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

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Abstract

OLD OUTDATED IEW-EXTENDED-ABSTRACT.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

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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)
NUTS Nomenclature of Territorial Units for Statistics
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

WORK-IN-PROGRESS-INCOMPLETE. 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 Mt p.a., 550 Mt p.a., up to 1100 Mt p.a. Range of green hydrogen production in 2050 goes up to 90 Mt p.a. Page 3: Europe has little to loose by committing to targets like 25 Mt pa H2 production by 2040, moderate target, 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. [?] ... 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. [18] 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 [19] 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 [20], 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, [21]

Doing both: Hofmann et al. [22] 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

... WORK-IN-PROGRESS-INCOMPLETE.

2.3. Addressing uncertainty in energy system models

WORK-IN-PROGRESS-INCOMPLETE.

- Regret analysis common in economics, also in energy system modelling
- Carbon networks
- Regret
- Cite Hobbs, Iegor, Möbius and Riepin two-stage, stochastic, regret approach [**?**] PCI projects gas

3. Research gaps and our contribution

TODO NOVELTIES:

- basically mega PINT CBA, which was not done before, neither for PCI projects nor for the sectors
- Chicken and egg problem. Assess 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)

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, 23]

4. Methodology

We build on the open-source, sector-coupled energy system model PyPSA-Eur [9, 24–26] 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]. Furthermore, electricity transmission projects from the TYNDP (SOURCE) and German Netzentwicklungsplan (SOURCE) are also enabled.

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 B.4). Depending on the scenario, additional offshore buses are introduced to appropriately represent offshore sequestration sites and PCI-PMI projects. To isolate the effect of PCI-PMI projects, Europe is self-sufficient in our study, i.e., we do not allow any imports or exports of the assessed carriers like electricity, H_2, or CO_2.

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). We assume CO_2 sequestration costs of 15 €/tCO_2 which can be considered in the mid-range of the cost spectrum (cf. TODO SOURCE 1 and 10 €/tCO_2 [22])

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 [32–36] and are shown in Figure A.9. 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 Mt p.a. in 2030 and 460 Mt p.a. in 2040, respectively (see Table 2).

PCI-PMI projects implementation. We implement all PCI-PMI projects of the electricity, CO_2 and H_2 sectors (excl. 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 [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. We consider the exact geographic information, build year, as well as available static technical parameters when adding individual assets to the respective modelling year. An overview of the implemented PCI-PMI projects is provided in Figure 1.

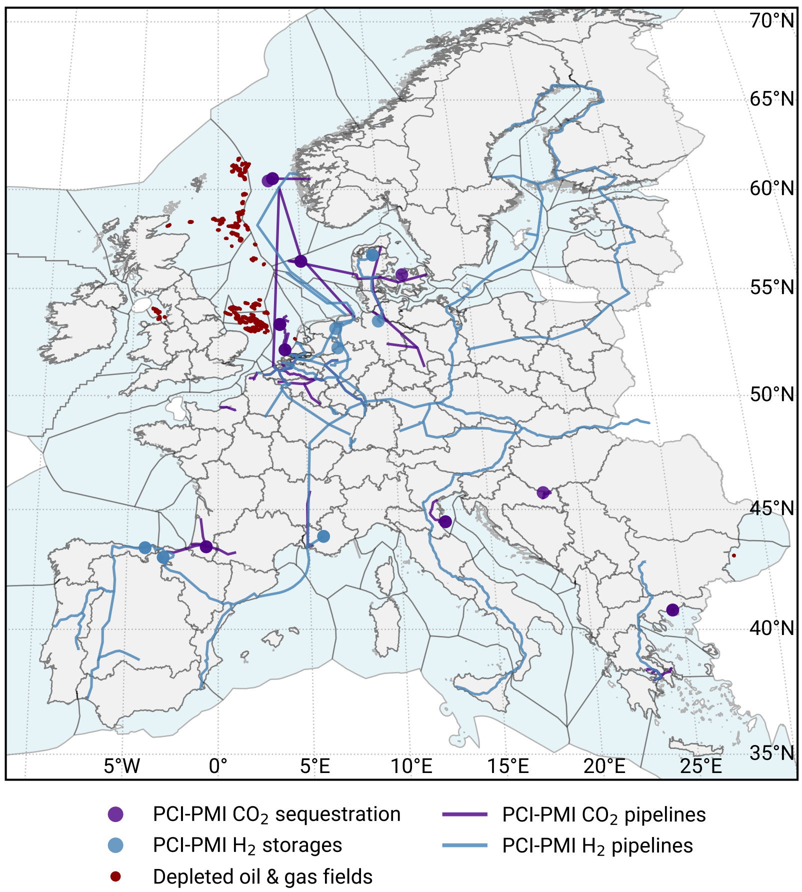


Figure 1: Map of the regional scope including clustered onshore (grey) and offshore regions (blue), as well as PCI-PMI CO_2 and H_2 pipelines, storage and sequestration sites. Depleted offshore oil and gas fields (red) provide additional CO_2 sequestration potential [22].

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. Here, all projects are mapped to the 99 NUTS regions, in this process, pipelines are are aggregated and connect all overpassing regions. Similar to how all electricity lines and carrier links are modelled in PyPSA-Eur, lengths are calculated using the haversine formula multiplied by a factor of 1.25 to account for the non-straight shape of pipelines. We apply standardised cost assumptions [31] across all existing brownfield assets, model-endogenously selected projects, and exogenously specified PCI-PMI projects, equally. Our approach is motivated by two key considerations: (i) cost data submitted by project promoters are often incomplete and may differ in terms of included components, underlying assumptions, and risk margins; and (ii) applying uniform cost assumptions ensures comparability and a level playing field across all potential investments, including both PCI-PMI and model-endogenous options.

CO_2 sequestration sites. 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 [22, 40]. While social and commercial acceptance of CO_2 storage has been increasing in recent years, however, concerns still exist regarding its long-term purpose and safety [41]. For this reason, we only consider conservative estimates from depleted oil and gas fields, which are primarily located offshore in the British, Norwegian, and Dutch North Sea (see Figure 1), yielding a total sequestration potential of 7164 Mt. Spread over a lifetime of 25 years, this translates into an annual sequestration potential of up to 286 Mt p.a. We then cluster all offshore potential within a buffer radius of 50 km per offshore bus region in each modelled NUTS region and connect them through offshore CO_2 pipelines to the closest onshore bus (TODO: add reference to cost assumptions in appendix).

4.2. Scenario setup and regret matrix

To assess the long-term impact of PCI-PMI projects on the European energy system and EU energy policies, we implement a regret-matrix based approach. This allows us to evaluate the performance of a set of long-term scenarios under three different short-term occurrences for each planning horizon, individually (Table 3).

4.2.1. Long-term scenarios

Scenario definition. We define the long-term 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 long-term scenarios, (i) a pessimistic scenario (Decentral Islands — DI) without any H_2 pipeline and onshore CO_2 pipeline infrastructure, (ii) a scenario that considers the on-time commissioning of all PCI-PMI CO_2 and H_2 projects (PCI-PMI — PCI) only, (iii) more ambitious scenarios that further allow investments into national and (iv) international pipelines (PCI-PMI nat. — PCI-n and PCI-PMI internat. — PCI-in), and (v) a scenario that 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 (Centralised Planning — CP). An overview of the long-term scenarios and their associated model-endogenous decision variables is provided in Table 1.

Table 1: 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	–	■	■	■	■
International build-out	–	–	–	■	■
PCI-PMI extendable	–	–	–	–	■

■ enabled – disabled * approx. 286 Mt p.a. ** approx. 114 Mt p.a.

Targets. In all long-term 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 greenhouse gas emissions compared to 1990 levels [1], 10 Mt p.a. of domestic green H_2 production [2] and 40 GW [42], and 50 Mt p.a. of CO_2 sequestration capacity [3]. For 2050, the CO_2

sequestration target is derived from impact assessment, modelling for European Commission's 2024 industrial carbon management strategy, in which 250 Mt p.a. out of 450 Mt p.a. (Carbon Capture Utilisation and Storage) is sequestered [43]. H_2 production targets for 2050 are based on the European Commission's METIS 3 study S5 [44], modelling possible pathways for industry decarbonisations 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. Note that we implement the green H_2 production target as a minimum H_2 production constraint from elecrolysers, hence we will refer to this H_2 as electrolytic H_2 within the scope of this paper.

Table 2: Pathway for implemented targets.

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

Model targets based on [1–3, 43, 44]

4.2.2. Short-term scenarios

In a second step, we assess the impact of three short-term scenarios on the long-term scenarios, by fixing or removing pipeline capacities (depending on the scenario). Further, the model can still react by investing into additional generation, storage, or conversion, or carbon-removal technologies in the short-term, assuming the technical potential was not exceeded in the long-term optimisation. In *Reduced targets*, we remove all of the long-term targets (Table 2) except for the GHG emission reduction targets to assess the value of the CO_2 and H_2 infrastructure in a less ambitious policy 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.

Table 3 gives an overview of this regret-analysis and their individual assumptions, where the long-term scenario serves as the *planned* or *anticipated* and the short-term scenario serves as the hypothetically *realised* outcome. By comparing the system costs of related long-term and short-term scenarios, we can calculate its associated economic regret. In total, we run 60 optimisations on a cluster, taking up to 160 GB of RAM and 8 to 16 hours each to solve: $(n_{LT} \times n_{planning\,horizons}) \times (1 + n_{ST}) = 60$. The models are solved using Gurobi.

Table 3: Regret 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 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

5. Results and discussion

We structure the results and discussion into three main sections. First, we present the results of the long-term scenarios. Then, we look at the impact of the short-term scenarios on the long-term scenarios, by comparing the economic regret and impacts on CO_2 and H_2 balances. Finally, we assess the benefits of the PCI-PMI projects with regard to reduced system costs and discuss the implications of our findings for the European energy system and its policy targets.

5.1. Long-term scenarios

In all long-term runs, we observe the highest total annual system costs in the planning horizon 2040, ranging from 912 to 968 bn. € p.a. (Figure 2), driven by high investments. This can be primarily attributed to the strict exogenously given GHG emission reduction pathway, facing the largest net change from 2030 to 2040 — a carbon budget reduction of more than 1600 Mt p.a. as opposed to the remaining 460 Mt p.a. in the last decade. 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. With CO_2 pipelines connecting depleted offshore oil and gas fields to their closest onshore region, the policy targets, incl. CO_2 sequestration can be achieved at a total of 865 bn. € p.a. Adding PCI-PMI projects in 2030 increases costs by less than 1 %.

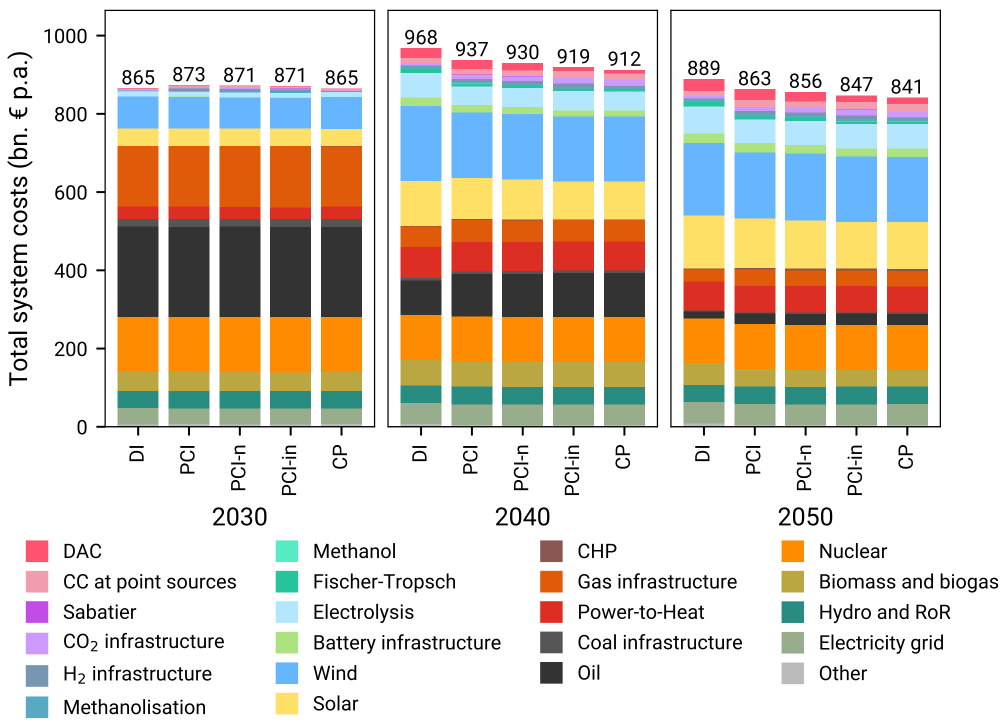


Figure 2: Total annual system costs (CAPEX + OPEX) by technology group.

Starting in 2040, all scenarios with PCI-PMI and endogenous pipeline investments unlock significant cost savings, from more than 30 bn. € p.a. in the *PCI* up to 50 bn. € p.a. in the *PCI-in* scenario. By giving the model complete freedom in pipeline expansions, additional annual cost savings of 6 to 7 bn. € are unlocked by investing in fewer, but more optimally located CO_2

and H_2 pipelines from a systemic perspective (see *PCI-in* pipeline utilisation in Figures C.23 to C.25 compared to *CP* pipeline utilisation in Figures C.26 to C.28). Further, this reduces the reliance on larger investments into wind generation and more expensive Direct Air Capture (DAC) technologies near the sequestration sites. These effects are slightly less pronounced in the 2050 model results, system costs can be reduced by 26 to 41 bn. € p.a. with PCI-PMI and endogenous pipeline investments.

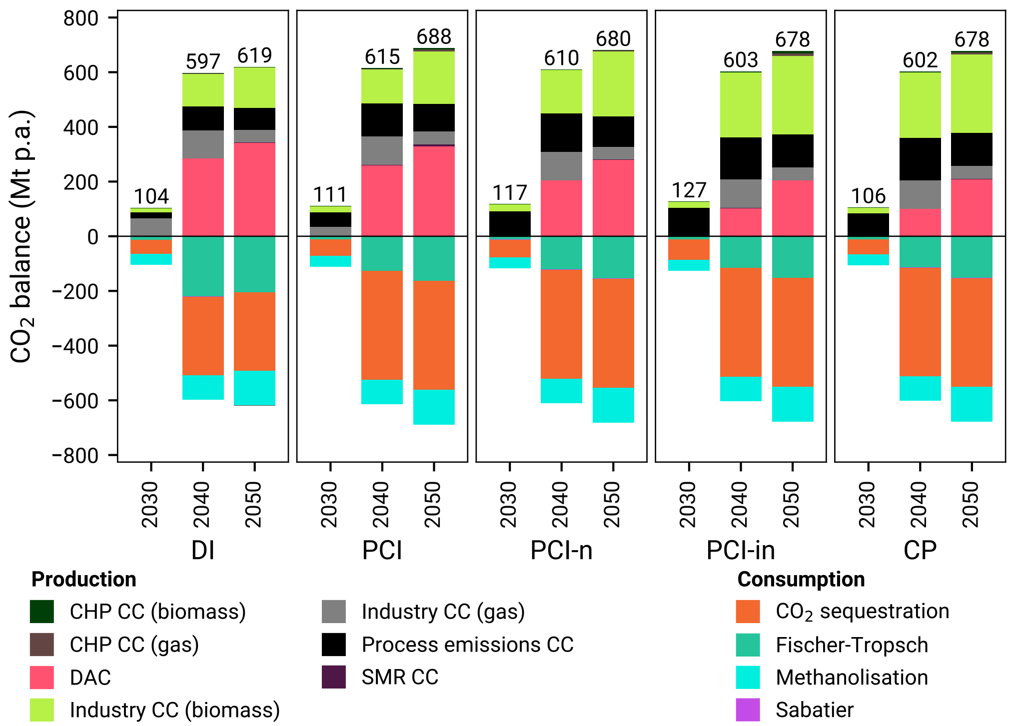
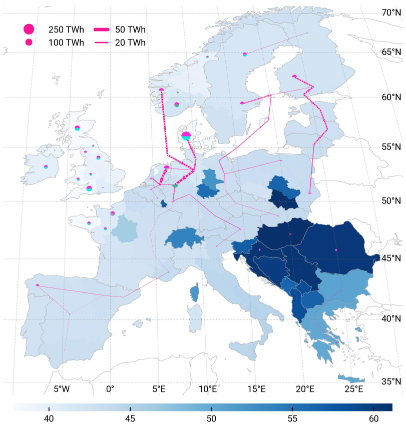


Figure 3: CO_2 balances in long-term scenarios.

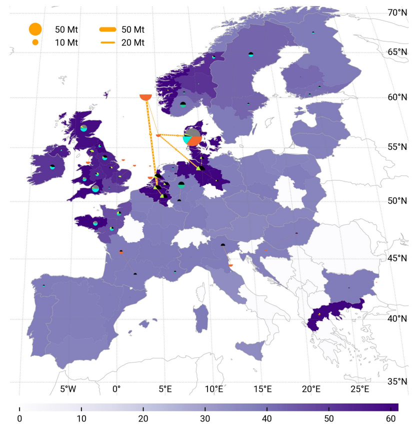
Carbon capture, utilisation, and storage. We find that most of the differences in system cost and savings can be attributed to the production and utilisation of CO_2, as shown in Figure 3. Lacking the option to transport CO_2 from industry and other point sources to the offshore sequestration sites, the model has to invest in expensive DAC technologies in the *DI* scenario. While the sequestration target of 50 Mt p.a. in 2030 is binding for the *DI* scenario, all other scenarios sequester more CO_2, the higher their CO_2 pipeline build-out.

The 53.9 Mt p.a. CO_2 sequestered in the *CP* serve as an indicator for what would be a cost-optimal amount for 2030 with perfectly located pipelines. 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 (see Figures 4b, 4d, and 4f).

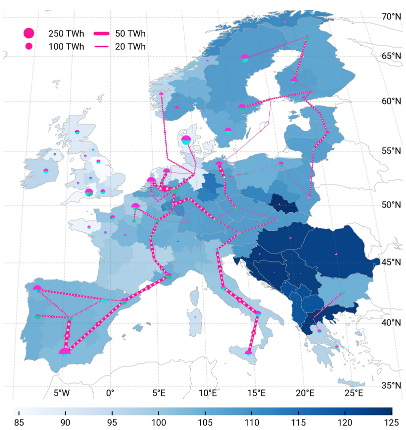
In 2040 and 2050, all sequestration targets (Table 2) are overachieved, as the full combined CO_2 sequestration potential of 398 Mt p.a. is exploited in all scenarios where PCI-PMI projects are included (*PCI* to *CP*. Emissions are captured from industrial processes equipped with carbon capture units, with biomass-based industry providing the largest share in carbon capture from point sources, ranging from 119 to 241 Mt p.a. in 2040 and 149 to 287 Mt p.a. in 2050, increasing with the build-out of CO_2 infrastructure (from left to right, see Figure 3). Being the most expensive carbon capture option, only up to 8 Mt p.a. of CO_2 is captured from SMR CC processes in the *PCI* scenario in 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 fuels instead — 221 Mt p.a. vs. 115-127 Mt p.a. (2040) and 206 Mt p.a. vs 153-163 Mt p.a. (2050), to meet the emission reduction targets for 2040 and 2050, respectively. Given the fixed exogenous demand for (shipping) methanol (Figure A.9), 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).



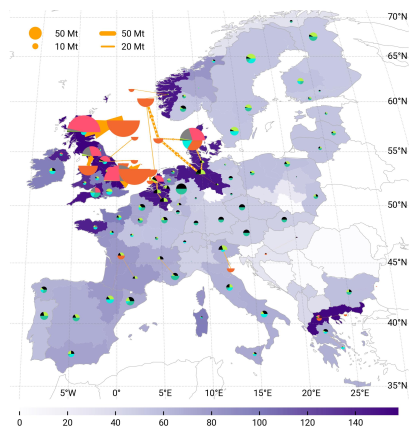
(a) H_2 2030.



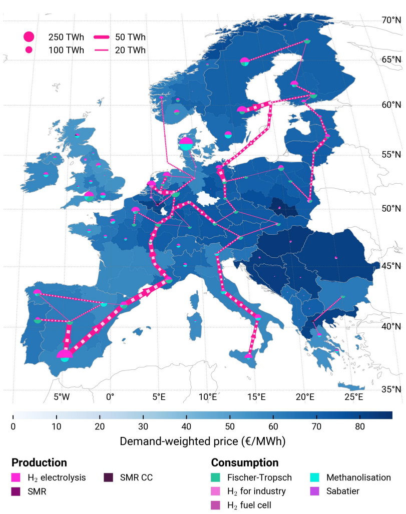
(b) CO_2 2030.



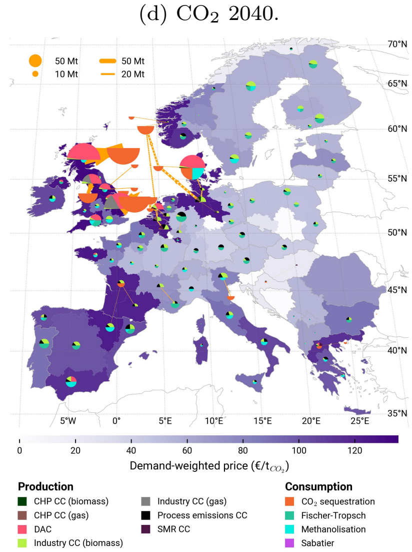
(c) H_2 2040.



(d) CO_2 2040.



(e) H_2 2050.



(f) CO_2 2050.

Figure 4: *PCI* long-term scenario — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.

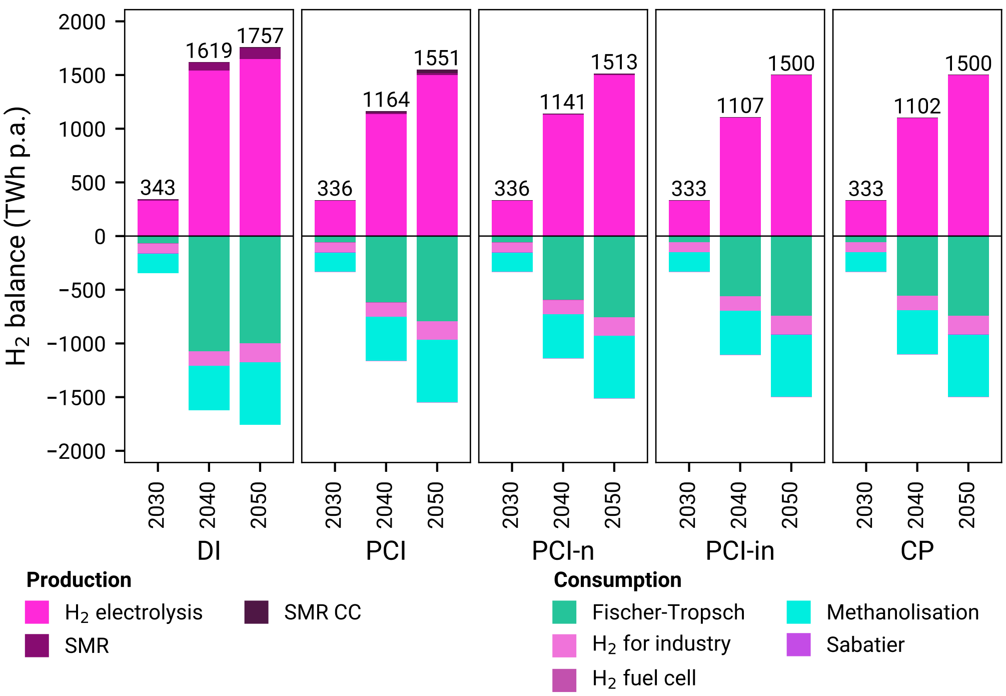


Figure 5: H_2 balances in long-term scenarios.

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 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 (see Table A.9). Only about about 93 to 173 TWh p.a. of H_2 is directly used in the industry. Throughout all long-term scenarios, H_2 is almost exclusively produced via electrolysis. Only without any H_2 pipeline infrastructure in the *DI*, the model reverts to steam methane reforming (SMR) to produce 71 to 102 TWh p.a. of H_2 in 2040 and 2050, respectively. Regionally, 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 4a, 4c, and 4e provide a map of the regional distribution of H_2 production, utilisation, and transport in the *PCI* scenario. Additional maps are provided in Appendix C.5. Note that PCI-PMI projects or candidates (in *CP* scenario) are plotted in dotted white lines.

TODO: Add section on H2 pipeline utilisation maybe histogram with all years overlapping in different colours

5.2. Performance in short-term scenarios

In this section, we assess the impact of the short-term scenarios on the long-term scenarios, by comparing the economic regret, as well as the impact on CO_2 utilisation and sequestration, H_2 production.

Regret analysis. We calculate the regret terms by subtracting the annual total system costs of the long-term scenarios (row) from the short-term scenarios (columns). Positive values reflect higher costs in the short-term scenarios compared to the long-term ones. Figure 6 shows the regret matrix for all scenarios and planning horizons. From left to right, the first column shows the regret terms for the *Reduced targets* scenario, where all long-term 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 column shows the regret terms for the *No pipelines* scenario, where all pipeline capacities are removed.

In the *Reduced targets* scenario, system costs barely change through the relaxation of the targets. The long-term results have shown that the model was overachieving the H_2 production targets in 2040. As for the CO_2 sequestration targets, the model is still incentivised by GHG emission targets, especially in 2040 and 2050. Only in 2030, we see minimal changes in total system costs. In all of the long-term scenarios, we have observed that in 2030 that especially CO_2 pipeline infrastructure is not essential yet (see Figure C.26b). As for H_2 pipeline infrastructure, the solution space seems to be quite flat, as the costs for the *DI* scenario without any pipelines (Figure C.20b) and the *CP* scenario (Figure C.26b) with notable pipeline investments are almost identical. By removing the H_2 production and CO_2 sequestration targets, pipelines become even less relevant, although the cost savings due to the dropped targets are minimal, ranging from 4.3 to 5 bn. € p.a. in 2030 and 2040.

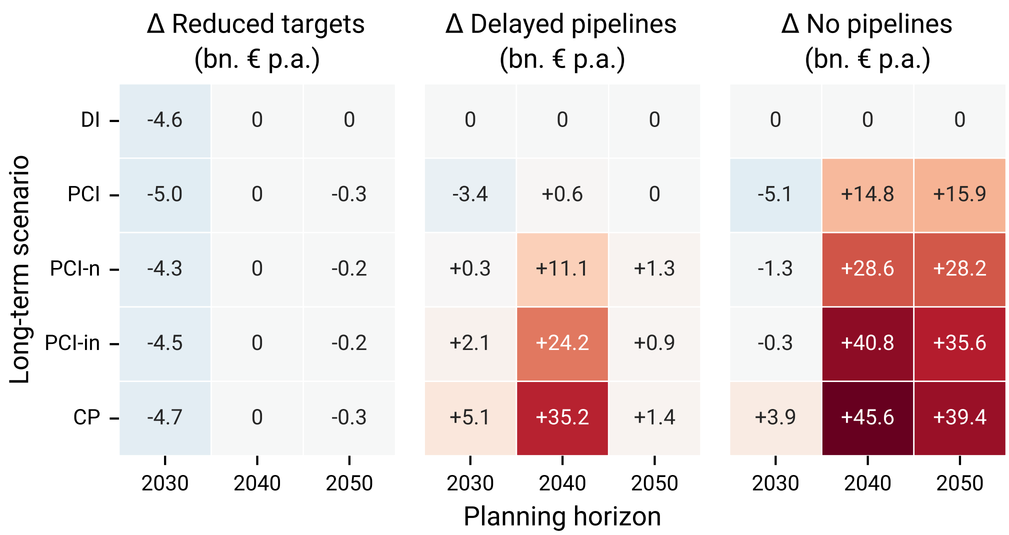


Figure 6: Regret matrix. Calculating regret terms by subtracting system costs of long-term scenarios (rows) from short-term scenarios (columns). Positive values reflect higher costs in the short-term scenarios compared to the long-term ones.

For the same reasons, the 2030 results for the *Delayed pipelines* and *No pipelines* scenarios show only minor differences in system costs compared to the long-term scenarios. Cost savings of 3.4 to 5.1 bn. € p.a. in the *PCI* long-term scenario indicate that for 2030, forcing in PCI-PMI projects are is cost- and topologically optimal in the short run. Whereas slight regret/cost increase of 3.9 to 5.1 bn € p.a. in the *CP* shows a small dependency on the invested pipeline infrastructure (Figure C.26), being the most cost-optimal 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 (incl. generation, transport, conversion technologies and storages) in the long-term scenario 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 to 24.2 bn. € p.a. in the scenarios with PCI-PMI projects and up to 35.2 bn. € p.a. in the *CP* scenario. Note that in the *PCI* scenario, almost all pipelines are originally commissioned by 2030. So a delay of projects from 2040 to 2050 only mildly impacts the system costs by 0.6 bn. € p.a. 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 bn. € p.a. The short-term scenario *No pipelines* shows the highest regrets, ranging from 14.8 to 45.6 bn. € p.a. in 2040 and 15.9 to 39.4 bn. € p.a. in 2050. Note that this scenario serves more of a hypothetical worst case as it is not likely to build out an energy system with pipelines in mind but none materialising at all.

Consistently throughout all short-term scenarios, most of the additional cost stem from the need to invest into additional carbon capture, renewable generation, and conversion technologies (see Figure C.11). 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.

Carbon capture. Further, the model has to invest in more than 28 GW of carbon capture 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 (see Figure C.12). 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 (see Figure C.13). 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 carbon capture (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 7. 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.

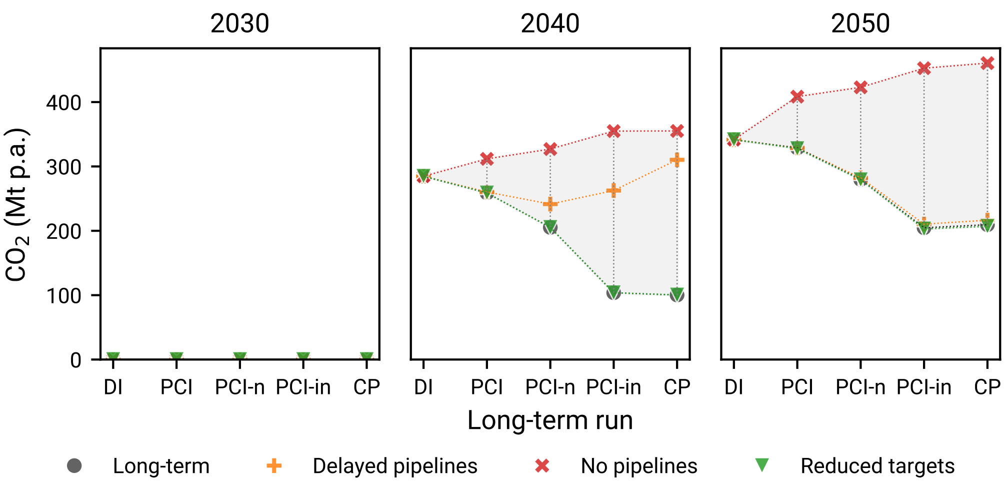


Figure 7: Delta balances — CO_2 from Direct Air Capture.

H_2 production. On the H_2 side, we find that the electrolytic H_2 production target of 10 Mt p.a. (333 TWh p.a.) in 2030 is overly ambitious. Figure C.18 shows that in the *Reduced targets* scenario, 132 to 151 TWh p.a. of H_2, corresponding to almost half of the target is produced from SMR instead of electrolysis. 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 carbon capture (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 (see Figure C.18).

5.3. Value of PCI-PMI projects

Looking at long-run we find that PCI-PMI projects, while not completely 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 bn. € p.a (Figure 8). Even when accounting for the additional costs of 0.6 bn. € faced in the *Delayed pipelines* and up to 15.9 bn. € p.a. 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 bn. € p.a. 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 pf all pipeline investments materialise after 2030, yielding lower net present values (NPV) of total system costs of potentially at least 75 bn. € over the course of the assets' lifetime.

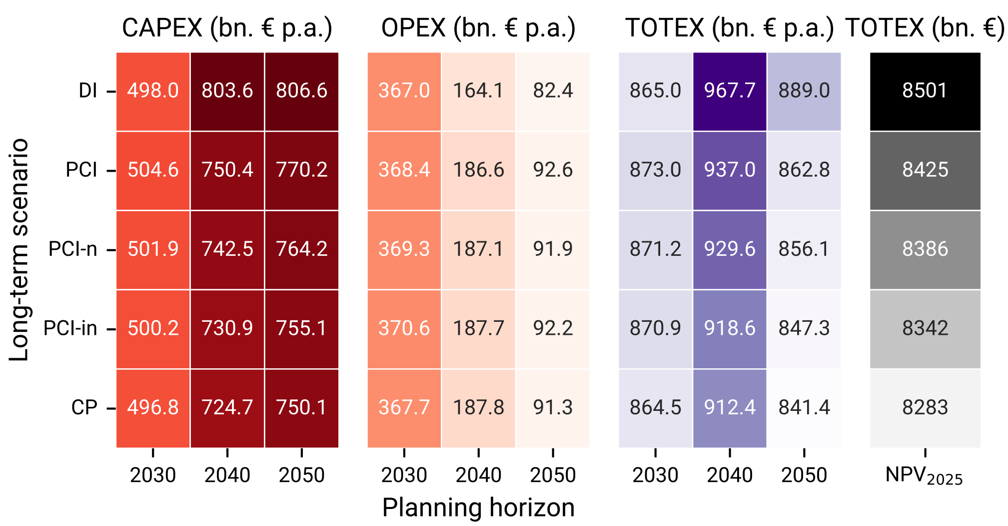


Figure 8: Annual system costs by long-term scenario and planning horizon.

5.4. Limitations of our study

While our study assesses a variety of topologies, planning horizons, and potential regret scenarios, it is not exhaustive and comes with limitations. As we focus on the impact of continental European PCI-PMI infrastructure, we neglect fuel and energy imports from outside Europe. H_2 and CO_2 demand is directly driven by fixed, exogenous demands for the respective carrier or their derivatives.

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 pipelines (due to computational complexity) and allow any capacity to be built. This assumption can lead to underestimation of the true costs of pipeline investments.

Further, all results are based on a single weather year, i.e., 2013. Other limitations include geographic and temporal clustering to make the problem solving computationally feasible.

6. Conclusion

Formulate full conclusions

- While PCI-PMI projects are not cost-optimal from a system perspective compared to an ideal centrally planned system, they have a positive impact on the system costs and are likely a no-regret investment based on our results.

- Additional cost savings can be unlocked with single, strategically placed pipelines to connect additional H_2 production sites and CO_2 point sources to the pipeline network.

- Further, the success of large-scale investment projects is largely driven by political support, public acceptance, which is especially given for PCI-PMI projects.

- 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).

- Pipelines basically serve as a tool to hedge risks of overbuilding solar and wind generation capacities and reduce excessive reliance on single carbon capture technologies like DAC and carbon capture at point sources.

- At the same time, there is a theoretical risk of needing more DAC investments, if pipelines do not materialise at all.

- Confirm findings of [22] findings, notably with higher sequestration costs and real planned projects.

- PCI-PMI projects including additional pipeline build-outs allow a lower-cost and less technology-dependent transition towards a decarbonised system compared to a system without any pipeline infrastructure. They help achieving the EUs ambitious policy targets in the long run.

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

All results, including solved PyPSA networks and summaries in .csv format are published on Zenodo:
https://doi.org/XX.YYYY/zenodo.10000000

The entire workflow, including the custom model based on PyPSA-Eur v2025.01.0, PCI-PMI project implementation, regret-matrix setup, postprocessing and visualisation routines can be completely reproduced from 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.

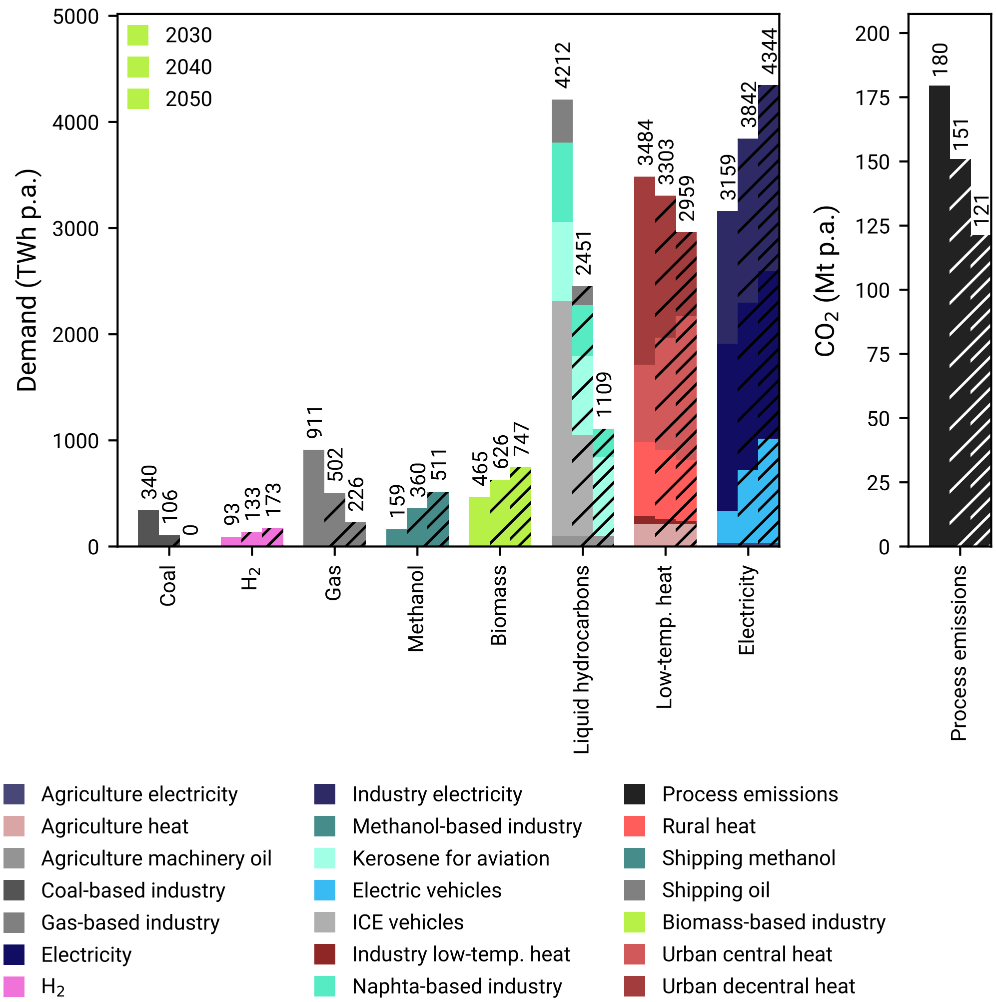


Figure A.9: Exogenous demand.

Appendix B. Supplementary material — Methodology

Table B.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 B.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

Appendix C. Supplementary material — Results and discussion

Appendix C.1. Installed capacities

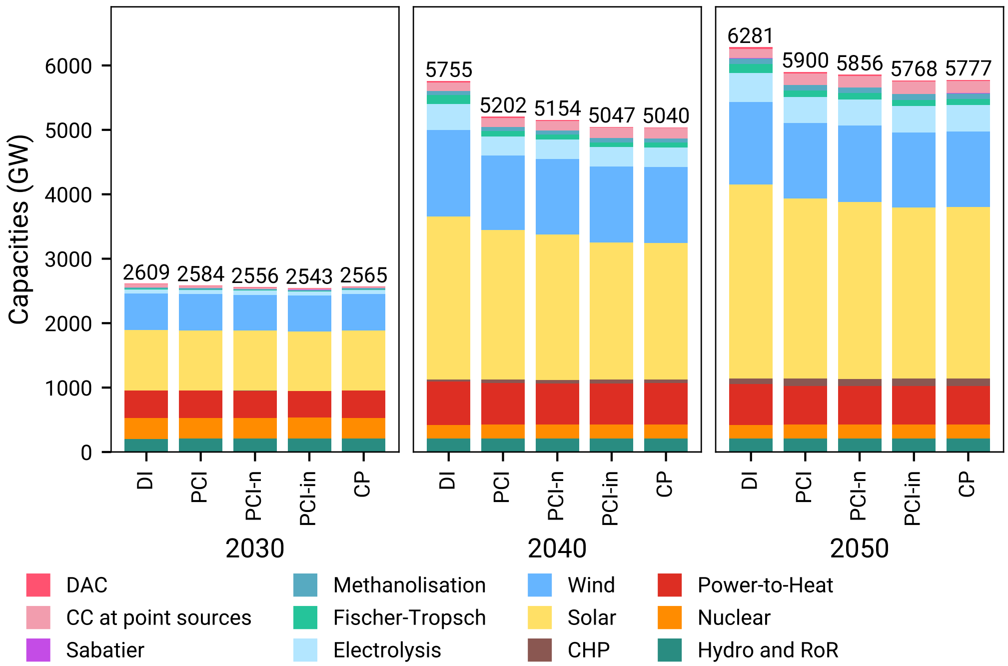


Figure C.10: Installed capacities in long-term scenarios.

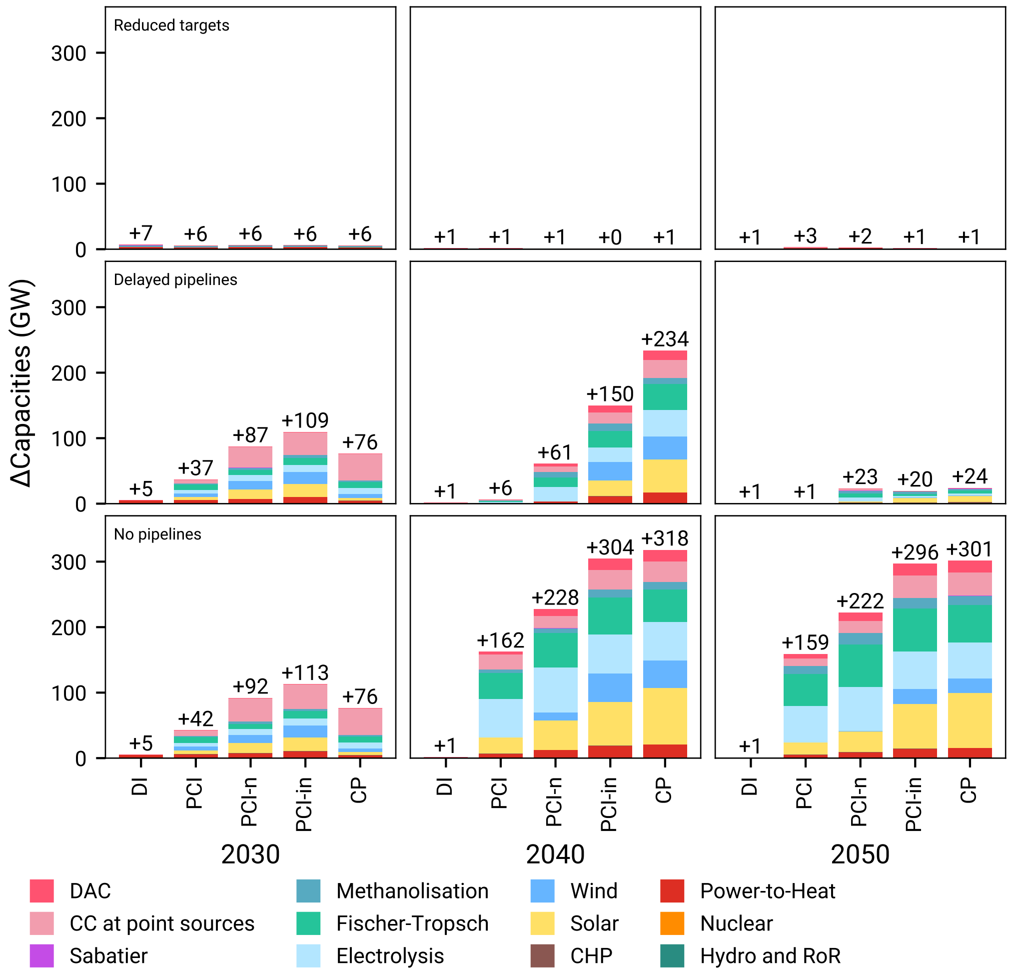


Figure C.11: ΔCapacities — Short-term minus long-term runs.

Appendix C.3. Delta system costs

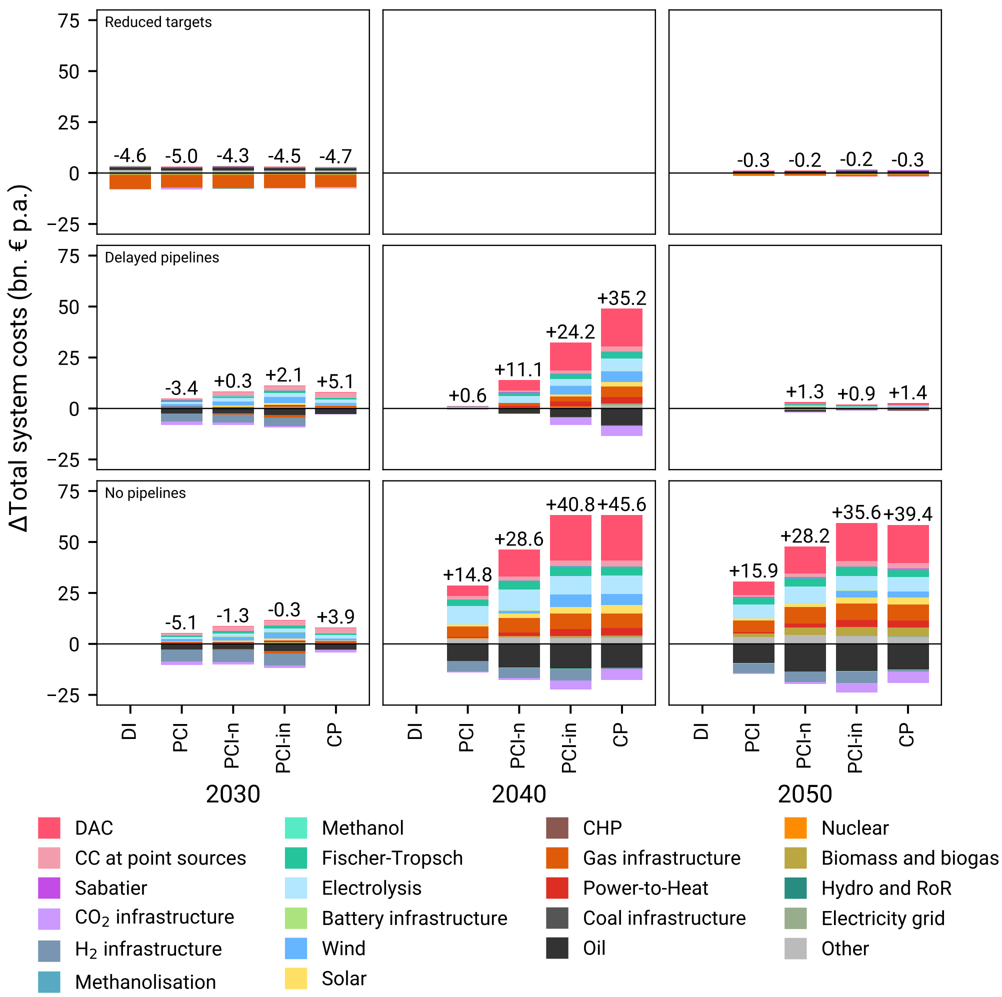


Figure C.12: ΔSystem costs — Short-term minus long-term runs.

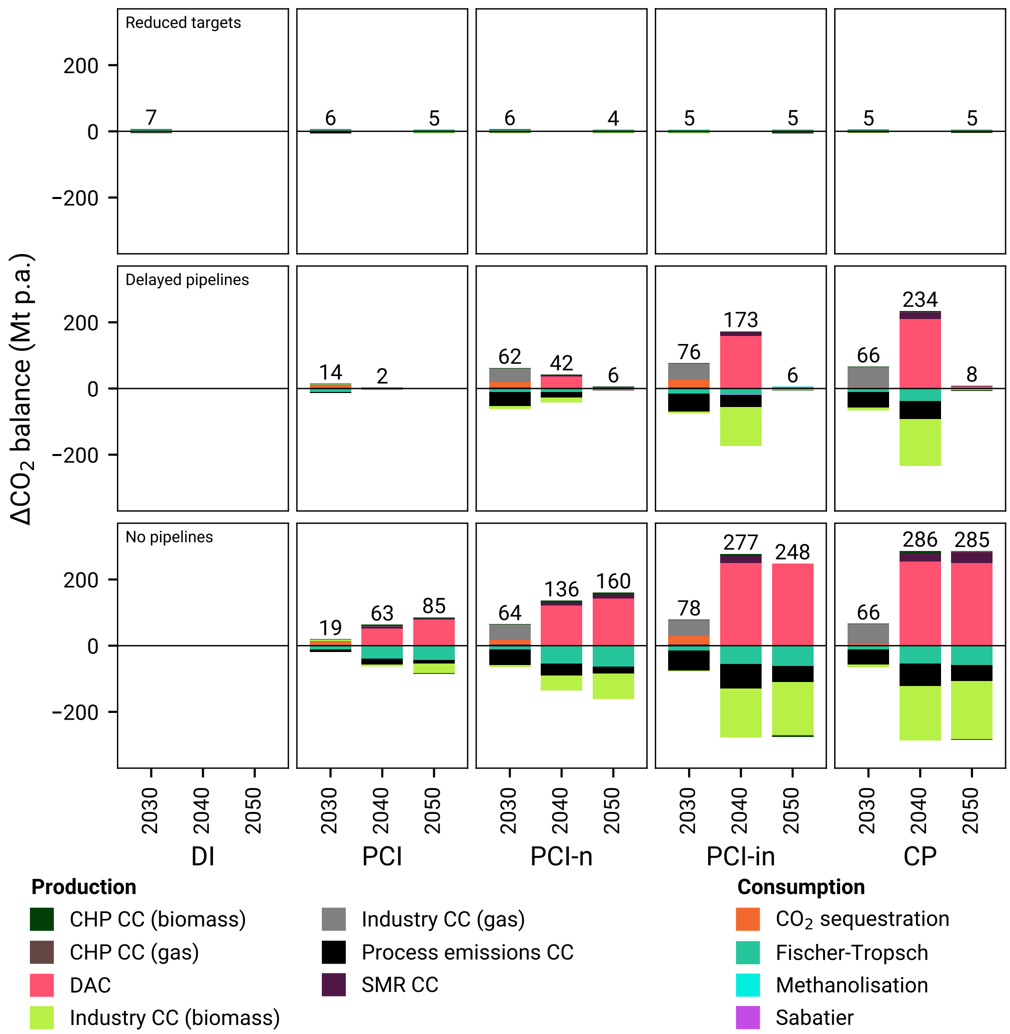


Figure C.13: ΔCO_2 balances — Short-term minus long-term runs.

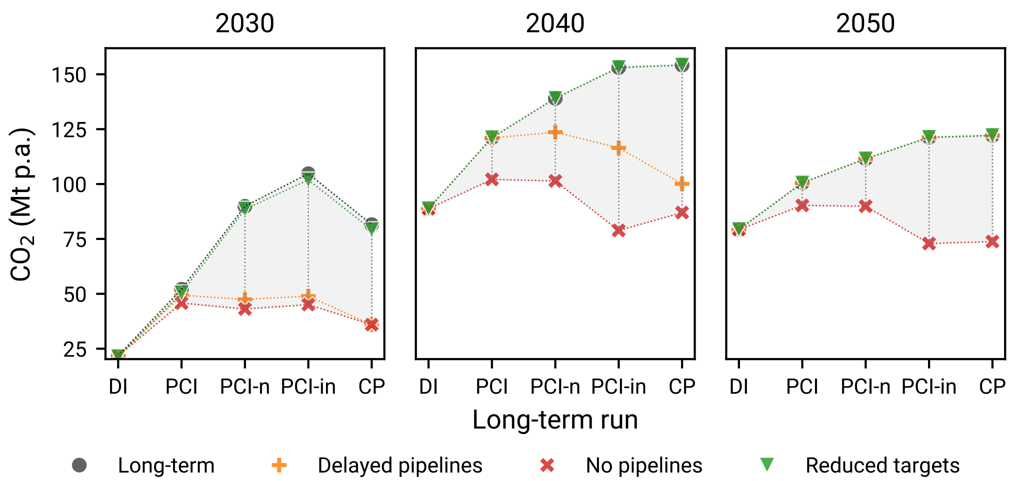


Figure C.14: ΔCO_2 balances — Process emissions including Carbon Capture.

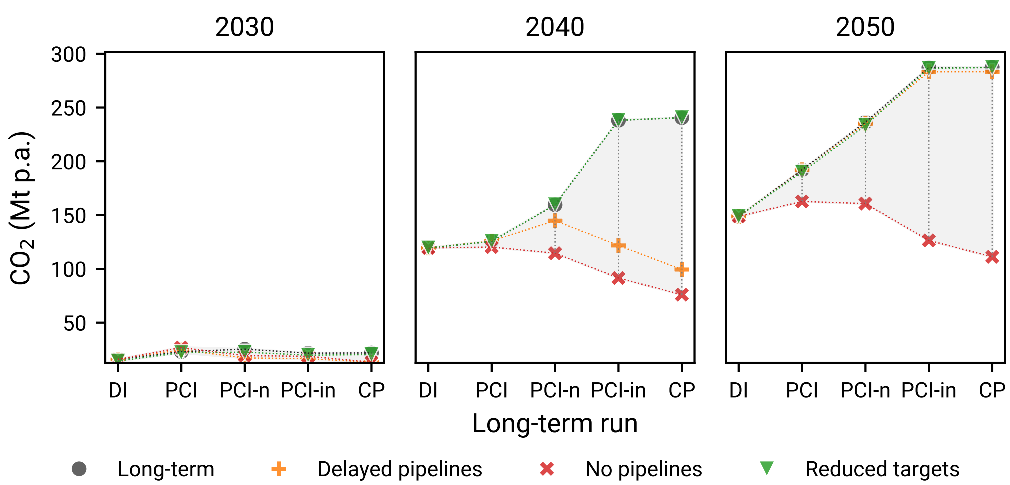


Figure C.15: ΔCO_2 balances — Carbon capture from solid biomass for industry point sources.

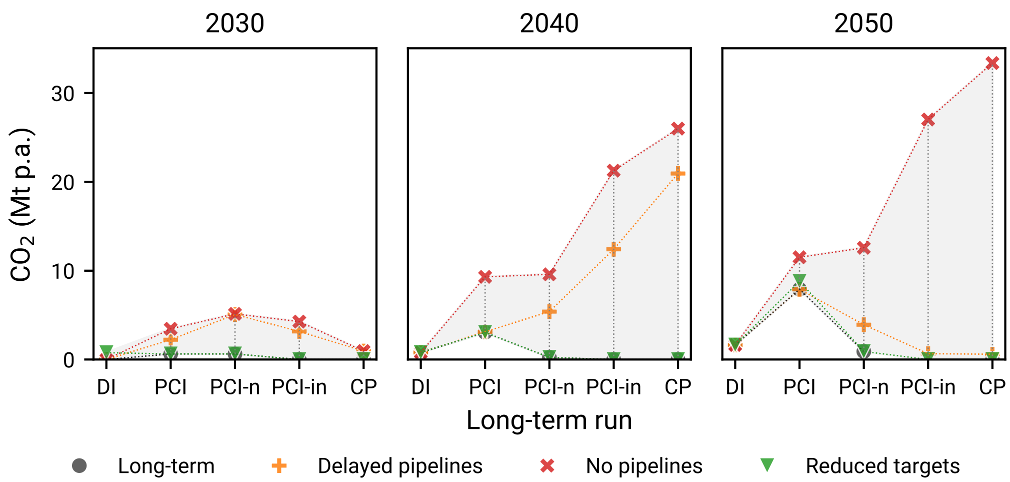


Figure C.16: ΔCO_2 balances — Carbon capture from steam methane reforming point sources.

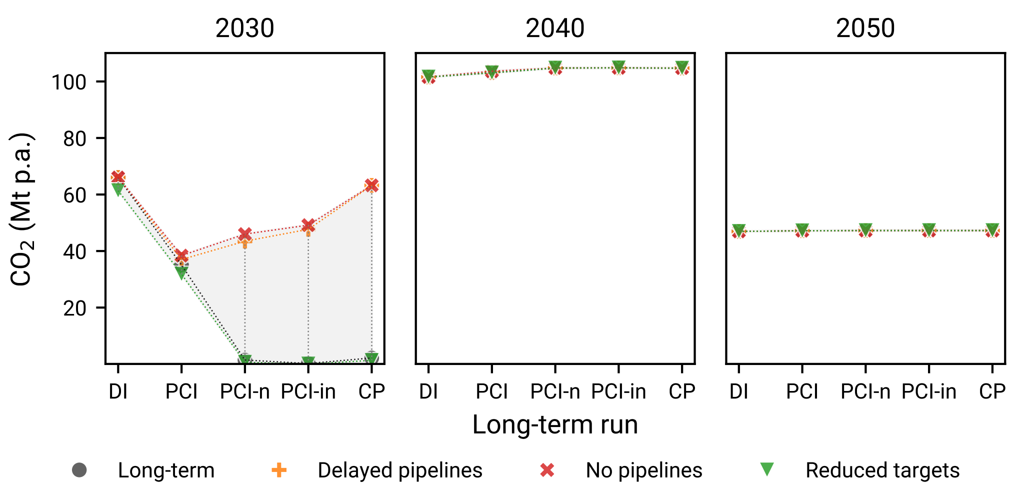


Figure C.17: ΔCO_2 balances — Carbon captured from gas for industry point sources.

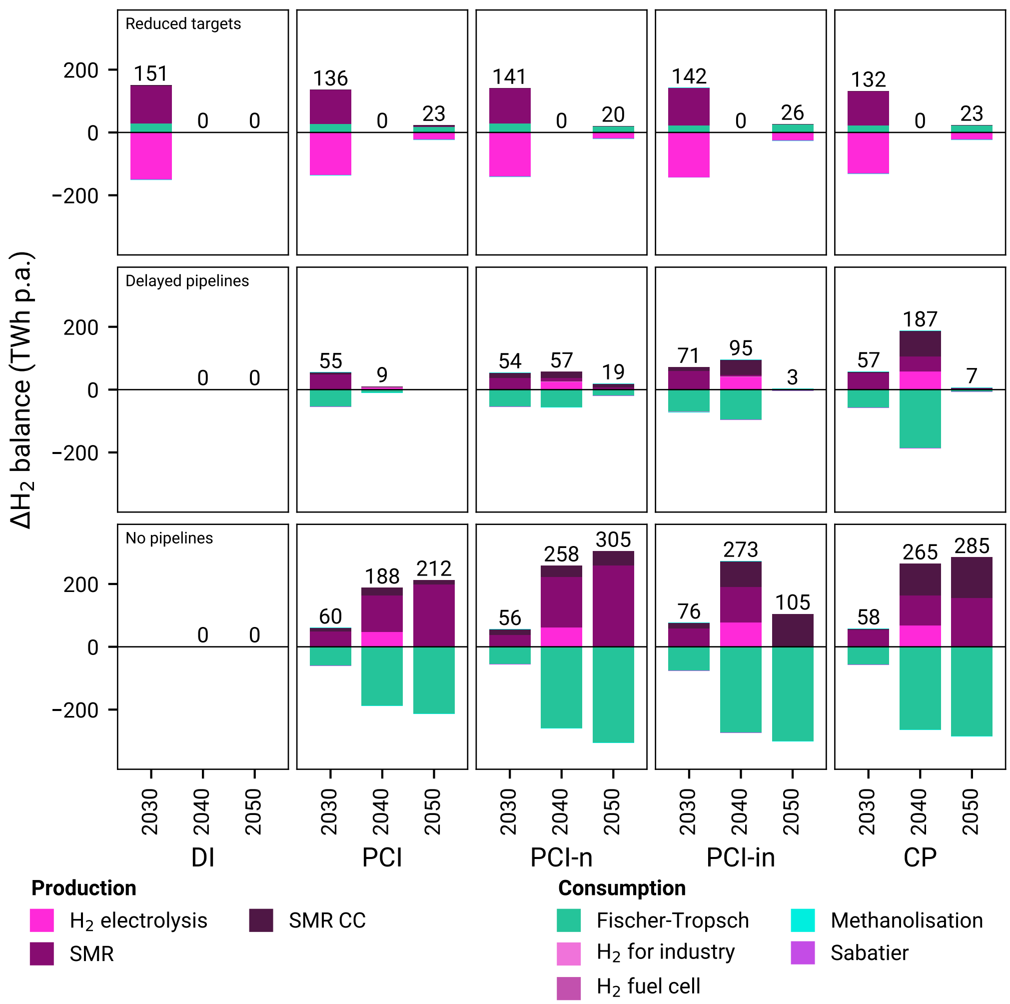


Figure C.18: ΔH_2 balances — Short-term minus long-term runs.

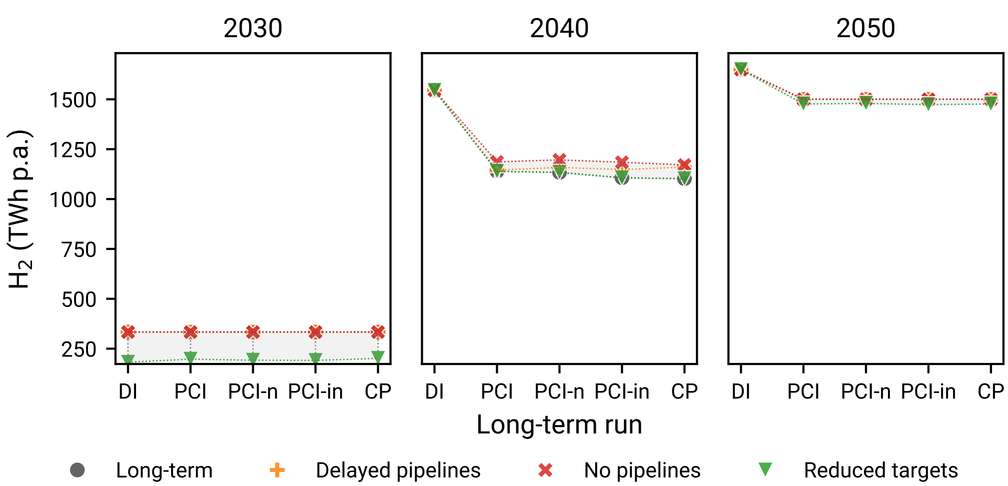
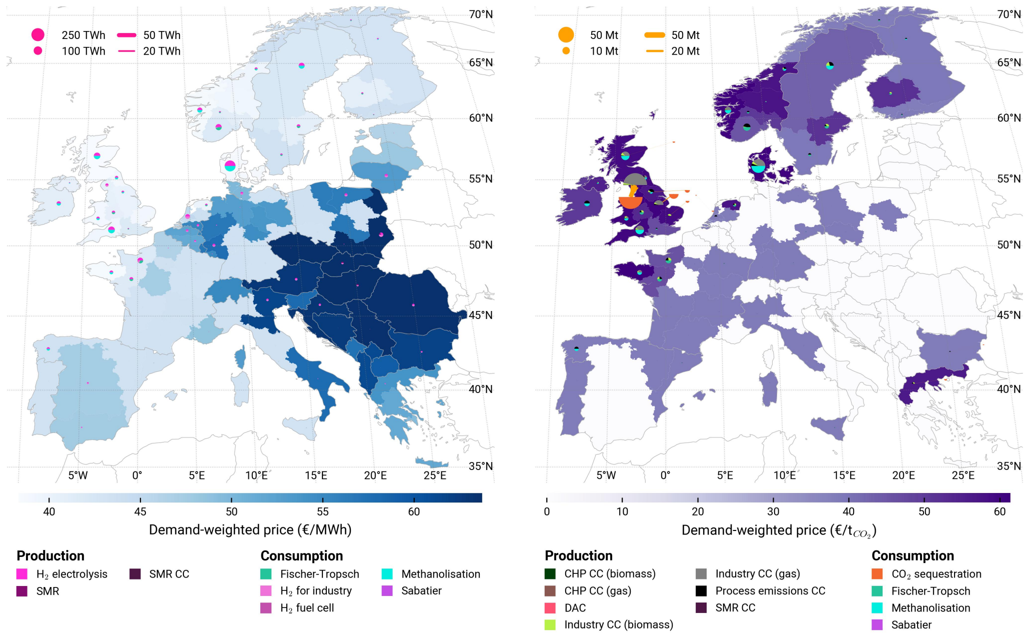


Figure C.19: Delta balances — Electrolytic H_2 production

Appendix C.5. Maps

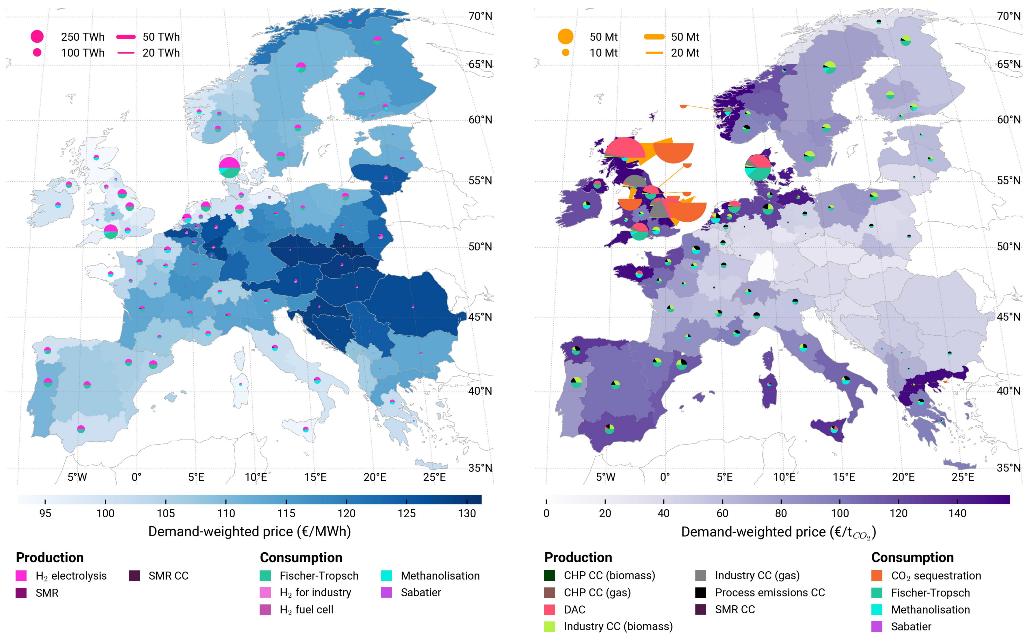
Appendix C.5.1. Decentral Islands



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

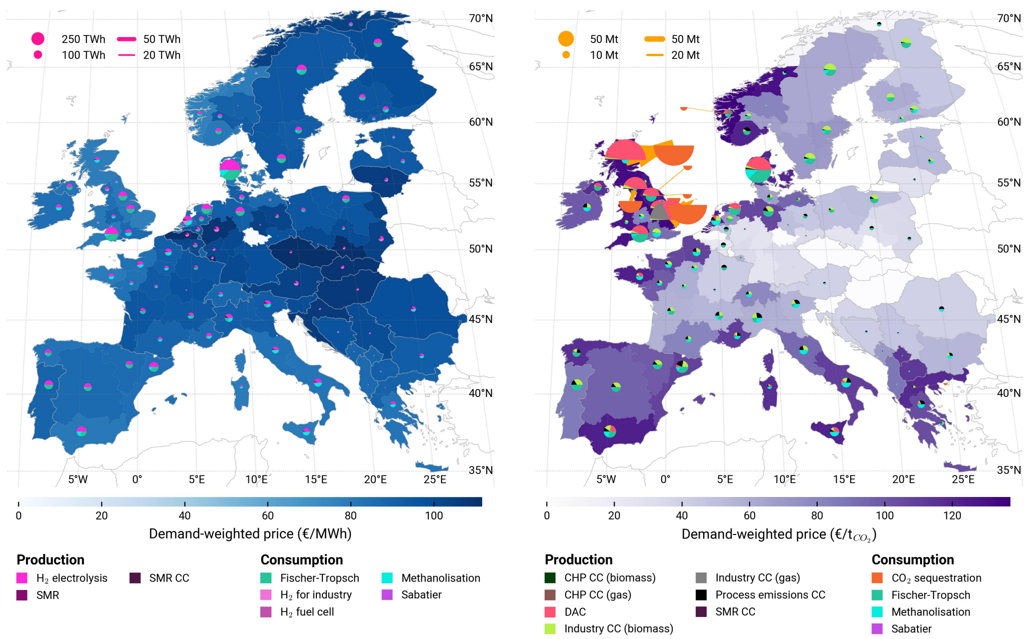
Figure C.20: *Decentral Islands* long-term scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

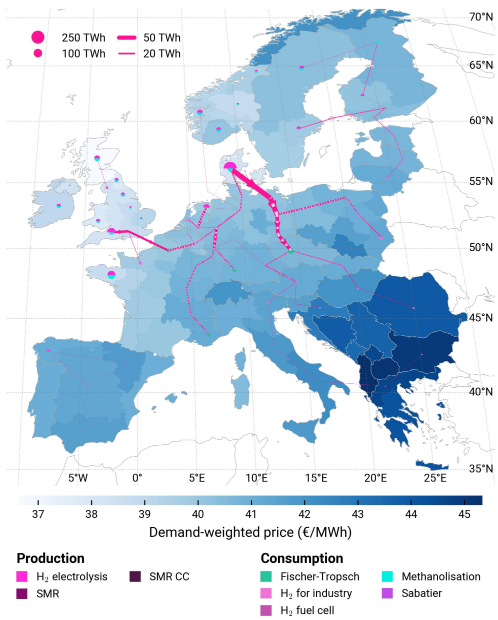
Figure C.21: *Decentral Islands* long-term scenario (2040) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



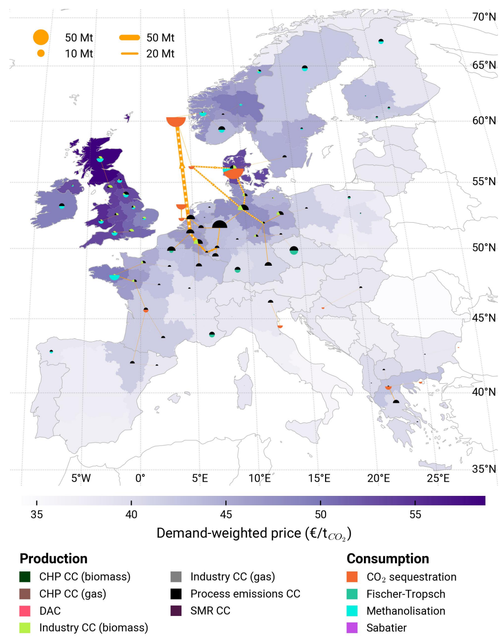
(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

Figure C.22: *Decentral Islands* long-term scenario (2050) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.

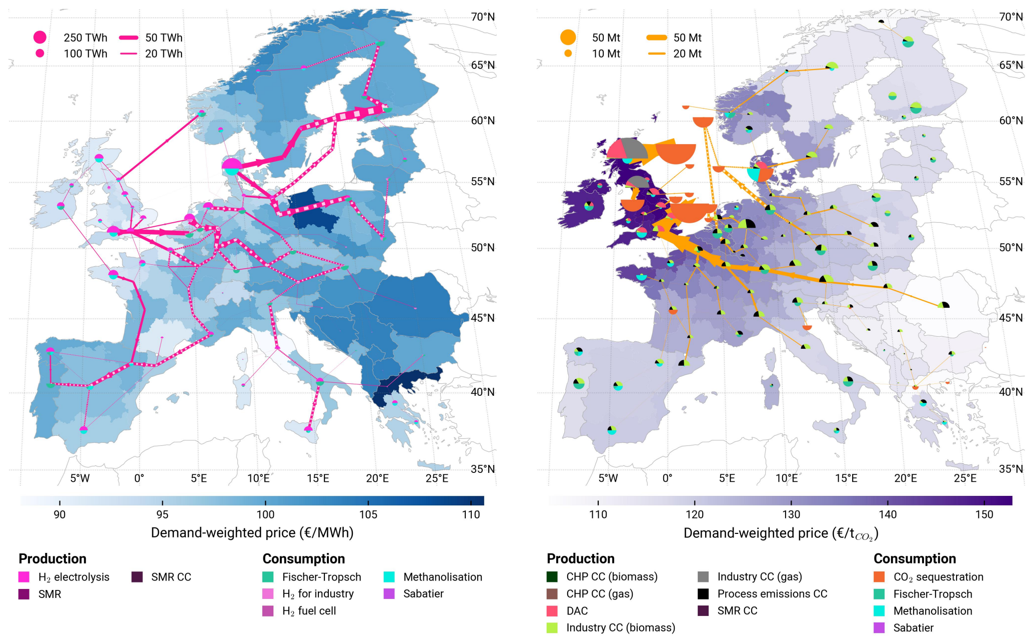


(a) H_2 regional balances and flows.



(b) CO_2 regional balances and flows.

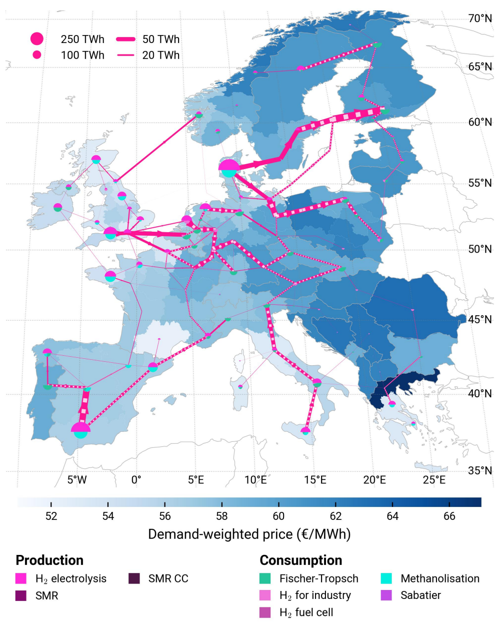
Figure C.23: *PCI* long-term scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport. Dotted white lines represent PCI-PMI projects.



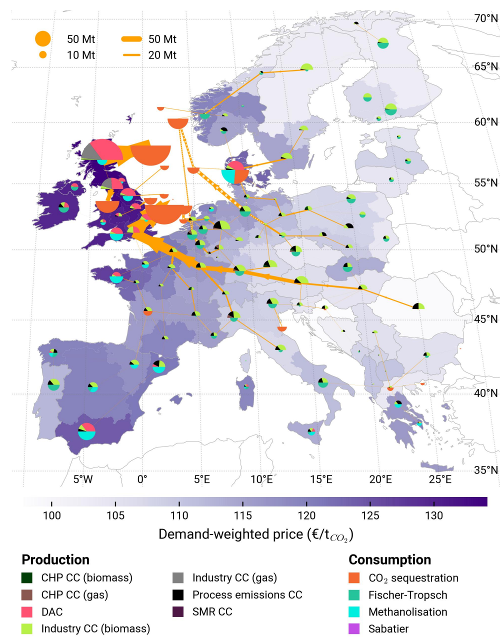
(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

Figure C.24: *PCI-in* long-term scenario (2040) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport. Dotted white lines represent PCI-PMI projects.

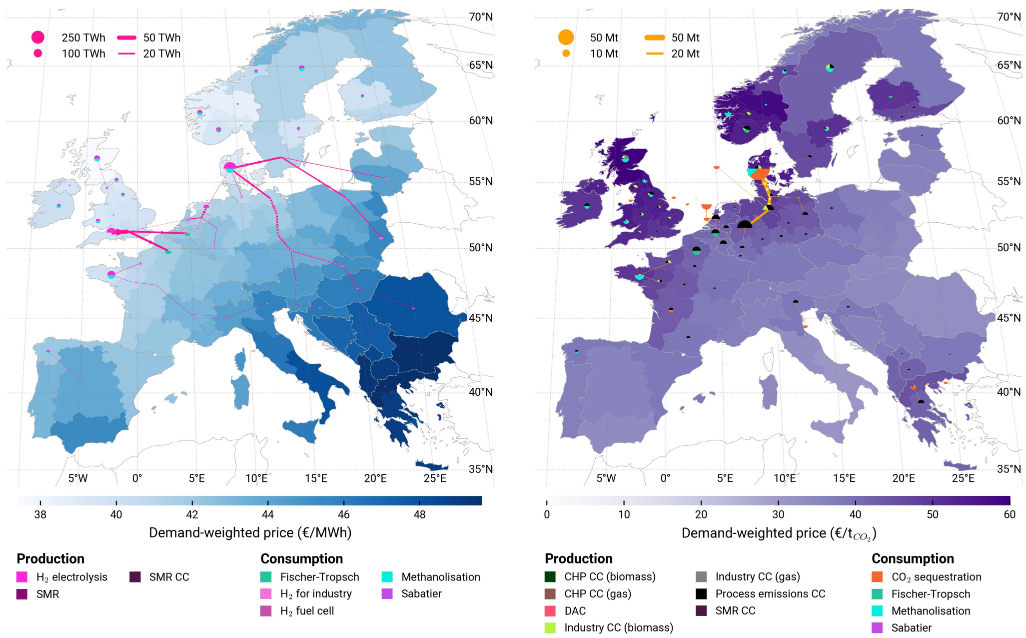


(a) H_2 regional balances and flows.



(b) CO_2 regional balances and flows.

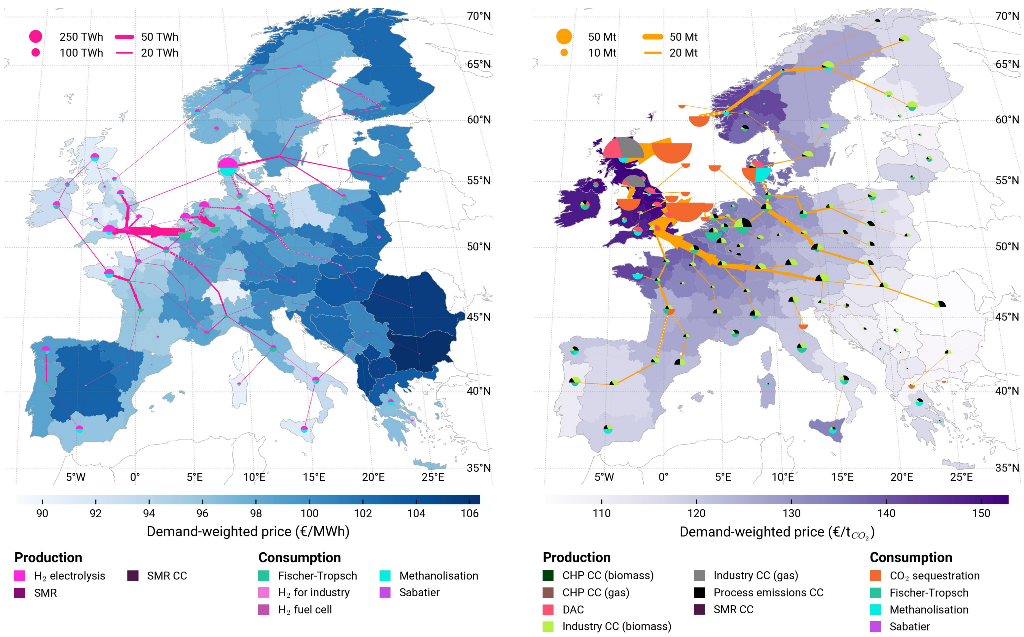
Figure C.25: *PCI-in* long-term scenario (2050) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

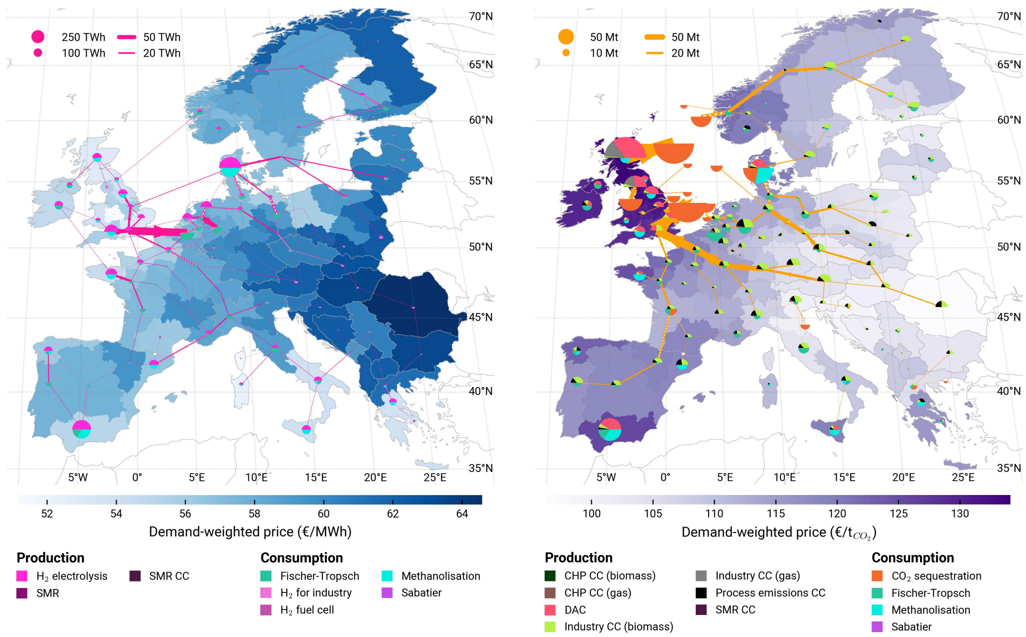
Figure C.26: *Central Planning* long-term scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

Figure C.27: *Central Planning* long-term 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 C.28: *Central Planning* long-term scenario (2050) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.

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] European 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] 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.

[19] 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.

[20] 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.

[21] 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.

[22] 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.

[23] 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).

[24] 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.

[25] 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.

[26] 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.

[27] 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.

[28] 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.

[29] 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.

[30] 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.

[31] 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.

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

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

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

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

[36] 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.

[37] 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.

[38] 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.

[39] 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).

[40] European Commission, European CO2 storage database (Aug. 2020).

[41] K. van Alphen, Q. van Voorst tot Voorst, M. P. Hekkert, R. E. H. M. Smits, Societal acceptance of carbon capture and storage technologies, Energy Policy 35 (8) (2007) 4368–4380. doi:10.1016/j.enpol.2007.03.006.

[42] European Commission, 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 (2020).

[43] European Commission, 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 (2024).

[44] European Commission. Directorate General for Energy., Fraunhofer Institute for Systems and Innovation Research., METIS 3, study S5: The impact of industry transition on a CO2 neutral European energy system. (2023). doi:10.2833/094502.