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LETTER

The role of projects of common interest in reaching Europe's energy policy targets

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Abstract

The European Union aims to achieve climate-neutrality by 2050, with interim 2030 targets including 55% greenhouse gas emissions reduction compared to 1990 levels, 10 Mt p.a. of a domestic green hydrogen production, and 50 Mt p.a. of domestic CO_2 injection capacity. To support these targets, projects of common and mutual interest (PCI-PMI)—large infrastructure projects for electricity, hydrogen and CO_2 transport, and storage—have been identified by the European Commission. This study focuses on PCI-PMI projects related to hydrogen and carbon value chains, assessing their long-term system value and the impact of pipeline delays and shifting policy targets using the sector-coupled energy system model PyPSA-Eur. Our study shows that PCI-PMI projects enable a more cost-effective transition to a net-zero energy system compared to scenarios without any pipeline expansion. Hydrogen pipelines help distribute affordable green hydrogen from renewable-rich regions in the north and southwest to high-demand areas in central Europe, while CO_2 pipelines link major industrial emitters with offshore storage sites. Although these projects are not essential in 2030, they begin to significantly reduce annual system costs by more than €26 billion from 2040 onward. Delaying implementation beyond 2040 could increase system costs by up to €24.2 billion per year, depending on the extent of additional infrastructure development. Moreover, our results show that PCI-PMI projects reduce the need for excess wind and solar capacity and lower reliance on individual CO_2 removal technologies, such as direct air capture, by 13–136 Mt annually, depending on the build-out scenario.

Acronyms

AC	Alternating current
CAPEX	Capital expenditures
CC	Carbon capture
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture utilisation and storage
CDR	Carbon dioxide removal
CEF	Connecting Europe facility
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
CP	Central planning
DAC	Direct air capture
DC	Direct current
DIs	Decentral islands
EHB	European hydrogen backbone
EU	European Union
FOM	Fixed operational and maintenance costs
GHG	Greenhouse gas
H_2	Hydrogen
ICE	Internal combustion engine
NPV	Net present value
NUTSs	Nomenclature of territorial units for statistics
NZIA	GW
OCGT	Open cycle gas turbine
OPEXs	Operational expenditures
PCI	Projects of common interest
PCI-in	PCI-PMI international
PCI-n	PCI-PMI national
PMI	Projects of mutual interest
PtH	Power-to-heat

PyPSA	Python for power system analysis
SMR	Steam methane reforming
TOTEXs	Total expenditures
WACC	Weighted average cost of capital

1. Introduction

With the European Green Deal, the EU set a strategic path to become climate-neutral by 2050, with interim GHG emission reduction targets of 55% by 2030 compared to 1990 levels [1]. Both the net-zero target and the interim 2030 goals are legally binding under the European Climate Law [2]. In practice, these policy targets mean transforming the EU into 'a modern, resource-efficient and competitive' economy with net-zero GHG emissions [3]. Current industrial processes and economic growth will need to be decoupled from fossil fuel dependencies. To achieve this transition across all sectors, the EU needs to scale up a portfolio of renewable energy sources, power-to-X solutions, CCUS, and CDR technologies, such as DAC. In parallel, complementing investments into the electricity grid, hydrogen (H_2) and carbon dioxide (CO_2) transport and storage infrastructure are essential for efficient distribution across the European continent [4].

1.1. Europe's hydrogen and CCUS ambitions

Hydrogen is expected to occupy a key position in this transition as it is considered essential for decarbonising hard-to-abate sectors, such as, but not limited to steel, refining, fertilisers, shipping, and aviation [5, 6]. To lay out the foundation for a future hydrogen economy, the EU has set ambitious targets for domestic hydrogen production and infrastructure build-out. Under the EU Hydrogen Strategy [7], reinforced by REPowerEU [8] and the NZIA [9], the EU aims to install at least 40 GW electrolysis capacity by 2030, domestically (with an additional 40 GW to be installed in so-called European Neighbourhood countries [10]). REPowerEU foresees the annual production of 10 Mt of domestic renewable hydrogen by 2030, alongside an additional 10 Mt sourced through imports [8]. Initiatives like the EHB aim to support this transition by proposing a hydrogen transport network across Europe. The EHB initiative envisions a H_2 pipeline network of almost 53 000 km by 2040 [11], including repurposing existing natural gas infrastructure and new potential routes.

Complementing its hydrogen ambitions, the EU has proposed similarly strategic plans for the carbon economy. In the Industrial Carbon Management Strategy, the EU envisages a single market for CO_2 in Europe, to enable CO_2 to become a tradable commodity for storage, sequestration, or utilisation [12]. Beyond a net-zero emission target in the European Climate Law [2], CO_2 serves as a key feedstock for the production of synthetic fuels, such as methanol, methane, as well as high-value chemicals [6]. Outside of CO_2 utilisation, CCS is considered indispensable for achieving net-zero emissions in sectors with unavoidable process-based CO_2 emissions, such as cement, chemicals, and waste-to-energy. Here, the NZIA mandates that all EU member states collectively ensure that at least 50 Mt p.a. of CO_2 can be injected and stored by 2030. The European Commission further estimates that up to 550 Mt p.a. of CO_2 will need to be captured by 2050 [9]. At least 250 Mt p.a. will need to be sequestered in the European Economic Area [13].

A growing body of literature has been investigating the long-term role of H_2 and CO_2 in low-carbon or net-zero energy systems (table 1). Both carriers see their primary value outside the electricity sector, i.e. in the decarbonisation of hard-to-abate sectors such as industry, transport, shipping, and aviation [14, 15]. While there are direct use cases for H_2 in the industry sector such as steel production, it is primarily expected to serve as a precursor for synthetic fuels, including methanol, Fischer–Tropsch fuels (e.g. synthetic kerosene and naphta) and methane [5, 6, 16–19]. To produce these carbonaceous fuels, CO_2 is required as a feedstock (Carbon utilisation—CU). This CO_2 can be captured from the atmosphere via DAC, biomass plants, or from industrial and process emissions (e.g. cement, steel, ammonia production) in combination with CC units [4, 20].

1.2. Transport infrastructure and PCI-PMI projects

To meet the need for green electricity, green H_2 and CO_2, significant investments into its transport and storage/sequestration infrastructure are needed [6, 18, 23]. A recent report by the European Commission confirms that investment needs into the EU's energy infrastructure will continue to grow [25], estimating planned expenditures of around €170 billion for H_2 and up to €20 billion for CO_2 infrastructure by 2040, respectively. It also emphasises that these investments face higher uncertainty, as both sectors are still in their infancy.

Within the transition towards net-zero, the EU has established a framework to support the development of key cross-border and national infrastructure projects, which are considered essential for achieving the EU's energy policy targets. These PCI are projects that link the energy systems of two or more EU member states [26]. In a biennial selection process, PCIs are identified through regional stakeholder groups and evaluated based on their contribution to the EU's energy security, e.g. by improving market integration, diversification of energy supply, and integration of renewables. So-called PMI transfer the same concept to projects that link the EU's energy system with third countries, such as Norway or the United Kingdom, the Western Balkans or North Africa, as long as they align with EU climate and energy objectives [27]. Approved PCI-PMI projects benefit from accelerated permitting and access to EU funding under the CEF.

Table 1. Literature overview of studies modelling CO_2 and H_2 in low-carbon energy systems.

Study	CO_2	H_2	Region	Planning horizon	Model
[15]	□	□	Europe	2025–2050 (myopic)	PyPSA-Eur
[4]	■	■	Europe	2050 (overnight)	PyPSA-Eur
[18]	□	■	Europe	2030–2050 (myopic)	Balmorel [21]
[6]	□	■	Europe	2050 (overnight)	PyPSA-Eur
[17]	□	■	Europe	2050 (overnight)	PyPSA-Eur, TRACE [22]
[5]	—	□	Europe	2050 (overnight)	JRC-EU-TIMES
[19]	□	■	Europe	2030, 2050 (overnight)	Enertile
[23]	—	■	Germany	2030 (overnight)	supply chain model [24]
[20]	□	—	Norway	2010–2030 (myopic)	investment model

■ considered, including pipelines
□ considered, copperplated
— not considered

Given the strong political and project promoter support, comprehensive reporting and monitoring processes, as well as their role as technological lighthouses, projects on the PCI-PMI list are more likely to be implemented than others [25]. Nonetheless, large infrastructure projects-including those on the PCI-PMI list-often face delays due to permitting hurdles, financing constraints, procurement bottlenecks, and other implementation challenges [28]. As a direct result of the revised TEN-E Regulation (EU 2022/869) [29], the 2023 PCI-PMI list [27, 30] for the first time includes H_2 and CO_2 transport and storage projects, alongside electricity and gas projects. A continent-wide hydrogen backbone—connecting regions rich in renewable energy potential to industrial and storage hubs—is viewed essential for transporting H_2 where it is needed. Likewise, CO_2 pipelines and sequestration sites are needed to capture, transport and sequester emissions from industrial processes and power plants. An overview of the PCI-PMI projects is provided in figure 1. With around 14 projects in the priority thematic area 'cross-border carbon dioxide network' and 32 projects listed in 'hydrogen interconnections' (including pipelines and electrolysers), this PCI-PMI list lays the foundation for a future pan-European H_2 and CO_2 value chain [31].

1.3. Research gaps and contribution of this study

Several studies (table 1) have begun to explore the interaction between CO_2 and H_2 infrastructure in sector-coupled energy system models, however important aspects remain insufficiently addressed—in particular the role of real planned infrastructure projects, transformation pathways, and the influence of uncertainties on the long-term performance of these projects. Many studies have demonstrated how uncertainty in future developments can significantly impact the cost-effectiveness of energy system investments [15, 16, 32–35]. Existing analyses abstract away from actual investment plans, such as whose under the PCI-PMI framework, potentially neglecting infrastructure options that are not perfectly cost-optimal but have a high likelihood of implementation, e.g. due to political support [15, 36]. While Hofmann *et al* [4] provide valuable insights into the synergies between H_2 and CO_2 infrastructure, the lack of inclusion of planned projects and focus on a single modelling year might yield overly optimistic results. To our knowledge, the contribution of PCI-PMI projects has not yet been evaluated within a sector-coupled modelling framework that incorporates future policy targets, uncertainty and transformation pathways.

Our study addresses these gaps by explicitly including PCI-PMI projects in PyPSA-Eur [37], a sector-coupled model of the European energy system. We assess various build-out levels of CO_2 and H_2 infrastructure across perturbation scenarios and transformation pathways. Using a myopic, iterative modelling approach, we simulate energy system development from 2030 to 2050 under non-anticipative foresight, reflecting the reality that market participants do not have perfect knowledge of long-term developments. This approach helps avoid the overly optimistic outcomes of long-term perfect foresight models. To quantify the economic value associated with PCI-PMI projects across scenarios reflecting a selected set of uncertainties—including changes in EU energy policy project delays, and cancellations—we use a regret-based approach (see section 2.4) By limiting the analysis to a set of scenarios, this regret analysis is manageable and computationally feasible.

This study also aims to reduce the uncertainty surrounding the 'chicken-and-egg' dilemma in infrastructure investment—whether to develop CO_2 and H_2 infrastructure in advance or to wait for demand to materialise. Specifically, we address the following research questions:

1. What is the long-term value of PCI-PMI projects in supporting the EU's climate and energy policy targets, and what are the associated costs?

2. What are the costs of adhering to the EU policy targets, even when the implementation of PCI-PMI projects is delayed?

2. Methods

2.1. Overview of European energy system model PyPSA-Eur

We build on the open-source, sector-coupled energy system model PyPSA-Eur [6, 37–39] to optimise investment and dispatch decisions in the European energy system. The model's endogenous decisions include the expansion and dispatch of renewable energy sources, dispatchable power plants, power-to-X conversion, and storage/sequestration capacities as well as transmission infrastructure for power, hydrogen, and CO_2. It also encompasses heating technologies and various hydrogen production methods (gray, blue, green). PyPSA-Eur integrates multiple energy carriers (e.g. electricity, heat, hydrogen, CO_2, methane, methanol, liquid hydrocarbons, and biomass) with corresponding conversion technologies across multiple sectors (i.e. electricity, transport, heating, biomass, industry, shipping, aviation, agriculture and fossil fuel feedstock). The model features high spatial and temporal resolution across Europe, incorporating existing power plant stocks [40], renewable potentials, and availability time series [41]. It includes the current high-voltage transmission grid (AC 220–750 kV and DC 150 kV and above) [42]. Furthermore, electricity transmission projects from the TYNDP [43] and German Netzentwicklungsplan [44] are also enabled. An overview of the technology, cost, and demand assumptions, as well as the geospatial and temporal clustering, is provided in *supplementary data* (tables S1, S2, and figure S1).

2.2. PCI-PMI H_2 and CO_2 transport, storage, and sequestration

We implement all PCI-PMI projects of the electricity, CO_2 and H_2 sectors (excluding offshore energy islands and hybrid interconnectors, as they are not the focus of our research) by accessing the REST API of the PCI-PMI Transparency Platform and associated public project sheets provided by the European Commission [30]. We add all CO_2 sequestration sites and connected pipelines, H_2 pipelines and storage sites, as well as proposed pumped-hydro storage units and transmission lines (AC and DC) to the PyPSA-Eur model (see figure 1). We consider the exact geographic information, build year, as well as available static technical parameters when adding individual assets to the respective modelling year. Beyond CO_2 sequestration site projects included in the latest PCI-PMI list (around 114 Mt p.a.), we consider additional technical potential from the European CO_2 storage database (see supplementary material for details)[4, 45].

2.3. Climate and energy policy targets

In all pathway scenarios, emission, technology, sequestration and production targets have to be met for each planning horizon (see table 2). For the year 2030, these targets are directly derived from the EU's policy targets, including a 55% reduction in GHG emissions compared to 1990 levels [1], 10 Mt p.a. of domestic green H_2 production [8] and 40 GW of electrolyser capacity [7], and 50 Mt p.a. of CO_2 sequestration capacity [9]. For 2050, the CO_2 are based on the modelling the impact assessment for the EU's 2040 climate targets, in 250 Mt p.a. need to be sequestered [13]. H_2 production targets for 2050 are based on the European Commission's *METIS 3 study S5* [47], modelling possible pathways for industry decarbonisation until 2040. For 2040, we interpolate linearly between the 2030 and 2050 targets. The electrolyser capacities for 2040 and 2050 are scaled by the ratio of H_2 production to electrolyser capacity in 2030. An overview of the targets and their values is provided in table 2. We implement the green hydrogen production target as a minimum production constraint on electrolysis. Accordingly, we refer to this hydrogen as *electrolytic* H_2 throughout this paper. Note that this implementation is based on an aggregated annual target without temporal matching rules.

2.4. Scenarios and regret-matrix setup

We define the pathway scenarios based on the degree of CO_2 and H_2 infrastructure build-out, including the roll-out of PCI-PMI projects as well additional pipeline investments. In total, we implement five pathway scenarios, varying in the degree of infrastructure build-out and associated model-endogenous decision variables (table 3).

In a subsequent step, we assess how different perturbations impact the five decarbonisation pathways using a regret-based approach. In decision theory [48], the concept of regret is typically defined as the difference in economic value, payoff, or cost between a chosen strategy and the optimal strategy under identical conditions [33]. The regret term then represents the additional cost incurred from not following the cost-optimal strategy. In energy modelling literature [32, 33], a regret analysis is usually designed in two steps: first, a set of scenarios is defined, representing different future developments (see pathway scenarios above). In a second step, the performance of the first-stage investments is evaluated under different realisations of the second-stage, or short-term, future scenarios [49]. It is particularly useful in energy system modelling, where future uncertainties can significantly impact the performance of investments in infrastructure and technologies.

Table 4 gives an overview of the regret matrix setup and its underlying assumptions, where the pathways serve as *planned* or *anticipated* and the perturbations serve as the hypothetically *realised* outcomes. Specifically, we assume that the CO_2 and H_2

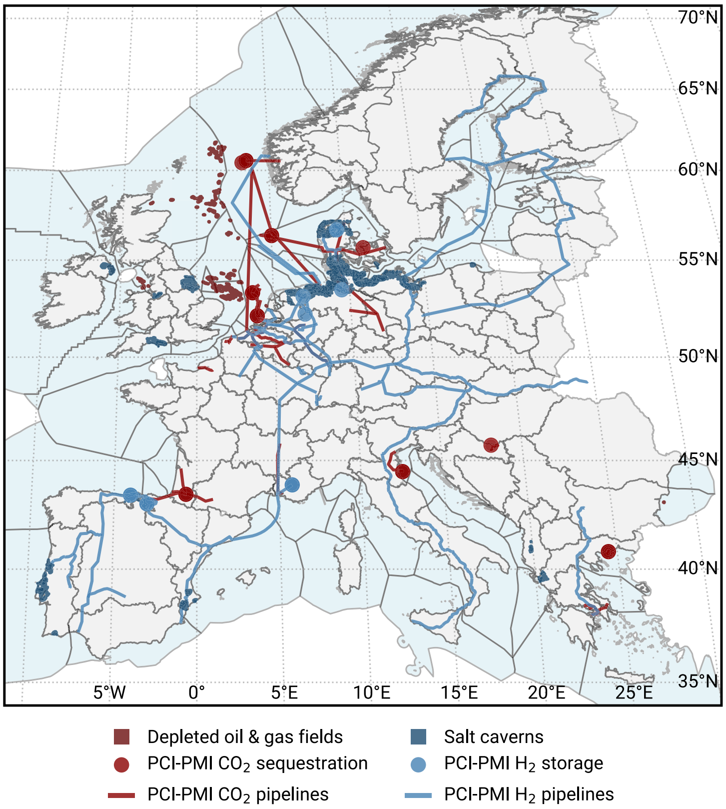


Figure 1. Map of the regional scope including clustered onshore (grey) and offshore regions (light blue), as well as PCI-PMI CO_2 and H_2 pipelines, storage and sequestration sites. *Depleted offshore oil and gas fields (red) provide additional* CO_2 *sequestration potential* [4]. *Nearshore* H_2 *salt caverns (dark blue) are considered for additional* H_2 *storage [46]. The regional scope consists of 34 European countries, including 25 of the EU27 member states (excluding Cyprus and Malta), as well as Norway, Switzerland, the United Kingdom, Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, Serbia, and Kosovo. Regional clustering is based on administrative NUTS boundaries, with higher spatial resolution applied to regions hosting planned PCI-PMI infrastructure, producing 99 onshore regions (see supplementary data, table S2).*

Table 2. Pathway for implemented targets. *Climate and energy policy targets based on* [1, 8, 9, 13, 47].

Planning horizon	2030	2040	2050
Targets			
GHG emission reduction	−55%	−90%	−100%
CO_2 sequestration	50 Mt p.a.	150 Mt p.a.	250 Mt p.a.
Electrolytic H_2 production	10 Mt p.a.	27.5 Mt p.a.	45 Mt p.a.
H_2 electrolyser capacity	40 GW	110 GW	180 GW

pipeline capacities identified in the pathway modelling exercise are either maintained at their planned levels, delayed in implementation, or not built at all. In perturbation scenarios, the model can still react by investing into additional generation, storage, or conversion, or carbon-removal technologies, assuming the technical potential was not exceeded in the pathway optimisation. At this step, we also simulate changes in energy policy.

3. Results

3.1. PCI-PMI infrastructure

Figure 2 shows the total annual system costs—distributed over all modelled technology groups—for each planning horizon and pathway scenario. We observe the highest total annual system costs in the planning horizon 2040, ranging from €912 to €968 billion per year. This cost increase is primarily driven by the sharp decarbonisation pathway planned for 2030 to 2040—a carbon budget reduction of more than 1600 Mt p.a. compared to the remaining 460 Mt p.a. in the last decade from 2040 to 2050. In 2030, total system costs are lowest in the *DI* and *CP* scenario, as the model does not see the need for large-scale investments into H_2 and CO_2 infrastructure yet (due to myopic foresight). Adding PCI-PMI projects in 2030 increases costs by less than 1% (figure 2). With CO_2 pipelines connecting depleted offshore oil and gas fields to their closest onshore region, the policy targets, including CO_2 sequestration can be achieved at a total of €865 billion per year.

Starting in 2040, all scenarios with PCI-PMI and endogenous pipeline investments unlock significant

Table 3. Overview of pathway scenarios and their key assumptions. *(i) Decentral islands (DI): pessimistic scenario, no* H_2 *pipeline and onshore* CO_2 *pipeline infrastructure, (ii) PCI-PMI (PCI): considers the on-time commissioning of all PCI-PMI* CO_2 *and* H_2 *projects only, (iii) PCI-PMI nat. (PCI-n): more ambitious scenarios that further allow investments into national pipelines, (iv) PCI-PMI internat. (PCI-in): builds on (iii) and allows for additional international investments, (v) Central planning (CP): does not assume any fixed PCI-PMI infrastructure but allows for a centralised, purely needs-based build-out of* CO_2 *and* H_2 *pipelines.*

Pathway	DI	PCI	PCI-n	PCI-in	CP
CO_2 sequestration					
Depleted oil & gas fields[a]	■	■	■	■	■
PCI-PMI seq. sites[b]	—	■	■	■	■
H_2 storage					
Endogenous build-out	■	■	■	■	■
PCI-PMI storage sites	—	■	■	■	■
CO_2 pipelines					
to depleted oil & gas fields	■	■	■	■	■
to PCI-PMI seq. sites	—	■	■	■	■
CO_2 and H_2 pipelines					
PCI-PMI	—	■	■	■	■
National build-out	—	—	■	■	■
International build-out	—	—	—	■	■
PCI-PMI extendable	—	—	—	—	■

■ enabled
– disabled
[a] approx. 286 Mt p.a.
[b] approx. 114 Mt p.a.

Table 4. Regret matrix setup: pathway and perturbation scenarios. *In 'Reduced targets', all policy targets except the GHG emission reduction target are removed to assess the value of the* CO_2 and H_2 *infrastructure under a less constrained technology environment. In 'Delayed pipelines', we assume that all PCI-PMI and endogenous pipelines are delayed by one period, i.e. the commissioning of the project is shifted to the next planning horizon. Lastly, we remove all pipeline capacities in 'No pipelines', including the PCI-PMI projects, allowing us to evaluate the impact of a complete lack of planned infrastructure. Considering the total number of pathway (5) and perturbation scenarios (3) as well as planning horizons (3), the regret matrix yields 60 optimisation problems (15+45).*

Perturbation scenarios	Reduced targets	Delayed pipelines	No pipelines
Pathway scenarios			
Decentral islands (**DI**)	■	—	–
PCI-PMI (**PCI**)	■	■	■
PCI-PMI nat. (**PCI-n**)	■	■	■
PCI-PMI internat. (**PCI-in**)	■	■	■
Central planning (**CP**)	■	■	■
Targets			
GHG emission reduction	■	■	■
CO_2 sequestration	—	■	■
Electrolytic H_2 production	—	■	■
H_2 electrolysers	—	■	■
$CO_2 + H_2$ infrastructure			
CO_2 sequestration sites	■	■	■
CO_2 pipelines to seq. site	■	■	■
CO_2 pipelines	■	□	—
H_2 pipelines	■	□	—

■ enabled
□ delayed by one period
— disabled

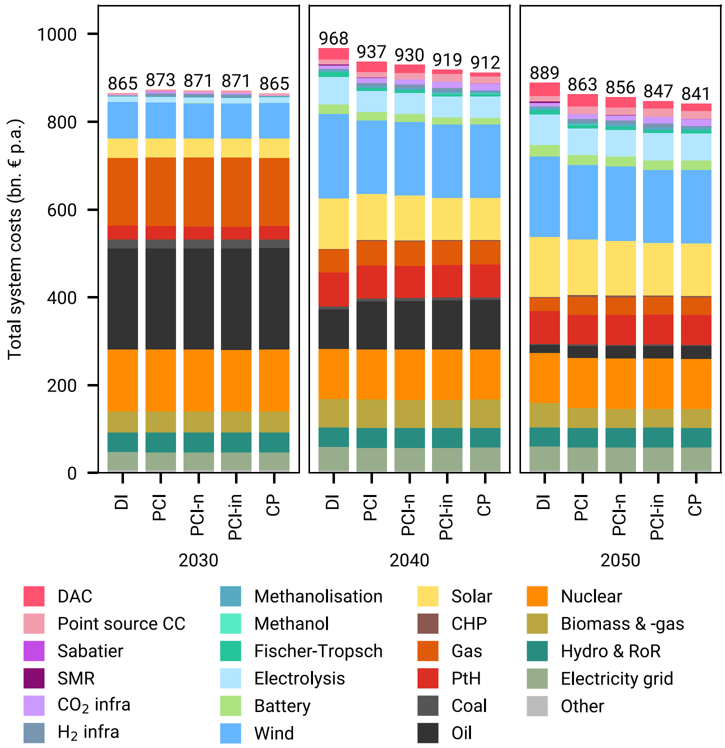


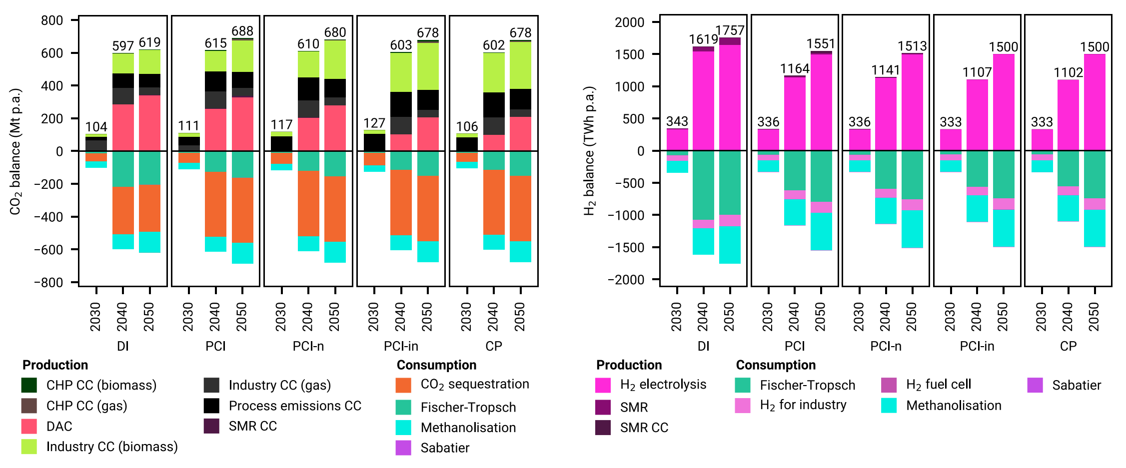
Figure 2. Total annual system costs (CAPEX + OPEX) by technology group. CO_2 and H_2 *infrastructure each include pipelines, storage and sequestration sites, respectively. Gas refers to gas power plants and boilers. Coal infrastructure refers to hard coal and lignite power plants. Other includes SMR, rural heat, and thermal storage.*

cost savings, from more than €30 billion per year in the *PCI* up to €50 billion per year in the *PCI-in* scenario, where additional pipeline build-out is allowed (see section 2.4). By granting the model complete flexibility to expand hydrogen and CO_2 infrastructure at any location beyond the PCI-PMI projects, we unlock additional annual cost savings of €6 to €7 billion per year through investments in fewer, yet more optimally located CO_2 and H_2 pipelines from a systemic perspective (see *supplementary data*, figures S4 and S5). Further, this reduces the reliance on larger investments into wind generation and costly DAC technologies near the sequestration sites. These effects are slightly less pronounced in the 2050 model results, where system costs can be reduced by €26 to €41 billion per year with PCI-PMI and endogenous pipeline investments. Here, higher CCU via methanol synthesis and Fischer–Tropsch processes, supported by increased H_2 production as a chemical feedstock, enhances system flexibility compared to 2040 (figures 3(a) and 3).

3.2. CCUS

We find that most of the differences in system cost and savings can be attributed to the production and utilisation of CO_2, as shown in figure 3(a). Lacking the option to transport CO_2 from industry and other point sources to the offshore sequestration sites, the system requires expensive DAC in the *DI* scenario. While the sequestration target of 50 Mt p.a. in 2030 is binding only in the *DI* scenario, all other scenarios achieve higher levels of CO_2 sequestration as their CO_2 pipeline build-out increases. The 53.9 Mt p.a. of CO_2 sequestered in the *CP* scenario serves as an indicator of the cost-optimal level of sequestration for the European energy system in 2030 assuming perfectly located pipeline infrastructure. With the inclusion of PCI-PMI projects, CO_2 sequestration ranges from 58.7 Mt p.a. in the *PCI* to 75 Mt p.a. in the *PCI-in* scenario. Looking at 2040 and 2050, in place of expensive DAC in the *DI* scenario, the model equips biomass-based industrial processes—primarily located in Belgium, the Netherlands and Western regions of Germany—with CC (see figures 4(d)–(f)).

In 2040 and 2050, all sequestration targets (table 2) are overachieved, as the full combined CO_2 sequestration potential of 398 Mt p.a. is exploited in all scenarios where PCI-PMI projects are included (*PCI* to *CP*). Emissions are captured from industrial processes equipped with CC units, with biomass-based industry contributing the largest share of point-source CC. This ranges from 119 to 241 Mt p.a. in 2040 and from 149 to 287 Mt p.a. in 2050, increasing with the build-out of CO_2 infrastructure (from left to right; see figure 3). As the most expensive CC option, CO_2 capture from SMR CC processes is limited to a maximum of 8 Mt p.a. in the *PCI* scenario by 2050. With a lower sequestration potential of 286 Mt p.a. in *DI* scenario, more CO_2 is used as a precursor for the synthesis of Fischer–Tropsch



(a) Carbon capture, utilisation, and storage. **(b)** Hydrogen production and utilisation.

Figure 3. CO_2 and H_2 balances in pathway scenarios. *Positive values indicate production, negative values indicate consumption of each carrier. An overview of the exogenous demand for synthetic fuels is provided in figure S1 (supplementary data).*

fuels instead—221 Mt p.a. vs 115–127 Mt p.a. in 2040 and 206 Mt p.a. vs. 153-163 Mt p.a. in 2050, to meet the emission reduction targets for 2040 and 2050, respectively. Given the fixed exogenous demand for shipping methanol (*supplementary data*, figure S1), CO_2 demand for methanolisation is constant across all scenarios (39 Mt p.a. in 2030, 89 Mt p.a. in 2040, and 127 Mt p.a. in 2050).

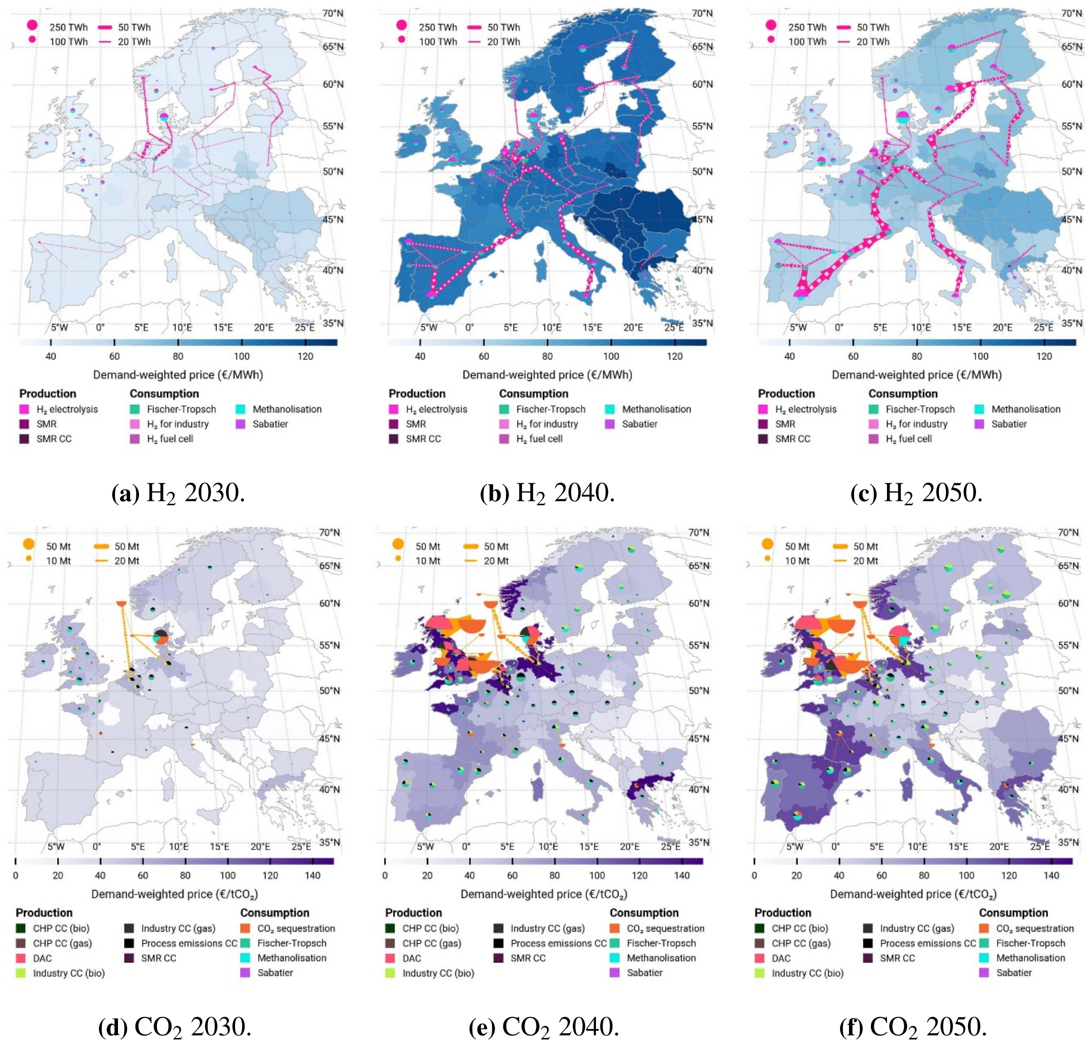
3.3. Hydrogen production and utilisation

H_2 production in the model is primarily driven by the demand for Fischer–Tropsch fuels and methanol. In 2030 and 2050, the electrolytic H_2 production target of 10 and 45 Mt p.a. is binding, equivalent to 333 and 1500 TWh p.a. (at a lower heating value of 33.33 kWh kg^{-1} for H_2). Only in 2040, the H_2 production target of 27.5 Mt p.a. (917 TWh p.a.) is overachieved by 185–247 TWh p.a. in the *PCI* to *CP* scenarios. H_2 production in the *DI* is significantly higher, given its need for additional Fischer–Tropsch synthesis to bind CO_2 as an alternative to sequestration, as described in the previous section. In 2050, Fischer–Tropsch fuels are primarily used to satisfy the demand for kerosene in aviation and naphta for industrial processes (*supplementary data*, table S1). Only about 93 to 173 TWh p.a. of hydrogen is directly used in the industrial sector. Across all pathway scenarios, hydrogen is almost exclusively produced via electrolysis. Note that the model includes a green hydrogen production constraint reflecting energy policy targets, though it does not enforce an hourly matching rule. In the *DI* scenario, where there is no hydrogen pipeline infrastructure, the model resorts to SMR to produce 71–102 TWh p.a. of hydrogen in 2040 and 2050, respectively. Geographically, H_2 production is concentrated in regions with high solar PV potential such as the Iberian and Italian Peninsula, as well as high wind infeed regions including Denmark, the Netherlands and Belgium. The produced H_2 is then transported via H_2 pipelines including PCI-PMI projects to carbon point sources in central, continental Europe where it is used as a precursor for Fischer–Tropsch fuels. Onsite H_2 production and consumption primarily occurs in conjunction with methanolisation processes. Figures 4(a)–(c) provide a map of the regional distribution of H_2 production, utilisation, and transport in the *PCI* scenario.

4. Discussion

In this section, we discuss the impact of the three perturbations on the decarbonisation pathways, by comparing the economic regret, as well as the effects on CO_2 utilisation, sequestration, and H_2 production. We calculate the regret terms by subtracting the annual total system costs of the pathway scenarios (row) from the perturbation scenarios (columns). In our analysis, regret values represent the additional costs incurred by a given perturbation scenario relative to the benchmark. Positive values indicate higher costs, driven by increased investments in alternative generation, conversion, storage, and CDR technologies, as well as changes in their operation due to (i) delays or (ii) cancellations of pipeline infrastructure including PCI-PMI projects. Negative values indicate cost savings, which may arise under relaxed policy ambitions-for example, when CO_2 and H_2 targets are removed in the *Reduced targets* scenario.

Figure 5 shows the regret for all scenarios and planning horizons. From left to right, the first column shows the regret terms for the *Reduced targets* scenario, where all policy targets are removed except for the GHG emission reduction target. The second column shows the regret terms for the *Delayed pipelines* scenario, where all PCI-PMI and endogenous pipelines are delayed by one period. The third



(a) H_2 2030. **(b)** H_2 2040. **(c)** H_2 2050.

(d) CO_2 2030. **(e)** CO_2 2040. **(f)** CO_2 2050.

Figure 4. *PCI-PMI* pathway scenario—regional distribution of H_2 and CO_2 production, utilisation, storage, transport and price. *Note that both the H_2 and CO_2 price refer to their value as a commodity, i.e. price is higher where there is a demand for it.*

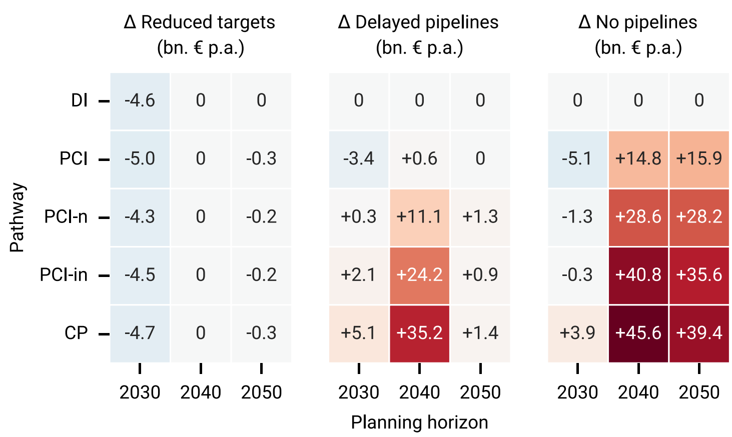


Figure 5. Regret matrix. *Positive values indicate higher costs, driven by increased investments in alternative generation, conversion, storage, and CDR technologies, as well as changes in their operation due to (i) delays or (ii) cancellations of pipeline infrastructure including PCI-PMI projects. Negative values indicate cost savings, when CO_2 and H_2 targets are removed in the reduced targets scenario.*

column shows the regret terms for the *No pipelines* scenario, where all hydrogen and CO_2 pipeline capacities are removed. In the *Reduced targets* scenario, overall system costs change only marginally despite the relaxation of specific targets. This is because CO_2 sequestration levels are primarily driven by the overarching GHG emission constraints—particularly the stringent 2040 and 2050 carbon budgets, which remain in place. With regard to hydrogen, the pathway results have previously shown that H_2 production targets were overachieved in 2040. Only in 2030, we see a net negative regret of around €4.3 to €4.6 billion per year, as the minimum H_2 production target was binding in the pathway scenario. Across all pathways, we have observed that CO_2 pipeline infrastructure is not essential in 2030 (*supplementary data*, figure S5d). In the case of H_2 pipeline infrastructure, the solution appears relatively flat: regrets in the *DI* scenario without any pipelines are nearly identical to those in the *CP* scenario (*supplementary data*, figures S2d and S5d) with substantial pipeline deployment. When the H_2 production and CO_2 sequestration targets are removed, pipelines become even less relevant, although the associated cost savings are minimal, ranging from €4.3 to €5 billion per year in 2030 and 2040.

For similar reasons, the 2030 results for the *Delayed pipelines* and *No pipelines* scenarios exhibit small regret terms. Cost savings of €3.4 to €5.1 billion per year in the *PCI* scenario suggest that, for 2030, mandating PCI-PMI projects is neither cost- nor topologically optimal in the short term. In contrast, a regret of €3.9 to €5.1 billion per year in the *CP* scenario indicates some dependency on the invested pipeline infrastructure (*supplementary data*, figure S5) which represents the systemically more optimised solution.

When looking at the more long-term perspective, we see significant regrets in the *Delayed pipelines* and *No pipelines* scenarios. Having originally planned the energy system layout (including generation, transport, conversion technologies and storage) in the pathways with PCI-PMI projects and/or endogenous pipelines, the model has to find alternative investments to still meet all targets, as the pipelines now materialise one period later or not at all. Regrets peak in 2040, where a delay of pipelines costs the system between €0.6 and €24.2 billion per year. in the scenarios with PCI-PMI projects and up to €35.2 billion p.a. in the *CP* scenario. 2050 regrets are lower than 2040 regrets, as almost all PCI-PMI pipelines are originally commissioned by 2030. Hence, a delay of projects from 2040 to 2050 only mildly impacts the system costs by €0.6 billion per year. The more pipelines invested beyond those of PCI-PMI projects, the higher the regret if they are delayed. In 2050, very few additional CO_2 and H_2 pipelines are built, as such, a delay only increases system costs by €0.9 to €1.4 billion per year. The perturbation scenario *No pipelines* shows the highest regrets, ranging from €14.8 to €45.6 billion per year in 2040 and €15.9 to €39.4 billion per year in 2050. Note that this scenario represents a hypothetical worst case, as it is highly unlikely to plan an energy system with pipeline investments in mind yet fail to implement any of them. Consistently throughout all perturbations, most of the additional cost stem from the need to invest into additional CC, renewable generation, and conversion technologies (*supplementary data*, figure S7). Additional renewable generation capacities are made up of solar PV and wind. A significant higher amount of electrolyser capacity of more than 50 GW is needed in 2040 if pipelines are delayed.

System pivots to high-cost DAC in the absence of pipeline infrastructure. Further, the model has to invest in more than 28 GW of CC units at point sources and an additional 14 GW in DAC technologies to meet the sequestration and emission reduction targets. Cost-wise, the short-term investments into DAC technologies make up to a half of the of the additional system costs in both the *Delayed pipelines* and *No pipelines* scenarios (*supplementary data*, figure S8). DAC utilisation can increase from 40 Mt p.a. in the *PCI-n* to more than 200 Mt p.a. in the *CP* scenario when pipelines are delayed (*Supplementary Data*, figure S9). If pipelines are not built at all, additional 60 Mt p.a. in the *PCI* up to 250 Mt p.a. in the *CP* scenario are captured from DAC, substituting a large share of CO_2 previously captured from point sources equipped with CC (biomass-based industry processes and non-abatable process emissions). Note that a clear trade-off between the reliance on pipeline infrastructure and the need for DAC technologies can be observed in figure 6. While the reliance on DAC decreases with the build-out of pipeline infrastructure, the model in return has to invest in more DAC if pipelines are delayed or not built at all. There is a risk involved, that the need for DAC is even higher in the scenarios with pipeline infrastructure compared to the *DI* scenario, especially in later years (2040 and 2050), if the pipelines do not materialise at all, seeing a potential increase of 50 Mt p.a. in 2040 and 80 Mt p.a. in 2050 in the *PCI* scenario.

Hydrogen production shifts to more costly SMR and decentral production when pipelines are delayed. We find that the electrolytic H_2 production target of 10 Mt p.a. (333 TWh p.a.) in 2030 is overly ambitious. In the *Reduced targets* scenario, 132 to 151 TWh p.a. of H_2 is produced from SMR instead of electrolysis, corresponding to almost half of the target (*supplementary data*, figure S15). When pipelines are delayed, the model has to fall back to more decentral H_2 production of an additional 55 to 187 TWh p.a. of H_2 from electrolysis, SMR and SMR with CC (the latter being the most expensive option). In the *No pipelines* scenario, this additional H_2 production increases to up to 305 TWh p.a. (*supplementary data*, figure S15).

In the long-run, PCI-PMI infrastructure deliver net system cost savings. Looking at the long-run we find that PCI-PMI projects, while not completely

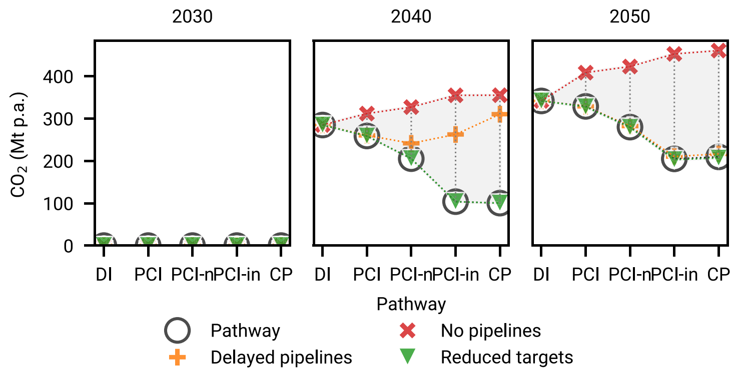


Figure 6. Delta balances—CO_2 from DAC.

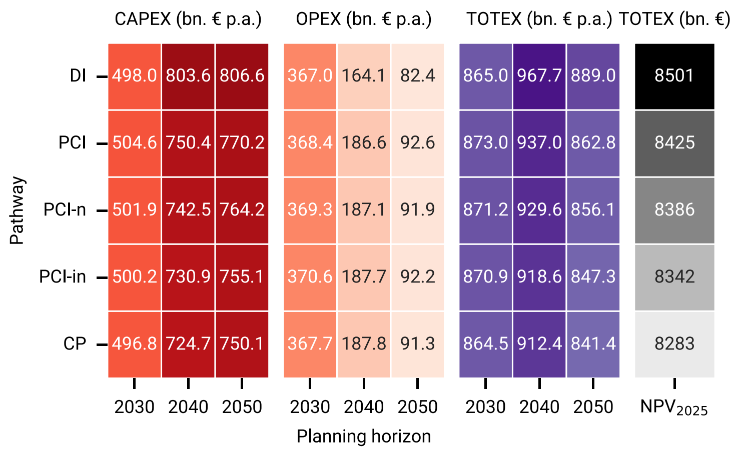


Figure 7. Annual system costs by pathway and planning horizon. *TOTEX refers to the total system costs, including CAPEX and OPEX.* NPV_{2025} *refers to the net present value of total system costs, discounted to the present year 2025 at an interest rate of 7% p.a.*

cost-optimal compared to a centrally planned system, are still cost-beneficial. Compared to a complete lack of H_2 and CO_2 pipeline infrastructure as well as lower CO_2 sequestration potential, the *PCI* scenario unlocks annual cost savings in up to €30.7 billion per year. Figure 7 shows the total system costs or TOTEXs p.a., decomposed into Capital (CAPEX) and OPEX p.a., as well as the NPV of total system costs, discounted at an interest rate of 7% p.a. Even when accounting for the additional costs of €0.6 billion per year faced in the *Delayed pipelines* and up to €15.9 billion per year in the *No pipelines* scenario, a net positive is achieved, indicating that investing into the PCI-PMI infrastructure is a no-regret option. By connecting further H_2 production sites and CO_2 point sources to the pipeline network, additional cost savings of up to €18.4 billion per year can be achieved in the *PCI-in* scenario. The *CP* scenario serves as a theoretical benchmark, allowing the model to invest freely, not bound by *forced* PCI-PMI projects. The model can invest in fewer, but more optimally located CO_2 and H_2 pipelines from a systemic perspective. Economic benefits of all pipeline investments materialise after 2030, yielding lower NPV of potentially at least €75 billion over the course of the assets' lifetime.

Sensitivity analysis. To assess the robustness of our results, we conduct multiple sensitivity runs by varying key model parameters, including the weather year (2010 and 2020) and cost assumptions for CO_2 and H_2 infrastructure (-10%, +10%, +20%, and +30%). We select these two weather years because they lie on opposite ends of the spectrum in terms of renewable generation potential and resulting system costs, as identified in previous studies using similar modelling setups [50]. The underlying weather data were derived from ERA5 [51] and converted to input renewable energy time series using the python package Atlite [41]. In addition, we explore the implications of hydrogen imports (10 Mt p.a., consistent with the EU's hydrogen import target [8] for 2030) and of discrete pipeline capacity investments.

We rerun all pathway scenarios for each sensitivity and compare the resulting changes in total annual system costs, installed capacities by technology group, and investments in CO_2 and H_2 pipelines against the main results based on weather year 2013 and the default cost assumptions (*supplementary data*, figures S18–S27). This yields a total of 120 additional model runs (5 pathway scenarios × 8 sensitivities × 3 planning horizons). In *supplementary data*, we provide a summary of the total annual system costs and NPV for all sensitivities in table S4.

Overall, the sensitivity analysis confirms the robustness of our main findings across a range of plausible future conditions. The highest system costs occur in weather year 2010, characterised by lower annual wind generation and higher heating demand [50, figure 1]. To meet policy targets, the system installs up to 6% more generation capacity, primarily wind, solar PV, natural gas and PtH, together with an increased reliance on DAC (*supplementary data*, figure S18). In contrast, weather year 2020 exhibits higher wind and solar availability, resulting in lower system costs and reduced dependence on costly CDR technologies (*supplementary data*, figure S19). The lower renewable build-out is offset by greater investment in battery storage. The weather year sensitivities also show that hydrogen pipeline expansion scales with the level of installed renewable capacity, larger in 2010 (*supplementary data*, figure S18) and smaller in 2020 (*supplementary data*, figure S19). Total annual system cost variations of ±7.4% align with ranges reported in previous studies [50].

Changes in pipeline cost assumptions and post-discretisation of pipelines have only a marginal effect on total system costs, with deviations below 1%. This impact is limited because pipeline costs represent only a small fraction of overall expenditures compared to generation, conversion, and storage technologies. When pipeline costs increase, investments in CO_2 and H_2 pipelines decline proportionally (*supplementary data*, figures S20-S23), which is compensated by higher investments in solar PV, battery storage, and DAC, alongside reduced deployment of point-source CC. Through post-discretisation, pipelines are constructed in fixed increments based on standardised diameters [11]. This approach removes small fractional expansions by rounding capacities up to the next discrete unit above a defined threshold (see *supplementary data*, sensitivity analysis), resulting in a modest increase in total pipeline capacity and slightly higher system costs (*supplementary data*, figure S24).

A minimal import target of 10 Mt p.a. of hydrogen reduces domestic electrolyser capacity by up to 47 GW and capacities from solar and wind by up to 245 GW. Although the topology for CO_2 and H_2 pipelines is affected (*supplementary data*, figure S27), our core findings regarding the economic viability of the assessed PCI-PMI projects remain unchanged (*supplementary data*, table S4).

Limitations of the study. While our study assesses a variety of topologies, planning horizons, potential regret scenarios and sensitivities, it is not exhaustive and comes with limitations. As we focus on the impact of continental European PCI-PMI infrastructure, we do not consider fuel and energy imports from outside Europe beyond a fixed hydrogen import in the sensitivity analysis. H_2 and CO_2 demand is directly driven by fixed, exogenous demands for the respective carrier or their derivatives. Our analysis assumes that today's industrial sites and associated point-source emissions remain fixed in their current locations, neglecting potential future shifts such as industrial relocation due to energy price changes or plant closures. However, emerging industrial demands, such as hydrogen production and the synthesis of carbonaceous fuels, can also develop in new locations. Regarding the modelling of both H_2 and CO_2 pipelines, we assume a level playing field for all pipeline projects through standardised costs and applying haversine distance, i.e. no discrimination between PCI-PMI projects and other projects, this is a simplification as real costs may differ. We also do not discretise the endogenously built pipelines (due to the added computational complexity of mixed integer programming) and allow any capacity to be built. While this assumption can lead to underestimation of the true costs of pipeline investments, our sensitivity analysis including post-discretised pipelines shows only minor impacts on total system costs and capacities. We implement the EU's domestic renewable hydrogen production target as an annual minimum constraint on electrolytic hydrogen, excluding alternative pathways such as SMR CC. While this annual matching approach may smooth renewable supply variability relative to stricter temporal requirements, Zeyen *et al* [52] demonstrate that monthly matching regulation produces similar system-level outcomes, whereas hourly matching ensures low emissions but incurs higher costs, unless supported by flexible electrolyser operation or hydrogen storage. In our case, the availability of salt caverns and PCI-PMI storage sites alleviates much of this cost difference by buffering temporal fluctuations between renewable generation and hydrogen production [6, 17, 46]. Other limitations include the spatial aggregation to 99 regions and the temporal clustering to 2190 representative time steps, which balance the need to capture variability in renewable generation and demand profiles with computational tractability [53]. We discuss qualitative considerations beyond cost-optimality in *Supplementary Data*.

5. Conclusion

In this study, we have assessed the impact of PCI-PMI projects on reaching European climate targets on its path to net-zero by 2050. We have modelled the European energy system with a focus on H_2 and CO_2 infrastructure, and evaluated the performance of different levels of pipeline roll-out under three perturbations.

Economic viability and policy targets. Our findings demonstrate that PCI-PMI CO_2 and H_2 infrastructure generate a net positive impact on total system costs, even when accounting for potential additional costs involved with the delay of pipelines. This positions PCI-PMI projects as a no-regret investment option for the European energy system, when treated as a whole. Their economic benefit increases considerably when strategic pipeline extensions are implemented, connecting additional H_2 production sites and CO_2 point sources to the pipeline network. Compared to a system without any pipeline infrastructure, PCI-PMI projects help to achieve the EU's ambitious policy targets, including net-zero emissions, H_2 production and CO_2 sequestration targets, while reducing system costs and technology dependencies.

CCUS and hydrogen utilisation. The pipeline infrastructure serves dual purposes in Europe's decarbonisation strategy: H_2 pipelines facilitate the distribution of more affordable green H_2 from northern and south-western regions rich in renewable energy potential to high-demand regions in central Europe. Complementarily, CO_2 transport and offshore sequestration sites enable industrial decarbonisation by linking major industrial sites and their process emissions to offshore sequestration sites in the North Sea, particularly in Denmark, Norway, and the Netherlands.

Technology and risk diversification. The build-out of CO_2 and H_2 pipeline infrastructure helps utilising renewable energy sources more efficiently. Hydrogen pipelines enable the transport of green H_2 over long distances while CO_2 pipelines reduce the reliance on single CC technologies such as DAC and point-source CC, confirming the findings of [4]. This diversification further enhances system resilience towards uncertainties involved with technologies that are not yet commercially available at scale, such as DAC.

Political support and public acceptance. While PCI-PMI may not achieve perfect cost-optimality in their entirety compared to a theoretically centrally planned system, they possess benefits beyond pure economic viability. The success of large-scale infrastructure investments highly depend on continuous political support and public acceptance—factors that are particularly favourable for PCI-PMI projects. Backed directly by the European Commission, PCI-PMI projects benefit from stronger political endorsement, institutional support structures, enhanced access to financing and grants, and accelerated permitting processes. Additionally, the requirement for frequent and transparent progress reporting increases their likelihood of gaining public acceptance.

Data availability statement

A dataset of the model results is published on Zenodo under https://doi.org/10.5281/zenodo.15 790 593 [54]. Data on techno-economic assumptions can be found at https://github.com/PyPSA/technology-data. The entire code and workflow to reproduce the results and sensitivity analysis is available at https://github.com/bobbyxng/pci-pmi-policy-targets, which is based on a derivative of PyPSA-Eur v2025.01.0. We share the code and workflow to extract and build PCI-PMI projects from public sources [30, 31] in a dedicated GitHub repository https://github.com/bobbyxng/pci-pmi-project-extractor, so that it can be reused and adapted for research purposes outside of this study. We also refer to the documentation of PyPSA-Eur at https://pypsa-eur.readthedocs.io/en/v2025.01.0 for more information on the model.

The data that support the findings of this study are openly available at the following URL/DOI:. https://doi.org/10.5281/zenodo.15 790 593. Q5

Supplementary data available at https://doi.org/10.1088/1748-9326/ae3846/data1.

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Conflict of interest

The authors declare no competing interests.

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Q7

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References

[1] European Commission 2021 Fit for 55: delivering the EU's 2030 Climate Target on the way to climate neutrality. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Q8 Committee and the Committee of the Regions, COM(2021) Q9 550 final, Brussels

[2] European Parliament and Council of the European Union 2021 Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (European Climate Law)

[3] European Commission 2021 European green deal: delivering on our targets Publications Office

[4] Hofmann F, Tries C, Neumann F, Zeyen E and Brown T 2025 H_2 and CO_2 network strategies for the European energy system *Nat. Energy* **10** 1–10

[5] Béres R, Nijs W, Boldrini A and van den Broek M 2024 Will hydrogen and synthetic fuels energize our future? Their role in Europe's climate-neutral energy system and power system Q10 dynamics *Appl. Energy* **375** 124053

[6] Neumann F, Zeyen E, Victoria M and Brown T 2023 The potential role of a hydrogen network in Europe *Joule* **7** 1793–817

[7] European Commission 2020 Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions: a hydrogen strategy for a climate-neutral Europe

[8] European Commission 2022 REPowerEU Plan. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions, COM(2022) 230 final, Brussels

[9] European Parliament and Council of the European Union 2024 Regulation (EU) 2024/1735 of the European parliament and of the council of 13 june 2024 on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724 (Text with EEA relevance)

[10] European Parliament and Council of the European Union 2021 Regulation (EU) 2021/947 of the European Parliament and of the Council of 9 June 2021 establishing the Neighbourhood, Development and International Cooperation Instrument – Global Europe, amending and repealing Decision No 466/2014/EU of the European Parliament and of the Council and repealing Regulation (EU) 2017/1601 of the European Parliament and of the Council and Council Regulation (EC, Euratom) No 480/2009 (Text with EEA relevance)

[11] European Hydrogen Backbone Initiative 2022 European hydrogen backbone: a European hydrogen infrastructure vision covering 28 countries *Technical Report* (European Hydrogen Backbone)

[12] European Court of Auditors 2024 The EU's industrial policy on renewable hydrogen: legal framework has been mostly adopted — time for a reality check. Special report 11, 2024 *Technical Report* (Publications Office)

[13] European Commission 2024 Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Towards an ambitious Industrial Carbon Management for the EU

[14] Reigstad G A *et al* 2022 Moving toward the low-carbon hydrogen economy: experiences and key learnings from national case studies *Adv. Appl. Energy* **8** 100108

[15] van Greevenbroek K, Schmidt J, Zeyringer M and Horsch A 2025 Little to lose: the case for a robust European green hydrogen strategy *Joule* **9** 101974

[16] Neumann F and Brown T 2021 The near-optimal feasible space of a renewable power system model *Electr. Power Syst. Res.* **190** 106690

[17] Neumann F, Hampp J and Brown T 2025 Green energy and steel imports reduce Europe's net-zero infrastructure needs *Nat. Commun.* **16** 5302

[18] Kountouris I, Bramstoft R, Madsen T, Gea-Bermúdez J, Münster M and Keles D 2024 A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production *Nat. Commun.* **15** 5517

[19] Fleiter T *et al* 2025 Hydrogen infrastructure in the future CO_2-neutral european energy system—how does the demand for hydrogen affect the need for infrastructure? *Energy Technol.* **13** 2300981

[20] Bakken B H and von Streng Velken I 2008 Linear models for optimization of infrastructure for CO_2 capture and storage *IEEE Trans. Energy Convers.* **23** 824–33

[21] Wiese F *et al* 2018 Balmorel open source energy system model *Energy Strategy Rev.* **20** 26–34

[22] Hampp J, Düren M and Brown T 2023 Import options for chemical energy carriers from renewable sources to Germany *PLoS One* **18** e0262340

[23] Cerniauskas S, Junco A J C, Grube T, Robinius M and Stolten D 2020 Options of natural gas pipeline reassignment for hydrogen: cost assessment for a Germany case study *Int. J. Hydrog. Energy* **45** 12095–107

[24] Reuß M, Grube T, Robinius M, Preuster P, Wasserscheid P and Stolten D 2017 Seasonal storage and alternative carriers: a flexible hydrogen supply chain model *Appl. Energy* **200** 290–302

[25] European Commission 2025 Directorate general for energy., trinomics., artelys., and LBST. Investment needs of European energy infrastructure to enable a decarbonised economy: final report (Publications Office)

[26] European Commission 2022 Regulation (EU) No 347/2013 of the European Parliament and of the Council of 17 April 2013 on guidelines for trans-European energy infrastructure and repealing Decision No 1364/2006/EC and amending Regulations (EC) No 713/2009, (EC) No 714/2009 and (EC) No 715/2009 (Text with EEA relevance) Text with EEA relevance

[27] European Commission 2023 Commission Delegated Regulation (EU) 2024/1041 of 28 2023 amending Regulation (EU) 2022/869 of the European Parliament and of the Council as regards the Union list of projects of common interest and projects of mutual interest

[28] ACER 2023 Consolidated report on the progress of electricity and gas Projects of Common Interest in 2023 *Technical Report* (European Union Agency for the Cooperation of Energy Regulators)

[29] European Parliament and Council of the European Union 2022 Regulation (EU) 2022/869 of the European Parliament and of the Council of 30 May 2022 on guidelines for trans-European energy infrastructure, amending Regulations (EC) No 715/2009, (EU) 2019/942 and (EU) 2019/943 and Directives 2009/73/EC and (EU) 2019/944, and repealing Regulation (EU) No 347/2013

[30] European Commission 2024 PCI-PMI transparency platform. Projects of Common Interest & Projects of Mutual Interest - Interactive map (available at: https://ec.europa.eu/energy/infrastructure/transparency_platform/map-viewer/main.html)

[31] European Commission 2023 Annex on the first union list of projects of common and mutual interest (available at: https://energy.ec.europa.eu/publications/annex-first-union-list-projects-common-and-mutual-interest_en)

[32] van der Weijde A H and Hobbs B F 2012 The economics of planning electricity transmission to accommodate renewables: using two-stage optimisation to evaluate flexibility and the cost of disregarding uncertainty *Energy Econ.* **34** 2089–101

[33] Möbius T and Riepin I 2020 Regret analysis of investment decisions under uncertainty in an integrated energy system *2020 17th Int. Conf. on the European Energy Market (EEM)* pp 1–5

[34] Price J and Keppo I 2017 Modelling to generate alternatives: a technique to explore uncertainty in energy-environment-economy models *Appl. Energy* **195** 356–69

[35] Yue X, Pye S, DeCarolis J, Li F G N, Rogan F and Gallachóir B O 2018 A review of approaches to uncertainty assessment in energy system optimization models *Energy Strategy Rev.* **21** 204–17

[36] Trutnevyte E 2016 Does cost optimization approximate the real-world energy transition? *Energy* **106** 182–93

[37] Hörsch J, Hofmann F, Schlachtberger D and Brown T 2018 PyPSA-Eur: an open optimisation model of the European transmission system *Energy Strategy Rev.* **22** 207–15

[38] Frysztacki M M, Recht G and Brown T 2022 A comparison of clustering methods for the spatial reduction of renewable electricity optimisation models of Europe *Energy Inf.* **5** 4

[39] Glaum P, Neumann F and Brown T 2024 Offshore power and hydrogen networks for Europe's North Sea *Appl. Energy* **369** 123530

[40] Gotzens F, Heinrichs H, Hörsch J and Hofmann F 2019 Performing energy modelling exercises in a transparent way - the issue of data quality in power plant databases *Energy Strategy Rev.* **23** 1–12

[41] Hofmann F, Hampp J, Neumann F, Brown T and Hörsch J 2021 Atlite: a lightweight Python package for calculating renewable power potentials and time series *J. Open Source Softw.* **6** 3294

[42] Xiong B, Fioriti D, Neumann F, Riepin I and Brown T 2025 Modelling the high-voltage grid using open data for Europe and beyond *Sci. Data* **12** 277

[43] ENTSO-E 2020 Ten-year network development plan (TYNDP) 2020 main report *Technical Report* (ENTSO-E)

[44] BNetzA 2024 Bestätigung des Netzentwicklungsplan Strom - NEP 2037/2045 (2023) *Technical Report* (Bundesnetzagentur)

[45] European Commission 2020 European CO_2 storage database

[46] Caglayan D G, Weber N, Heinrichs H U, Linßen J, Robinius M, Kukla P A and Stolten D 2020 Technical potential of salt caverns for hydrogen storage in Europe *Int. J. Hydrog. Energy* **45** 6793–805

[47] European Commission 2023 Directorate General for Energy and Fraunhofer Institute for Systems and Innovation Research. METIS 3, study S5: the impact of industry transition on a CO_2 neutral European energy system.

[48] Loomes G and Sugden R 1982 Regret theory: an alternative theory of rational choice under uncertainty *Econ. J.* **92** 805–24

[49] Salvatore D and Srivastava R 2008 *Managerial Economic Principles and Worldwide Application* (Oxford University Press)

[50] Gøtske E K, Andresen G B, Neumann F and Victoria M 2024 Designing a sector-coupled European energy system robust to 60 years of historical weather data *Nat. Commun.* **15** 10680

[51] C3S 2018 ERA5 hourly data on single levels from 1940 to present

[52] Zeyen E, Riepin I and Brown T 2024 Temporal regulation of renewable supply for electrolytic hydrogen *Environ. Res. Lett.* **19** 024034

[53] Kotzur L, Markewitz P, Robinius M and Stolten D 2018 Impact of different time series aggregation methods on optimal energy system design *Renew. Energy* **117** 474–87

[54] Xiong B, Brown T and Riepin I 2025 Result data for 'The role of Projects of Common Interest in reaching Europe's energy policy targets'