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Research article

Deployment of CO_2 capture and storage in Europe under limited public acceptance—An energy system perspective

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ABSTRACT

In this paper we analyse how in Europe large-scale deployment of CO_2 capture and storage (CCS) technology may be hindered by limited public acceptance. We develop scenarios for how public acceptance may constrain the diffusion of CCS, either by reducing the overall amount of installable CCS capacity or by delaying its introduction, and show with an integrated assessment model how the type of limitation in CCS acceptance can critically impact the development of all sectors in the overall energy system over time. We also demonstrate that a reduction or delay in CCS diffusion as a result of critical public opinion can have substantial energy system impacts that differ across not only the nature of acceptance profile but also the sector(s) in which limited public acceptance materializes. Applying a constraint to CCS deployment in both industry and the power sector simultaneously leads to an energy system that is fundamentally different from the one that emerges if the constraint is only applied to the power sector. Depending on how and where CCS diffusion is constrained, net additional annual energy system costs in 2050 can vary between -50 billion up to nearly 800 billon \$/yr.

1. Introduction

Many flagship publications dedicated to the global energy transition foresee an essential role played by carbon dioxide capture and storage (CCS) in combating climate change, at least in the short term (see, for example, IEA-WEO, 2020; IEA-ETP, 2020). CCS entails the capturing of CO_2 at industrial installations or power plants and transporting the CO_2 to an onshore or offshore storage field (e.g. empty gas field or aquifer) where it is stored indefinitely. The necessity to achieve net zero greenhouse gas (GHG) emissions by 2050 in order to reach the target of 2 °C – preferably 1.5 °C – maximum average temperature increase of the Paris Agreement (with no or limited overshoot) stimulates in principle the use of all low-emission energy technologies, including CCS (IPCC, 2005; IPCC, 2018; IPCC, 2022; COP-21, 2015). While strictly speaking 'only' *carbon* neutrality is required in 2050 to reach this goal (rather than *GHG* neutrality, which typically may be achieved a decade later), there are multiple reasons for aiming at GHG neutrality in 2050 (see Detz and van der Zwaan, 2019), also because the EU has formally set the more stringent target of GHG neutrality by 2050 (EC, 2019; EC, 2020).

For many years CCS has been called a promising way to address the problem of global climate change (IPCC, 2005; Tavoni and van

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der Zwaan, 2011; ALIGN-CCUS, 2021), but it has to date been deployed on only a modest scale (GCCSI, 2022). One of the main reasons, along with e.g. the elevated costs of CCS technology, is that CCS diffusion is hindered by limited public acceptance: this has already happened in the past (such as in Barendrecht, the Netherlands; see Kuijper, 2011) and may accrue under large CCS deployment. In the present paper, we proffer a novel approach towards analyzing CCS in relation to the skeptical public opinion it is subject to, by investigating how the rate of CCS development is slowed down as a result of limited public acceptance through the use of an Integrated Assessment Model (IAM), particularly TIAM-ECN, operated at TNO and used during more than a decade for a long list of energy transition studies. IAMs are models that merge learnings from both the natural and social sciences to assess climate change mitigation pathways, and are extensively used by the Intergovernmental Panel on Climate Change to increase our understanding of how to transition to net zero GHG emissions for our global economy (IPCC, 2018; IPCC, 2022). The novelty of the present paper is that we embed IAM research in the broader existing literature on public acceptance in relation to transition studies (such as in Demski et al., 2019, and Geels, 2019).

The limits on public acceptance for CCS have been the subject of social scientific research for the past two decades (L'Orange Seigo et al., 2014, Tcvetkov et al., 2019, Buck, 2021). Public acceptance is commonly defined as "the attitude or behavioral response to the implementation or adoption of a proposed technology held by the lay public of a given country, region or town" (Upham et al., 2015, pp. 105). *Public* acceptance centers on attitudes of the public, whose attitudes shape and are shaped by the acceptance of other actors, such as local governments, citizen collectives or market actors (Upham et al., 2015). *Limited* public acceptance is defined here as public acceptance under constraints, such as storing CO_2 only in offshore fields or developing CCS only in particular locations or in specific sectors. The implementation of CCS is likely to be met with such limited public acceptance for several reasons.

First, some CCS projects may encounter public opposition due to historical experiences. For example, CCS projects in Barendrecht and the North of the Netherlands were cancelled as a result of public opposition, combined with conflicting views from key stakeholders and an unclear division of responsibilities in the latter case (Cuppen et al., 2015, Terwel et al., 2019, van Egmond et al. 2014, van Os et al., 2014). Support for such projects is more likely to come about when they are perceived as 'just' (Jenkins et al., 2016), when the parties responsible for implementation are trusted (Terwel et al., 2009), and when the project fits with meanings the local communities give to their place of residence (Devine-Wright and Batel, 2017). This implies that some locations or regions may be more conducive to CCS projects than others. It also implies that participation procedures and community benefits that are provided may be a key determinant in fostering support for these projects (Boomsma et al., 2020). Hence, because of the inherent diversity between locations, public acceptance may be achievable for some projects, while remaining limited for others.

Second, public acceptance for CCS is likely to be highly context-dependent. Recent public opinion surveys conducted in many countries show that public opinion on CCS is commonly indifferent, lukewarm or skeptical (Broecks et al., 2021, Whitmarsh et al., 2019, Pianta et al., 2021, Arning et al., 2019, Saito et al., 2019, Kahlor et al., 2020, Ashworth et al, 2019, Moon et al., 2020). These studies have shown that citizens' attitude toward CCS depends – among other factors – on the costs of CCS, the policy package for stimulating and guiding its deployment, such as subsidies, taxes and permits (Pianta et al., 2021), and how the economic impacts of implementing CCS (e.g. jobs and economic development) will be managed (Broecks et al., 2021). Citizens may also prefer some applications of CCS over others. Studies show that industrial CCS may be perceived more positively (Dütschke et al., 2016) or more negatively (Whitmarsh et al., 2019) than CCS at power plants, and that citizens may interpret differently the effects these two alternatives have on jobs and the economy (Thomas et al., 2018). A recent informed opinion survey showed that the currently envisioned applications of industrial CCS with offshore storage may count on relatively positive responses in certain areas in Europe (Broecks et al., 2021). Hence, public acceptance is likely to manifest itself differently for diverse CCS applications, and thus limited public acceptance of CCS for certain projects or at certain locations cannot be excluded.

Third, positioning CCS as a 'regulated breathing space' is likely the most viable narrative going forward (Janipour et al., 2021). Currently, two conflicting narratives for CCS exist, where CCS is either positioned as a technology that strengthens fossil fuel lock-in, complicating a transition towards alternatives, or as a vehicle for a just transition through retaining jobs and economic activity in regions dependent on the fossil fuel industry (Swennenhuis et al., 2020, Williams et al., 2021). The narrative of CCS as a regulated breathing space may offer an alternative to these two extremes by specifying a timeline for policy support, as well as an exit strategy for CCS (Janipour et al., 2021). Until the exit of CCS has been achieved, however, and quite certainly in the first of these two extremes, the probability of limited public support for CCS remains sizeable.

For these reasons, the deployment of CCS will likely be subjected to substantial constraints in many locations (see also IPCC, 2022). Yet, these constraints can manifest in myriad ways: through a reduction of the installable CCS capacity or through a delay in the deployment of CCS facilities, among others (Watson et al., 2014). The effects of such constraints on the net annual energy system costs, as well as the deployment of other technologies is currently unclear. Furthermore, the public acceptance for CCS may develop differently in the industrial and power sectors, as suggested by several studies (Broecks et al., 2021, Whitmarsh et al., 2019, Dütschke et al., 2016, Thomas et al., 2018). Recent developments in the Netherlands – where CCS subsidies are given exclusively to the industrial sector for regulatory reasons – show that such differences in policy regimes between these sectors may indeed come about (Akerboom et al., 2021). The present paper aims at investigating not only what the broader energy system impacts are of reductions or delays in the deployment of CCS (in line with recent literature in this domain, some of it dedicated to carbon dioxide removal – CDR, which may face different public perception challenges but may also share some of them – including Bellamy et al., 2019; Fridahl and Lehtveer, 2018; Romanak et al., 2021; Schenuit et al., 2021; Stigson et al., 2012), but specifically also to what extent these system effects depend on whether CCS is only obstructed in the power sector, or in industry and electricity production simultaneously. With this work we intend to increase our understanding of the effects of limited public acceptance for CCS diffusion, for example in terms of their implications for the deployment requirements of renewable energy options like solar and wind power (see e.g. Hansen et al., 2019).

2. Methodology

2.1. TIAM-ECN

TIAM-ECN is a global technology-rich linear optimization model that identifies cost-minimal energy system scenarios under a set of exogenous constraints. It is an established global IAM (IAMC, 2021) developed and maintained at TNO Energy Transition, based on the TIMES model generator. For a general description of TIMES and its global implementation – TIAM – see e.g. Loulou and Labriet (2008), Loulou (2008) and Syri et al. (2008). TIAM-ECN encompasses energy use in all main sectors and its input database includes hundreds of processes simulating energy conversion from resource extraction to end-use. In the current version of TIAM-ECN the world is broken down in 36 separate geographical entities (see Kober et al., 2016; van der Zwaan et al., 2018). TIAM-ECN has been employed to provide long-term projections for many different technologies, including in transport (see Rösler et al., 2014) and power generation (Kober et al., 2016), and has been used to investigate climate-change mitigation (Kober et al., 2014) and technology diffusion (see, for instance, van der Zwaan et al., 2013; van der Zwaan et al., 2016). Among recent exercises with TIAM-ECN was a study dedicated to CCS (Dalla Longa et al., 2020). In that article we found that, under 2 °C policy, CO_2 capture in Europe may grow to some 1700 $MtCO_2$/yr in 2050. CCS applied to natural gas and biomass could then account for about 25% of electricity generation, and natural gas with CCS could contribute over 35% of energy use in industry. Another important conclusion in Dalla Longa et al. (2020) was that strict climate policy is a bigger driver of broad CCS diffusion than technology cost reductions. More in particular, we estimated with TIAM-ECN that a 30% CCS capital cost reduction could yield about 17 billion US$/yr energy system cost savings in Europe in 2050.

TIAM-ECN represents several CCS technologies across different sectors, notably electricity supply, industrial processes and fuel production. In particular, the model simulates fossil-fuel-based CCS in the power sector, industry and fuel production, as well as biomass-based CCS in the power sector and fuel production (where it can contribute to realizing negative emissions; see e.g. Lehtveer and Emanuelsson, 2021). For the moment, biomass-based CCS is not represented in industrial applications other than fuel production, as this falls beyond the more limited scope of the present article, and because it involves substantial model adaptations that require a dedicated research project. While the omission of biomass-based CCS in industry (other than for fuel production purposes) may impact the results of TIAM-ECN globally and for specific regions in the world, we think that for Europe (the focus of our current work) the energy system effect is relatively small. The first reason is that biomass deployment without CCS as a fuel for industry in Europe is limited to at most a few percent of the industrial mix in all TIAM-ECN scenarios that we investigated thus far. The second reason is that the overall potential for biomass use for energy purposes is typically constrained by stringent conditions related to the possible negative impacts – in terms of e.g. land use change, food prices, and biodiversity loss – that large-scale cultivation of energy crops may entail.

In Dalla Longa et al. (2020) we updated the simulation of CCS costs in the power and industrial sectors, which allowed us to better project the prospects for CCS into the future. We there also enabled TIAM-ECN to account for cost reductions that fundamental research may deliver for CCS technology. One of the R&D efforts recently undertaken to realize cost reductions for CCS was the European GENESIS project, funded by the EC under its Horizon 2020 programme (GENESIS, 2021), for which reason we focus our analysis on Europe. The GENESIS project is performed under the premise that CCS applications are among the main options technically available to reduce CO_2 emissions from fossil fuel based factories or plants in industry and the power sector. Among the barriers for the broad diffusion of CCS are its relatively high costs, which we investigated in Dalla Longa et al. (2020). We here analyse how the deployment of CCS in Europe could be affected by limited public acceptance.[1]

2.2. Modeling CCS diffusion under limited acceptance

The solid dots in Fig. 1 show the projection for CCS deployment in Europe until 2050 from Dalla Longa et al. (2020) under conservative assumptions for future cost declines of CCS technologies. This projection, corresponding to a scenario named CHC in that article, is the starting point for the present analysis, which we refer to here as our Base scenario. The trend of the Base projection can be described by a confined exponential (C-exp) diffusion curve of the form:

$$f_{c-exp}(t) = A\left(1 - e^{-k_e(t-t_0)}\right),$$

in which A, k_e and t_0 represent, respectively, the asymptotic value of the function, its growth rate and the point at which it crosses the horizontal axis. A least-square fit using this function yields $A = 347$ GW, $k_e = 0.052$ yr^{-1} and $t_0 = 2020$. In order to better grasp the significance of the time scale expressed by k_e, we can calculate the characteristic time, Δt_e, of the diffusion curve, defined as the time required for the function to go from 10% to 90% of its asymptotic value (Banks, 1994). For the C-exp curve it can be determined as:

$$\Delta t_e = \frac{\ln 9}{k_e} = 42.25\ yr,$$

in which we used the value of k_e obtained from our least-square fit.

[1] Europe in the model used for this analysis refers to the ensemble of the following countries (that jointly form one entity in TIAM-ECN): Andorra; Austria; Belgium; Channel Islands; Denmark; Faeroe Islands; Finland; France; Germany; Gibraltar; Greece; Greenland; Iceland; Ireland; Isle of Man; Italy; Liechtenstein; Luxembourg; Malta; Monaco; Netherlands; Norway; Portugal; San Marino; Spain; Sweden; Switzerland; United Kingdom.

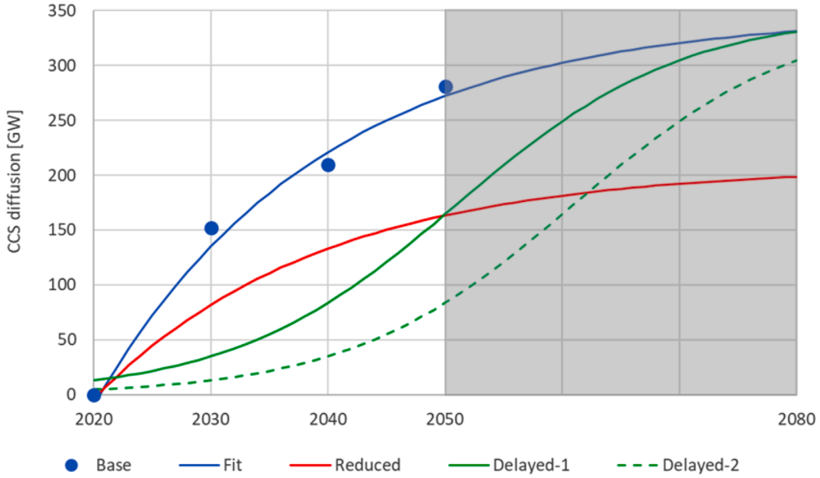

Fig. 1. CCS diffusion in Europe. Blue dots: TIAM-ECN projection until 2050 according to Dalla Longa et al. (2020). Blue line: confined exponential least-square fit. Red and green lines: maximum CCS deployment levels used to define low-acceptance scenarios. The grey area beyond our modeling horizon is shown to illustrate the long-term trend of the curves.

A confined exponential diffusion is typical for systems that are driven by external factors (Banks, 1994). As Banks (1994) points out, there are examples of technologies that have followed diffusion pathways other than a typical logistic curve, including confined exponential patterns, which provides a reason to diversify our set of assumptions in this respect. In the present case the exogenous driver is the need to reduce CO_2 emissions at the lowest possible costs. Limited acceptance of CCS technologies might modify the diffusion dynamics in essentially two categories of ways: (i) by reducing the maximum CCS deployment, or (ii) by slowing down the diffusion rate[2].

To illustrate these two possibilities we create a set of alternative diffusion curves: Reduced (the red line in Fig. 1), Delayed-1 and Delayed-2 (solid, respectively, dashed green lines in Fig. 1). The Reduced curve is described by the same C-exp function used to fit the datapoints, but with the asymptotic value decreased by 40%. The idea behind our choice for the number of 40% is to roughly halve the maximum CCS deployment in 2050, while keeping the same diffusion dynamics: a 40% reduction in the asymptotic value achieves this purpose.[3] This curve simulates the case in which limited acceptance of CCS leads to a lower deployment of this technology, but the diffusion process still follows the same dynamics as in the Base case. This situation can occur as a result of the application of more stringent requirements for the allocation and realization of CO_2 storage sites (for instance, induced by high public aversion toward risks of CO_2 leakage), which limits the overall availability of CO_2 storage locations.

The Delayed-1 and Delayed-2 lines are logistic curves (also referred to as S-curves; see e.g. Grubler et al., 2016, who point out that many technologies have historically followed logistic curves). They represent cases in which the asymptotic value remains unaltered, but the diffusion towards it follows different dynamics than that expressed by the C-exp function. A logistic diffusion is characteristic of systems that are driven by imitation rather than by external factors (Banks, 1994). We choose this particular curve for delayed diffusion so as to simulate the situation in which consensus needs to be built for broad-scale CCS deployment to become publicly accepted. Only after early adopters have slowly established an initial set of successful examples can the diffusion process proceed at a faster pace (less hindered by insufficient public acceptance) determined by external economic and environmental factors. The equation for the two S-curves depicted in Fig. 1 is given by:

$$f_{S-curve}(t) = \frac{A}{1 - e^{-k_s\left(t - t_{0,s}\right)}},$$

in which A is (as before) the asymptotic value of the function, and $t_{0,s} = 2051$ and 2061 for the solid and dashed green lines, i.e. the Delayed-1 and Deleayed-2 scenarios, respectively. The offset parameter $t_{0,s}$ (used for tuning purposes, to calibrate the scenarios against each other) represents the point at which the concavity of the S-curve changes from positive to negative. The growth rate parameter k_s is set to twice the value of k_e, i.e. $k_s = 2k_e = 0.104\ \mathrm{yr}^{-1}$. This ensures that the characteristic time, expressed for an S-curve by $\Delta t_s = \frac{\ln 81}{k_s}$, is still 42.25 yr. Since today insufficient empirical data are available to determine how the onset of diffusion might look like, we have created two versions of the S-curve case, Delayed-1 and Delayed-2, by tuning the offset parameter, $t_{0,s}$, so that the 2050 value is equal to and, respectively, half of that in Reduced.

[2] Technically, the combination of these two might be considered a third possibility, but we do not explore it since it would lead to a similar projection as that in the other two cases, given our modeling horizon until 2050.

[3] The purpose of our study is to explore illustrative pathways. For this reason, and due to the fact that actual data on CCS deployment are scarce, we had to rely on expert-insight-based realizable choices for the parametrization of our scenarios. Most of our parameter choices are geared towards inducing significant changes in the energy mix, that we can subsequently inspect and analyze.

Table 1
Summary of scenarios.

Scenario	Description	Curve in Fig. 1 used to define maximum CCS deployment and affected sectors
Base	CCS free to diffuse according to dynamics driven by cost-optimality	No restrictions to CCS deployment
Reduce	Same CCS diffusion dynamics as in Base, but limited overall deployment	Reduced – aggregated electricity and industry
Delay-1	CCS diffusion dynamics driven by consensus-building	Delayed-1 – aggregated electricity and industry
Delay-2	CCS diffusion dynamics driven by consensus-building, but later onset	Delayed-2 – aggregated electricity and industry
eReduce	Same as Reduce, but CCS diffusion is only limited in the electricity sector	Electricity: 70% of Reduced; Industry: no bounds
eDelay-1	Same as Delay-1, but CCS diffusion is only limited in the electricity sector	Electricity: 70% of Delayed-1; Industry: no bounds
eDelay-2	Same as Delay-2, but CCS diffusion is only limited in the electricity sector	Electricity: 70% of Delayed-2; Industry: no bounds

2.3. Model scenarios

We use the Reduced, Delayed-1 and Delayed-2 curves depicted in Fig. 1 to build the scenarios that we explore with TIAM-ECN for illustrative purposes. Each curve defines an envelope that restricts the level of CCS deployment to a maximum at every point in time. The curves thus constitute upper-bounds for CCS diffusion, which can be applied to overall CCS deployment aggregated over industry and power production, or to CCS deployment in either of these two sectors individually.

On this basis we construct six scenarios that can be studied with the TIAM-ECN model (see Table 1). Our starting point is the Base scenario in which no constraints are applied to the deployment of CCS technologies. In this scenario Europe reaches net-zero greenhouse gas (GHG) emissions by 2050, while the rest of the world maintains emission reduction policies compatible with the 2°C upper-target of the Paris Agreement (COP-21, 2015). The costs of CCS technologies are based on relatively conservative cost reduction assumptions, used for the CHC scenario reported in Dalla Longa et al. (2020). In the present study our assumptions on climate policy and CCS costs are held constant across all scenarios, since we already undertook sensitivity tests for these assumptions in Dalla Longa et al. (2020). In the Reduce scenario, growth of CCS in the aggregate of industry and power sector is limited to the envelope defined by the Reduced curve shown in Fig. 1. In eReduce CCS diffusion is only limited in the electricity sector, while its growth in industry is unbounded. For CCS in electricity production the limit is set to 70% of the envelope defined by the Reduced curve in Fig. 1 (we chose the level of 70% in the 'e' scenarios, since we observed that in the base scenario CCS in the power sector is about 70% of the total CCS deployment in all periods). Similarly, scenarios Delay-1 and Delay-2 are obtained by using the Delayed-1 and Delayed-2 curves, respectively, to create an upper-bound for the overall deployment of CCS in Europe, while eDelay-1 and eDelay-2 are constructed by only introducing a maximum CCS deployment level for the electricity sector, corresponding to 70% of the respective curves in Fig. 1. Table 1 summarizes these six scenarios.

3. Results

Fig. 2 through 7 shows the main outputs of our TIAM-ECN scenario runs for Europe (while the cost optimal energy system solutions calculated with TIAM-ECN are obtained for the entire world). The plots are organized in two panels: the top one reports the results of the Base, Reduce, Delay-1 and Delay-2 scenarios, while the bottom one presents the outcomes for the Base and the three respective 'e' scenarios. In each panel, the scenarios are sorted in decreasing order of CCS deployment level, i.e. Base, (e)Reduce, (e)Delay-1, (e) Delay-2. The data are presented as stacked bar charts, in which each bar represents a unique combination of scenario and period. The data shown in Fig. 2 through 7 for 2020 are TIAM-ECN output values that we calibrated to publicly available statistics from the IEA (IEA-WEO, 2020); they are the same for all scenarios.

Fig. 2 shows TIAM-ECN projections for the overall level of CCS deployment (expressed in GW; see Fig. 6 in the Appendix for the same projections expressed in MtCO_2), split into its two applications in electricity generation and industry, respectively. In the top panel, total installed CCS capacity in each scenario closely follows the public acceptance envelope defined by the diffusion curves in Fig. 1. In other words, the model deploys as much CCS capacity as possible in all time periods. When the total amount of CCS capacity is limited, in the Reduce, Delay-1 and Delay-2 scenarios, CCS deployment occurs almost exclusively in the power sector. This is mainly a consequence of the cost assumptions adopted in this study (Dalla Longa et al., 2020), which imply CO_2 storage costs per unit of installed CCS capacity that, in the absence of additional constraints (i.e. in the Base scenario), are on average lower in the electricity sector than in industry (see Fig. 7 in the Appendix). This effect starts to level off in 2050, as shown in Fig. 7 in the Appendix, which causes the small but non-negligible uptake of industrial CCS for this time period in the Delay-1 scenario in Fig. 2. Even though the total CCS capacity limit in 2050 is the same in Reduce and Delay-1, the industrial CCS level in Reduce remains negligible. The latter likely occurs because the relatively large CCS capacity already deployed in previous decades in the power sector leads to a partial lock-in.

The 'e' scenarios in the bottom panel of Fig. 2 correspond to the case in which the maximum on CCS deployment is only enforced for applications in the power sector. The overall trends are the same as those in the top panel, but the total amount of installed CCS capacity in industrial applications is much larger, as expected, and uniform across the three 'e' scenarios in all periods. Interestingly, industrial CCS deployment levels in 2030 and 2040 become higher in the three 'e' scenarios than in the Base scenario: when a limit on CCS capacity is imposed only for the power sector, the model deploys higher amounts of this technology in industry than in the unconstrained case (Base scenario) as this becomes the best option to ensure cost-optimal compliance with the CO_2 reduction target.

The electricity generation mix for the various scenarios is presented in Fig. 3 (corresponding installed capacities for the power sector are reported in Fig. 8 in the Appendix). After a slight decrease in 2030, mainly explained by the application of energy savings on

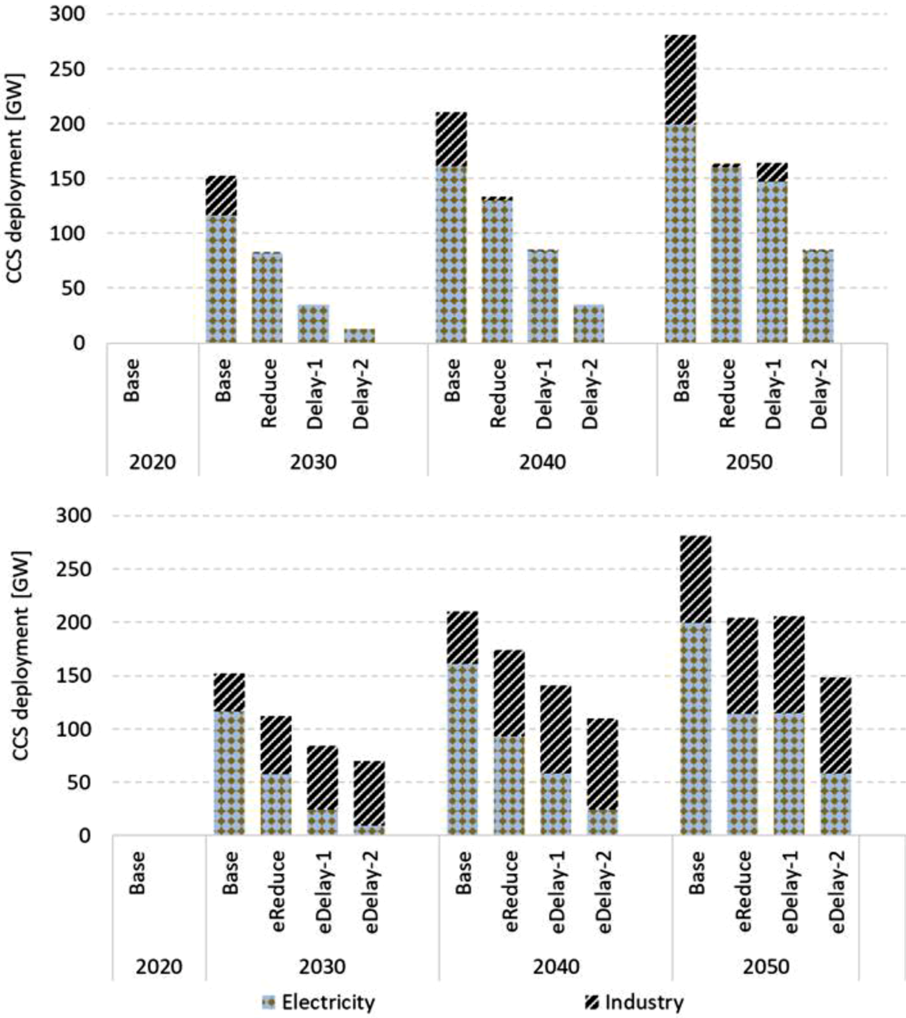

Fig. 2. Projections for CCS deployment by TIAM-ECN.

the demand side, electricity generation is projected to expand over time in all scenarios. Production of electricity from low-carbon technologies based on solar, wind, geothermal and – to some extent – hydro energy increases steadily over time. Nuclear power provides roughly constant contributions across scenarios until the time-horizon that we consider in this study. The decreasing acceptance levels for CCS depicted in Fig. 1 until 2050 in the Reduce, Delay-1 and Delay-2 scenarios induce a progressively lower uptake of CCS technologies. This mainly affects CCS applications in processes based on fossil-fuels (coal and natural gas), while bio-energy based CCS (BECCS) is impacted to a lesser extent, thanks to the fact that TIAM-ECN exploits the possibility of realizing negative emissions with BECCS technology in order to reach the imposed emission reduction targets (a feature that CCS in combination with fossil fuels cannot benefit from, hence it being penalized more). In 2040 and 2050 CCS deployment levels are directly correlated with total electricity generation. This can be explained by considering that with more CCS available for electricity generation, significant CO_2 reductions in the energy system can be achieved at relatively low cost by increasing the size of the power sector, hence electrifying energy services on the demand side. Conversely, when the availability of CCS technologies is constrained and low-cost renewable energy potentials (solar, wind, geothermal and hydro) have already been exploited (as is the case in 2040 and 2050 in our scenarios), CO_2 emission reduction targets can be more cost-efficiently met by exercising energy savings in the demand sectors, which implies a lower overall level of electricity generation. In 2030 the correlation between CCS deployment and total power generation is reversed, mainly due to the fact that at this time more renewable energy generation (especially from wind) can be deployed at low costs to achieve the desired CO_2 emission reduction.

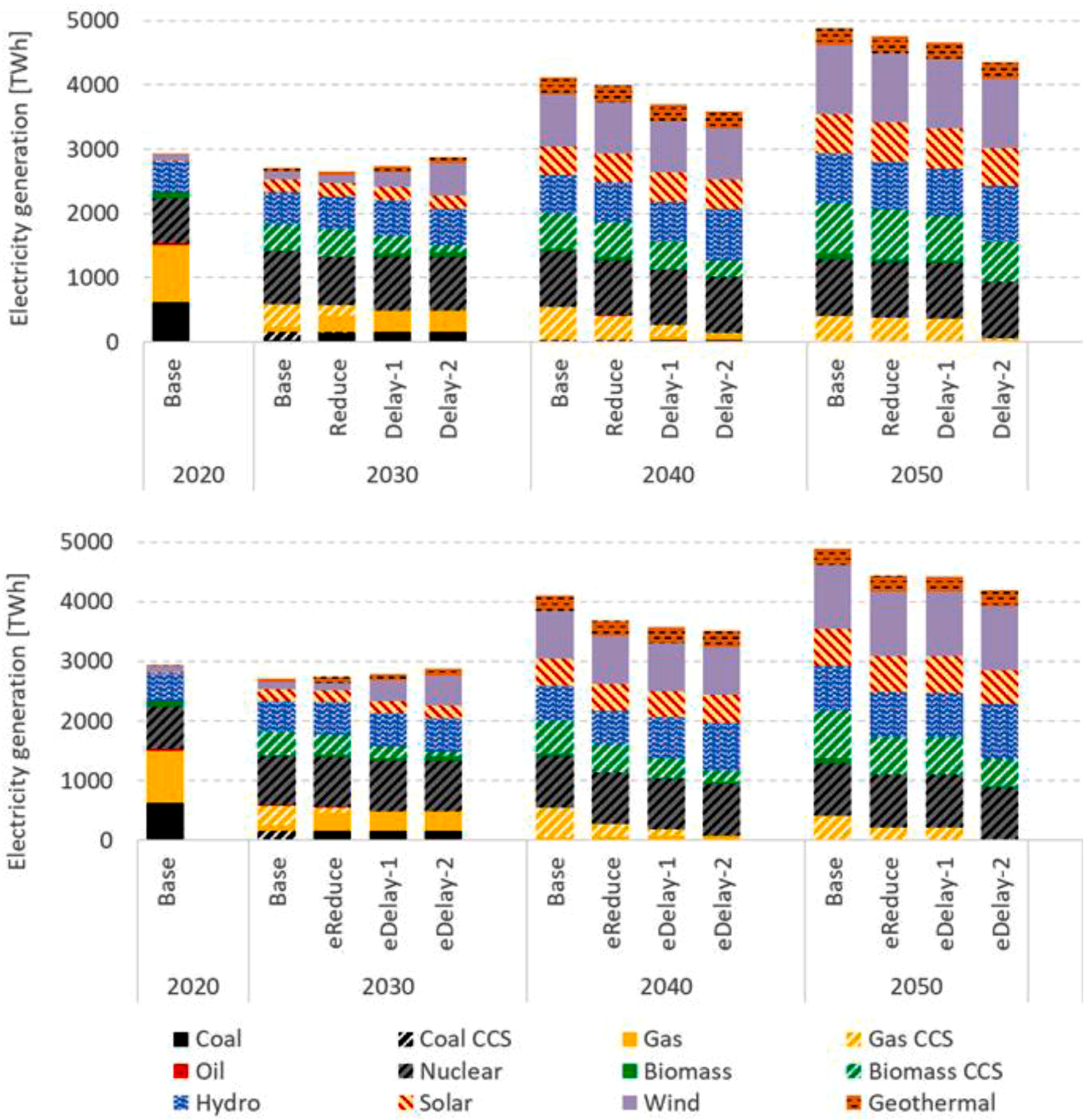

Fig. 3. Projections for electricity generation by TIAM-ECN.

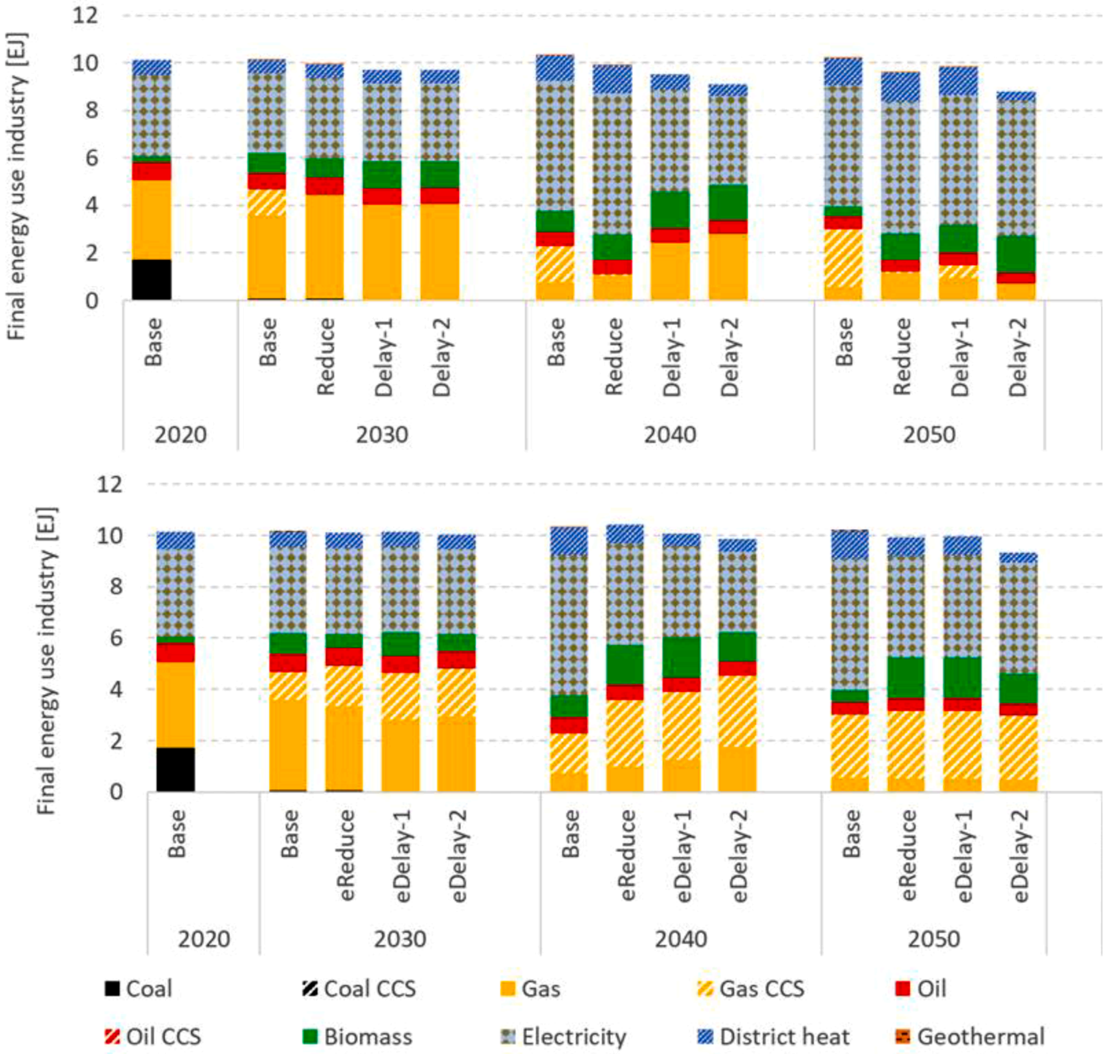

Fig. 4. Projections for final energy in industry by TIAM-ECN.

Fig. 4 presents TIAM-ECN projections for final energy use in industry. Following Dalla Longa et al. (2020) we model industrial CCS processes based on coal, natural gas and oil. While biomass-based CCS processes can in principle also be applied in industry for multiple purposes, these are (by design) not yet part of our model solution, i.e. not beyond their use for biomass-based fuel production, as we defer their assessment to future studies (including for the reasons mentioned in section 2.1). In the Base scenario, total energy in industry remains nearly constant until the middle of the century, while the technology mix changes significantly. Coal has been completely phased out in 2030, natural gas (without CCS) plays a progressively smaller role, and oil provides a constantly small contribution in all periods. CCS applied to processes based on natural gas has taken over nearly one quarter of the industrial energy mix in 2050. Yet electrification also becomes increasingly more prevalent in industry, achieving a share of over 50% by the middle of the century. District heat deployment increases steadily over the modeled time horizon, while biomass use substantially increases initially

Table 2
Effects of reduced CCS in the power sector on the industrial energy mix.

	Electricity share in the industry mix in 2050 (i)	Shrinking of total energy use in industry w.r.t. Base in 2050 (ii)
Base	50%	-
eReduce	40%	3%
eDelay-1	40%	3%
eDelay-2	46%	9%

but decreases again by 2050.

As already observed, when the maximum overall CCS capacity in the energy system is constrained, CCS is preferentially deployed in the power sector. This results in only a limited role for CCS processes in the three low-acceptance scenarios in the top panel of Fig. 4. At the same time, total energy use in industry shrinks as a result of the application of energy savings in demand-side sectors when the deployment of CCS is bounded. This effect is also visible in the 'e' scenarios of the bottom panel in Fig. 4.

In the 'e' scenarios, unlike in the non-'e' scenarios, CCS processes based on natural gas take over a sizable share of the industrial energy mix, while the limited availability of CCS technologies in the power sector triggers (i) a reduction of the electricity share in industry, adding to (ii) the overall decrease of energy use in industry. The relative importance of effects (i) and (ii) depends in non-trivial ways on the specifics of each scenario. For example, as shown in Fig. 4, the reduction in industrial electrification dominates for scenarios eReduce and eDelay-1, while the overall reduction of energy use in industry is the main effect observed for scenario eDelay-2. This finding is quantified and reported in Table 2.

Further inspection of the bottom panel of Fig. 4 reveals that effect (i) is typically accompanied by an increase of bio-based technologies with respect to Base, which replace part of the electricity use in industry, while effect (ii) is also associated with a substantial reduction of district heat applications, caused by the relatively high costs of these options for the provision of heat for industrial use.

Figs. 3 and 4 show that, from 2040 onwards, both total electricity generation and energy use in industry are related to the maximum allowed deployment level of CCS in the power sector. With decreasing availability of CCS capacity in electricity generation, total power production and final industrial energy use are reduced. Similarly, a decrease in final energy use is triggered in other demand sectors, such as the built environment (residences and commercial buildings) and transportation (all modes combined). For these latter sectors, this is the main change across the scenarios as a result of CCS restrictions in power production, while the breakdown in energy carriers remains roughly the same. The reduction of final energy use can be achieved through two endogenous pathways in our model: either by deploying higher levels of energy savings, which will on average lead to higher investment costs (given that for most high-efficiency appliances we do not assume significant future cost reductions), or by increasing prices of certain energy services, which triggers a lower final energy use (due to price-demand elasticity[4] simulated in TIAM-ECN). Both of these pathways lead in principle to higher energy system costs (see Fig. 5). At the same time, however, reduced levels of energy use in the model imply lower system costs, as the smaller overall size of the underlying energy system necessitates lower investments in energy service appliances on the demand side, and in installed production capacity on the supply side. In summary, overall energy system costs in the limited CCS acceptance scenarios are likely to differ from those in Base, due to at least three effects: (a) price-demand elasticity, (b) deployment of high-efficiency appliances, and (c) a smaller energy system. Note that (a) and (b) always yield higher energy system costs, while (c) induces lower costs.

In Fig. 5 we explore the magnitude of the various cost components by projecting the additional total annual energy system costs with respect to the Base scenario. We split the costs into capital expenditures (CAPEX), fixed and variable operational costs (OPEX-fix and OPEX-var, respectively), and costs related to price-demand elasticity. We exclude costs associated with trade of energy commodities, since these bring no relevant additional insights in the context of the present analysis. Fig. 5 demonstrates that price-demand elasticity and investment costs are the two dominant origins of change in overall energy system costs in all scenarios and time periods. The contribution from price-demand elasticity is always larger than in the Base scenario, while investments present a non-trivial trend. Until 2040 additional investments are always positive, which indicates that the larger deployment of expensive high-efficiency technologies in e.g. the built environment and transportation (effect (b) above) dominates over the cost reductions related to the decreased size of the energy system (c). This continues to be the case in 2050 for Delay-2 and eDelay-2, while Reduce and Delay-1 display the opposite trend, that is, (c) prevails over (b). In the latter case, reducing demand allows for removing some of the most expensive technologies from the system, in particular decreasing the amount of electrification in the commercial sector and reducing the fleet of high-end electric and hybrid plug-in vehicles based on hydrogen in the transport sector. The increase in costs as the result of the use of high-efficiency appliances is smaller than the reduction in CAPEX, which results in total net savings for the energy system as a whole. Net additional annual energy system costs in 2050 vary between -50 billion $/yr up to nearly 800 billon $/yr depending on the constraints on CCS deployment.

Note that a constrained scenario will always entail higher energy system costs than the corresponding reference scenario. The TIAM-ECN model, however, determines the cost-optimal energy system on a global scale, while the costs reported in Fig. 5 refer to Europe only. Whereas a constrained scenario will always result in higher costs for the world as a whole, the additional energy system costs need not be distributed uniformly across regions: some regions may bear (much) higher costs, while others may even realize some (moderate) savings. This explains why in some periods in time (see the first two scenarios in the upper plot of Fig. 5) the overall additional energy system costs may actually be (slightly) negative.

[4] The price-demand elasticity is a measure for expressing the extent to which demand for energy is affected by its price.

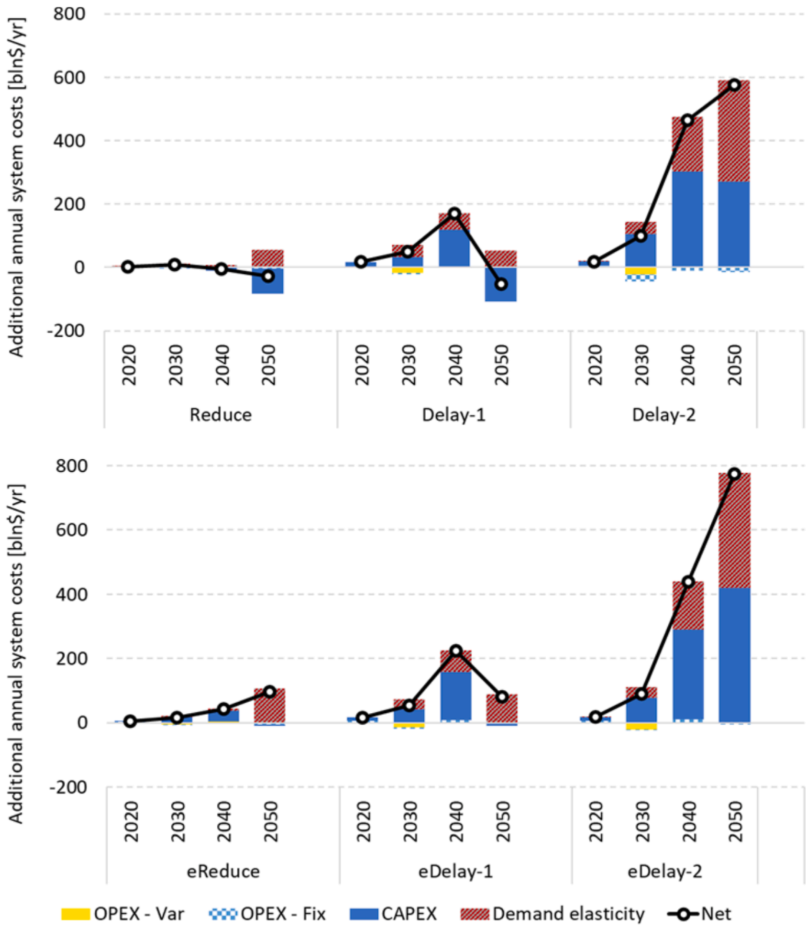

Fig. 5. Projections for additional energy system costs by TIAM-ECN.

4. Conclusions

We have started this paper by observing that in Europe CCS deployment may be obstructed not only by the costs associated with its use but also by limited public acceptance. We analyse how large-scale deployment of CCS technology may be hindered by limited public acceptance, and for this purpose develop scenarios for how public acceptance may constrain the diffusion of CCS. We distinguish two types of CCS diffusion limitations: a reduction of the overall amount of installable CCS capacity or a delay in an otherwise unaltered ultimate level of overall deployment. We demonstrate that the type of limitation in CCS acceptance can critically impact the development of all sectors, not just the two sectors that are the prime focus of our attention, the power sector and industry. We show that a reduction or delay in CCS diffusion as a result of critical public opinion can have substantial energy system impacts that differ not only across the pattern of CCS acceptance but also depending on the sector in which limited public acceptance materializes. Applying a constraint to CCS deployment in both industry and the power sector simultaneously leads to an energy system that is fundamentally different from the one that emerges if the constraint is only applied to the power sector. Depending on how and where CCS diffusion is constrained, net additional annual energy system costs in 2050 can vary between -50 billion up to nearly 800 billon $/yr.

Given the size of these variations, a narrative for CCS deployment should be developed that clarifies the constraints that are likely to be put on deployment (Janipour et al., 2021, Akerboom et al., 2021), the policies that are needed to guide these constraints, as well as insight into the economic impact (e.g. on jobs) of these constraints, primarily in areas dependent on fossil fuel industries (Swennenhuis et al., 2020). Social science studies may help to show in what type of locations CCS projects are more likely to land (e.g. those with favorable place meanings) and to provide methods that account for public acceptance in CCS deployment. For example, by using social site characterization methods to select storage fields with a higher likelihood of finding support from the local community (Von et al., 2021, Brunsting et al., 2015) or including social acceptance criteria in the design of CCS supply chains and transport networks (d'Amore et al., 2020).

In terms of our contribution to the literature on public acceptance, the results of our IAM analysis imply that the effects of reducing the deployment of CCS may be much more intricate and far-reaching than many studies account for (see, amongst others, Bellamy et al., 2019; Fridahl and Lehtveer, 2018; Romanak et al., 2021; Schenuit et al., 2021; Stigson et al., 2012), e.g. the effects on final energy use, the use of biomass as a fuel source, or the attractiveness of district heating. This complicates the assessment of informed public opinions where the aim is to identify how citizens respond to the outcomes of (not) implementing CCS. Given the importance of costs and economic effects to citizens (Broecks et al., 2021, Pianta et al., 2021, Thomas et al., 2018) and the cost differences between the various constraints put on CCS development, substantial trade-offs may need to be made between the various options for climate change mitigation. As other authors have suggested, providing insight into such trade-offs should be a primary focus of this type of research going forward (Pianta et al., 2021).

Our work suffers from several limitations. First, our scenarios did not account for differences in the public acceptance of fuel sources (e.g. biomass, coal or natural gas). Some studies show that citizens may be more positive about CCS at biomass-fired power plants than about CCS at coal- or gas-fired power plants (Whitmarsh et al., 2019; Dütschke et al., 2016). Second, we did not include scenarios where a negative consensus is built over time for CCS developments, reducing its legitimacy to such a degree that its deployment is no longer feasible. Given experiences with other technologies (e.g. nuclear energy), such a scenario may indeed be possible. Yet, this scenario would eventually default to the Reduced scenario, albeit with lower installable capacity. Future modeling studies should explore the impact of these types of scenarios.

Finally, we recognize that the term 'acceptance' yields a risk of oversimplifying complex interactions between individual citizens and other societal actors (e.g. local governments, project developers and citizen collectives) (Upham et al., 2015). We have nevertheless opted to utilize the term 'acceptance' owing to its widespread use and recognition in the community. For the purposes of this paper, alternative terms like 'support' or 'acceptability' would have served just as well. Future work may bring our approach a step further by creating modelling scenarios that explicitly take into account that certain regions, CCS applications, and CCS policies may be more conducive than others in delivering CCS projects that have the support of local communities as well as the general public, when guided by suitable participation procedures and community benefit approaches.

Declaration of Competing Interest

In view of the submission of our research article "Deployment of CO2 Capture and Storage in Europe Under Limited Public Acceptance", we hereby declare that there is no conflict of interest in any possible way.

Data Availability

Data will be made available on request.

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Appendix

Fig. 6 shows TIAM-ECN projections for the overall level of CCS deployment, expressed in $MtCO_2$, split into its two applications in electricity generation and industry, respectively.

In Fig. 7 we show the average costs of CO_2 capture and storage per unit of installed CCS capacity in the power sector and in industry for the Base scenario. These are derived by dividing the total system costs related to the deployment of CCS processes in each sector (i.e. summed over all CCS processes in each sector) by the corresponding installed CCS capacity and amount of captured CO_2.

In Fig. 8 we present electricity capacity projections obtained with TIAM-ECN for the various scenarios. The trends are similar in all scenarios: the European power sector is projected to more than double in size during the next three decades, reaching about 1400 GW of total installed capacity by 2050, with solar PV, wind energy and hydropower possessing the largest share in the overall electricity capacity mix. It can be observed from Fig. 8 that a decrease in CCS acceptance induces a lower level of CCS deployment.

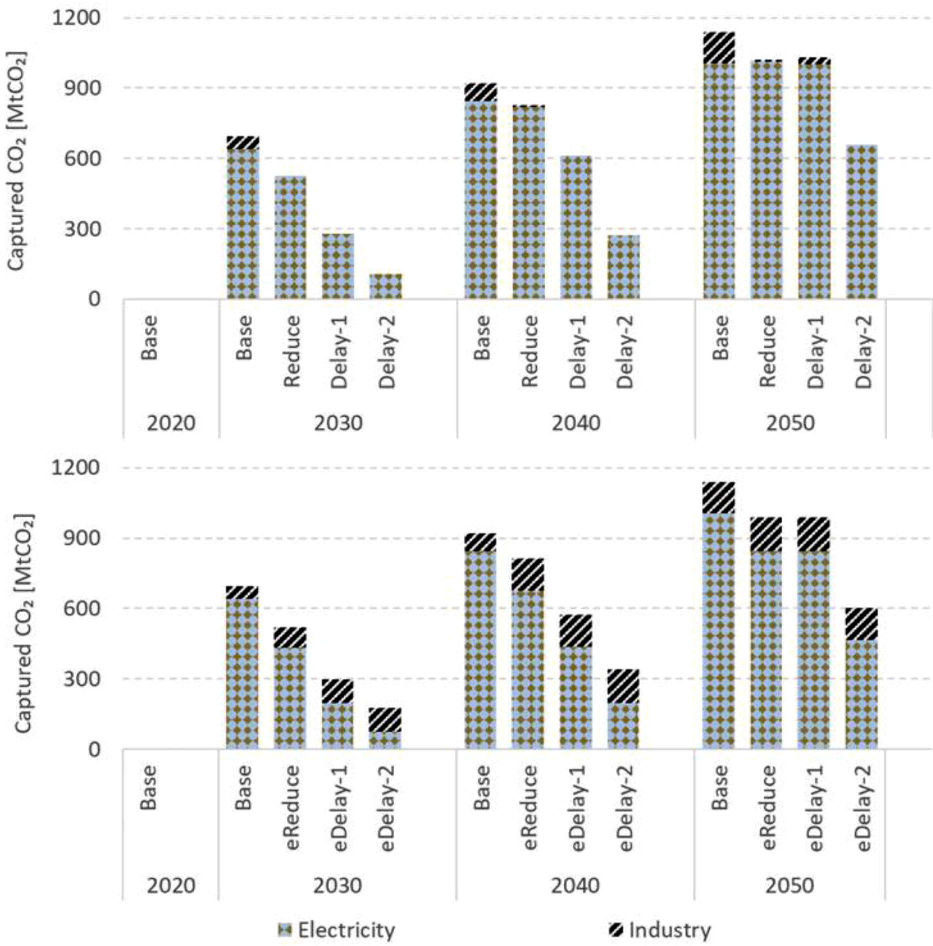

Fig. 6. Projections for CCS deployment by TIAM-ECN.

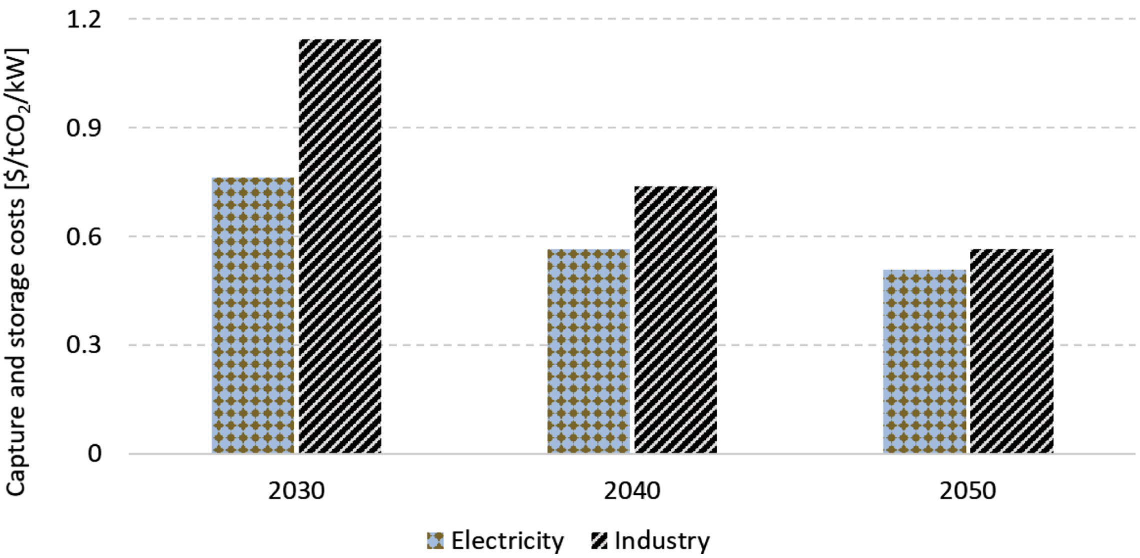

Fig. 7. Average capture and storage costs in the Base scenario.

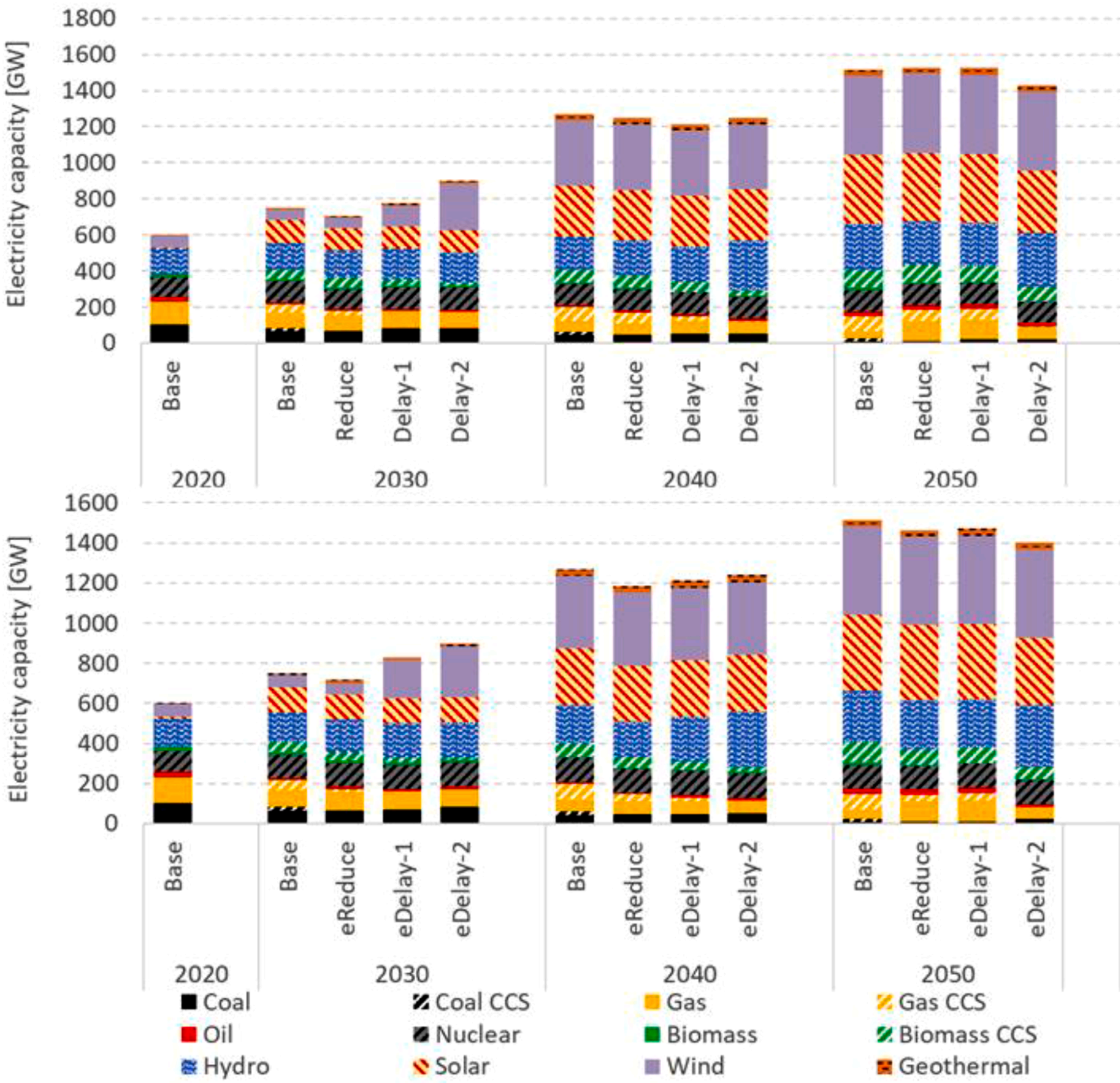

Fig. 8. Projections for electricity capacity by TIAM-ECN.

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