# The role of Projects of Common Interest in reaching Europe's energy policy targets

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## Abstract

The European Union (EU) aims to achieve climate-neutrality by 2050, with ambitious 2030 target, such as 55 % greenhouse gas emissions reduction compared to 1990 levels, 10 Mt p.a. of a domestic green $H_2$ production, and 50 Mt p.a. of $CO_2$ injection capacity, which should be sequestered within the EU. The European Commission selects so-called Projects of Common Interest (PCI) and Projects of Mutual Interest (PMI)—a large infrastructure projects for electricity, hydrogen and $CO_2$ transport, and storage—that are of transnational importance as they link the energy systems of European countries. In this work, we evaluate the impact of PCI-PMI projects for the European energy system and EU energy policies. To achieve this, we investigate how delays in these projects could affect the EU's policy targets and examine potential conflicts between various policy objectives and the overarching greenhouse gas reduction goal. **Our preliminary results for 2030 indicate that policy targets can be met even without PCI-PMI projects; however, these projects offer additional benefits: (i) $\mathbf{H_2}$ pipelines enhance the affordability and distribution of green $\mathbf{H_2}$, thereby jumpstarting the hydrogen economy, and (ii) $\mathbf{CO_2}$ transport projects connect major industrial emissions to offshore sequestration sites in the North Sea. In our future work, we will analyse long-term pathway effects up to 2050, and incorporate hybrid interconnectors and $\mathbf{CO_2}$ shipping routes from the PCI-PMI list. Overall, our findings highlight the critical interplay between cross-border cooperation, infrastructure investments, and policy targets in the European energy transition across all sectors.**

*Keywords:* energy system modelling, policy targets, infrastructure, resilience, hydrogen, carbon, Europe

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## List of abbreviations

**AC** Alternating Current
**API** Application Programming Interface
**CC** Carbon Capture
**CU** Carbon Utilisation
**CS** Carbon Storage
**CCUS** Carbon Capture, Utilisation, and Storage
**DAC** Direct Air Capture
**DC** Direct Current
**EU** European Union
**GHG** Greenhouse gas
**NEP** Netzentwicklungsplan (German grid development plan)
**PCI** Projects of Common Interest
**PMI** Projects of Mutual Interest
**REST** Representational State Transfer
**tsam** Time Series Aggregation Module
**TYNDP** Ten-Year Network Development Plan
**WACC** Weighted Average Cost of Capital

## 1. Introduction

On the pathway to a climate-neutral Europe by 2050, the European Union (EU) has set ambitious targets for 2030. These targets include a reduction of 55 % in greenhouse gas emissions compared to 1990 levels [1], 10 Mt p.a. domestic green $H_2$ production [2], and 50 Mt p.a. of $CO_2$ injection capacity with sequestration in within the EU [3].

To support reaching these targets, the European Commission bi-annually identifies a list of Projects of Common Interest (PCI), which are key cross-border infrastructure projects that link the energy systems of the EU members, including transmission and storage projects for electricity, hydrogen and $CO_2$ [4]. The pool of project sutable for PCI status is based on projects submitted by transmission system operators, consortia, or third parties. Projects of Mutual Interest (PMI) further include cooperations with countries outside the EU, such as Norway or the United Kingdom. With a PCI-PMI status, project awardees receive strong political support and are, amongst others, eligible for financial support (e.g. through funding of the Connecting Europe Facility) and see accelerated permitting processes. On the other hand, project promoters are obliged to undergo comprehensive reporting and monitoring processes. In order for projects to be eligible for PCI-PMI status, their *potential benefits need to outweigh their costs* [4]. Given the political and lighthouse character, these projects are highly likely to be implemented. However, any large infrastructure project, including PCI-PMI projects, commonly face delays due to permitting, financing, procurement bottlenecks, etc. [5].

- Net zero law by 2050 **(author?)** [3]

### *1.1. Fuels, carriers, targets*

*Hydrogen ($H_2$).*

- "net zero systems: H2 feedstock for synthetic fuels, fuel transportation sector, feedstock and heat source in industry," [6], [7]

### *1.2. Projects of Common/Mutual Interest*

## 2. Literature review

We structure the literature review into three main sections: (i) the value of $CO_2$ and $H_2$ in low-carbon energy systems, (ii) transporting $CO_2$ and $H_2$ through pipelines, and (iii) addressing uncertainty in energy system models. Based on this review, identify research gaps and position our work as a novel contribution to the current state of the art (iv).

### *2.1. The value of $CO_2$ and $H_2$ in low-carbon energy systems*

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. 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 [8]. 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. The demand for these fuels is driven by the aviation, shipping, industry, and agriculture sectors [9]. To produce these carbonaceous fuels, $CO_2$ is required as a feedstock (Carbon Utilisation — CU). The $CO_2$ can be captured from the atmosphere via Direct Air Capture (DAC) or from industrial and process emissions (e.g. cement, steel, ammonia production) in combination with Carbon Capture (CC) units.

van Greevenbroek et al. [6]: Look at near optimal solution space by assessing a wide range. Derived from a wide set of literature, modelling hydrogen and CS, CU [10, 7, 11, 12, 13, 14, 9, 15, 16]

Range of assessed CO2 sequestration potential from 275 Mtpa, 550 Mtpa, up to 1100 Mtpa. Range of green hydrogen production in 2050 goes up to 90 Mtpa. Page 3: Europe has little to loose by committing to targets like 25 Mt pa H2 production by 2040, moderate taregt, feasible.

"Cost optimal modelling results with a central planning approach may not capture system designs that are politically more viable but slightly more costly." from Koens paper, [17]

### *2.2. Transporting $CO_2$ and $H_2$ through pipelines*

Recent publications show that transporting $CO_2$ and $H_2$ via dedicated pipeline infrastructure can unlock additional benefits and net cost-savings in a sector-coupled energy system. Victoria et al. [18] ... TODO

Neumann et al. [9] examine the complex interaction between electricity grid expansion and a European-wide deployment of hydrogen pipelines in a net-zero system (new and retrofitting of existing gas pipelines). While $H_2$ pipelines are not essential, their build-out can significantly reduce system costs by up to 26 bn. € p.a. (3.4 % of annual CAPEX and OPEX) by connecting regions with excessive renewable potential, storage sites and load centres. Extending their previous work, Neumann et al. [19] investigate the trade-off between relying on different energy import strategies and domestric infrastructure build-out. By coupling the global energy supply chain model TRACE [20] and the sector-coupled PyPSA-Eur model, they assess different energy vector import combinations (e.g. electricity, $H_2$ or $H_2$ derivatives) and their impact on Europe's infrastructural needs. By

In a study by Kontouris et al. [16], the authors explore BALMOREL

Fleiter et al. [10] modelled the future hydrogen infrastructure in Europe, including the conversion of existing natural gas pipelines to hydrogen transport. They found that a significant share of the hydrogen infrastructure could be built on existing natural gas pipelines, which would reduce costs and accelerate the deployment of hydrogen infrastructure.

Fleiter et al. [10], single node per country, modelled as net transfer capacities, assumed "that 70 percent of hydrogen pipelines will be converted from existing natural gas pipelines"

Hofmann et al. [21] address previous research gap in assessing the interaction between $H_2$ and $CO_2$ infrastructure, including their production, transport, storage, utilisation, and sequestration. They find that ...

### *2.3. Addressing uncertainty in energy system models*

- Regret analysis common in economics, also in energy system modelling
- Carbon networks
- Regret
- Cite Hobbs, Iegor, Koen, Fhofmann

Möbius and Riepin two-stage, stochastic, regret approach [22] PCI projects gas

## 3. Research gaps and our contribution

TODO NOVELTIES:

- MEGA carbon
- real planned projects
- high spatial and temporal resolution
- regret matrix approach
- Time, myopic, iterative dimension, usually studies look directly at the target 2050, yielding overly optimistic results (overnight 2050 optimisation will yield different result than pathway-dependent solutions)

Chicken and egg problem. Assess real planned projects

This paper aims to evaluate the impact of PCI-PMI projects on the European energy system and EU energy policies. We focus on the following key research questions:

1. What is the impact of delay in PCI-PMI projects' realisation on the EU's policy targets for 2030?
2. What are the costs associated with adhering to the EU policy targets, even if PCI-PMI projects are delayed?
3. Do the green hydrogen production and carbon sequestration targets conflict with the cost-effective achievement of the greenhouse gas emission reduction goals?

Key motivations for the questions as the EU targets especially for 2030 have have been criticised as unrealistic, primarily politically motivated. [23, 6]

## 4. Methodology

We build on the open-source, sector-coupled energy system model PyPSA-Eur [9, 24, 25, 26] 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, electricity storage, power-to-X conversion capacities, and 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 [27], renewable potentials, and availability time series [28]. It includes the current high-voltage transmission grid (AC 220 kV to 750 kV and DC 150 kV and above) [29].

### 4.1. Model setup

*Temporal resolution.* To assess the long-term impact of PCI-PMI projects on European policy targets across all sectors, we optimise the sector-coupled network for three key planning horizons 2030, 2040, and 2050, myopically. The myopic approach ensures that investment decisions across all planning horizons are coherent and build on top of the previous planning horizon. We use the built-in Time Series Aggregation Module (tsam) to solve the model for 2190 time steps, yielding an average resolution of four hours. tsam is a Python package developed by Kotzur et al. [30] to aggregate time series data into representative time slices to reduce computational complexity while maintaining their specific intertemporal characteristics, such as renewable infeed variability, demand fluctuations, and seasonal storage needs.

*Geographical scope.* We model 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 Table A.4). Depending on the scenario, additional offshore buses are introduced to appropriately represent offshore sequestration sites and PCI-PMI projects. In our application, Europe is self-sufficient, we do not allow for any imports or exports of the assessed carriers.a

*Technology assumptions.* As part of the PyPSA-Eur model, we source all technology-specific assumptions including lifetime, efficiency, investment and operational costs from the public *Energy System Technology Data* repository, v.0.10.1 [31]. We use values projected for 2030 and apply a discount rate of 7 %, reflecting the weighted average cost of capital (WACC).

*Demand and $CO_2$ emissions.* Energy and fuel carrier demand in the modelled sectors, as well as non-abatable $CO_2$ process emissions are taken from various sources [32, 33, 34, 35, 36]. Regionally and temporally resolved demand includes electricity, heat, gas, biomass and transport. Internal combustion engine vehicles in land transport are expected to fully phase out in favour of electric vehicles by 2050 [37]. Demand for hydrocarbons, including methanol and kerosene are primarily driven by the shipping, aviation and industry sector and are not spatially resolved.

To reach net-zero $CO_2$ emissions by 2050, the yearly emission budget follows the EU's 2030 (−55 %) and 2040 (−90 %) targets [1, 38], translating into a carbon budget of 2072 Mtpa in 2030 and 460 Mtpa in 2040, respectively

### *4.2. PCI-PMI projects implementation*

By accessing the REST API of the PCI-PMI Transparency Platform and associated public project sheets provided by the European Commission [39]. We add all $CO_2$ sequestration sites and connected pipelines, $H_2$ pipelines and storage sites, as well as proposed pumped-hydro storages and transmission lines (AC and DC) to the PyPSA-Eur model. To isolate the effect of the $CO_2$ and $H_2$ infrastructure, PCI-PMI projects representing single hybrid interconnectors/energy islands or offshore wind farms are not considered within the scope of our research. We consider the exact geographic information, build year, as well as available static technical parameters when adding individual assets to the respective modelling year. Our implementation can adapt to the needs and configuration of the model, including selected technologies, geographical and temporal resolution, as well as the level of sector-coupling.

Note that we use standardised costs [31] for all existing brownfield, model-endogenous greenfield and PCI-PMI projects, equally. There are two major reasons for this approach: (i) Cost data provided by project promoters can be incomplete and may not include the same cost components, assumptions, risk margins, etc., and (ii) to ensure comparability and level-playing field between all potential projects, including both PCI-PMI and model-endogenous investments. An overview of the implemented PCI-PMI projects is shown in Figure 1.

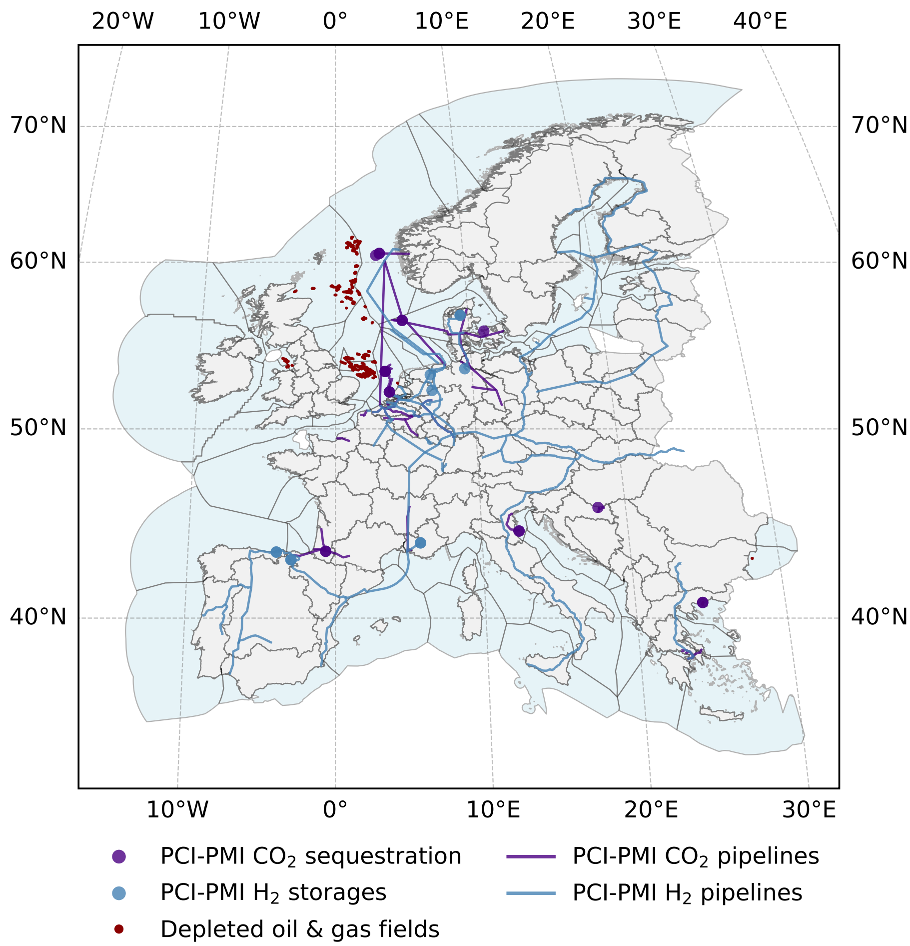



Figure 1: Map of the regional scope including clustered onshore (grey) and offshore regions (blue), as well as PCI-PMI $CO_2$ and $H_2$ pipelines, storage and sequestration sites. Depleted offshore oil and gas fields (red) provide additional $CO_2$ sequestration potential [21].

### *4.3. $CO_2$ sequestration sites*

TODO: Add description on all co2 sequestration sites, cite Fabian Hofmann, connection to closest onshore link, accounting for offshore connection, total sequestration potential. Not allowing for onshore sequestration and not accounting for even higher technical sequestration potential. NIMBY behaviour, low acceptance by society, fear of leakage, cite sources.

TODO: Add potential increase over years for co2 sequestration sites In total around 400 Mtp.a. (total potential), enough to offset XXX Mtpa of non-abatle process emissions (160 Mt?)

### *4.4. Scenario setup*

### *4.5. Technology stack*

- Limited use of fossil fuels in 2050 technically still possible, emissions compensation by DAC/CO2 removal or capturing at source (CC) with capture rate of 90 Percent.

TODO:DESCRIBE REGRET APPROACH

As of the date of submission, we model three key scenarios for the target year 2030 which will set the base year for pathways towards 2050: a *Base* scenario in which policy targets are achieved and all projects are commissioned on time as well as two PCI-PMI delay scenarios *A* and *B*. Table 1 gives an overview of the scenarios' key assumptions and their differences. Depending on the scenario, we formulate and activate additional constraints to ensure the fulfilment of the EU policy targets.

Regret-matrix approach, resulting in 60 runs (15 long-term investments and their individual performance in three short-term scenarios for each year) see Table 1

Table 1: Scenario matrix setup: Long-term and short-term scenarios.

| Short-term | Reduced targets | Delayed pipelines | No pipelines |
|---|---|---|---|
| **Long-term scenarios** | | | |
| Decentral Islands (**DI**) | ■ | – | – |
| PCI-PMI (**PP**) | ■ | ■ | ■ |
| PCI-PMI Exp (**PPE**) | ■ | ■ | ■ |
| PCI-PMI Exp+ (**PPE+**) | ■ | ■ | ■ |
| Central Planning (**CP**) | ■ | ■ | ■ |
| **Targets** | | | |
| GHG emission reduction | ■ | ■ | ■ |
| $CO_2$ sequestration | – | ■ | ■ |
| Green $H_2$ 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 | ■ | □ | – |
| **Model configuration** | | | |
| Planning horizons | Myopic: [2030, 2040, 2050] | | |
| Electricity grid | OSM, TYNDP, NEP, PCI-PMI | | |

■ active □ delayed by one period – inactive

Table 2: Overview of long-term scenarios and their key assumptions.

| Long-term scenarios | DI | PP | PPE | PPE+ | CP |
|---|---|---|---|---|---|
| **$CO_2$ sequestration** | | | | | |
| Depleted oil & gas fields | ■ | ■ | ■ | ■ | ■ |
| PCI-PMI seq. sites | – | ■ | ■ | ■ | ■ |
| **$H_2$ 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 | – | ■ | ■ | ■ | ■ |
| Int. build-out | – | – | – | ■ | ■ |
| PCI-PMI extendable | – | – | – | – | ■ |

■ active – inactive

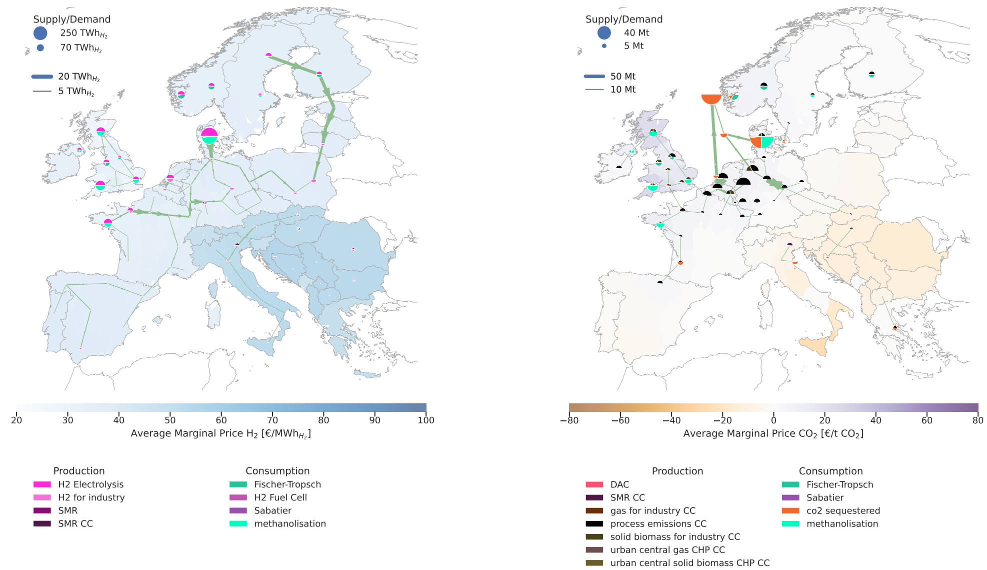
Table 3: Pathway for implemented targets.

| Planning horizon | 2030 | 2040 | 2050 |
|---|---|---|---|
| **Targets** | | | |
| GHG emission reduction | $-55\,\%$ | $-90\,\%$ | $-100\,\%$ |
| $CO_2$ sequestration | 50 Mtpa | 150 Mtpa | 250 Mtpa |
| Electrolytic $H_2$ production | 10 Mtpa | 27.5 Mtpa | 45 Mtpa |
| $H_2$ electrolyser capacity | 40 GW | 110 GW | 180 GW |

TODO: NOTE ON GREEN vs. ELECTROLYTIC $H_2$ PRODUCTION

## 5. Results and discussion

*Base scenario.* Figure 2 shows the regional distribution of the $H_2$ and $CO_2$ value chain in the Base scenario. Note that for the specific year of 2030, a disconnect in $H_2$ infrastructure between central and southeastern Europe can be observed, due to the delay in commissioning of the project connecting the two networks. Within the two interconnected regions, almost homogenous average marginal prices for $H_2$ can be observed. Note that Figure 2a shows the cost of all $H_2$ produced, weighted by the respective regional demand at a certain point in time. $CO_2$ prices are higher in demand regions for industry processes and methanolisation located in northwestern Europe — primarily Norway and the United Kingdom (Figure 2b). Negative $CO_2$ prices in souhtheastern Europe indicate a lack of demand and missing economic value. Utilisation of $H_2$ pipelines vary strongly across the PCI-PMI projects. In most of the times, pipelines serve the purpose of transporting $H_2$ in a single direction only, i.e. from high renewable potential regions to $H_2$ consumption sites, where it serves as a precursor for methanolisation or direct use in industry and shipping (see Figure 2a). Prominent PCI-PMI projects with particularly high full-load hours include P9.9.2 *Hydrogen Interconnector Denmark-Germany* (6937 h) and P11.2 *Nordic-Baltic Hydrogen Corridor* (2295 h), followed by projects connecting major steel-industrial and chemical sites of Germany (southwest) with Belgium (P9.4 *H2ercules West*, 1634 h), the Netherlands (P9.6 *Netherlands National Hydrogen Backbone*, 1967 h and P9.7.3 *Delta Rhine Corridor H2*, 1510 h), and France (P9.2.2 *MosaHYyc*, 4662 h). PCI project P13.8 *EU2NSEA* connects $CO_2$ from process emissions in Germany, Belgium and the Netherlands to major geological sequestration sinks close to the Norwegian shore *Smeaheia* and *Luna* with an annual injection potential of 20 Mt p.a. and 5Mt p.a., respectively.




(a) $H_2$ regional balances and flows (all $H_2$ produced).

(b) $CO_2$ regional balances and flows.

Figure 2: Results *Base* scenario — Regional distribution of $H_2$ and $CO_2$ production, utilisation, storage, and transport in the Base scenario.

*Scenario A compared to Base.* PCI-PMI infrastructure account for a total of around 30 bn. € p.a. in additional total system costs, indicating that for the target year 2030, the projects are not cost-optimal. With a delay of PCI-PMI projects in scenario *A*, Europe's policy targets can still be achieved at significantly lower cost. However, this comes at the expense of a less interconnected energy system, which may lead to higher costs in the long run. Further, $H_2$ prices vary more strongly across regions, seeing higher costs in southeastern Europe due to industrial demand and lower renewable potentials (Figure B.6a). We make similar observations for $CO_2$ — a lack of pipeline infrastructure increases spread of $CO_2$ prices, seeing higher values for $CO_2$ in regions with high demand (e.g. for industrial processes or methanolisation).

*Scenario B compared to Base.* By omitting a green $H_2$ target, almost no electrolysers are installed. Around 8 Mt are still produced to cover industrial $H_2$ and methanol (primarily shipping) demand (Figures B.4 and B.5). However, this demand is met by decentral steam methane reforming instead of electrolysers (Figure B.4). Without specifying a $CO_2$ sequestration target, the system still collects around 21 Mt of $CO_2$ p.a. primarily from process emissions in the industry sector and sequesters it in carbon sinks near industrial sites where a sequestration potential is identified (see Figure 1) [21]. This carbon sequestration is incentivised by the emission constraint for 2030. As no pipeline infrastructure is built in these scenarios, the chosen locations differ in the delay scenarios — this can be observed for regions near the coast, such as the United Kingdom and Norway (see Figure 1). Given the lack of infrastructure, both the average cost for $H_2$ and $CO_2$ are higher in scenario *B* compared to the Base scenario (Figures B.6c and B.6d.

Overall, the results for the modelling year 2030 show that reaching the EU's 2030 $H_2$ production and $CO_2$ sequestration targets translates into around 20 bn. € p.a. in total system costs for all included sectors (Figure 3). This is true for both comparing scenario *A* and *Base* scenario with scenario *B*, respectively, deducting the cost of the PCI-PMI projects.

### *5.1. Limitations of our study*

- Haversine distance for level playing field
- No discetisation of pipelines
- Regional resolution for computational reasons
- ...

Our study focuses primarily on the effects on real, planned infrastructure in the European energy system. Most final energy demand is given exogenously, naturally a key driver of infrastructure utilisation. We somewhat reduce the impact with the reduced targets scenario where at least the key carriers H2 and CO2 are freely optimised.

Single weather year assessment, this particular year has the properties, ...

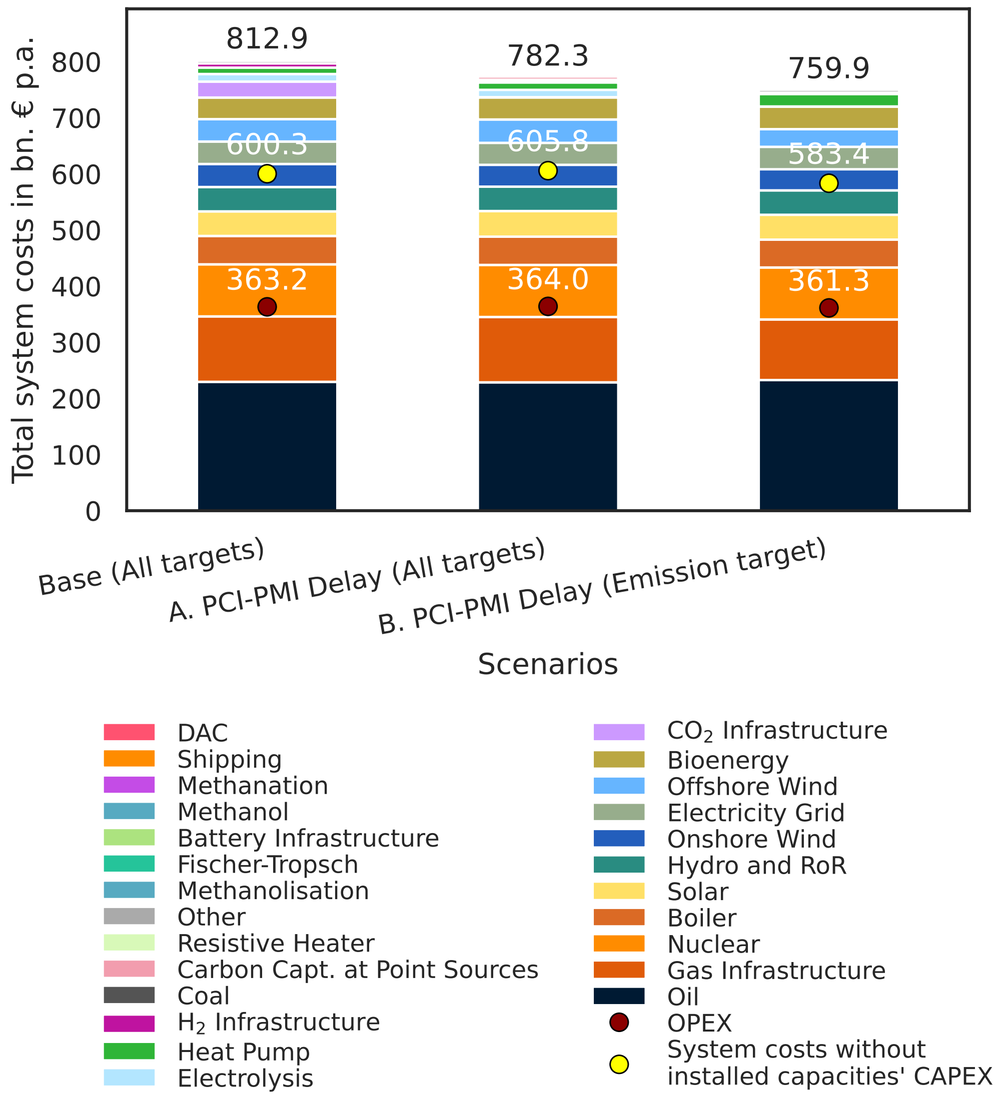



Figure 3: Results — Total system costs by technology and infrastructure.

## 6. Conclusion

We conclude that although all three EU policy targets for 2030 can be achieved without PCI-PMI infrastructure, they bring additional benefits: i) $H_2$ pipelines projects help distribute more affordable green $H_2$ from northern and south-western Europe to high-demand regions in central Europe; ii) $CO_2$ transport and storage projects help decarbonising the industry by connecting major industrial sites and their process emissions to offshore sequestration sites in the North Sea (Denmark, Norway, and the Netherlands). Preliminary results have further shown that most PCI-PMI projects seem to be over-dimensioned and are not cost-optimal, as very few projects show utilisation above 1000 full-load hours. However, to adequately assess the value of PCI-PMI projects, we need to assess their benefits in future target years. Further, policy targets for 2030 are not cost-effective, although needed in the long run to reach net-zero emissions by 2050.

*Research outlook.* Next steps include the implementation of remaining PCI-PMI projects, such as hybrid offshore interconnectors (energy islands), electricity storages, and $CO_2$ shipping routes. To evaluate the long-term value of PCI-PMI projects in a sector-coupled European energy system, we will model pathway dependencies towards 2050. We will also assess the sensitivity of the infrastructure to technology-specific build-out rates.

## CRediT authorship contribution statement

**Bobby Xiong**: Conceptualisation, Methodology, Software, Validation, Investigation, Data Curation, Writing — Original Draft, Review & Editing, Visualisation. **Iegor Riepin**: Conceptualisation, Methodology, Investigation, Writing — Review & Editing, Project Administration, Funding acquisition. **Tom Brown**: Investigation, Resources, Writing — Review & Editing, Supervision, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data and code availability

The entire workflow, including the custom model based on PyPSA-Eur, PCI-PMI project implementation, scenario setup, postprocessing and visualisation routines can be accessed via the GitHub repository:
https://github.com/bobbyxng/pcipmi-policy-targets

## Acknowledgements

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## Appendix A. Supplementary material — Methodology

Table A.4: Regional clustering: A total of 99 regions are modelled, excl. offshore buses.

| | **Country** | **Buses** |
|---|---|---|
| **Administrative level** | $\sum$ | **99** |
| NUTS2 | Finland (FI) | 4 |
| | Norway (NO) | 6 |
| NUTS1 | Belgium (BE)** | 2 |
| | Switzerland (CH) | 1 |
| | Czech Republic (CZ) | 1 |
| | Germany (DE)* | 13 |
| | Denmark (DK) | 1 |
| | Estonia (EE) | 1 |
| | Spain (ES)* | 5 |
| | France (FR) | 13 |
| | Great Britain (GB)* | 11 |
| | Greece (GR) | 3 |
| | Ireland (IE) | 1 |
| | Italy (IT)* | 6 |
| | Lithuania (LT) | 1 |
| | Luxembourg (LU) | 1 |
| | Latvia (LV) | 1 |
| | Montenegro (ME) | 1 |
| | Macedonia (MK) | 1 |
| | Netherlands (NL) | 4 |
| | Poland (PL) | 7 |
| | Portugal (PT) | 1 |
| | Sweden (SE) | 3 |
| | Slovenia (SI) | 1 |
| | Slovakia (SK) | 1 |
| NUTS0 | Albania (AL) | 1 |
| | Austria (AT) | 1 |
| | Bosnia and Herzegovina (BA) | 1 |
| | Bulgaria (BG) | 1 |
| | Croatia (HR) | 1 |
| | Hungary (HU) | 1 |
| | Romania (RO) | 1 |
| | Serbia (RS) | 1 |
| | Kosovo (XK) | 1 |

City-states (*) (i.e., Berlin, Bremen, Hamburg, Madrid, and London) and regions without substations (**) (one in BE) are merged with neighbours. Sardinia and Sicily are modelled as two separate regions.

Table A.5: DUMMY Overview of technology cost assumptions. TODO compare with FLEITER PAPER TABLE 9

| | Unit | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| **Technology** | | | | |
| CO2 pipelines | XX | 1000 | 1000 | 1000 |
| Onshore, offshore | XX | 1000 | 1000 | 1000 |
| Electrolysers | XX | 1000 | 1000 | 1000 |

356 # Appendix B. Supplementary material — Results and discussion

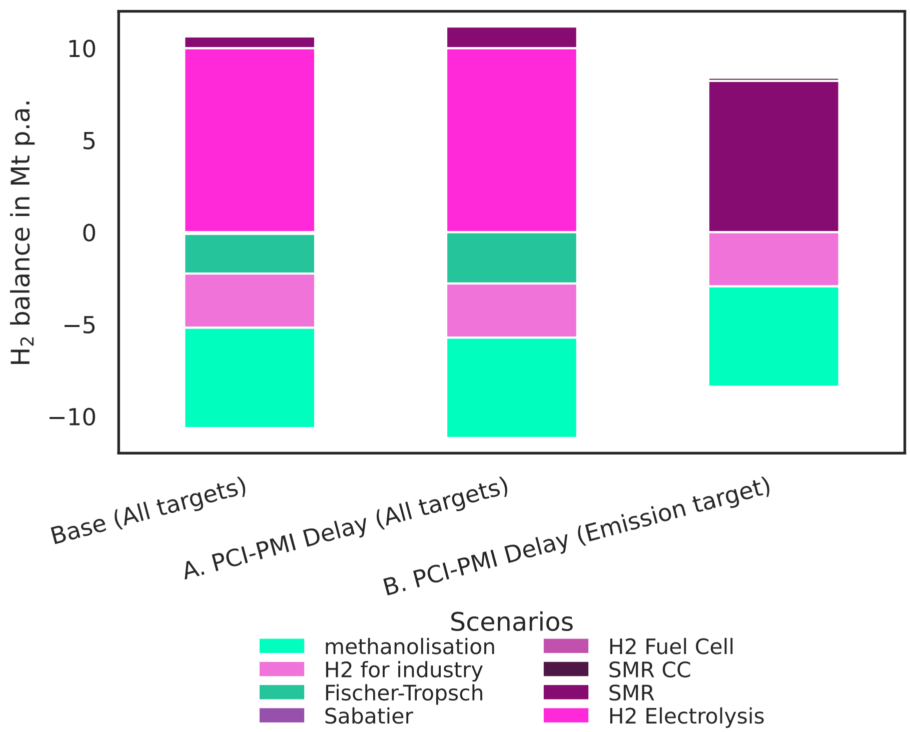



Figure B.4: Results — $H_2$ balance.

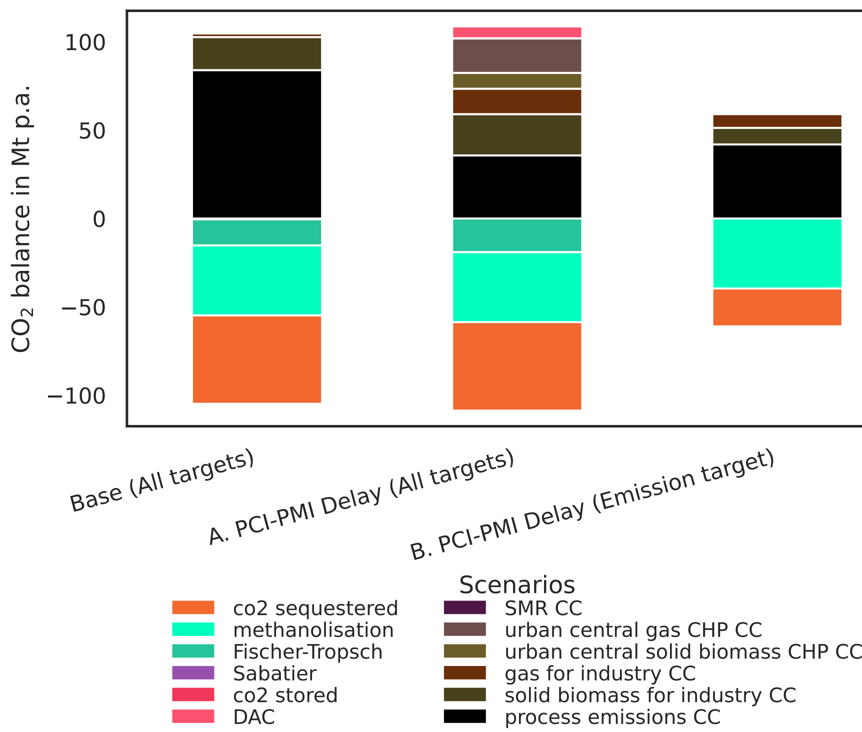
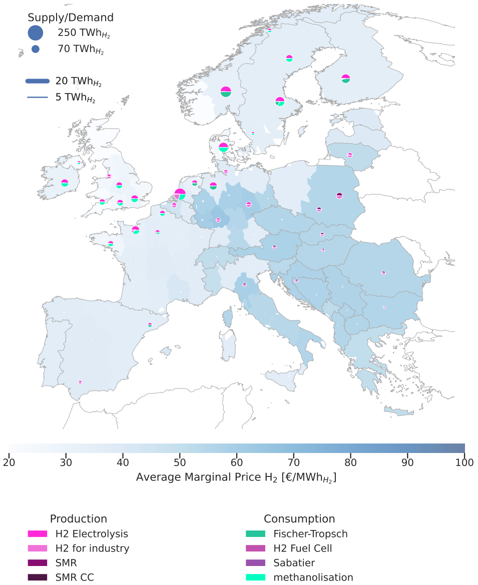
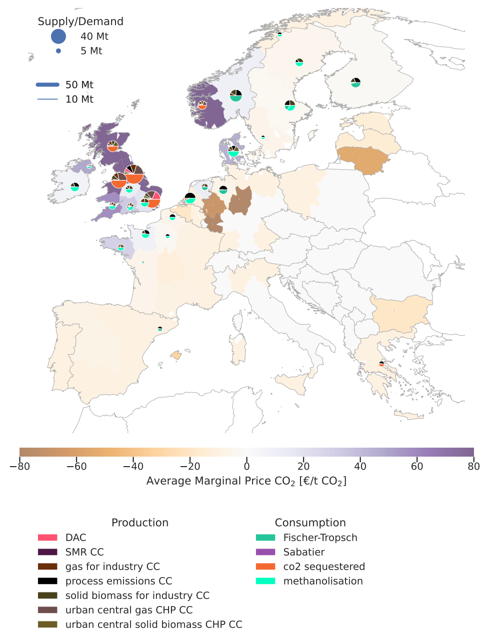


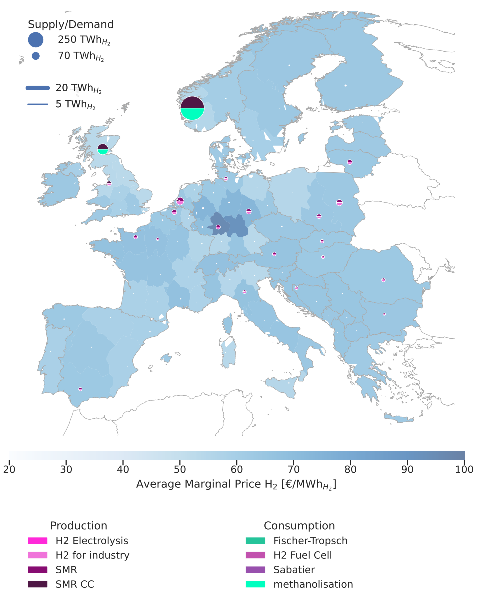

Figure B.5: Results — $CO_2$ balance.



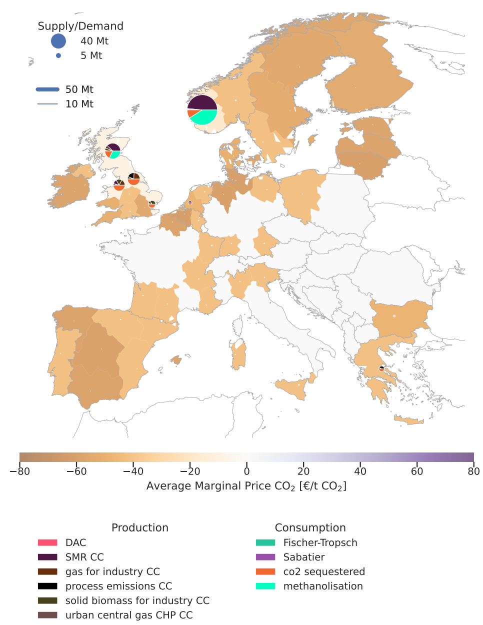

(a) $H_2$ regional balances and flows (Scenario A, all $H_2$ produced).




(b) $CO_2$ regional balances and flows (Scenario A).




(c) $H_2$ regional balances and flows (Scenario B, all $H_2$ produced).




(d) $CO_2$ regional balances and flows (Scenario B).

Figure B.6: Results scenarios *A* and *B* — Regional distribution of $H_2$ and $CO_2$ production, utilisation, storage, and transport.

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