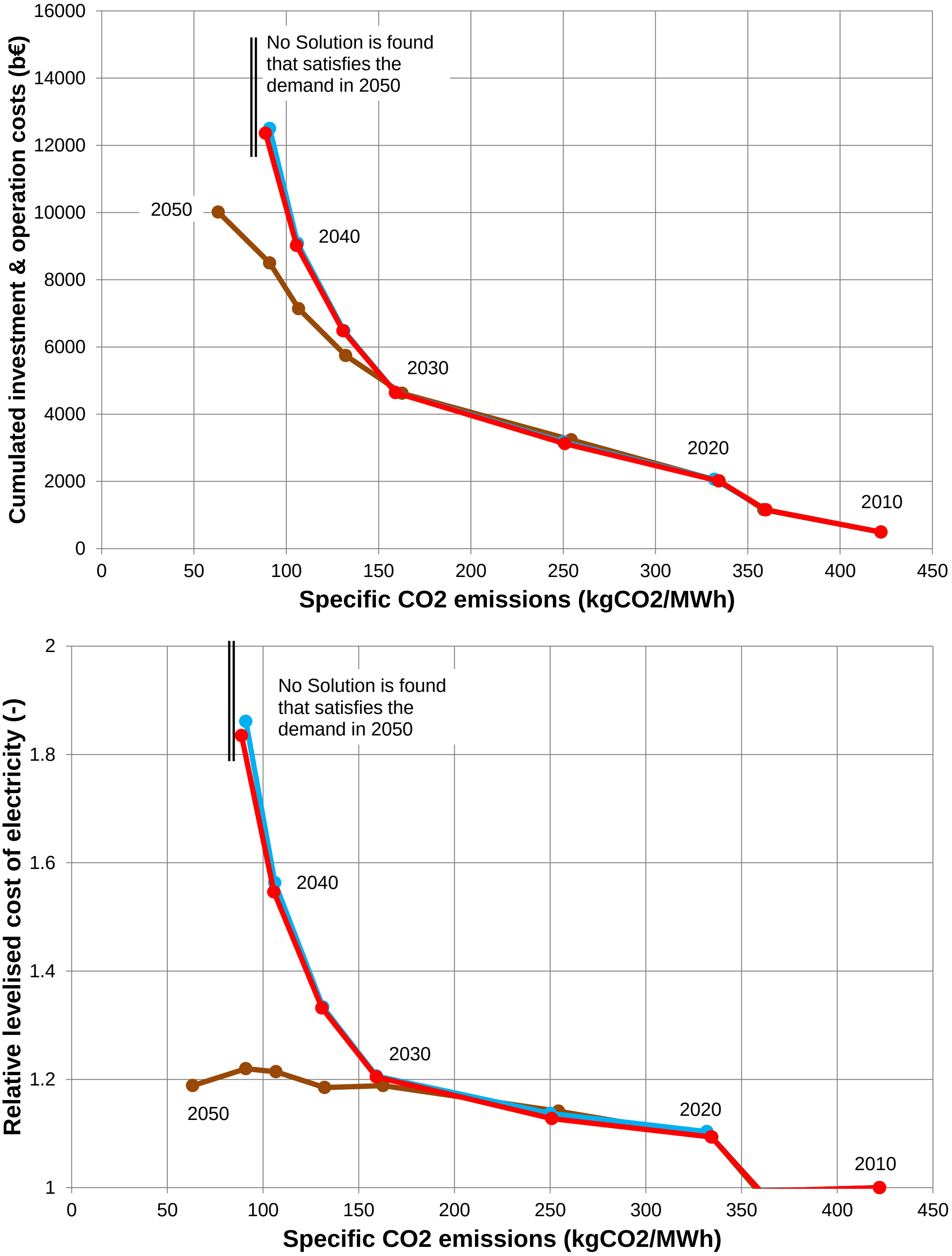

Figure 7: Scenario 1: high constrained, high PV costs: ▬ CCS, with electricity storage; ▬ no CCS, no electricity storage; ▬ no CCS, with electricity storage

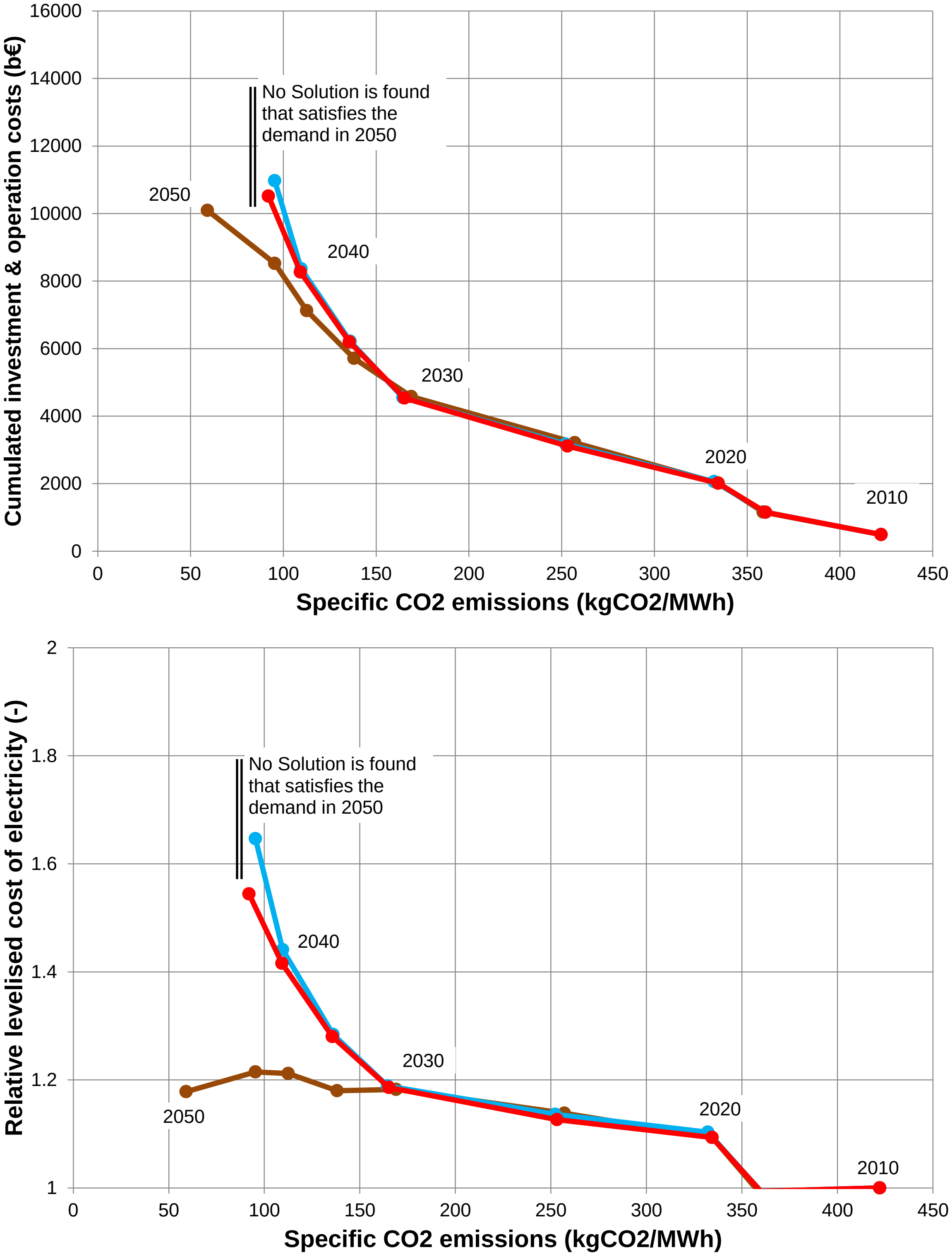

Figure 8: Scenario 2: high constrained, low PV costs: — *CCS, with electricity storage;* — *no CCS, no electricity storage*; — *no CCS, with electricity storage*

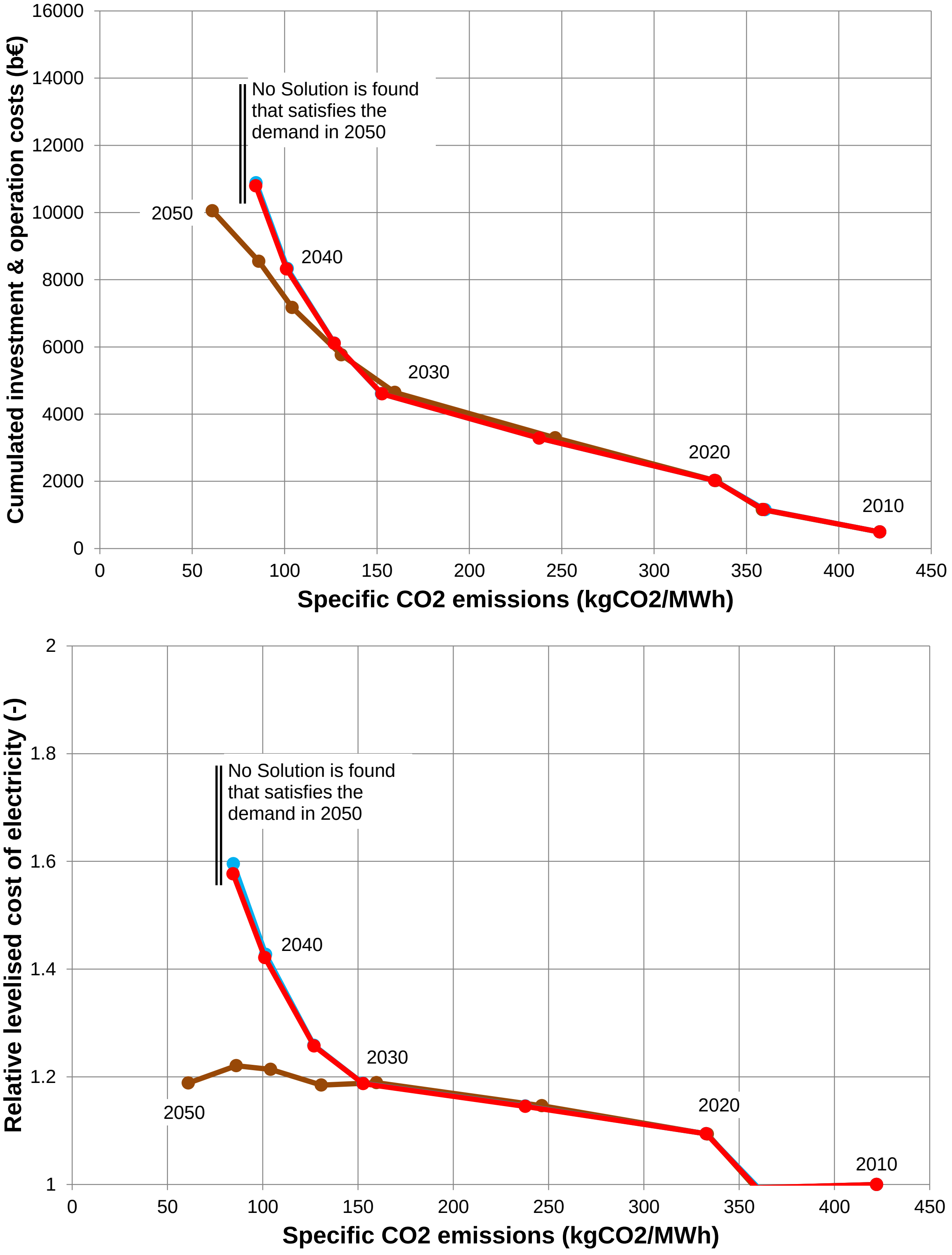

Figure 9: Scenario 3: weak constrained, high PV costs: ▬ CCS, with electricity storage; ▬ no CCS, no electricity storage; ▬ *no CCS, with electricity storage*

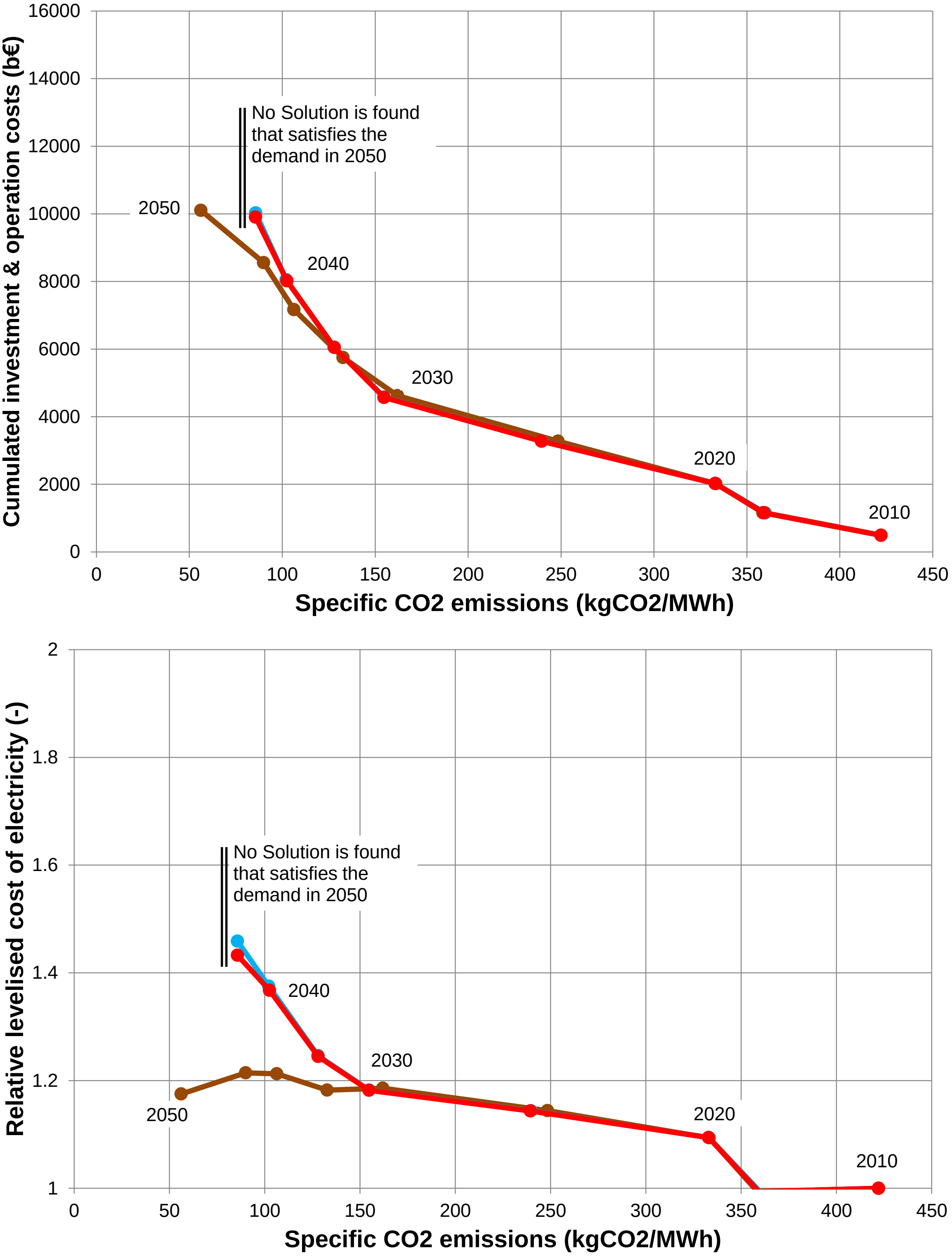

Figure 10: Scenario 4: weak constrained, low PV costs: ▬ CCS, with electricity storage; ▬ no CCS, no electricity storage; ▬ no CCS, with electricity storage

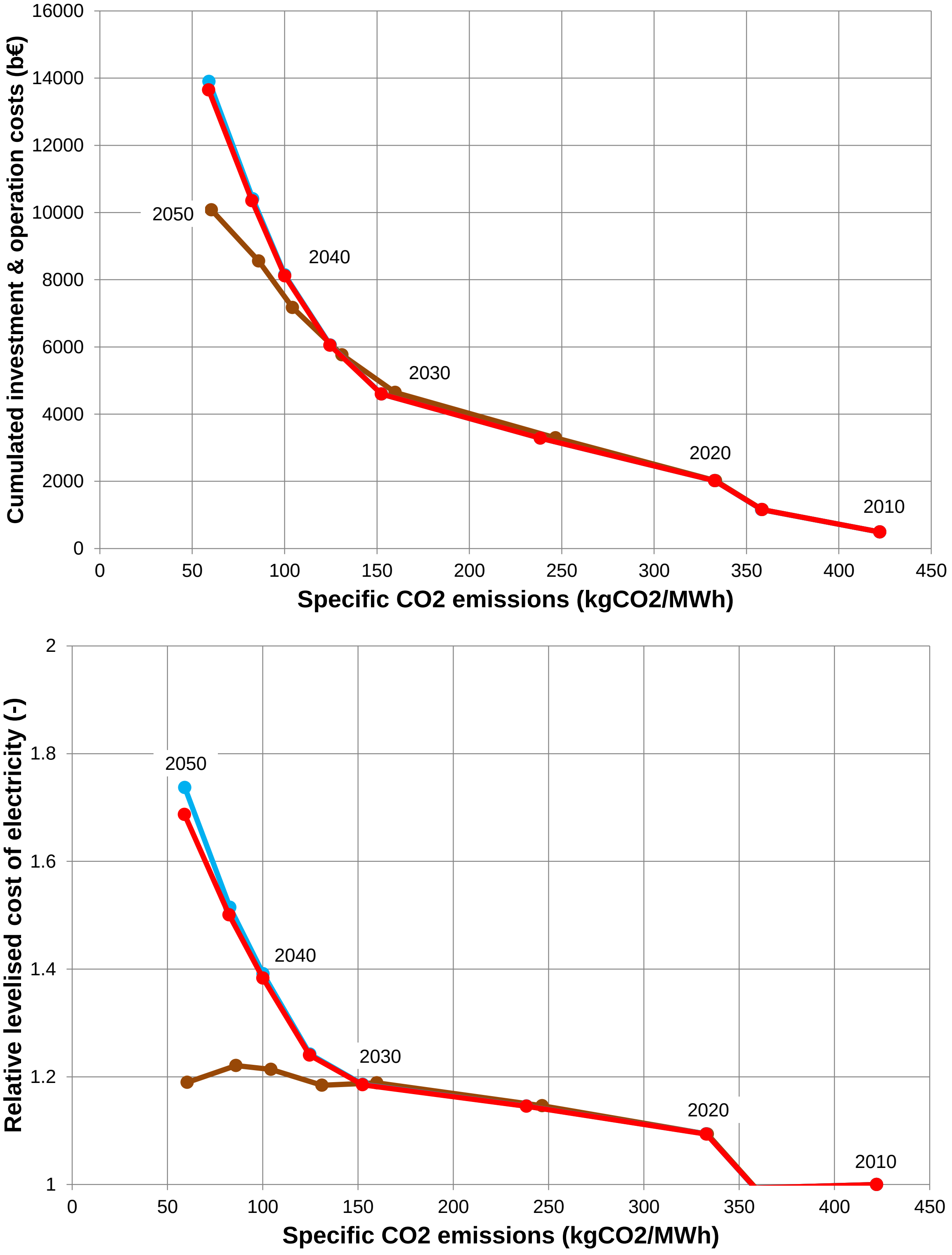

Figure 11: Scenario 5: no limits, high PV costs: ▬ CCS, with electricity storage, ▬ no CCS, no electricity storage, ▬ no CCS, with electricity storage

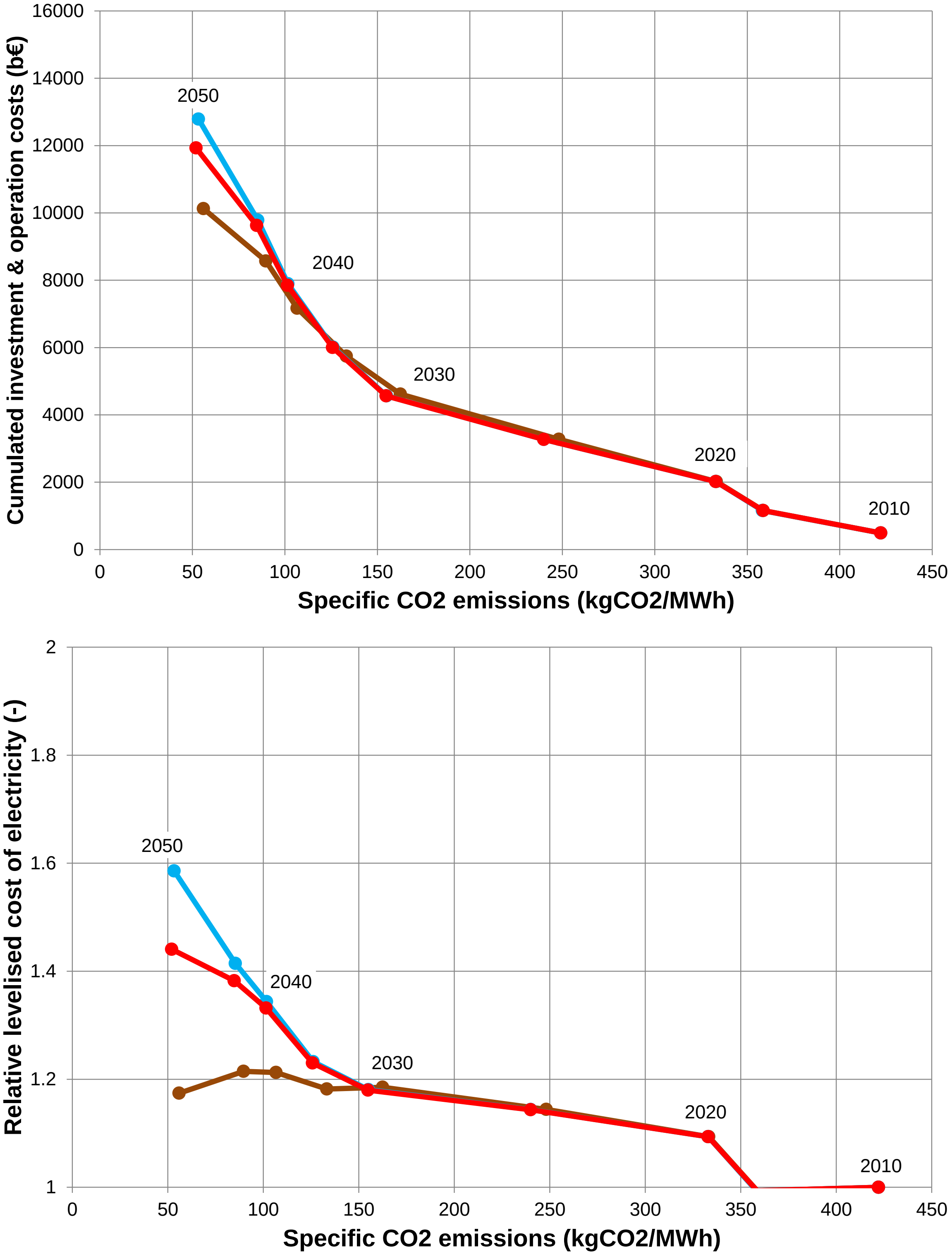

Figure 12: Scenario 6: no limits, low PV costs: ▬ CCS, with electricity storage; ▬ no CCS, no electricity storage; *▬ no CCS, with electricity storage*

Breakdown by European country

The CCS cases are mainly driven towards CO_2 reductions by the increasing CO_2 price. The no-CCS cases are forced to follow the same trajectory of CO_2 reductions in order to make them comparable to the CCS case. None, however, considers European countries on an individual basis: the model chooses freely how to realise CO_2 reductions in order to minimise the overall costs for Europe.

The consequences are shown in Figure 13. Based on Scenario 5, this demonstrates the emission intensity in each European country in 2010 and 2050, both for the “with CCS” case and the “no-CCS, with electricity storage” case. This shows that all countries start from different emission intensities and that they reach different levels in 2050.

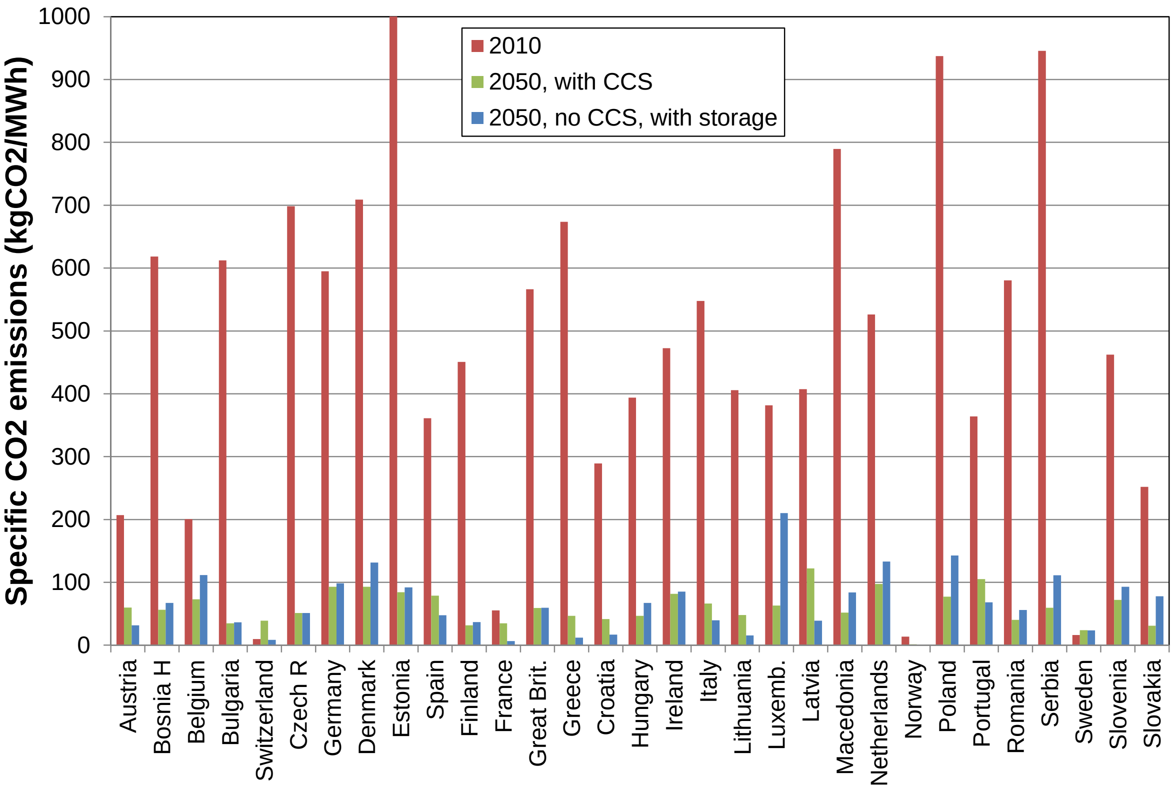

Figure 13: CO_2 emissions by country in 2010 and 2050 (Scenario 5 – no limits, high PV costs)

Figure 14 below shows the relative CO_2 reduction from 2010 to 2050. Again, countries vary in their contribution to the overall Europe-wide reduction. For some countries, such a reduction is meaningless because they start from very low emissions levels (e.g. France, Switzerland, Norway etc).

In order to achieve an equal reduction for all countries, an additional simulation was run where *every* country had to reduce absolute CO_2 emissions by 80% in 2050 (countries which started from very low levels were exempted from this rule). Figure 15 below shows the reductions for the different countries. When compared to Figure 14, the scatter has strongly reduced and all countries meet the 80% reduction target.

Finally, a comparison was made of electricity generation costs in 2050 for Europe-wide cases and those with country-specific emission limits. A moderate increase of 3% and 4.5% was found for the “with CCS” and the “no CCS, with electricity storage” cases, respectively. The cost optimal solution for Europe as a whole therefore implies different emission reductions for each country – costs increase when emission reductions are forced to be equal for all countries.

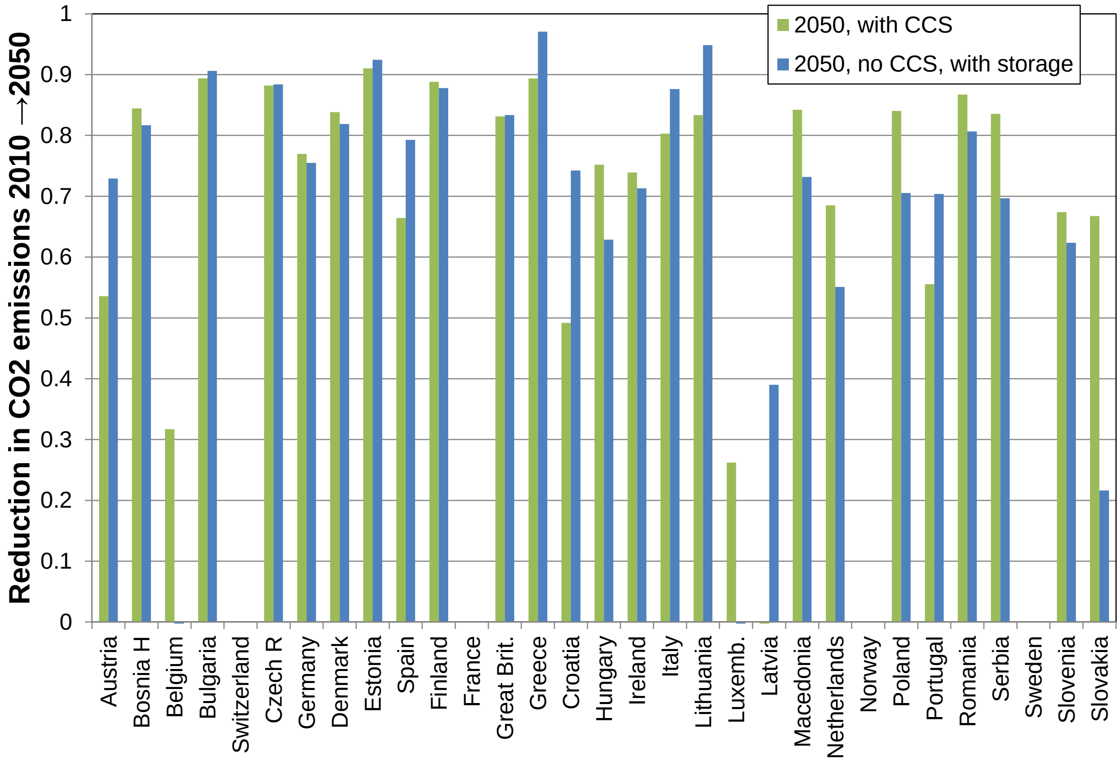

Figure 14: Reduction in absolute CO_2 emissions from 2010 to 2050; 80% target prescribed for Europe overall (“No CCS, with electricity storage” case follows emission reduction achievable in CCS case)

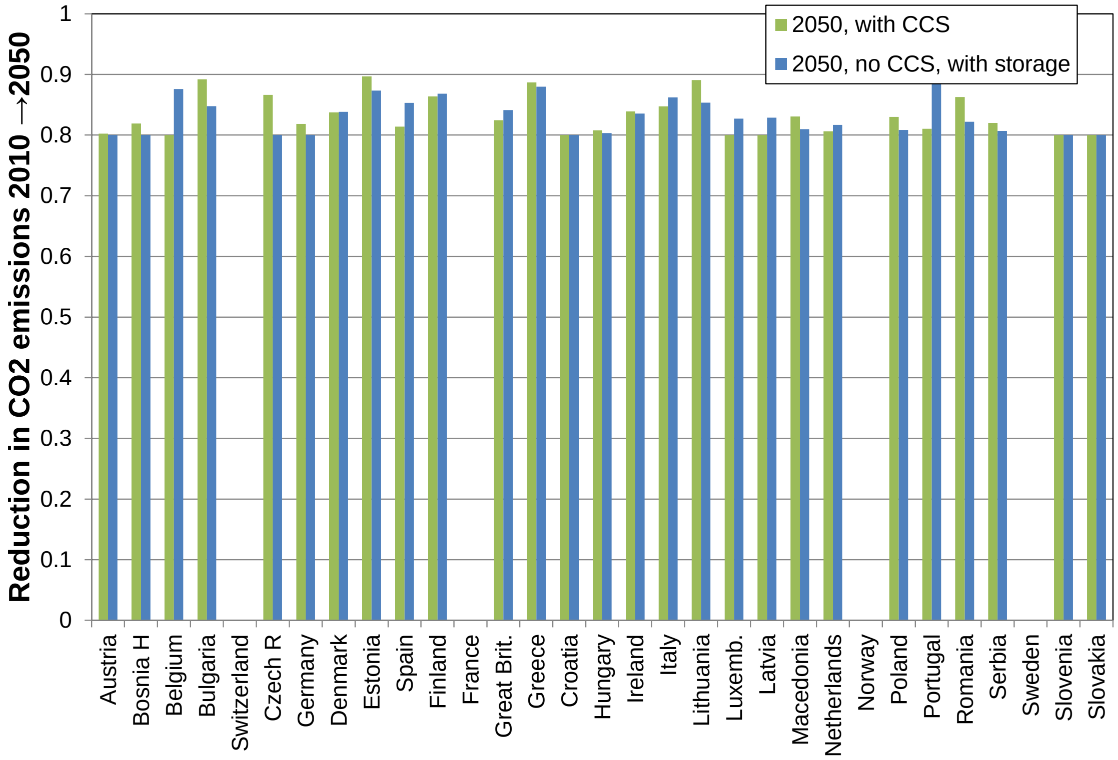

Figure 15: Reduction in absolute CO_2 emissions from 2010 to 2050; 80% target prescribed for each individual country

Key conclusions

- If CCS is excluded from the model altogether, and limits on onshore wind and solar PV from the original modelling are maintained, electricity demand in Europe is not met after 2045 because the model's 80% emission reduction target cannot be achieved without CCS.

- Even if the cost of PV is reduced to 200 €$_{(2010)}$/kW installed in 2050 – requiring a significant technology breakthrough compared to today – demand is still not met after 2045 and the cost of electricity is 20-50% higher than cases with CCS (see Figure 16).

- If there are no limits on wind and solar PV whatsoever, this results in 600 GW of PV and 1,000 GW of wind in 2050 for the original (1,000 €$_{(2010)}$/kW PV costs in 2050) scenario; up to 1,500 GW of PV and 640 GW of wind in 2050 for the low PV cost scenario. This represents 100,000-200,000 5 MW-class wind turbines and up to 10,000 km^2 of Europe's surface covered by PV. Even if this was practically possible, the cost to Europe is 35-45% higher than equivalent cases with CCS (see Figure 16).

- Even if electricity storage is selected to help integrate the renewables, it only has a limited effect from 2040 onwards and plays a small role in reducing costs.

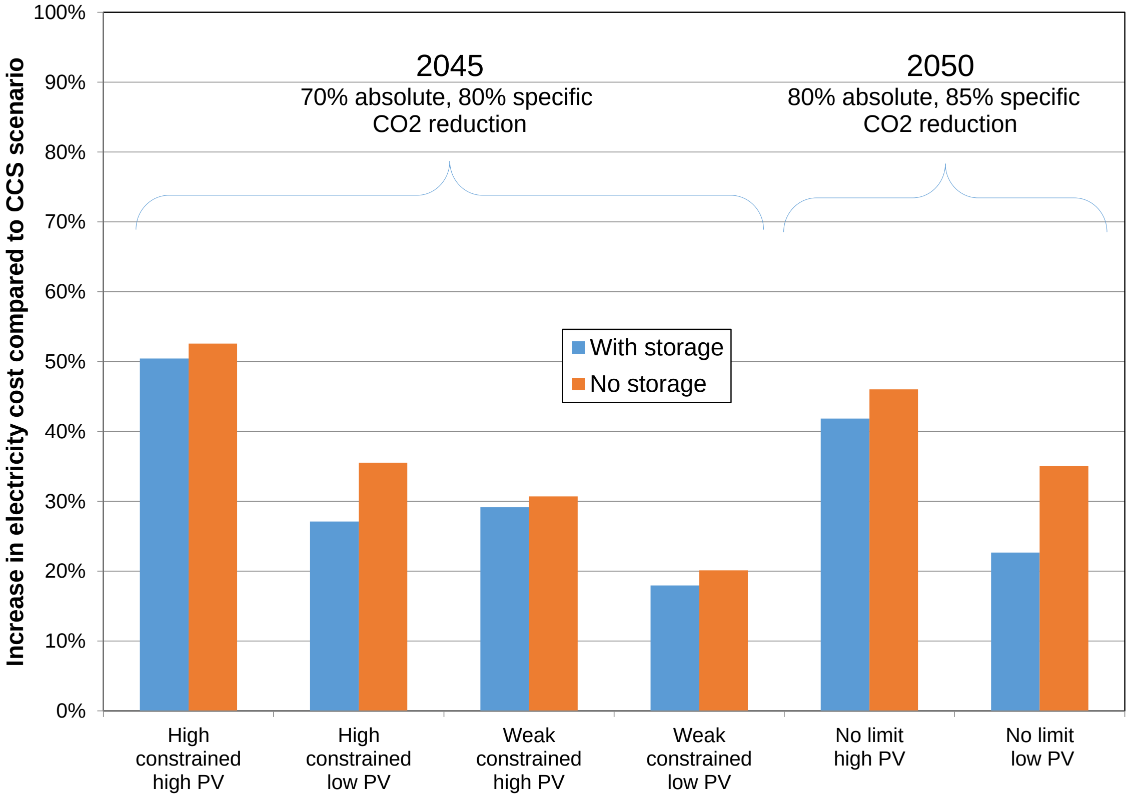

Figure 16: Increase in electricity costs from CCS to non-CCS variants in 2045/2050

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

Name	**Country**	**Organisation**
Daniele Agostini	Italy	ENEL S.p.A.
Heinz Bergmann	Germany	RWE
Paula Coussy	France	IFP Énergies nouvelles
Gianfranco Guidati	Switzerland	Alstom
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Jonas Helseth	Belgium	Bellona Europa
Emmanuel Kakaras	Greece	Centre for Research and Technology Hellas (CERTH)
Juliette Langlais	Belgium	Alstom
Goran Lindgren	Sweden	Vattenfall
Wilfried Maas	The Netherlands	Shell
Giulio Montemauri	Italy	ENEL S.p.A.
Anca Popescu	Romania	ISPE
Hermione St. Leger	UK	St. Leger Communications Ltd.
Christian Skar	Norway	Norwegian University of Science and Technology (NTNU)
Charles Soothill	Switzerland	Alstom and Chair of ZEP TWG ME; Vice-Chair of ZEP Advisory Council
Graeme Sweeney	UK	Chairman of ZEP
Kazimierz Szynol	Poland	PKE S.A.
Bill Thompson	UK	BP
Asgeir Tomasgard	Norway	Norwegian University of Science and Technology (NTNU)
Marc Trotignon	France	EdF
Keith Whiriskey	Belgium	Bellona Europa
Karl-Josef Wolf	Germany	RWE

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