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

Bobby Xiong[a,*], Iegor Riepin[1], Tom Brown[1]

[a] *TU Berlin, Department of Digital Transformation in Energy Systems, Berlin, Germany*

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) H_2 pipelines enhance the affordability and distribution of green H_2, thereby jumpstarting the hydrogen economy, and (ii) 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 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

---

*Corresponding author: xiong@tu-berlin.de

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). This 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 [7, 9–16]

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 H_2 and CO_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 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 to 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. Depending on the import costs, they observe up to 14 % in system cost savings. Further, with an increasing share of H_2 imports, the need for domestic H_2 pipelines would decrease.

In a study by Kontouris et al. [16], the authors explore pathways for a potential integrated hydrogen infrastructure in Europe while considering sector-coupling and energy imports. Using the European energy system model Balmorel [21], the authors implement three scenarios varying between domestic and imported H_2 levels as well as H_2 production technologies. In their findings they identify main H_2 transport corridors from Spain and France, Ireland and the United Kingdom, Italy, and Southeastern Europe. When synergies through sector-coupling are exploited, domestic H_2 production can be competitive, seeing an increase in up to 3 % in system costs.

Fleiter et al. [10] use a mixed simulation and optimisation method to model H_2 uptake and transport by coupling three models, (i) FORECAST for buildings and industry, (ii) ALADIN for transport together with (iii) the European energy system model Enertile. Total demand for H_2 ranges from 690 TWh to 2800 TWh in 2050, 600 TWh to 1400 TWh for synthetic fuels. In their study, the chemical and steel industry in Northwest Europe (incl. western regions of Germany, Netherlands and northern regions of Belgium), display a demand of more than 100 TWh each. With regard to crossborder transport, they mainly obser hydrogen flows from Norway, UK and Ireland to continental Europe (around 53 TWh to 72 TWh). Depending on the scenario, the Iberian Peninsula exports around 72 TWh to 235 TWh via and to France.

On the carbon networks side, [22]

Do both! Hofmann et al. [23] 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 [24] 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. [6, 25]

4. Methodology

We build on the open-source, sector-coupled energy system model PyPSA-Eur [9, 26–28] 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 [29], renewable potentials, and availability time series [30]. It includes the current high-voltage transmission grid (AC 220 kV to 750 kV and DC 150 kV and above) [31].

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. [32] 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 [33]. 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 [34–38]. 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 [39]. 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, 40], 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 [41]. 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 [33] 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.

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

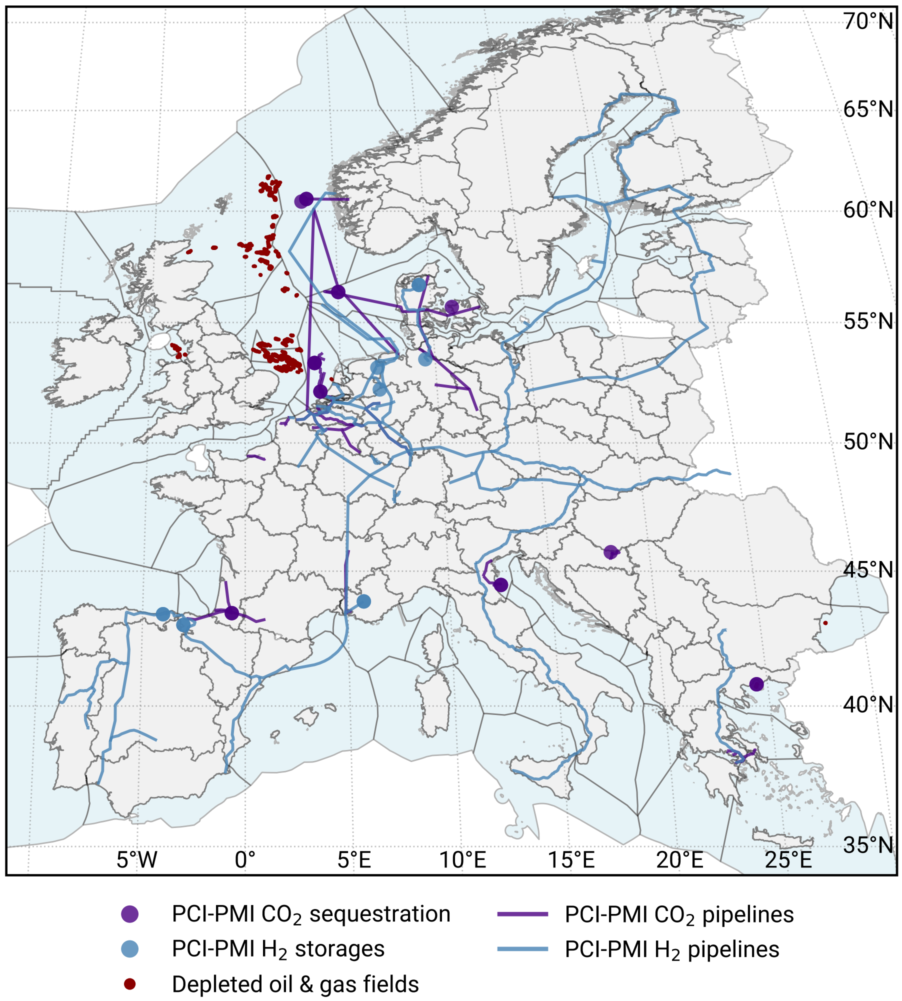


Figure 1: Map of the regional scope including clustered onshore (grey) and offshore regions (blue), as well as PCI-PMI CO_2 and H_2 pipelines, storage and sequestration sites. Depleted offshore oil and gas fields (red) provide additional CO_2 sequestration potential [23].

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 (**PCI**)	■	■	■
PCI-PMI Exp (**PCI-n**)	■	■	■
PCI-PMI Exp+ (**PCI-in**)	■	■	■
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**	**PCI**	**PCI-n**	**PCI-in**	**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 **??** 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 **??** 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 **??**). 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 **??**). 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.

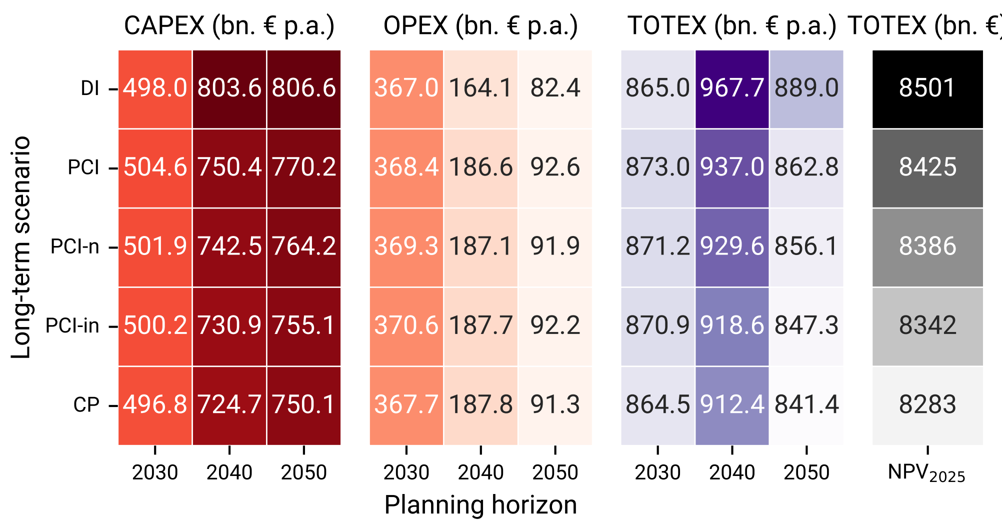


Figure 2: Annual system costs by long-term scenario and planning horizon.

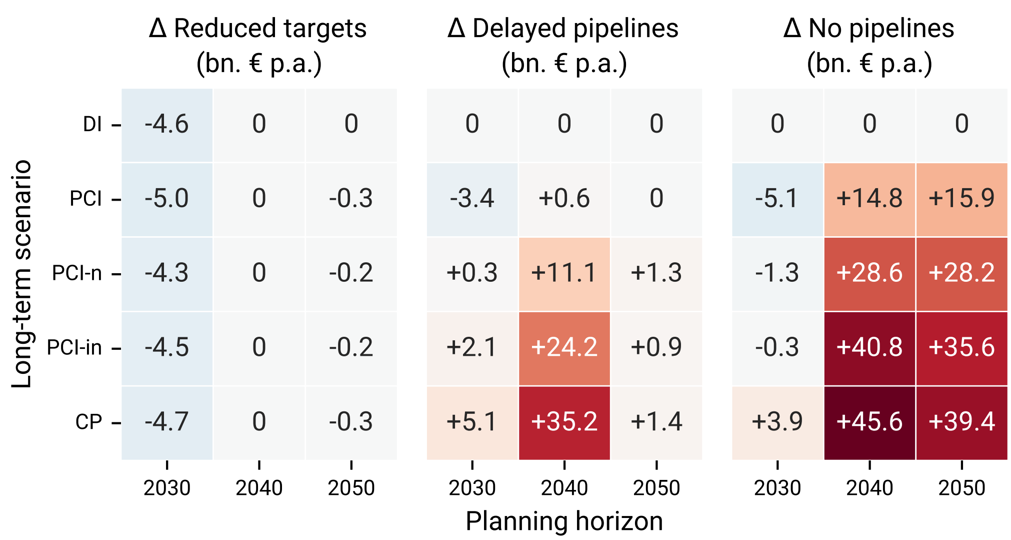


Figure 3: Regret matrix. Calculating regret terms by subtracting system costs of long-term scenarios (columns) from short-term scenarios (rows). Positive values reflect higher costs in the short-term scenarios compared to the long-term ones.

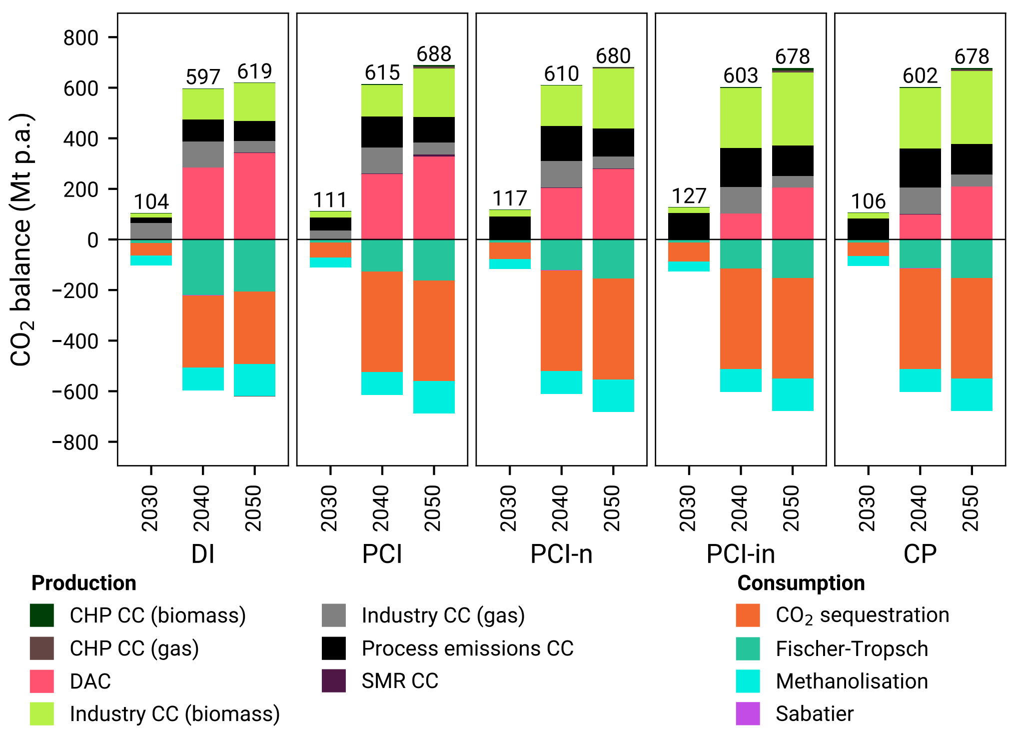


Figure 4: ceCO2 balances in long-term scenarios.

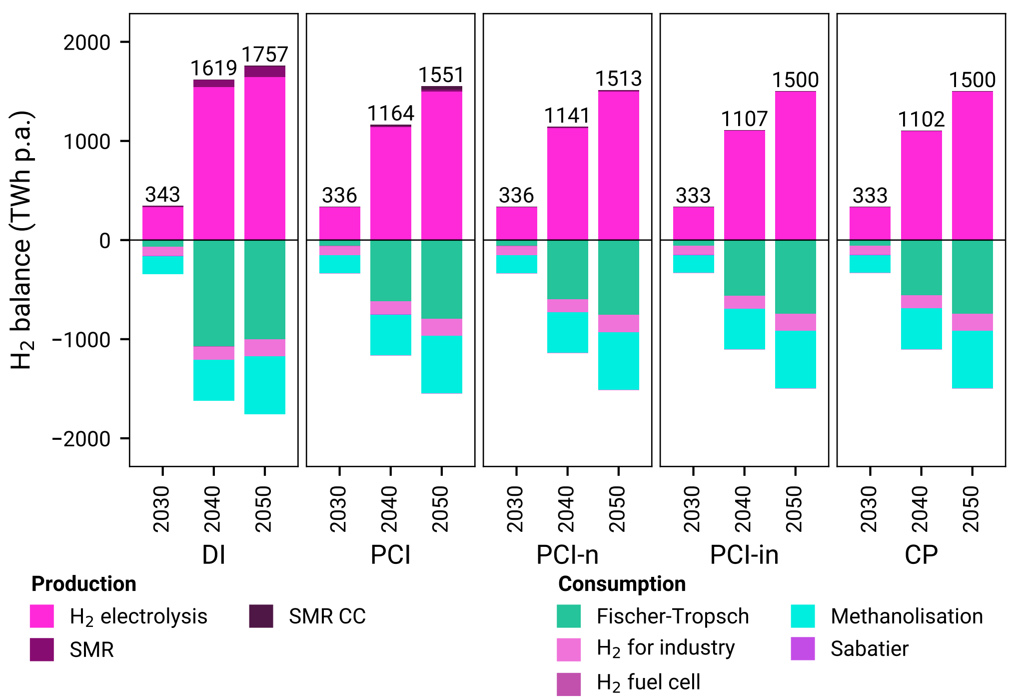


Figure 5: H_2 balances in long-term scenarios.

- Regarding DAC Fig. 6
- No DAC in 2030 yet, primarily from CC from point sources
- 2040 sees strong effect in shor-term runs, delaying the pipelines means a much higher utilisation in DAC to compensate for missing pipelines

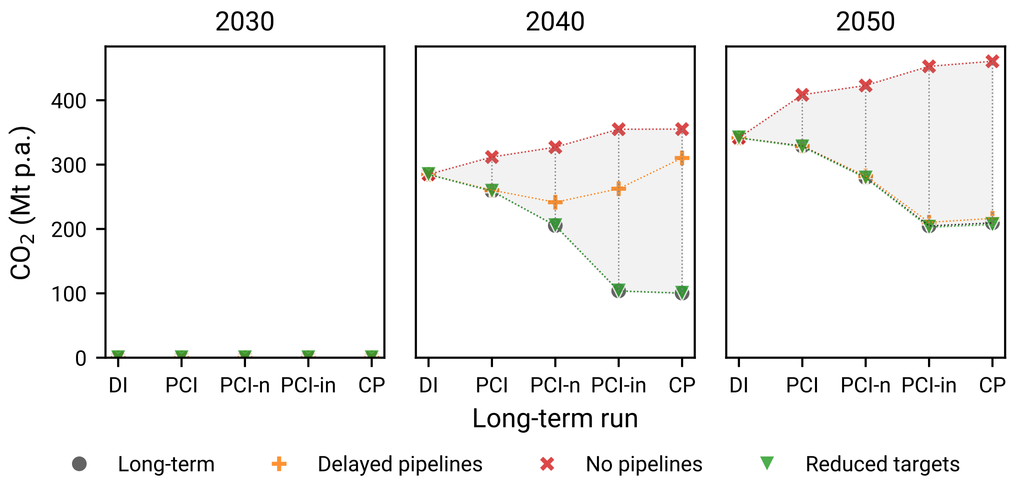


Figure 6: Delta balances — CO_2 from Direct Air Capture.

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 **??**). 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 **??** and **??**). However,

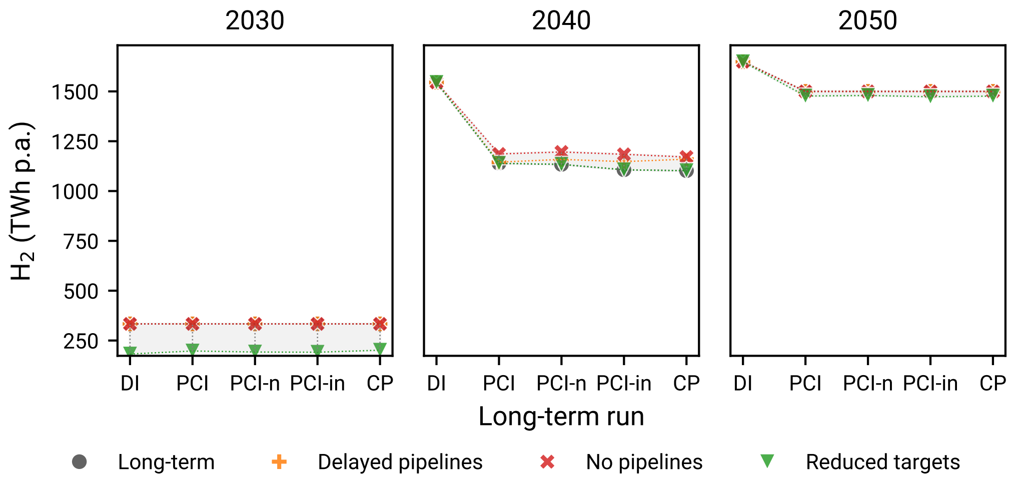
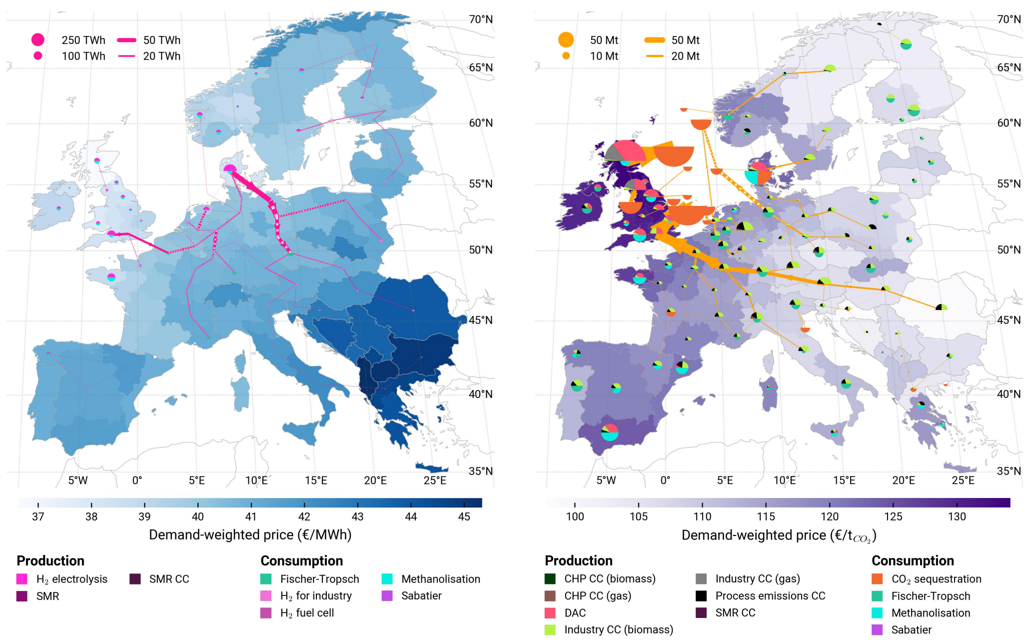


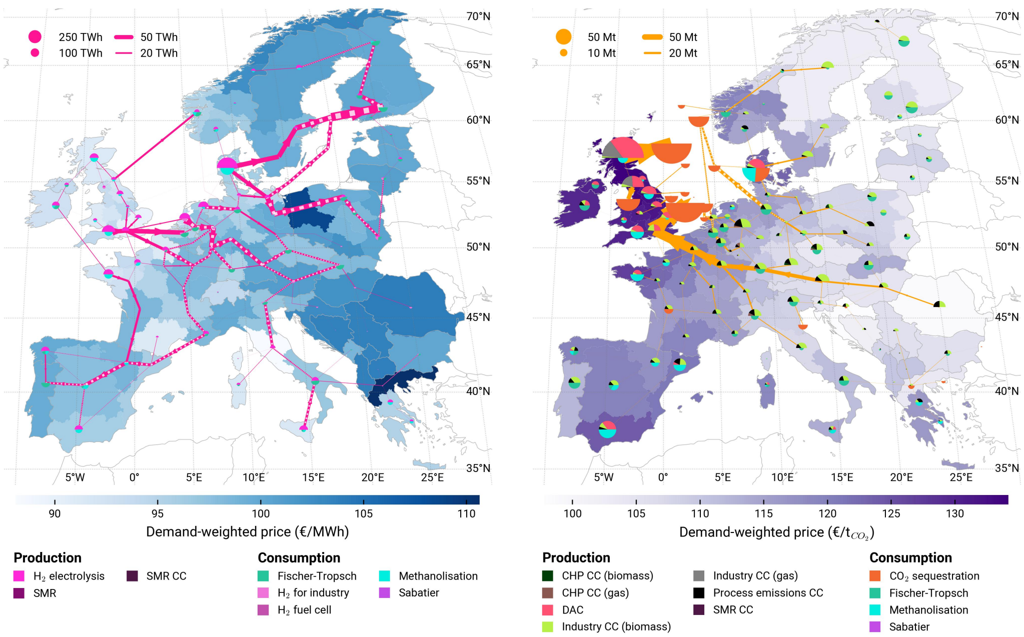
Figure 7: Delta balances — Electrolytic H_2 production



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

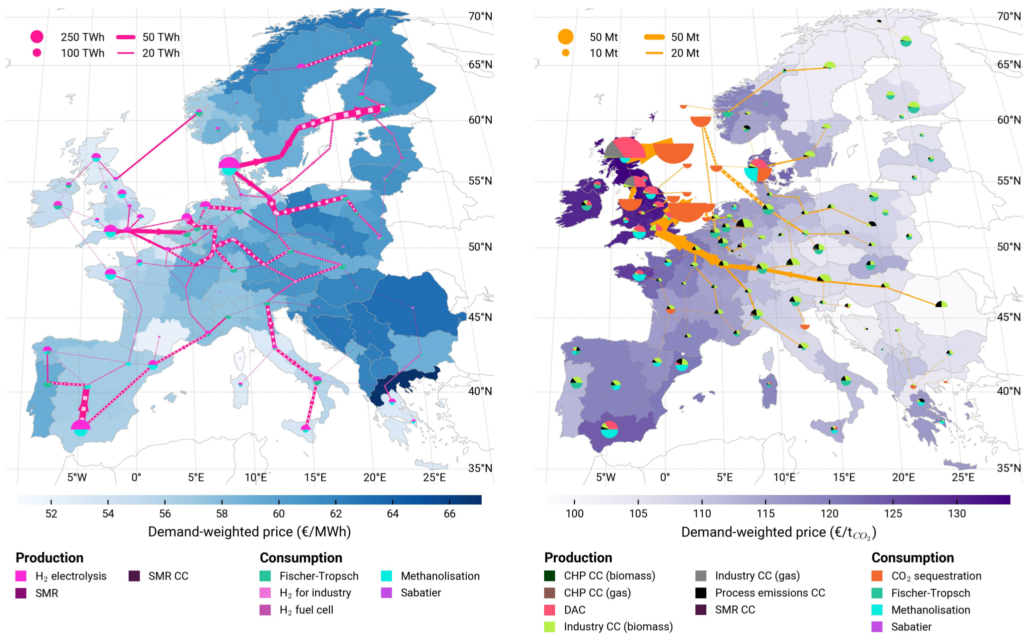
Figure 8: *PCI-in long-term* scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

Figure 9: *PCI-in long-term* scenario (2040) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances.

(b) CO_2 regional balances and flows.

Figure 10: *PCI-in long-term* scenario (2050) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.

this demand is met by decentral steam methane reforming instead of electrolysers (Figure **??**). 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) [23]. 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 **??** and **??**.

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 11). 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, ...

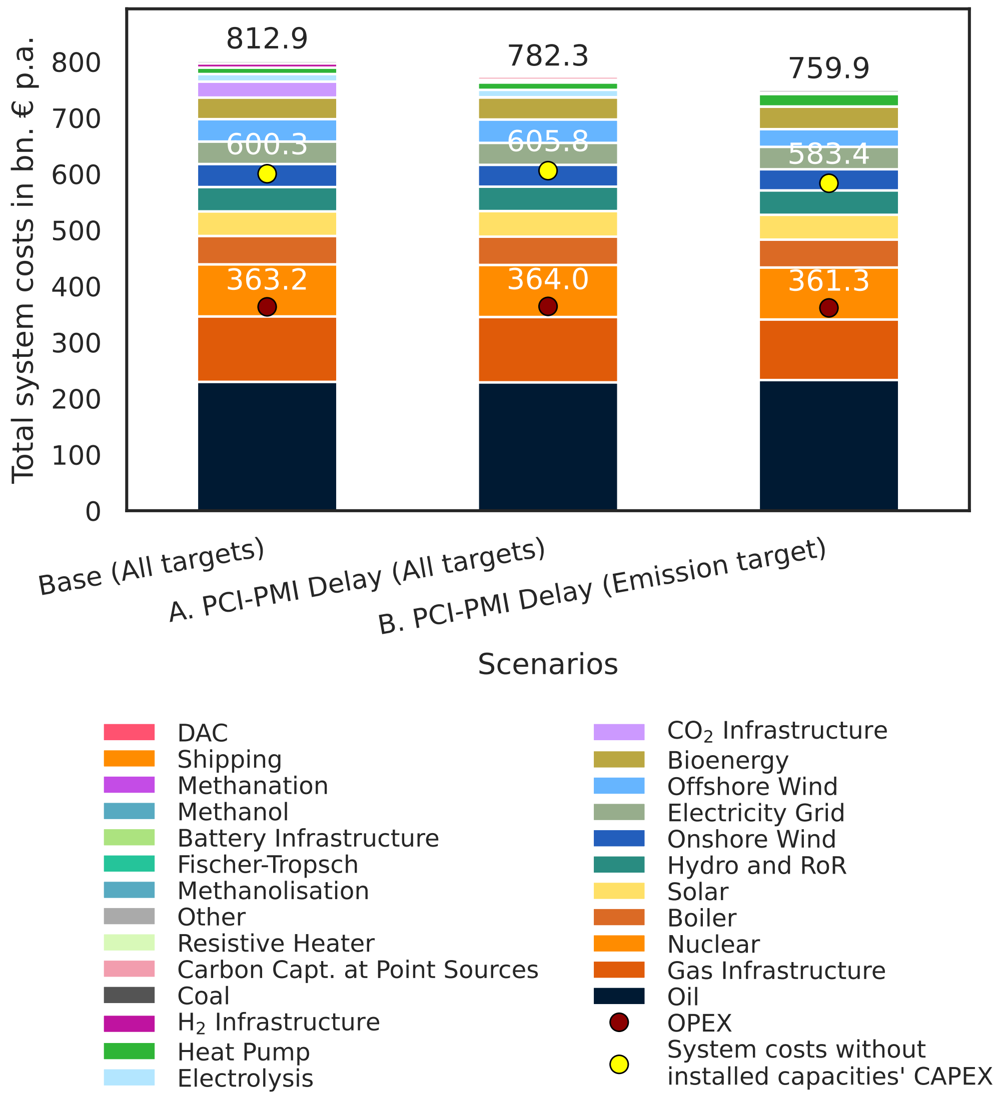


Figure 11: Results — Total system costs by technology and infrastructure.

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

This work was supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) under Grant No. 03EI4083A (RESILIENT). This project has been funded by partners of the CETPartnership (https://cetpartnership.eu) through the Joint Call 2022. As such, this project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no. 101069750.

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

374 # Appendix B. Supplementary material — Results and discussion

375 ## *Appendix B.1. Total energy balances*

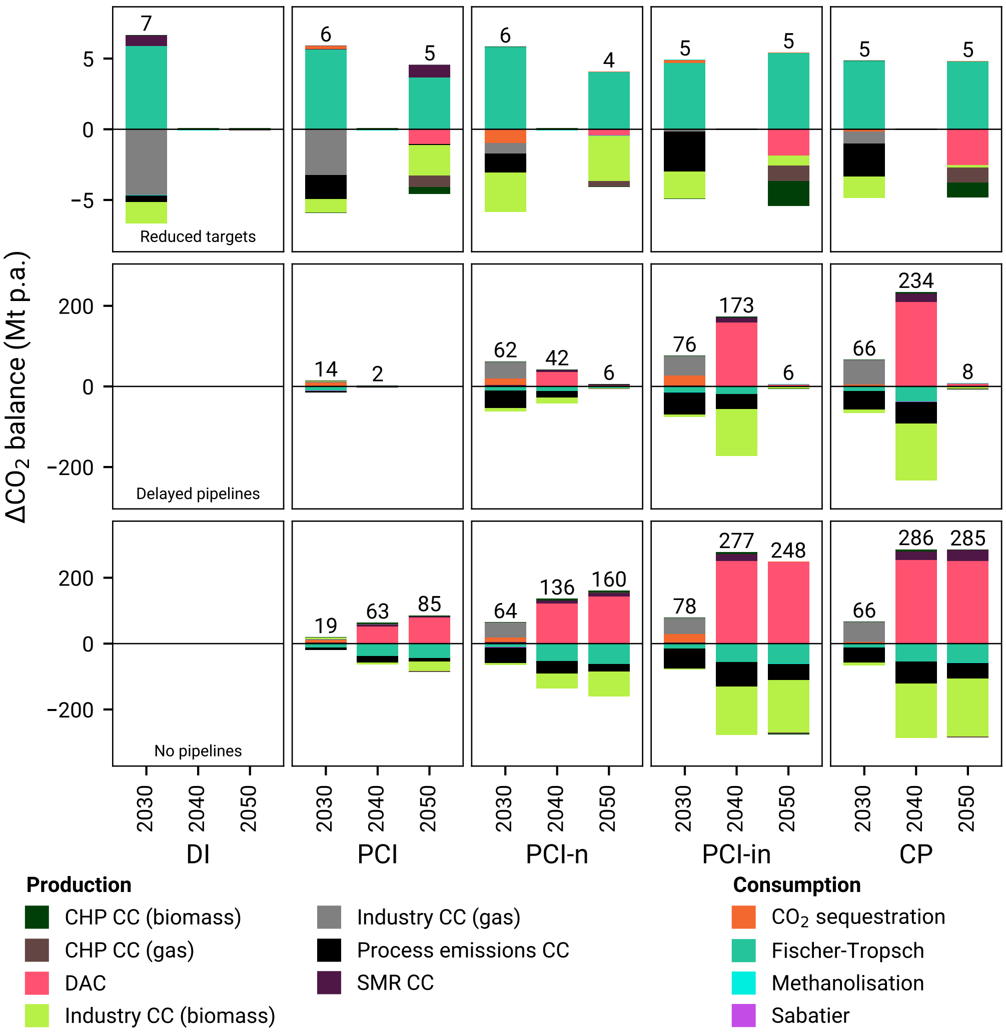


Figure B.12: ΔCO_2 balances — Long-term minus short-term runs.

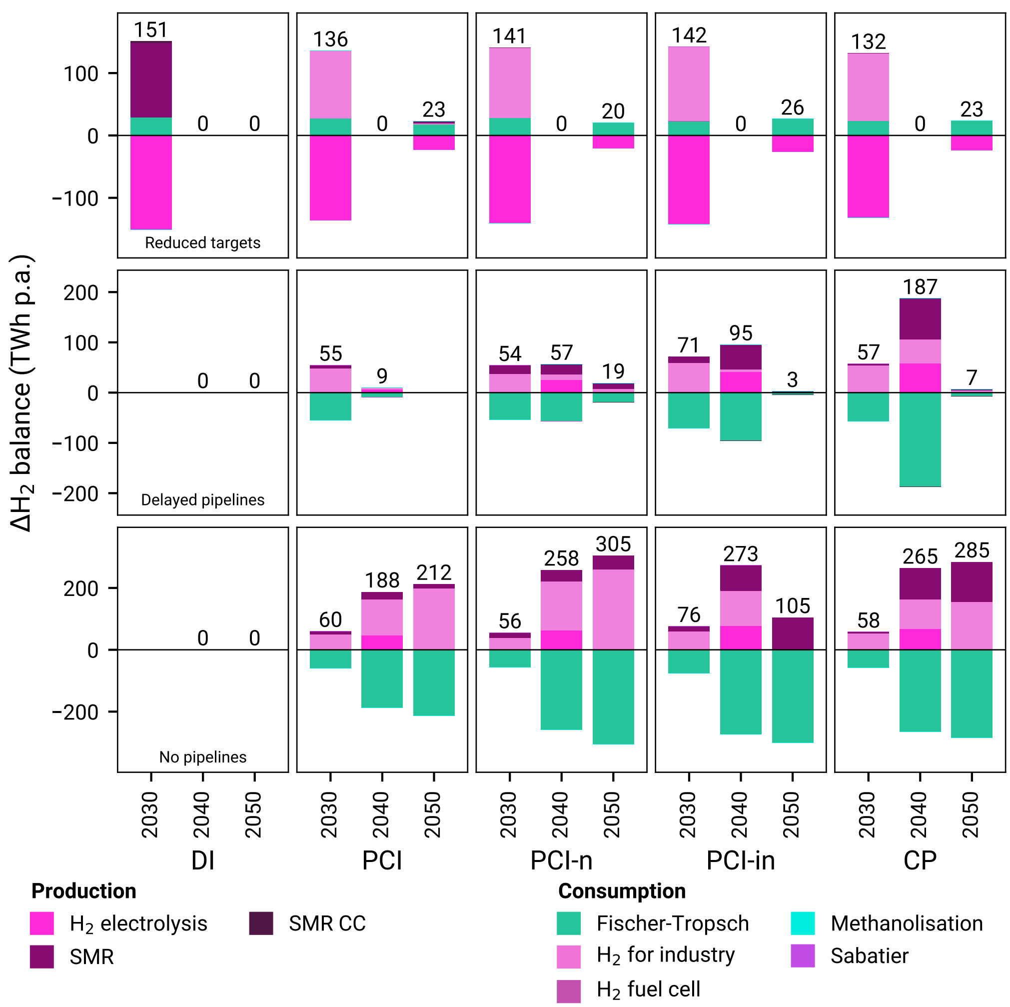
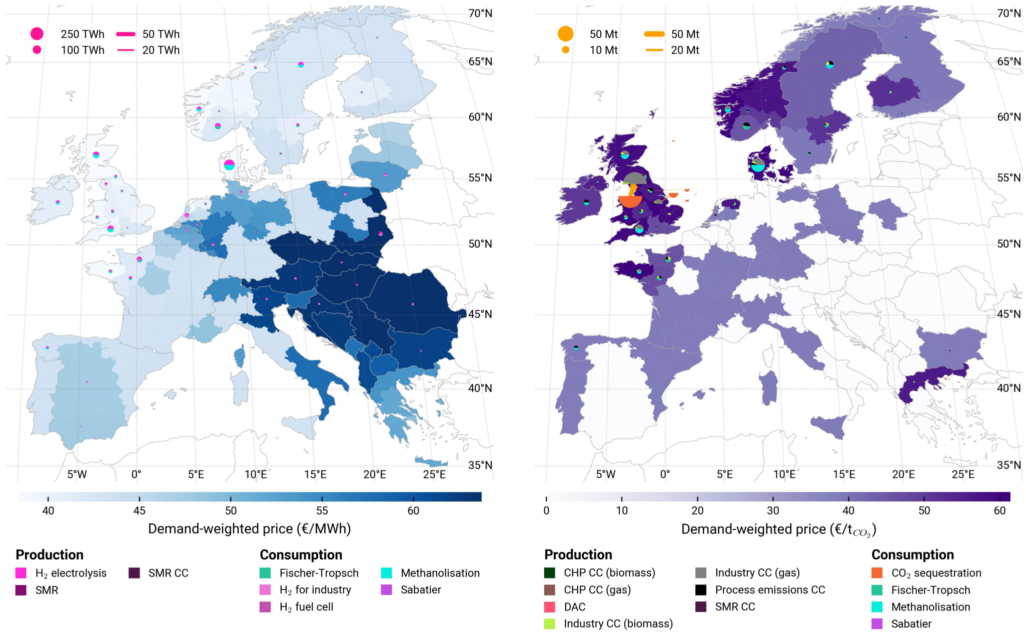


Figure B.13: ΔH_2 balances — Long-term minus short-term runs.

Appendix B.2. Maps

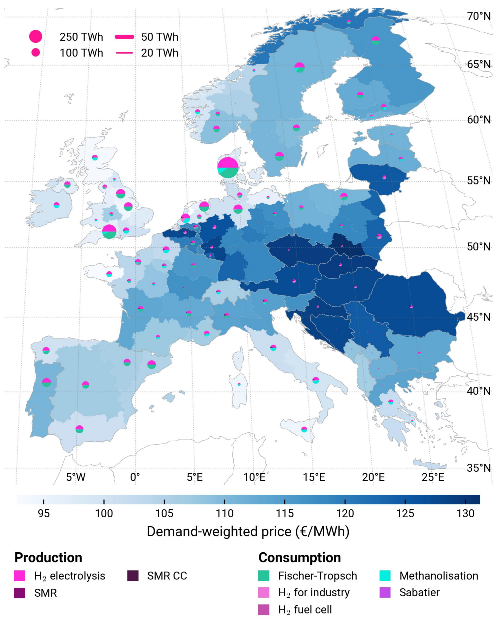
Appendix B.2.1. Decentral Islands



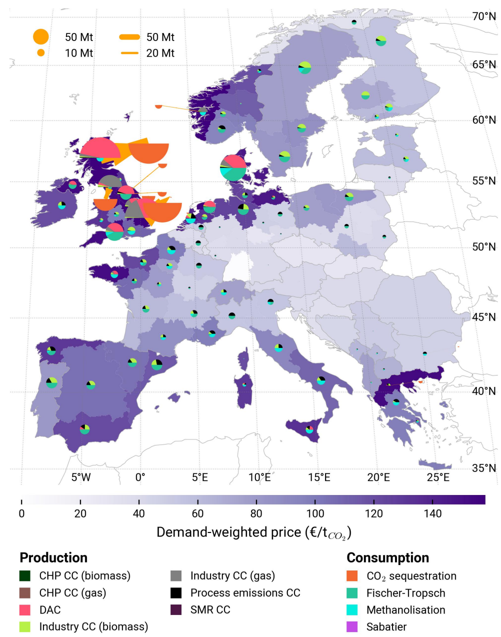
(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

Figure B.14: *Decentral Islands* scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.

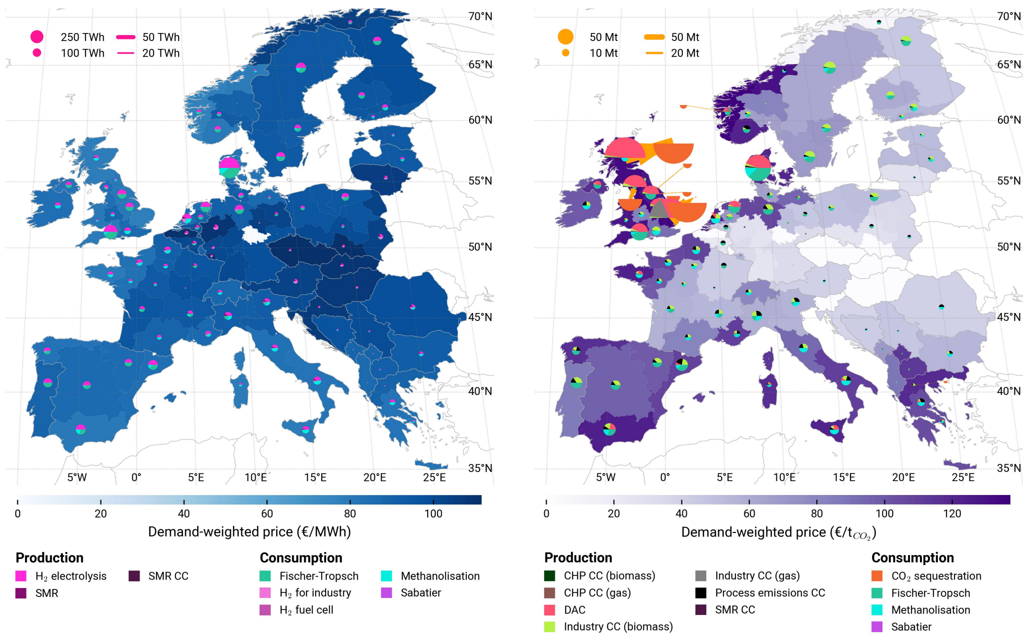


(a) H_2 regional balances and flows.



(b) CO_2 regional balances and flows.

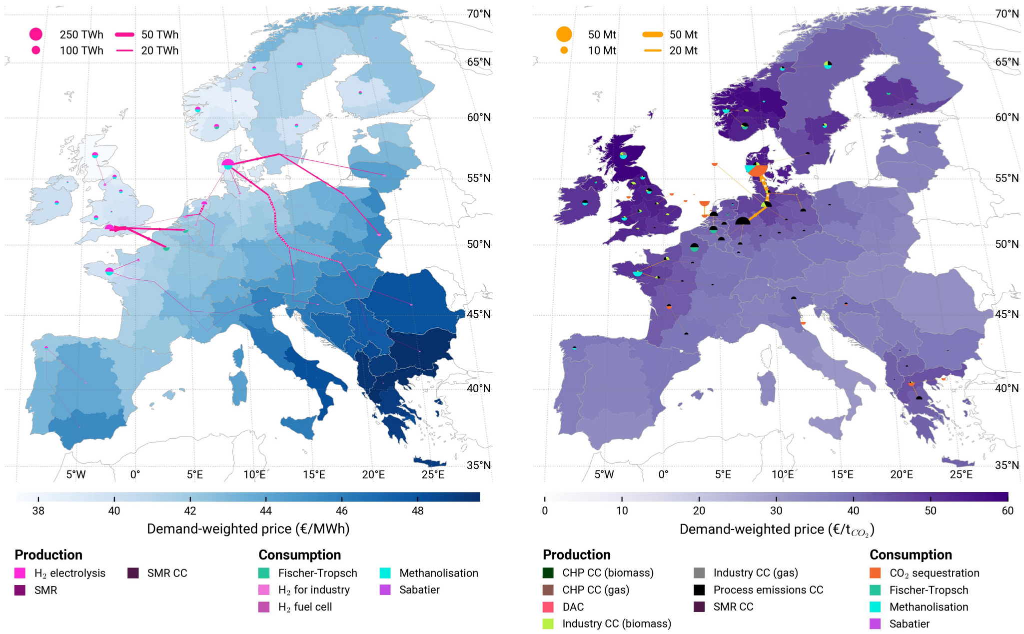
Figure B.15: *Decentral Islands* scenario (2040) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

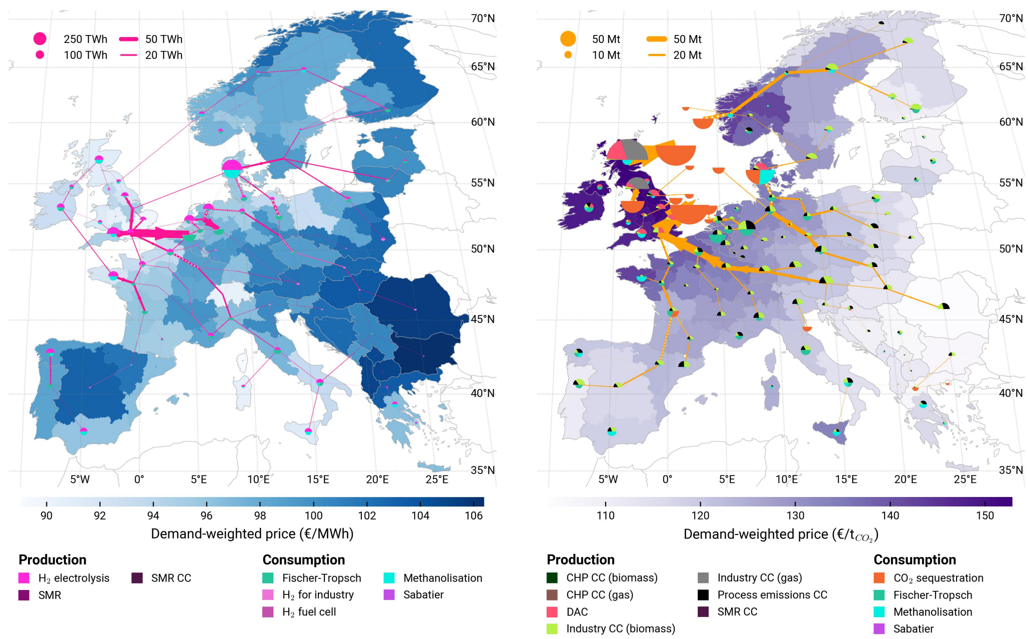
Figure B.16: *Decentral Islands* scenario (2050) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

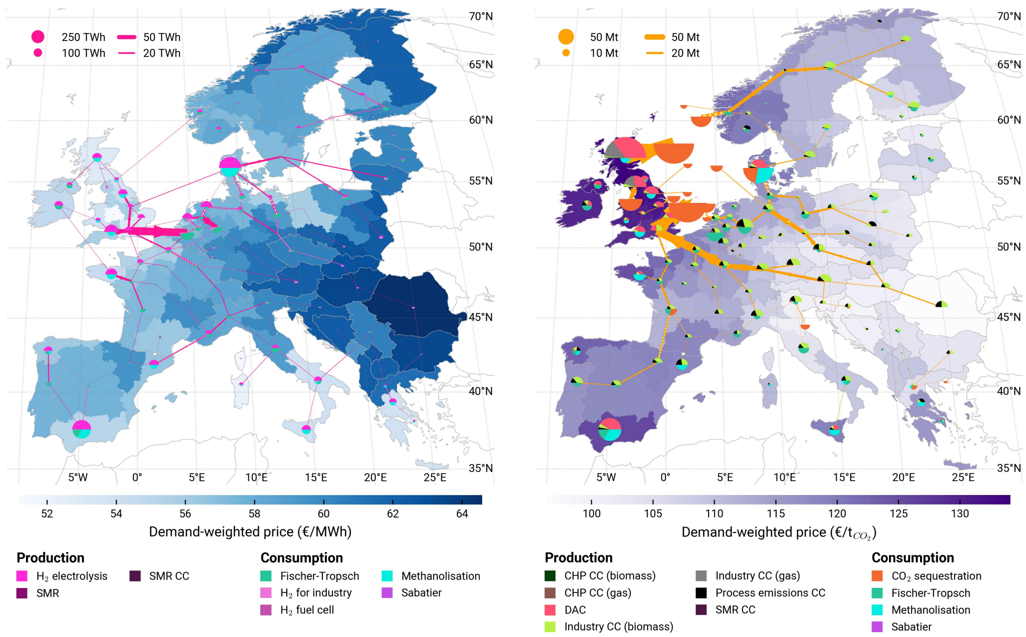
Figure B.17: *Central Planning* scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

Figure B.18: *Central Planning* scenario (2040) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

Figure B.19: *Central Planning* scenario (2050) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.

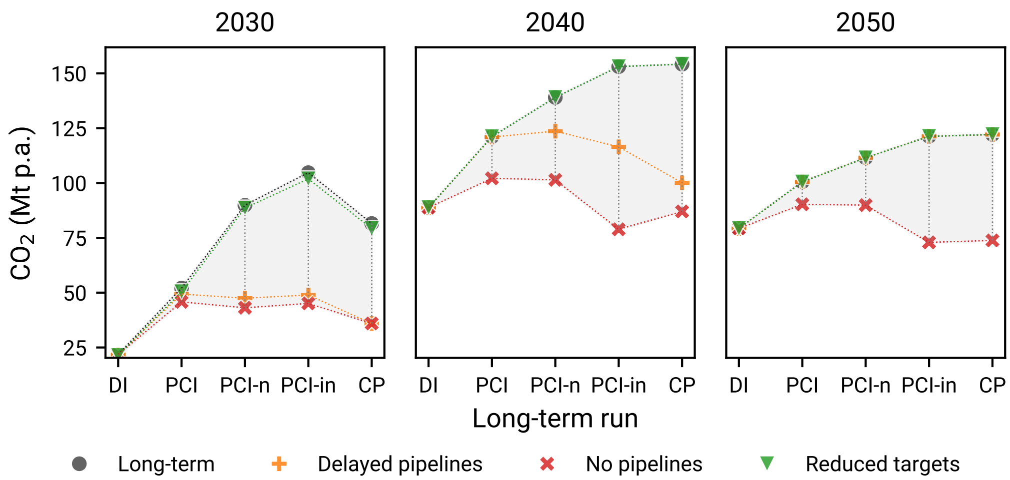


Figure B.20: Delta balances — Process emissions including Carbon Capture.

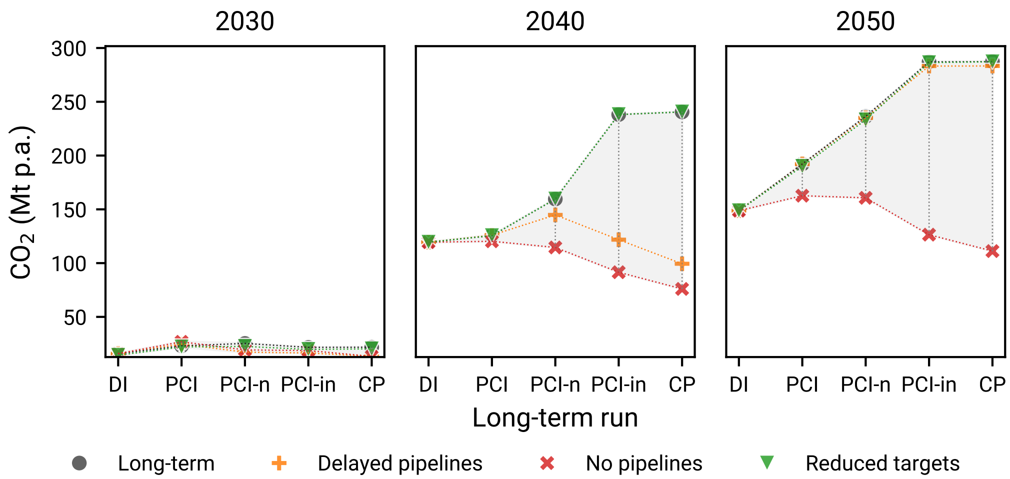


Figure B.21: Delta balances — CO_2 captured from solid biomass for industry point sources.

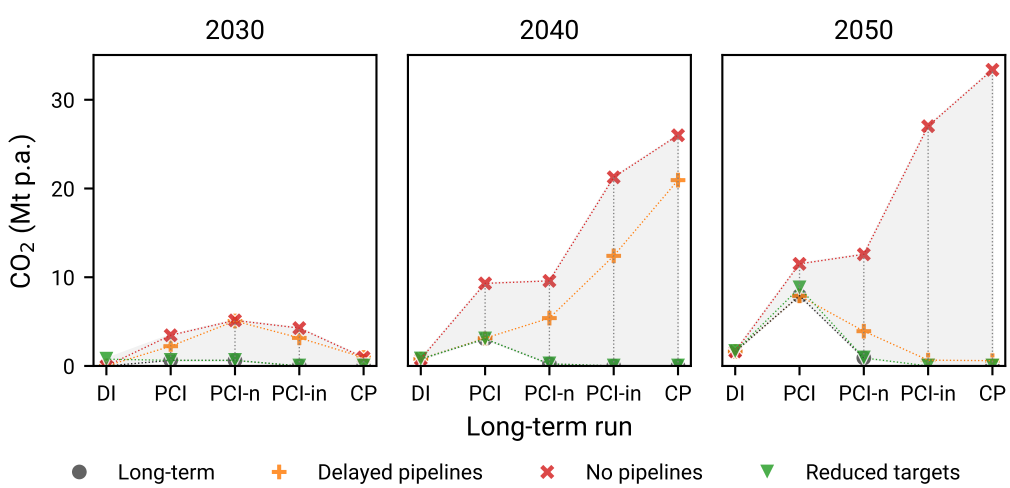


Figure B.22: Delta balances — CO_2 captured from steam methane reforming point sources.

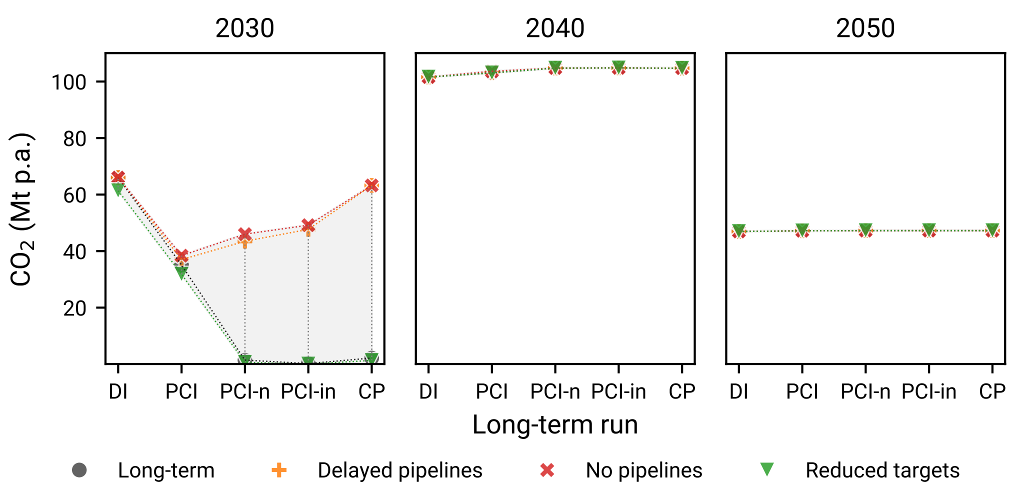


Figure B.23: Delta balances — CO_2 captured from gas for industry point sources.

References

[1] European Commission, '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 Committee and the Committee of the Regions, COM(2021) 550 final, Brussels. (2021).

[2] European Commission, 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. (2022).

[3] E. Parliament, Council of the European Union, 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) (Jun. 2024).

[4] European Commission, Commission Delegated Regulation (EU) 2024/1041 of 28 November 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 (Nov. 2023).

[5] ACER, Consolidated report on the progress of electricity and gas Projects of Common Interest in 2023, Tech. rep., European Union Agency for the Cooperation of Energy Regulators, Ljubljana (Jun. 2023).

[6] K. van Greevenbroek, J. Schmidt, M. Zeyringer, A. Horsch, Little to lose: The case for a robust European green hydrogen strategy (Dec. 2024). `arXiv:2412.07464`, `doi:10.48550/arXiv.2412.07464`.

[7] R. Béres, W. Nijs, A. Boldrini, M. van den Broek, Will hydrogen and synthetic fuels energize our future? Their role in Europe's climate-neutral energy system and power system dynamics, Applied Energy 375 (2024) 124053. `doi:10.1016/j.apenergy.2024.124053`.

[8] G. A. Reigstad, S. Roussanaly, J. Straus, R. Anantharaman, R. de Kler, M. Akhurst, N. Sunny, W. Goldthorpe, L. Avignon, J. Pearce,

S. Flamme, G. Guidati, E. Panos, C. Bauer, Moving toward the low-carbon hydrogen economy: Experiences and key learnings from national case studies, Advances in Applied Energy 8 (2022) 100108. doi:10.1016/j.adapen.2022.100108.

[9] F. Neumann, E. Zeyen, M. Victoria, T. Brown, The potential role of a hydrogen network in Europe, Joule 7 (8) (2023) 1793–1817. doi:10.1016/j.joule.2023.06.016.

[10] T. Fleiter, J. Fragoso, B. Lux, Ş. Alibaş, K. Al-Dabbas, P. Manz, F. Neuner, B. Weißenburger, M. Rehfeldt, F. Sensfuß, Hydrogen Infrastructure in the Future CO2-Neutral European Energy System—How Does the Demand for Hydrogen Affect the Need for Infrastructure?, Energy Technology 13 (2) (2025) 2300981. doi:10.1002/ente.202300981.

[11] H. Blanco, W. Nijs, J. Ruf, A. Faaij, Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization, Applied Energy 232 (2018) 617–639. doi:10.1016/j.apenergy.2018.09.216.

[12] B. Pickering, F. Lombardi, S. Pfenninger, Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system, Joule 6 (6) (2022) 1253–1276. doi:10.1016/j.joule.2022.05.009.

[13] F. Schreyer, F. Ueckerdt, R. Pietzcker, R. Rodrigues, M. Rottoli, S. Madeddu, M. Pehl, R. Hasse, G. Luderer, Distinct roles of direct and indirect electrification in pathways to a renewables-dominated European energy system, One Earth 7 (2) (2024) 226–241. doi:10.1016/j.oneear.2024.01.015.

[14] G. S. Seck, E. Hache, J. Sabathier, F. Guedes, G. A. Reigstad, J. Straus, O. Wolfgang, J. A. Ouassou, M. Askeland, I. Hjorth, H. I. Skjelbred, L. E. Andersson, S. Douguet, M. Villavicencio, J. Trüby, J. Brauer, C. Cabot, Hydrogen and the decarbonization of the energy system in europe in 2050: A detailed model-based analysis, Renewable and Sustainable Energy Reviews 167 (2022) 112779. doi:10.1016/j.rser.2022.112779.

[15] E. Zeyen, M. Victoria, T. Brown, Endogenous learning for green hydrogen in a sector-coupled energy model for Europe, Nature Communications 14 (1) (2023) 3743. doi:10.1038/s41467-023-39397-2.

[16] I. Kountouris, R. Bramstoft, T. Madsen, J. Gea-Bermúdez, M. Münster, D. Keles, A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production, Nature Communications 15 (1) (2024) 5517. doi:10.1038/s41467-024-49867-w.

[17] E. Trutnevyte, Does cost optimization approximate the real-world energy transition?, Energy 106 (2016) 182–193. doi:10.1016/j.energy.2016.03.038.

[18] M. Victoria, E. Zeyen, T. Brown, Speed of technological transformations required in Europe to achieve different climate goals, Joule 6 (5) (2022) 1066–1086. doi:10.1016/j.joule.2022.04.016.

[19] F. Neumann, J. Hampp, T. Brown, Energy Imports and Infrastructure in a Carbon-Neutral European Energy System (Apr. 2024). arXiv:2404.03927, doi:10.48550/arXiv.2404.03927.

[20] J. Hampp, M. Düren, T. Brown, Import options for chemical energy carriers from renewable sources to Germany, PLOS ONE 18 (2) (2023) e0262340. doi:10.1371/journal.pone.0281380.

[21] F. Wiese, R. Bramstoft, H. Koduvere, A. Pizarro Alonso, O. Balyk, J. G. Kirkerud, Å. G. Tveten, T. F. Bolkesjø, M. Münster, H. Ravn, Balmorel open source energy system model, Energy Strategy Reviews 20 (2018) 26–34. doi:10.1016/j.esr.2018.01.003.

[22] B. H. Bakken, I. von Streng Velken, Linear Models for Optimization of Infrastructure for CO2 Capture and Storage, IEEE Transactions on Energy Conversion 23 (3) (2008) 824–833. doi:10.1109/TEC.2008.921474.

[23] F. Hofmann, C. Tries, F. Neumann, E. Zeyen, T. Brown, H2 and CO2 network strategies for the European energy system, Nature Energy (2025) 1–10doi:10.1038/s41560-025-01752-6.

[24] T. Möbius, I. Riepin, Regret analysis of investment decisions under uncertainty in an integrated energy system, in: 2020 17th International

Conference on the European Energy Market (EEM), 2020, pp. 1–5. doi:10.1109/EEM49802.2020.9221935.

[25] European Court of Auditors, The EU's industrial policy on renewable hydrogen: Legal framework has been mostly adopted — time for a reality check. Special report 11, 2024., Tech. rep., Publications Office, LU (2024).

[26] M. M. Frysztacki, G. Recht, T. Brown, A comparison of clustering methods for the spatial reduction of renewable electricity optimisation models of Europe, Energy Informatics 5 (1) (2022) 4. doi:10.1186/s42162-022-00187-7.

[27] P. Glaum, F. Neumann, T. Brown, Offshore power and hydrogen networks for Europe's North Sea, Applied Energy 369 (2024) 123530. doi:10.1016/j.apenergy.2024.123530.

[28] J. Hörsch, F. Hofmann, D. Schlachtberger, T. Brown, PyPSA-Eur: An open optimisation model of the European transmission system, Energy Strategy Reviews 22 (2018) 207–215. doi:10.1016/j.esr.2018.08.012.

[29] F. Gotzens, H. Heinrichs, J. Hörsch, F. Hofmann, Performing energy modelling exercises in a transparent way - The issue of data quality in power plant databases, Energy Strategy Reviews 23 (2019) 1–12. doi:10.1016/j.esr.2018.11.004.

[30] F. Hofmann, J. Hampp, F. Neumann, T. Brown, J. Hörsch, Atlite: A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series, Journal of Open Source Software 6 (62) (2021) 3294. doi:10.21105/joss.03294.

[31] B. Xiong, D. Fioriti, F. Neumann, I. Riepin, T. Brown, Modelling the high-voltage grid using open data for Europe and beyond, Scientific Data 12 (1) (2025) 277. doi:10.1038/s41597-025-04550-7.

[32] L. Kotzur, P. Markewitz, M. Robinius, D. Stolten, Impact of different time series aggregation methods on optimal energy system design, Renewable Energy 117 (2018) 474–487. doi:10.1016/j.renene.2017.10.017.

[33] L. Zeyen, J. Hampp, N. Fabian, M. Millinger, Parzen, L. Franken, T. Brown, J. Geis, P. Glaum, M. Victoria, C. Schauss, A. Schledorn, T. Kähler, L. Trippe, T. Gilon, K. van Greevenbroek, T. Seibold, PyPSA/technology-data: V0.10.1 (Jan. 2025). doi:10.5281/ZENODO.14621698.

[34] L. Mantzos, N. A. Matei, E. Mulholland, M. Rózsai, M. Tamba, T. Wiesenthal, JRC-IDEES 2015 (Jun. 2018). doi:10.2905/JRC-10110-10001.

[35] Eurostat, Complete energy balances (2022). doi:10.2908/NRG_BAL_C.

[36] P. Manz, T. Fleiter, Georeferenced industrial sites with fuel demand and excess heat potential (Mar. 2018). doi:10.5281/ZENODO.4687147.

[37] J. Muehlenpfordt, Time series (Jun. 2019). doi:10.25832/TIME_SERIES/2019-06-05.

[38] U. Krien, P. Schönfeldt, B. Schachler, J. Zimmermann, J. Launer, F. Witte, F. Maurer, A. Ceruti, C. Möller, M.-C. Gering, G. Becker, S. Birk, S. Bosch, Oemof/demandlib: V0.2.2, Zenodo (Apr. 2025). doi:10.5281/ZENODO.2553504.

[39] E. Zeyen, S. Kalweit, M. Victoria, T. Brown, Shifting burdens: How delayed decarbonisation of road transport affects other sectoral emission reductions, Environmental Research Letters 20 (4) (2025) 044044. doi:10.1088/1748-9326/adc290.

[40] European Commission. Directorate General for Climate Action., Technopolis Group., COWI., Eunomia., In-Depth Report on the Results of the Public Consultation on the EU Climate Target for 2040: Final Report., Publications Office, LU, 2024.

[41] European Commission, PCI-PMI transparency platform. Projects of Common Interest & Projects of Mutual Intereset - Interactive map, https://ec.europa.eu/energy/infrastructure/transparency_platform/map-viewer (2024).