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OLD OUTDATED IEW-EXTENDED-ABSTRACT.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 A.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]. 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.

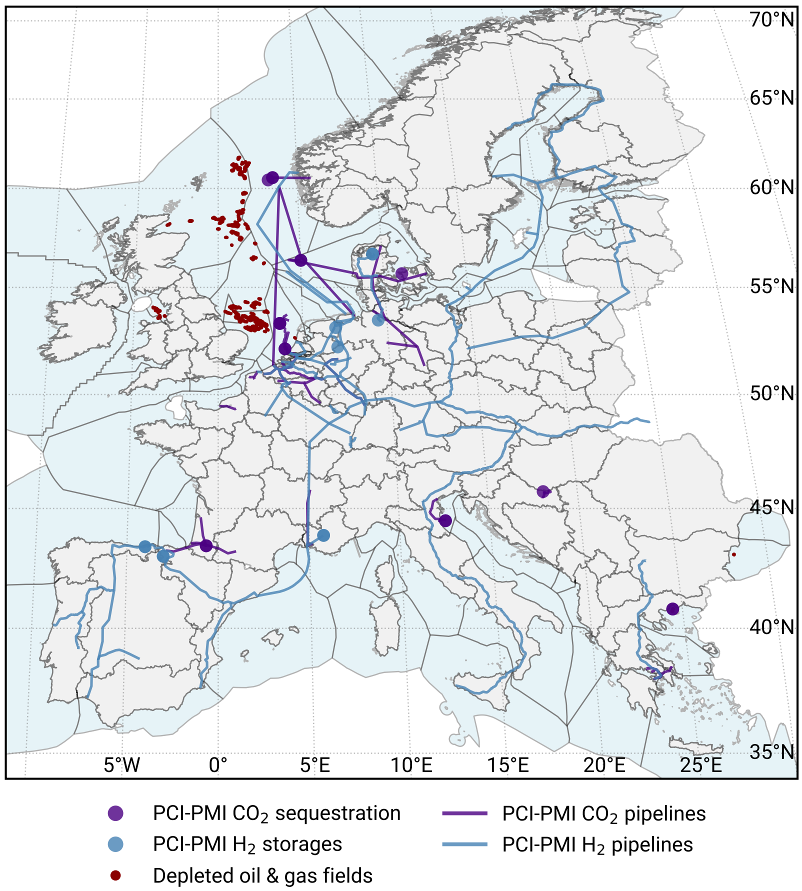


Figure 1: Map of the regional scope including clustered onshore (grey) and offshore regions (blue), as well as PCI-PMI CO_2 and H_2 pipelines, storage and sequestration sites. Depleted offshore oil and gas fields (red) provide additional CO_2 sequestration potential [22].

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]

4.3. 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. Even with only CO_2 pipelines to the depleted offshore oil and gas fields, the policy targets can be achieved at 865 bn. € p.a.

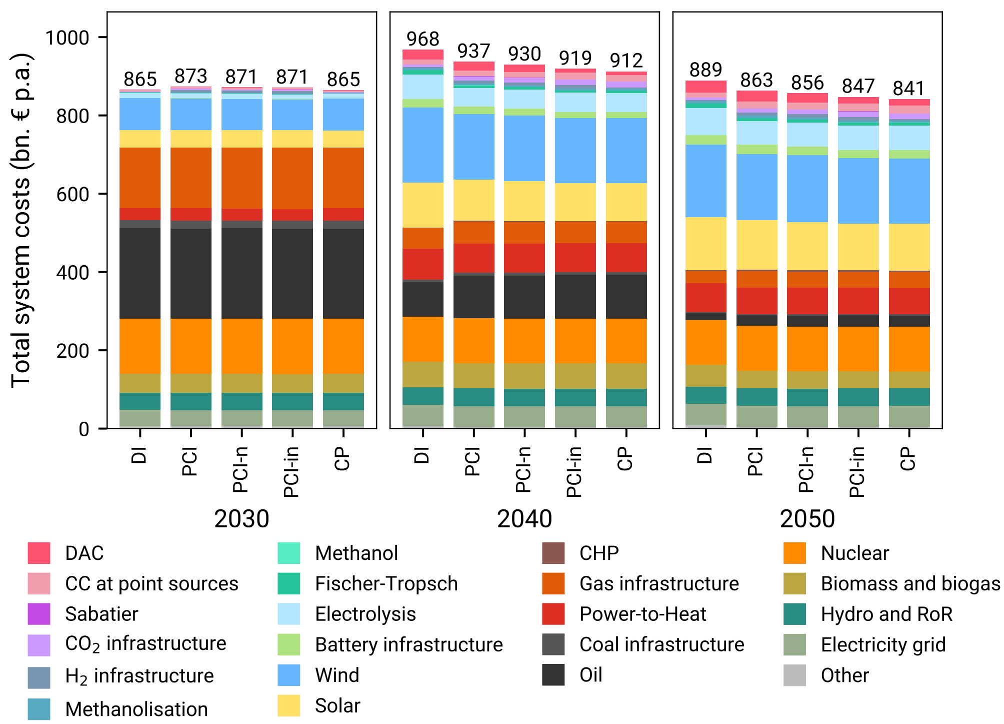


Figure 2: Total annual system costs (CAPEX + OPEX) by technology group.

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.

- Regarding DAC Figure 5
- 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

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.

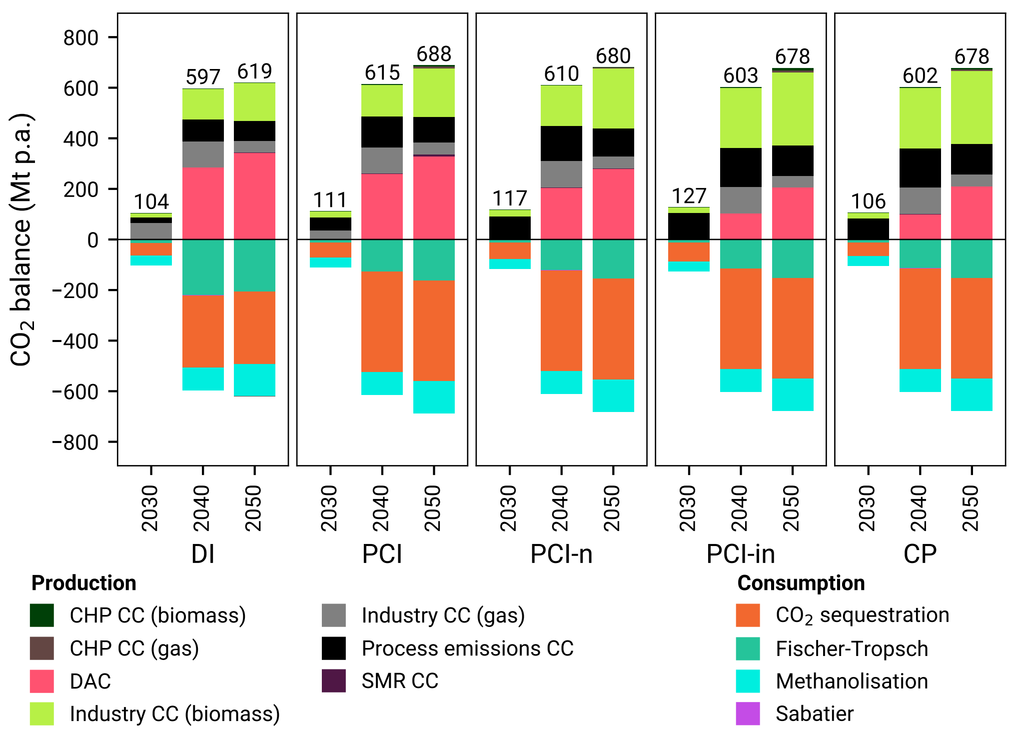


Figure 3: CO_2 balances in long-term scenarios.

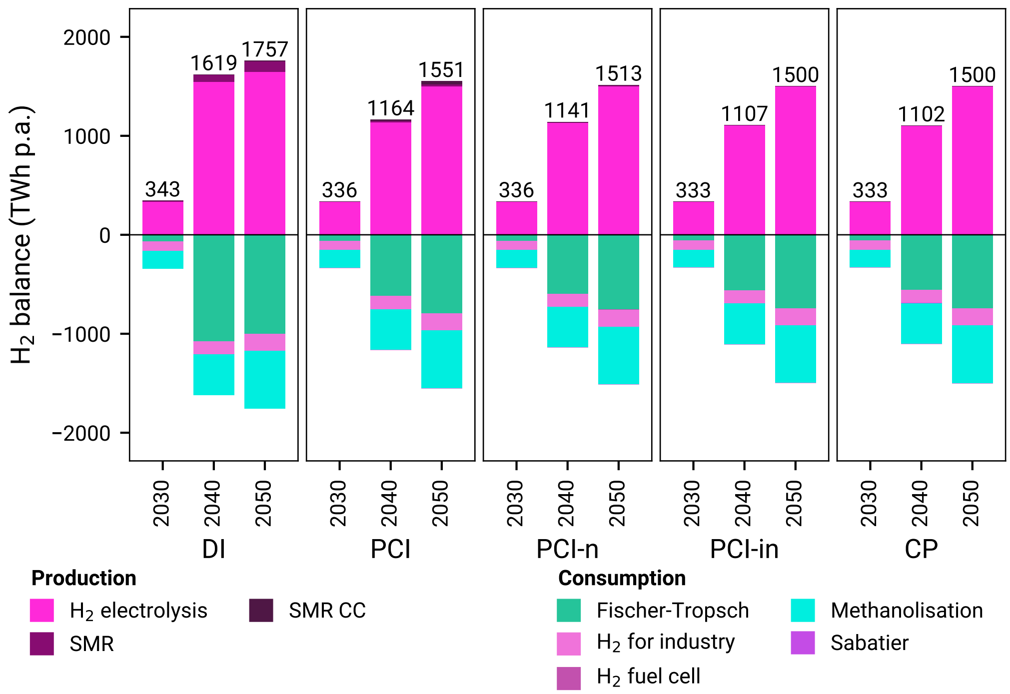


Figure 4: H_2 balances in long-term scenarios.

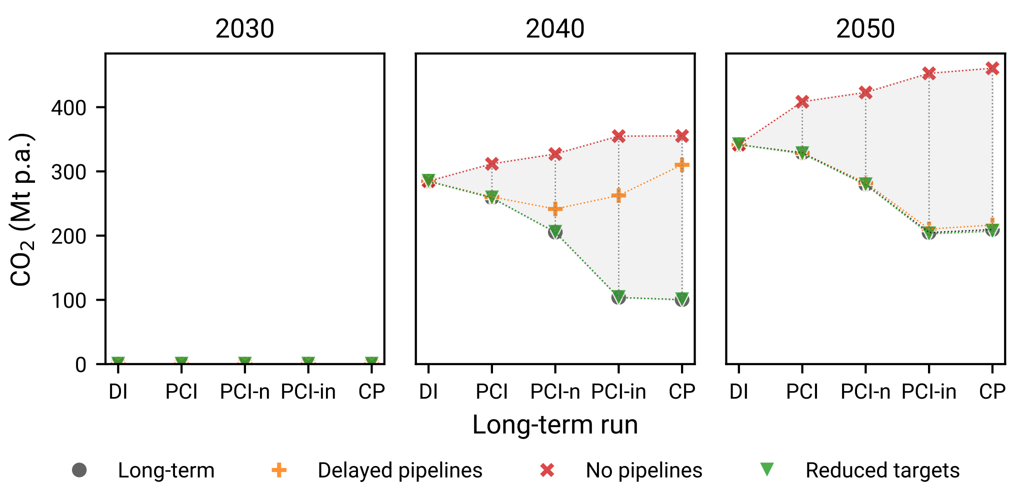


Figure 5: Delta balances — CO_2 from Direct Air Capture.

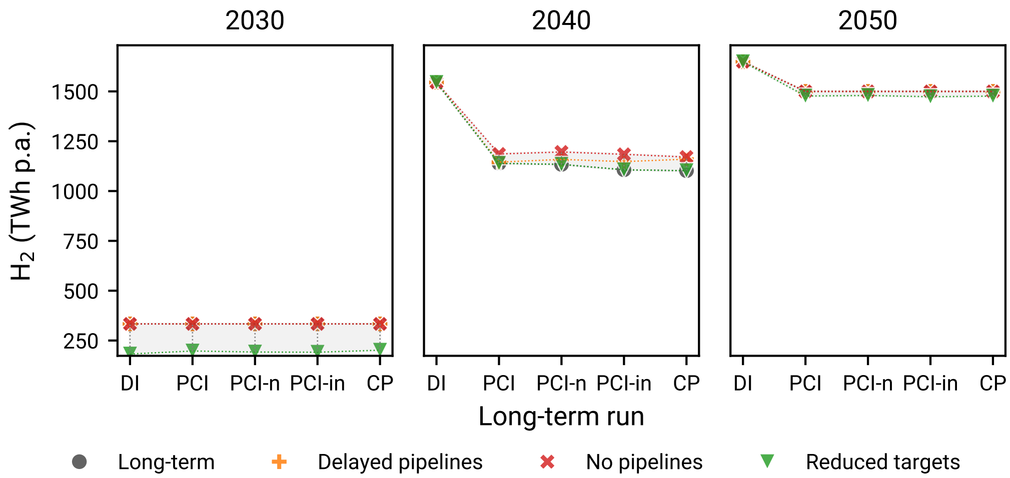
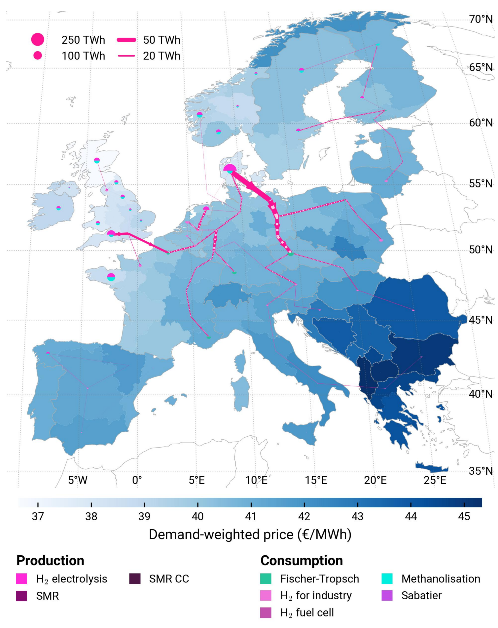
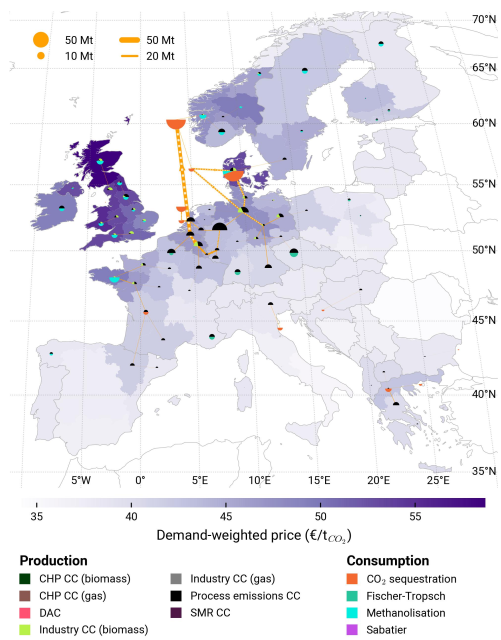


Figure 6: Delta balances — Electrolytic H_2 production

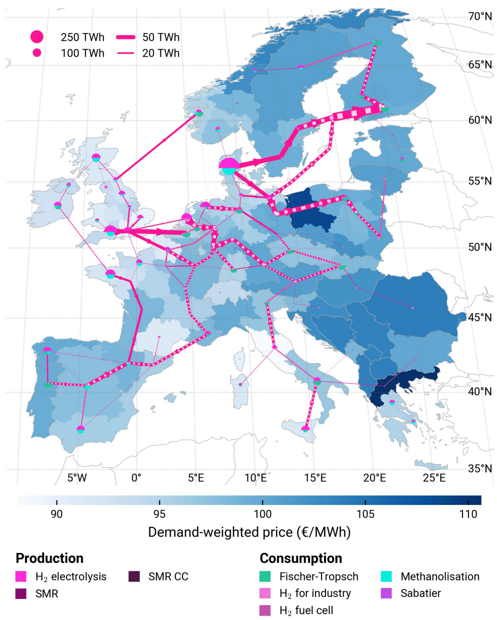


(a) H_2 regional balances and flows.

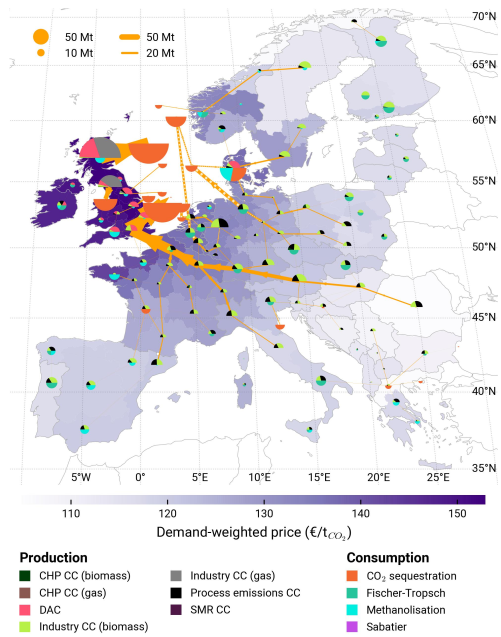


(b) CO_2 regional balances and flows.

Figure 7: *PCI-in long-term* scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.

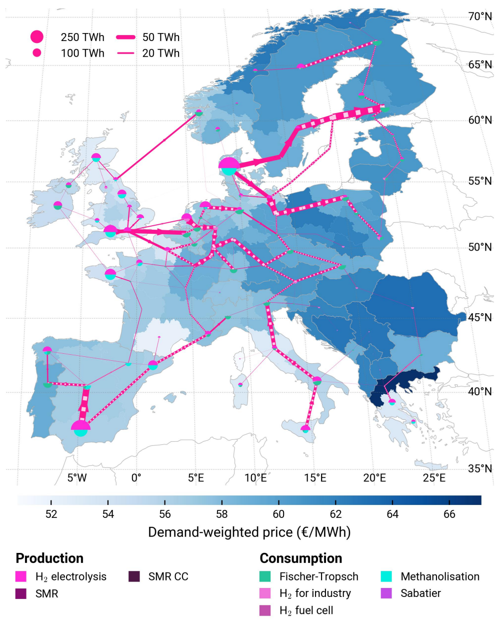


(a) H_2 regional balances and flows.

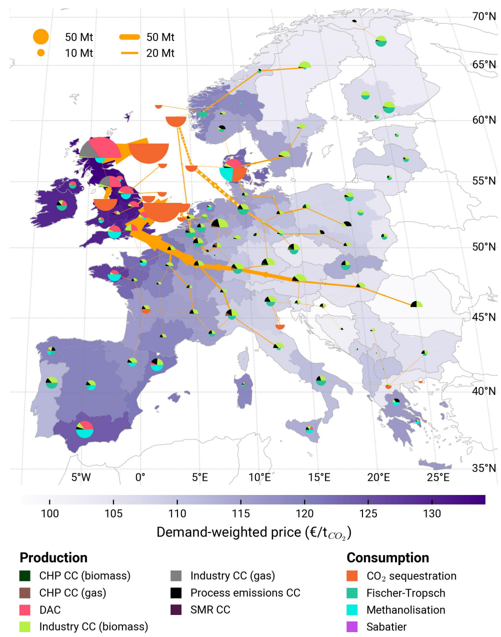


(b) CO_2 regional balances and flows.

Figure 8: *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 9: *PCI-in long-term* scenario (2050) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.

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, 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) [22]. 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 **??**). This is true for both comparing scenario *A* and *Base* scenario with scenario *B*, respectively, deducting the cost of the PCI-PMI projects.

5.2. 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.

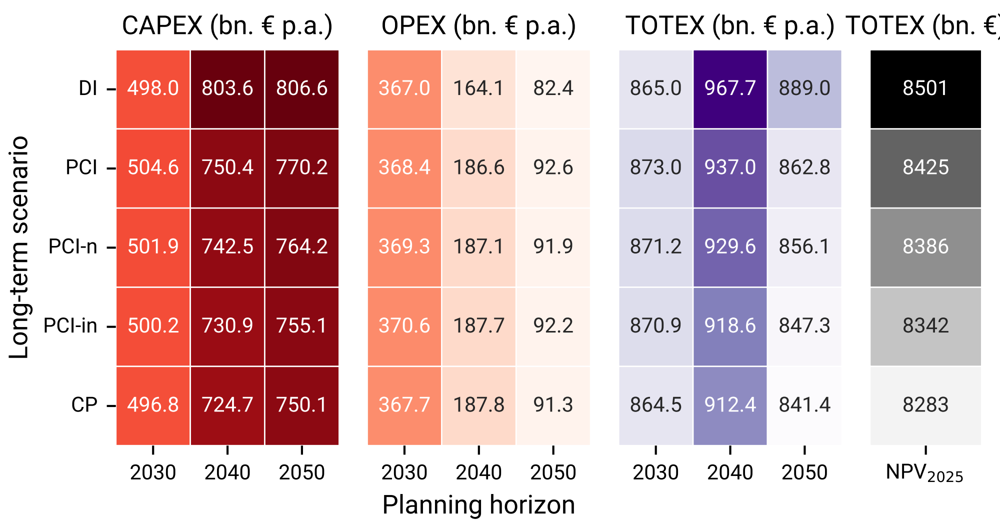


Figure 10: Annual system costs by long-term scenario and planning horizon.

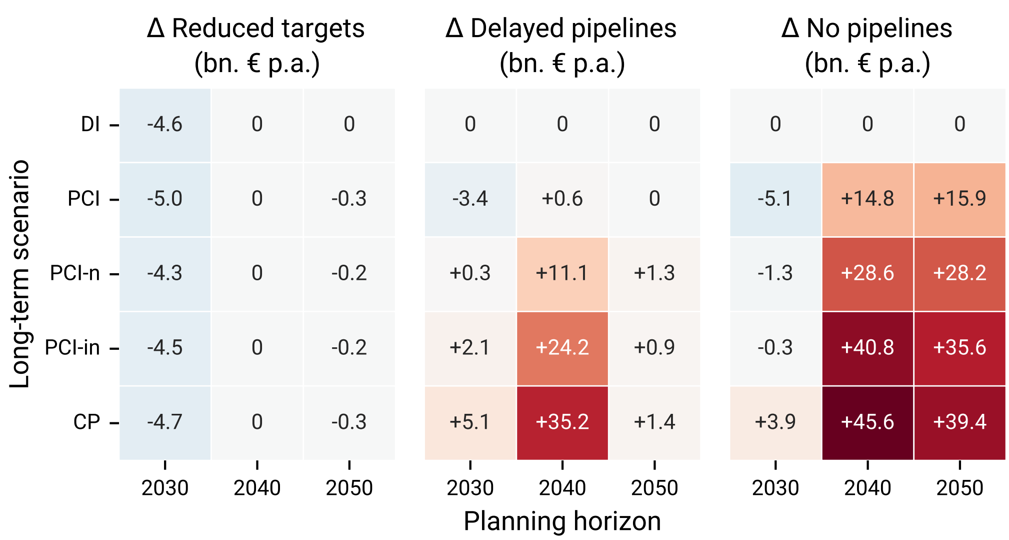


Figure 11: Regret matrix. Calculating regret terms by subtracting system costs of long-term scenarios (columns) from short-term scenarios (rows). Positive values reflect higher costs in the short-term scenarios compared to the long-term ones.

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

…

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

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

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Appendix A. Supplementary material — Methodology

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

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

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

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

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

Appendix B. Supplementary material — Results and discussion

Appendix B.1. Delta system costs

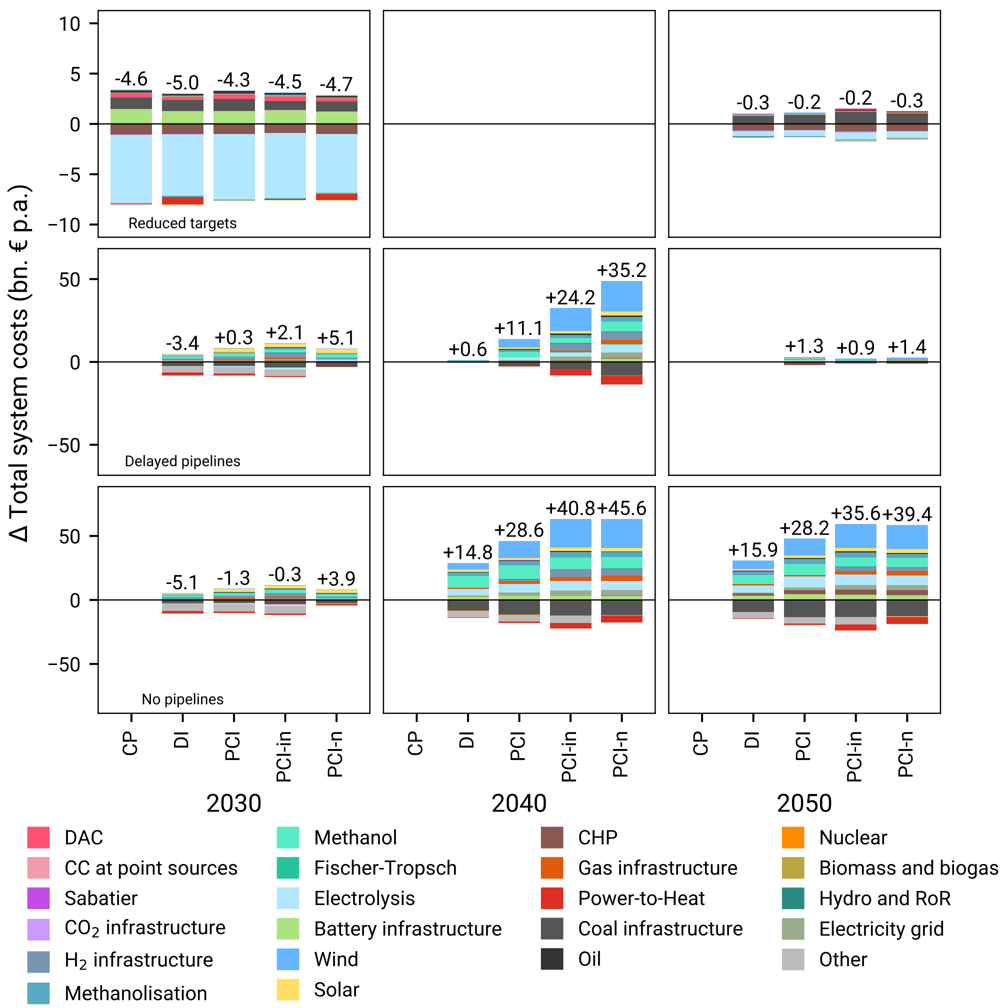


Figure B.12: Delta system costs — Short-term minus long-term runs.

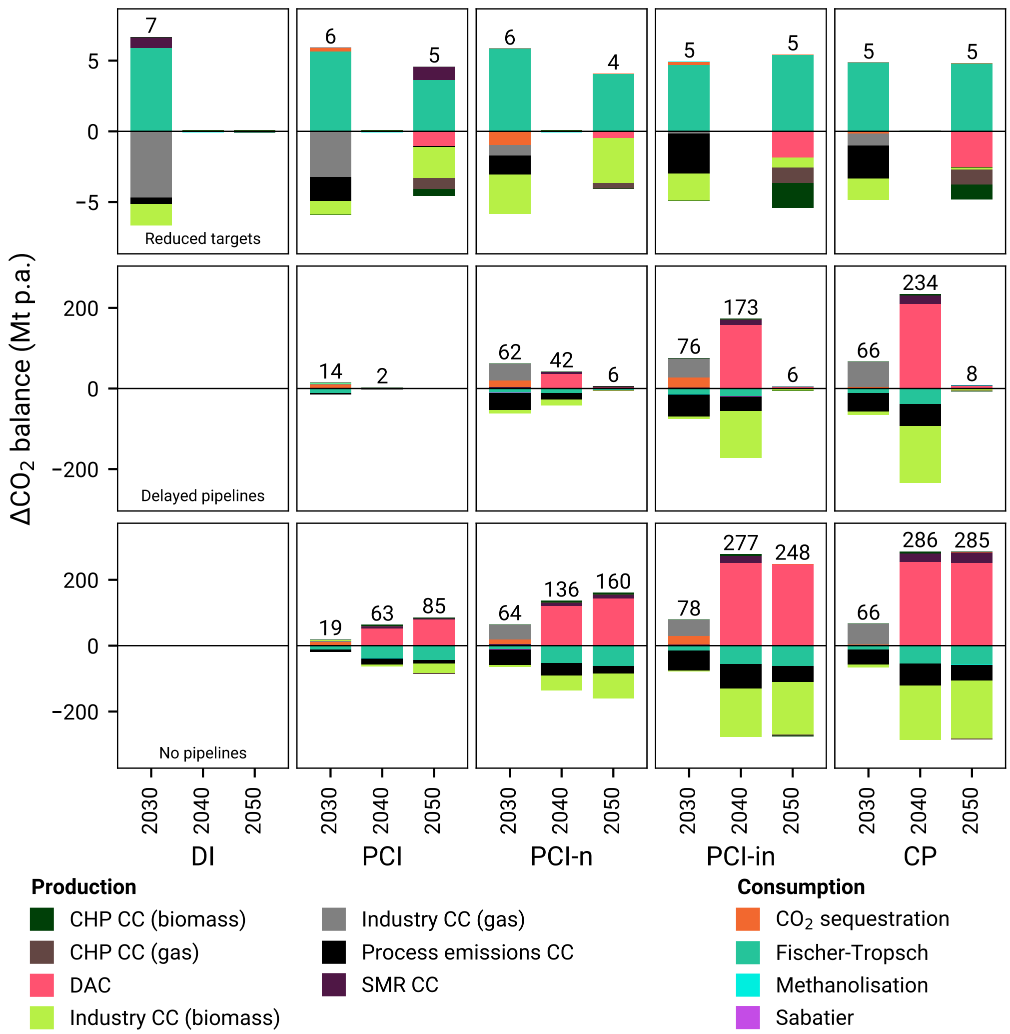


Figure B.13: ΔCO_2 balances — Short-term minus long-term runs.

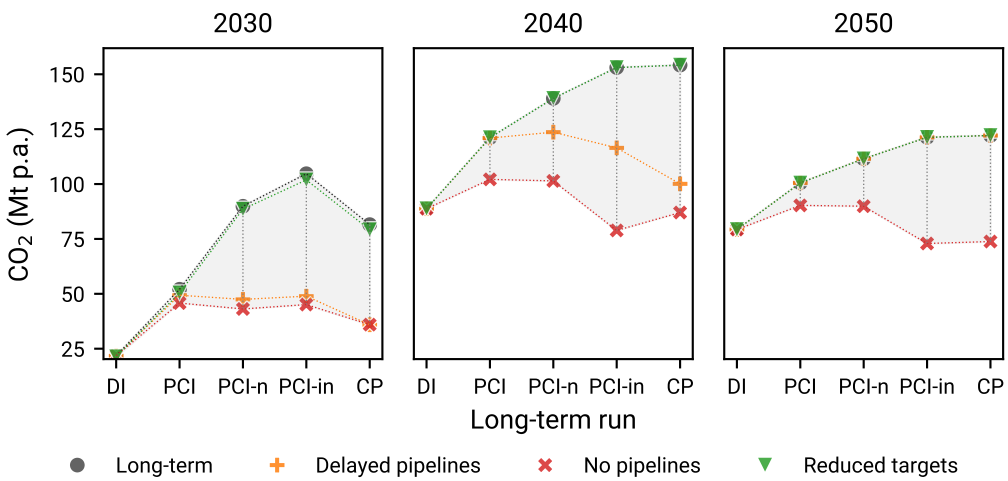


Figure B.14: ΔCO_2 balances — Process emissions including Carbon Capture.

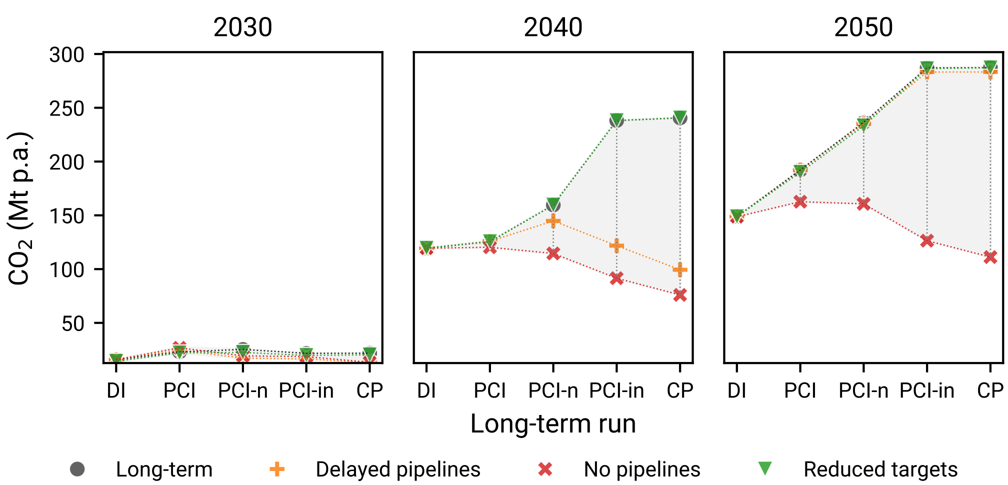


Figure B.15: ΔCO_2 balances — Carbon capture from solid biomass for industry point sources.

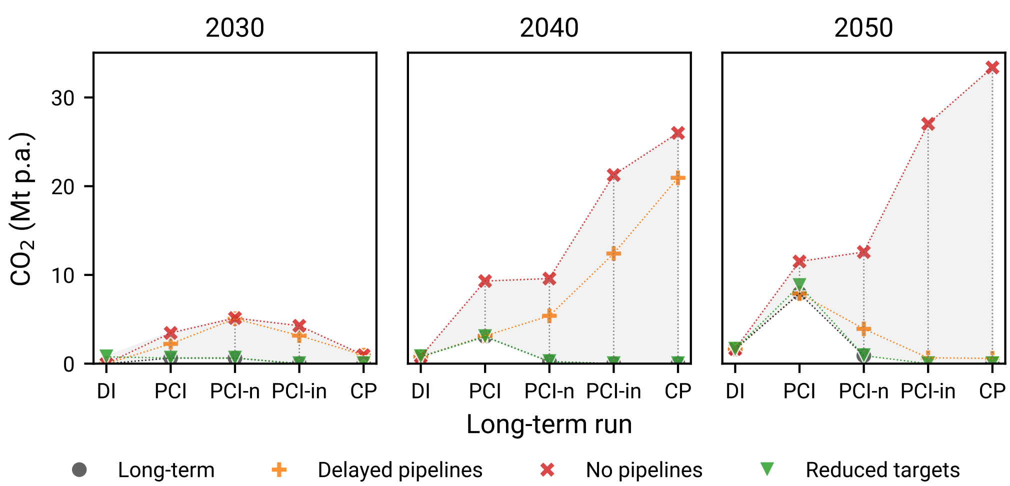


Figure B.16: ΔCO_2 balances — Carbon capture from steam methane reforming point sources.

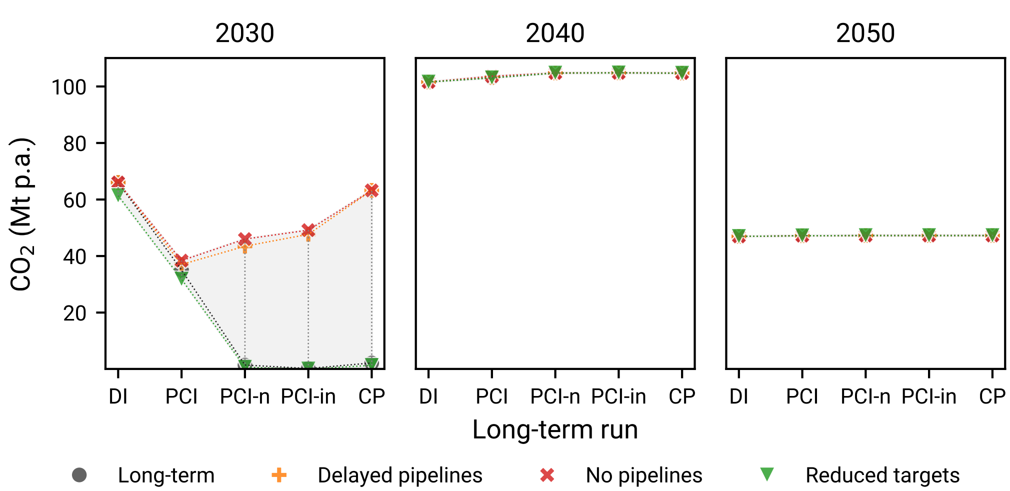


Figure B.17: ΔCO_2 balances — Carbon captured from gas for industry point sources.

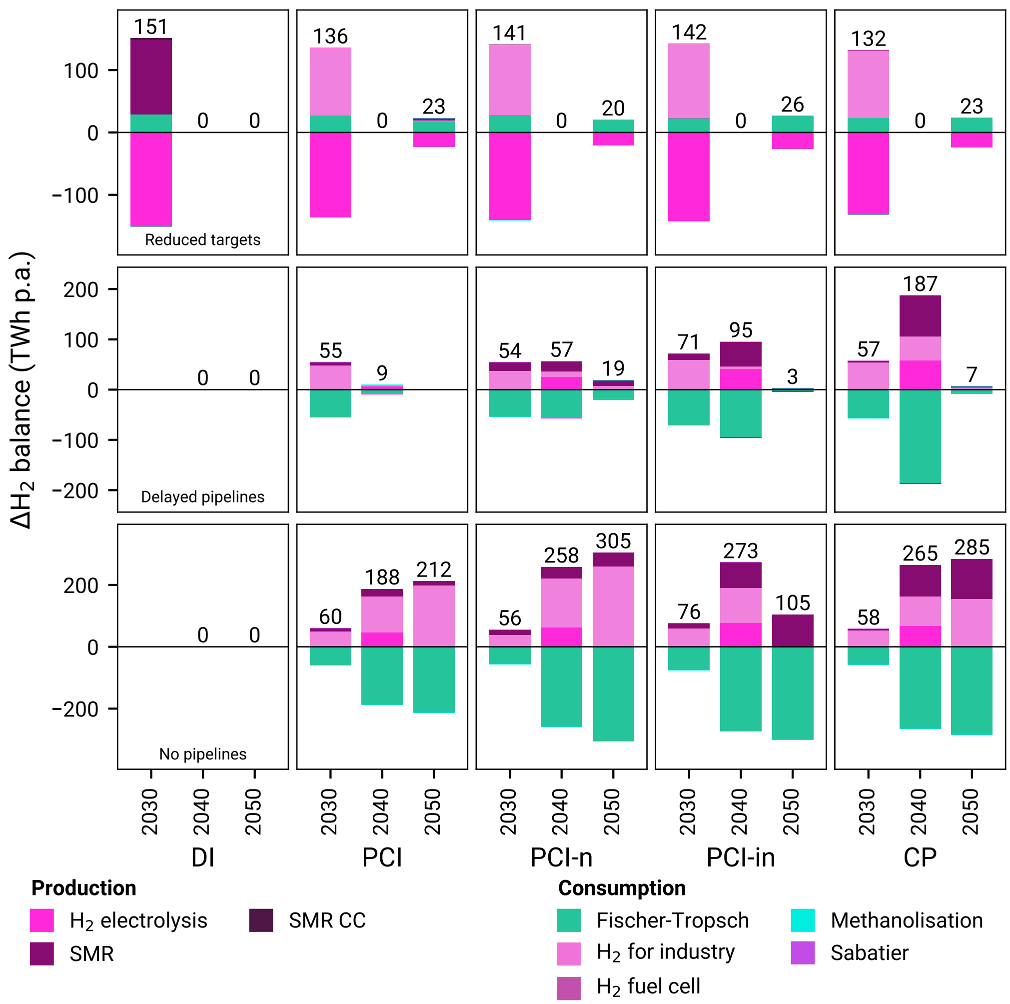
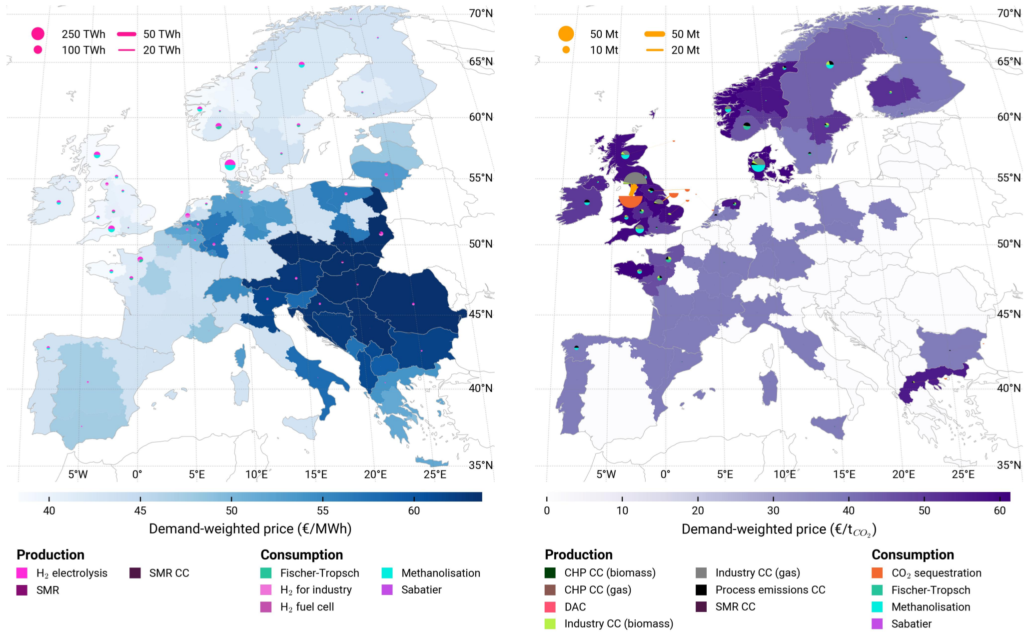


Figure B.18: ΔH_2 balances — Short-term minus long-term runs.

Appendix B.3. Maps

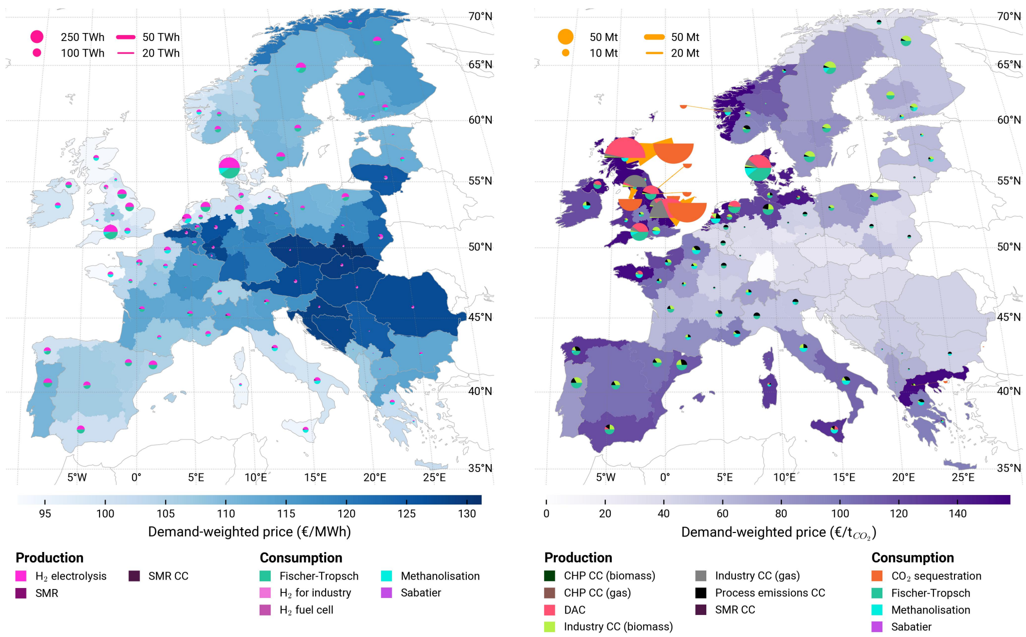
Appendix B.3.1. Decentral Islands



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

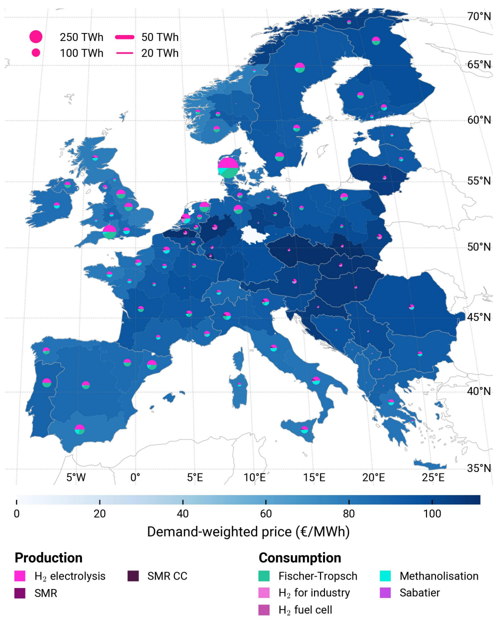
Figure B.19: *Decentral Islands* scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



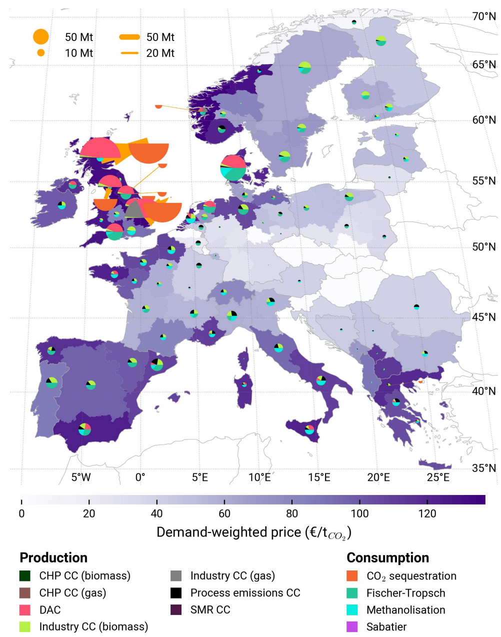
(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

Figure B.20: *Decentral Islands* scenario (2040) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.

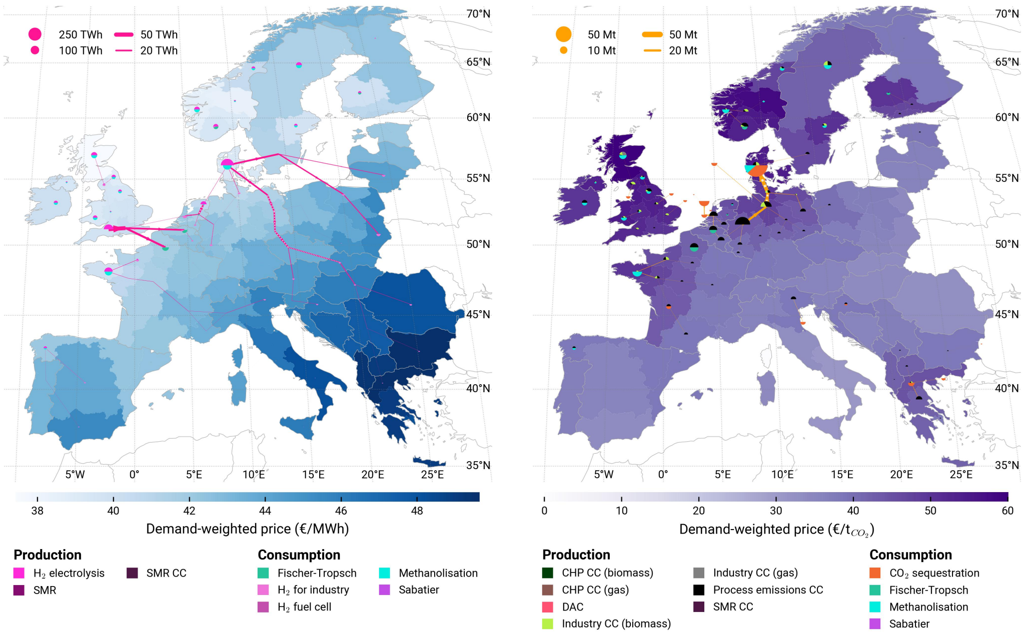


(a) H_2 regional balances and flows.



(b) CO_2 regional balances and flows.

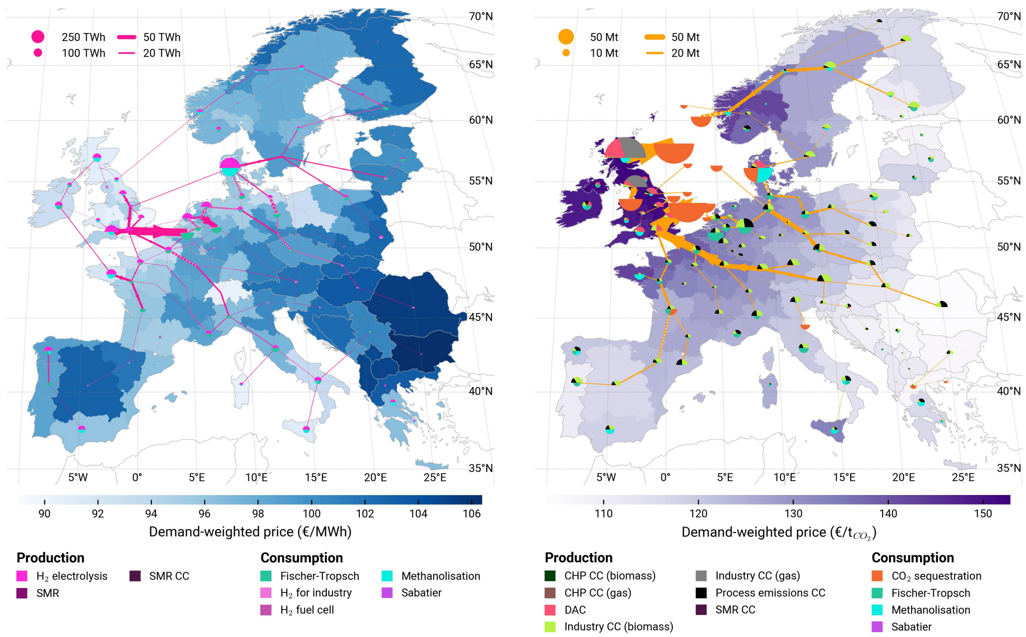
Figure B.21: *Decentral Islands* scenario (2050) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

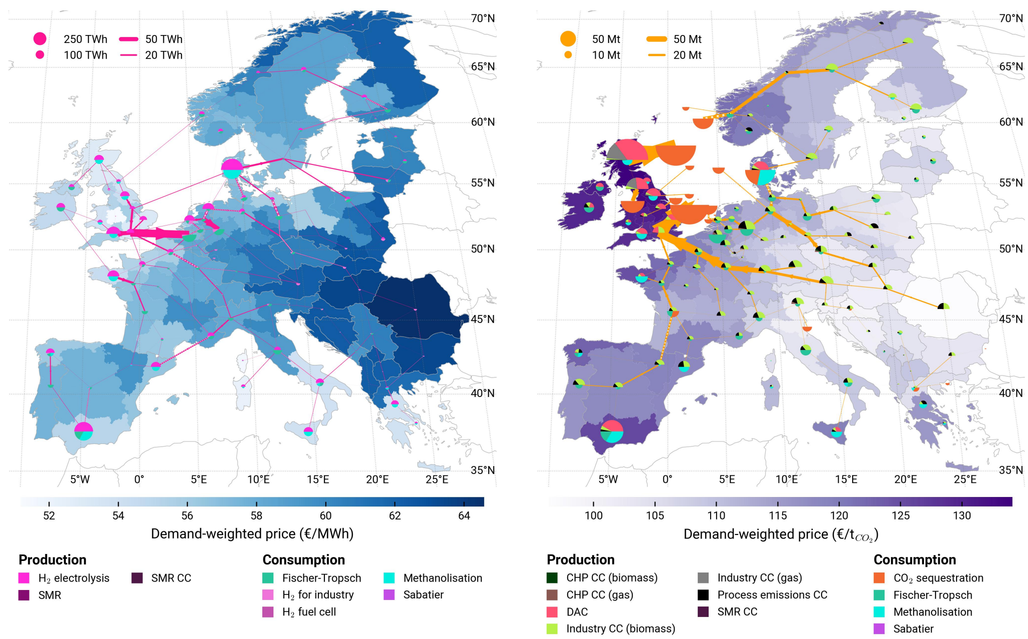
Figure B.22: *Central Planning* scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

Figure B.23: *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.24: *Central Planning* scenario (2050) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.

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