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

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Abstract

The European Union (EU) aims to achieve climate-neutrality by 2050, with interim 2030 targets including 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 domestic CO_2 injection capacity. To support these targets, Projects of Common and Mutual Interest (PCI-PMI) — large infrastructure projects for electricity, hydrogen and CO_2 transport, and storage — are identified by the European Commission. This study focuses on PCI-PMI projects related to hydrogen and carbon value chains, assessing their long-term system value and the impact of policy delays or relaxations using a myopic, deterministic two-stage regret analysis.

Our study finds that PCI-PMI projects contribute to reaching a net-zero energy system in a more cost-efficient way compared to a system without any pipeline build-out. Hydrogen pipelines facilitate the distribution of more affordable green hydrogen from northern and south-western regions rich in renewables to high-demand regions in central Europe while CO_2 pipelines link major industrial sites and process emissions to offshore sequestration sites. Finally, our results show that the build-out of pipelines serve as a hedge against overbuilding in solar and wind generation capacities while reducing excessive reliance on single technologies, such as Direct Air Capture (DAC) for CO_2 removal.

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

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

Hydrogen. Hydrogen is expected to occupy a key position in this transition as it is considered essential for decarbonising hard-to-abate sectors, such as, but not limited to steel, refining, agricultural fertilisers, maritime shipping, and aviation [5, 6]. To lay out the foundation for a future hydrogen economy, the EU has set ambitious targets for domestic hydrogen production and infrastructure build-out. Under the EU Hydrogen Strategy [7], reinforced by REPowerEU [8] and the Net-Zero Industry Act (NZIA) [9], the EU aims to install at least 40 GW of domestic renewable hydrogen electrolysis capacity by 2030 (with an additional 40 GW in neighbouring countries). REPowerEU further foresees to produce 10 Mt p.a. of domestic green hydrogen by 2030, with an additional 10 Mt p.a. imported from neighbouring countries [8]. Initiatives like the European Hydrogen Backbone (EHB) aim to support this transition by proposing a hydrogen transport network across Europe. The EHB envisions a H_2 pipeline network of almost 53 000 km by 2040 [10], including repurposing existing natural gas infrastructure and additional potential routes.

CCUS. Complementing its hydrogen ambitions, the EU has proposed similarly strategic plans for the carbon economy. In the Industrial Carbon Management Strategy, the EU envisages a single market for CO_2 in Europe, to enable CO_2 to become a tradable commodity for storage, sequestration, or utilisation [11]. Beyond a net-zero emission target in the European Climate Law [2], CO_2 — in conjunction with H_2 — serves as a key feedstock for the production of synthetic fuels, such as methanol, methane, as well as high-value chemicals [6]. Outside of CO_2 utilisation, Carbon Capture and Storage (CCS) is considered indispensable for achieving net-zero emissions in sectors with unavoidable process-based CO_2 emissions, such as cement, chemicals, and waste-to-energy. Here, the NZIA mandates that all EU member states collectively ensure that at least 50 Mt p.a. of CO_2 can be injected and stored by 2030. The European Commission further estimates that up to 550 Mt p.a. of CO_2 will need to be captured and stored by 2050 [9].

Transport infrastructure and PCI-PMI projects. To meet the need for green electricity, green H_2 and CO_2, significant investments into its transport and storage/sequestration investment are needed. A recent report by the European Commission [12] confirms that investment needs into the EU's energy infrastructure will grow continuously, with the largest share (around 1200 bn. €) of the investment volume going into electricity distribution and transmission by 2040. Beyond the electricity sector, the report also emphasises on significant investments into H_2 and CO_2 infrastructure, expecting around 170 bn. € and up to 20 bn. € p.a. by 2040, respectively, emphasising that these investments are facing higher uncertainty given both sectors being in their early infancy.

Within the transition towards net-zero, the EU has established a framework to support the development of key cross-border (and national) infrastructure projects, which are considered essential for achieving the EU's energy policy targets. These Projects of Common Interest (PCI) are projects that link the energy systems of two or more EU member states [13]. In a biennial selection process, PCIs are identified through regional stakeholder groups and evaluated based on their contribution to the EU's energy security, e.g. by improving market integration, diversification of energy supply, and integration of renewables. So-called Projects of Mutual Interest (PMI) transfer the same concept to projects that link the EU's energy system with third countries, such as Norway or the United Kingdom, the Western Balkans or North Africa, as long as they align with EU climate and energy objectives [14]. Approved PCI-PMI projects benefit from accelerated permitting and access to EU funding under the Connecting Europe Facility (CEF). Given the strong political and project promoter support, comprehensive reporting and monitoring processes, as well as their role as technological lighthouses, projects on the PCI-PMI list are more likely to be implemented than others [12]. Nonetheless, large infrastructure projects—including those on the PCI-PMI list—often face delays due to permitting hurdles, financing constraints, procurement bottlenecks, and other implementation challenges [15].

As a direct result of the revised TEN-E Regulation (Regulation (EU 2022/869)) [16], the 2023 PCI-PMI list [14, 17] for the first time includes H_2 and CO_2 transport and storage projects, alongside electricity and gas projects. A continent-wide hydrogen backbone — connecting regions rich in renewable energy potential to indistrual and storage hubs — is viewed essential for transporting H_2 where it is needed. Likewise, CO_2 pipelines and sequestration sites are needed to capture and sequester emissions from cement, steel, refining industries and power plants. With around 14 projects in the priority thematic area 'cross-border carbon dioxide network' and 32 projects listed in 'hydrogen interconnections' (including pipelines and electrolysers), this PCI-PMI list lays the foundation for a future pan-European H_2 and CO_2 value chain [18].

Contribution of this paper. Given this evolving infrastructure landscape, the question arises, what the long-term value of these PCI-PMI projects under varying implementation risks and policy uncertainties? This paper contributes to the policy debate around H_2 and CO_2 by quantitatively assessing the long-term value of strategic cross-border infrastructure, such as Projects of Common Interest and Projects of Mutual Interest. Given the rising complexity and the interdependency between the carriers, systemic approaches are needed that consider the interactions between different energy carriers. Hence, we build on the open-source energy system model PyPSA-Eur to assess their value in fully sector-coupled decarbonisation pathways — linking electricity, heating, industry, and agriculture, transport, shipping, and aviation — under varying short term impacts such as infrastructure delays and changes in policy ambitions. To our knowledge, this is the first study to jointly evaluate electricity, hydrogen, and CO_2 transport and storage infrastructure within a large-scale, high-temporal, and high-spatial-resolution sector-coupled energy system model.

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 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 (iii).

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 [19]. 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 [6]. 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.

Béres et al. [5] evaluate the interaction between electricity, H_2, and synthetic fuel demand by linking the JRC-EU-TIMES long-term energy system model with PLEXOS. In their findings, H_2 production varies between 42 (1400 TWh) and 66 Mt (2200 TWh) p.a. in 2050.

Van Greevenbroek et al. [20] investigate the cost-optimal development of green H_2 by assessing the near-optimal space of an extensive scenario set. They find a moderate level of green H_2 production is cost-optimal, with production levels depending primarily on the availability of green fuel imports and carbon, capture, and storage. Eliminating green H_2 entirely would come at a total system cost increase of 2 %.

By including H_2 and CO_2 transport infrastructure, additional benefits and net cost-savings can be unlocked in a sector-coupled system.

Neumann et al. [6] 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. [21] 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 [22] 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. [23], 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 [24], 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. [25] 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, Bakken and Velken [26] formulate linear models for the optimisation of CO_2 infrastructure, including pipelines, shipping, CO_2 capture, and storage and demonstrate the applicability in a regional case study for Norway. Hofmann et al. [4] address previous research gap in assessing the interaction between H_2 and CO_2 infrastructure, by combining the the production, transport, storage, and utilisation of both H_2, CO_2 and their products. They specifically raise the question whether H_2 should be transported to CO_2 point sources or vice versa. They find that most cost savings can be achieved in a hybrid setup where both networks are present, as the CO_2 network complements the H_2 network by promoting carbon capture from point sources and reducing reliance on Direct Air Capture (DAC).

2.2. Addressing uncertainty in energy system models

While the previous section have examined the value of CO_2 and H_2 in low-carbon energy systems, they do not take into account potential uncertainties regarding future policy targets or infrastructure build-outs. Energy system models can address such uncertainties through a range of approaches, including scenario analysis, sensitivity analysis, stochastic programming, and regret-based methods. Within the scope of this research, we focus on the (deterministic) scenario analysis and regret-based methods, as they are particularly suitable for complex, large-scale, sector-coupled system models.

Regret analysis. A regret analysis is a common and widely established approach in economics that systematically evaluates the regret, i.e., additional system costs, incurred by not having made the optimal decision in hindsight. Usually, a regret-analysis is designed in two steps, first, a set of scenarios is defined, which represent different future developments, such as policy targets, infrastructure build-out, or technology costs. In a second step, the performance of first-stage investment is evaluated under the realisation of second-stage or short-term realisations of the future [27]. It is particularly useful in energy system modelling, where future uncertainties can significantly impact the performance of investments in infrastructure and technologies.

Möbius and Riepin [28] investigate the regret of investment decisions into electricity generation capacities, by developing a two-stage, stochastic cost-minimisation model of the European electricity and gas markets. In the first stage, the model determines optimal investment decisions, accounting for three TYNDP scenarios, while the second step solves the optimal dispatch for all assets in the electricity and gas sector. They find that ignoring uncertainty may result in investment decisions that lead to higher costs and regrets.

Van der Weijde and Hobbes [29] demonstrate the importance of considering uncertainty in energy system models, by applying a two-stage optimisation model to evaluate grid reinforcements in Great Britain. Including the status quo scenario, they consider six scenarios, which represent different future developments of electricity demand, generation, fuel, and CO_2 prices. As part of their study, they calculate the regret for given first-stage transmission decisions under the realisation of second-stage scenarios. Note that the regret matrix is symmetric, i.e., the regret of each first-stage decision is evaluated under all second-stage scenarios.

3. Research gaps and our contribution

Based on the literature review, we have identified that there is still a lack of comprehensive studies that assess the complex interaction of CO_2 and H_2 infrastructure in a large-scale, sector-coupled energy system model. Further, not many studies have considered real planned projects, such as PCI-PMI projects, potentially neglecting investment options that may not be perfectly cost-optimal, but are politically supported and have a high likelihood of being implemented [20, 30]. To the best of our knowledge, the performance of PCI-PMI projects has not yet been evaluated in a sector-coupled energy system model. Given the variety of project promoters involved, the complexity and the high cost of these projects, we believe it is crucial to transparently assess the impact of these projects on the European energy system and key EU policy targets.

Our study aims to fill this gap by evaluating different build-out levels of CO_2 and H_2 infrastructure, including PCI-PMI projects and their performance under a defined set of short-term scenarios. By using a myopic and hence, iterative modelling approach, we consider long-term pathway effects. This also reduces the risk of overly optimistic results that are often observed in studies that look directly at the target year 2050. We implement a deterministic, two-stage regret matrix approach to assess the performance of different scenarios under three short-term occurrences for each planning horizon, individually. This allows us to consider future uncertainties, including changes in policy ambitions and infrastructure delays. By limiting the analysis to a discrete set of scenarios, the regret analysis is manageable and computationally feasible. We deliberately keep a deterministic approach, as this would increase the complexity of the model and the computational time significantly.

With this study, we also bring more certainty into the chicken-and-egg problem of investing into CO_2 and H_2 infrastructure first vs. waiting for their demand to materialise. Our paper aims in particular to address the following research questions:

1. Do PCI-PMI projects contribute to achieving the EU's energy policy targets and a net-zero transition in the long run?

2. What are the costs associated with adhering to the EU policy targets, even if PCI-PMI projects are delayed?

4. Methodology

In this section we first describe the basic energy system model PyPSA-Eur, before detailing the implementation of the PCI-PMI projects, the scenarios, and the regret matrix.

We build on the open-source, sector-coupled energy system model PyPSA-Eur [6, 31–33] 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 [34], renewable potentials, and availability time series [35]. It includes the current high-voltage transmission grid (AC 220 kV to 750 kV and DC 150 kV and above) [36]. 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. [37] 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 [38]. 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 [4]). add source

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 [39–43] and are shown in Figure A.9. Regionally and temporally resolved demand includes electricity, heat, gas, biomass and transport.

Gas (methane/CH_4) demand includes direct use in gas-based industrial processes, as well as fuel in the electricity and heating sector. Note that we do not explicitly enable the gas transmission grid as opposed to the CO_2 and H_2 infrastructure. We do this for different reasons: (i) the modelled PCI-PMI projects overlap in some parts with the gas grid, i.e., include CH_4 pipelines that will be retrofitted to H_2 pipelines, however, input data is not always clear; (ii) we do not assume the gas transport to be bottlenecked by the existing gas grid, as such, gas transport is assumed to be copper plated; and (iii) the computational complexity is already high due to the geospatial and temporal resolution, as well as the number of components. Instead, given the focus on the CO_2 and H_2 sector, we decide to make trade-offs here.

Internal combustion engine vehicles in land transport are expected to fully phase out in favour of electric vehicles by 2050 [44]. 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, 45], 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 [17]. We add all CO_2 sequestration sites and connected pipelines, H_2 pipelines and storage sites, as well as proposed pumped-hydro storage units and transmission lines (AC and DC) to the PyPSA-Eur model. 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.

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

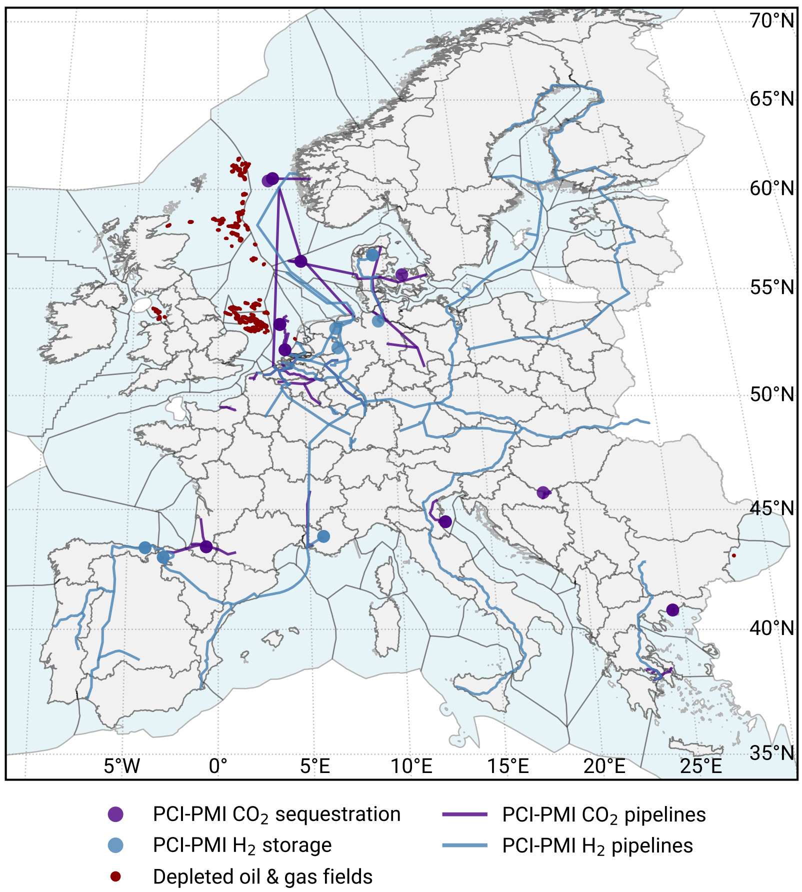


Figure 1: Map of the regional scope including clustered onshore (grey) and offshore regions (blue), as well as PCI-PMI CO_2 and H_2 pipelines, storage and sequestration sites. Depleted offshore oil and gas fields (red) provide additional CO_2 sequestration potential [4].

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 [38] 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 and H_2 storage 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 [4, 46]. The dataset includes storage potential from depleted oil and gas fields as well as saline aquifers. While social and commercial acceptance of CO_2 storage has been increasing in recent years, concerns still exist regarding its long-term purpose and safety [47]. 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. Our focus is motivated by the following reasons: (i) infrastructure such as wells, platforms, and pipelines already exist for depleted oil and gas fields and can be repurposed, significantly lowering costs and project risk; (ii) depleted fields are generally better understood geologically and have demonstrated sealing capacities, further reducing uncertainty; and (iii) repurposing former production sites is often more publicly and politically acceptable than developing entirely new storage locations, entirely. In contrast, while saline aquifers represent a substantial share of the total technical potential, they carry higher development costs and risks and are less likely to be advanced without strong policy and financial support [46]. Note that the PCI-PMI project list includes some aquifer-based sequestration projects, however, their inclusion as PCI-PMI project indicates a higher likelihood of development.

Spread over a lifetime of 25 years, the selected depleted oil and gas fields translate 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).

The model also includes H_2 storage sites from the PCI-PMI list and allows for endogenous build-out of additional storage capacities by repurposing salt caverns [6].

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.

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 [8] and 40 GW of electrolyser capacity [7], and 50 Mt p.a. of CO_2 sequestration capacity [9]. For 2050, the CO_2 are based on the modelling the impact assessment for the EU's 2040 climate targets, in 250 Mt p.a. need to be sequestered [48]. H_2 production targets for 2050 are based on the European Commission's METIS

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.

3 study S5 [49], modelling possible pathways for industry decarbonisation until 2040. For 2040, we interpolate linearly between the 2030 and 2050 targets. The electrolyser capacities for 2040 and 2050 are scaled by the ratio of H_2 production to electrolyser capacity in 2030. An overview of the targets and their values is provided in Table 2. Note that we implement the green H_2 production target as a minimum H_2 production constraint from electrolysis , 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, 8, 9, 48, 49]

4.2.2. Short-term scenarios

In a second step, we assess the impact of three short-term scenarios on the long-term scenarios, i.e., the CO_2 and H_2 pipeline capacities built in the long-term scenarios are either frozen or removed. 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 [11]. 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. A regret matrix provides a decision-making framework that evaluates the potential loss (*regret*) associated with choosing one strategy over the other by comparing the outcomes, i.e., the total system costs. Here, the regret is quantified as the difference between system costs of the short-term scenario and the long-term (anticipated) scenario for each scenario. 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 linear optimisation problems are solved using Gurobi.

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

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

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 %.

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.25 to C.27 compared to *CP* pipeline utilisation in Figures C.28 to C.30). 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

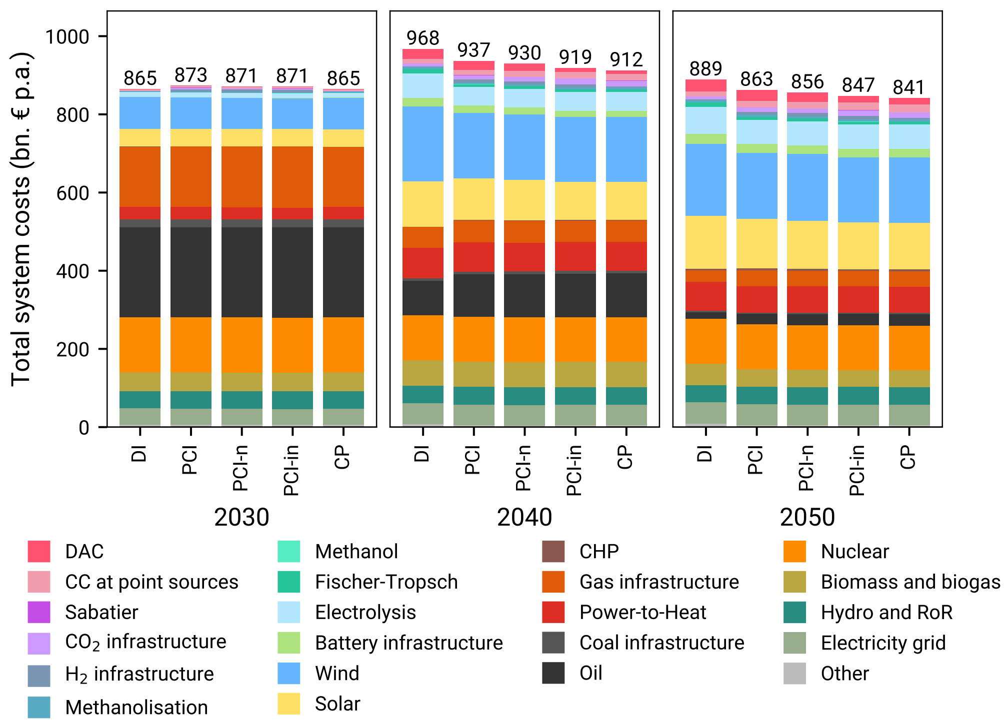


Figure 2: Total annual system costs (CAPEX + OPEX) by technology group.

PCI-PMI and endogenous pipeline investments.

TB: why? perhaps more CCU and FT and H2 makes system more flexible

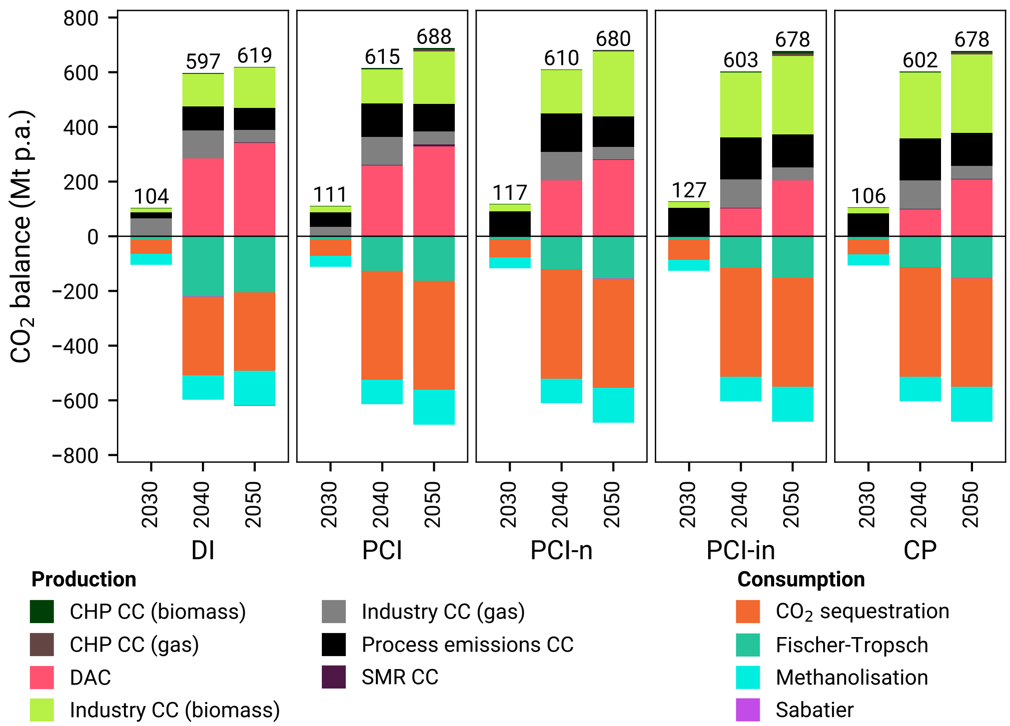
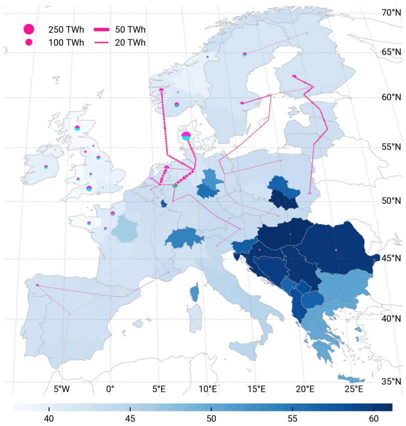


Figure 3: CO_2 balances in long-term scenarios.

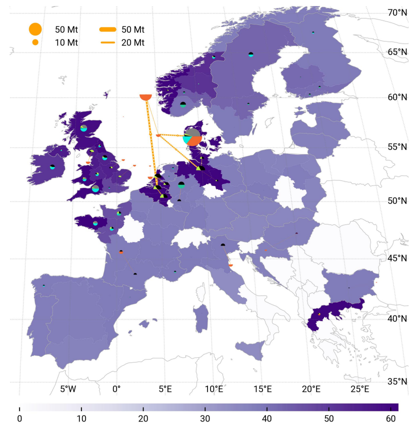
Carbon capture, utilisation, and storage. We find that most of the differences in system cost and savings can be attributed to the production and utilisation of CO_2, as shown in Figure 3. Lacking the option to transport CO_2 from industry and other point sources to the offshore sequestration sites, 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).

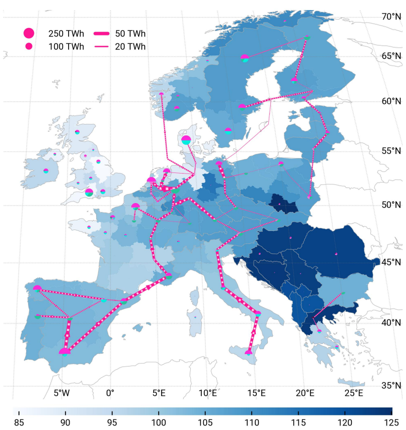
In 2040 and 2050, all sequestration targets (Table 2) are overachieved, as the full combined CO_2 sequestration potential of 398 Mt p.a. is exploited in all scenarios where PCI-PMI projects are included (*PCI* to *CP*). Emissions are captured from industrial processes equipped with carbon capture units, 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).



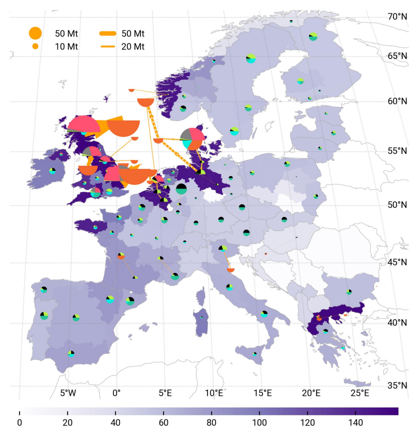
(a) H_2 2030.



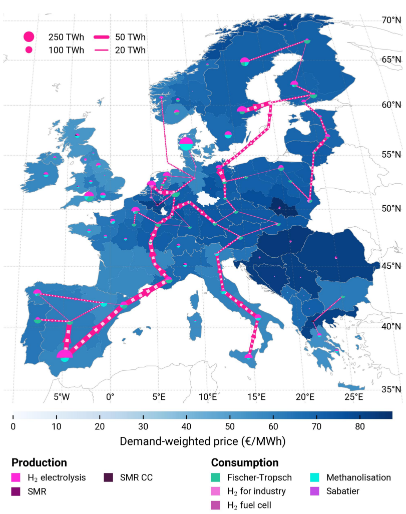
(b) CO_2 2030.



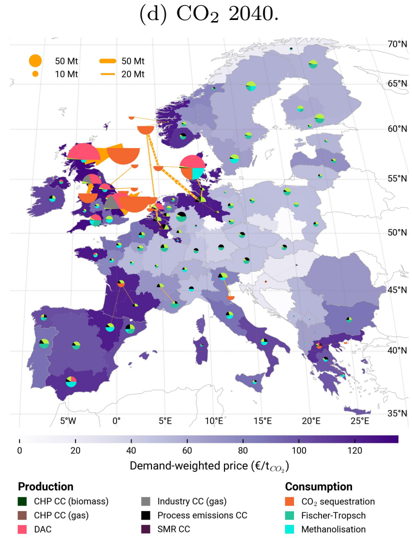
(c) H_2 2040.



(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.

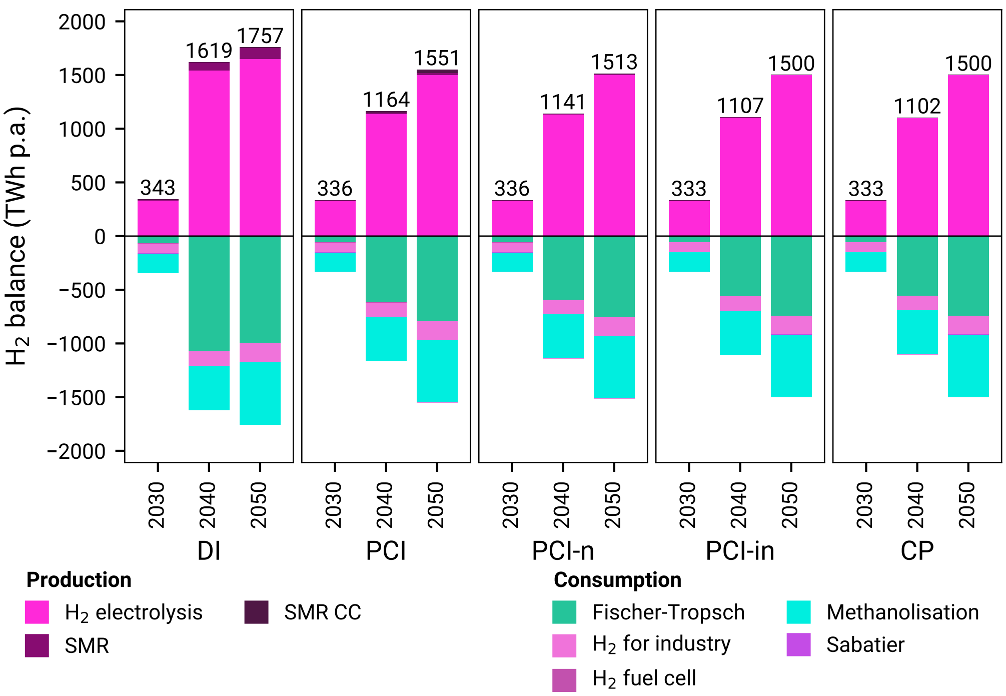


Figure 5: H_2 balances in long-term scenarios.

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, as the 2030 targets are not cost-optimal. However, they are required to stimulate the build-out necessary to reach 2040 and 2050 targets. 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.28b). 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.22b) and the *CP* scenario (Figure C.28b) 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.

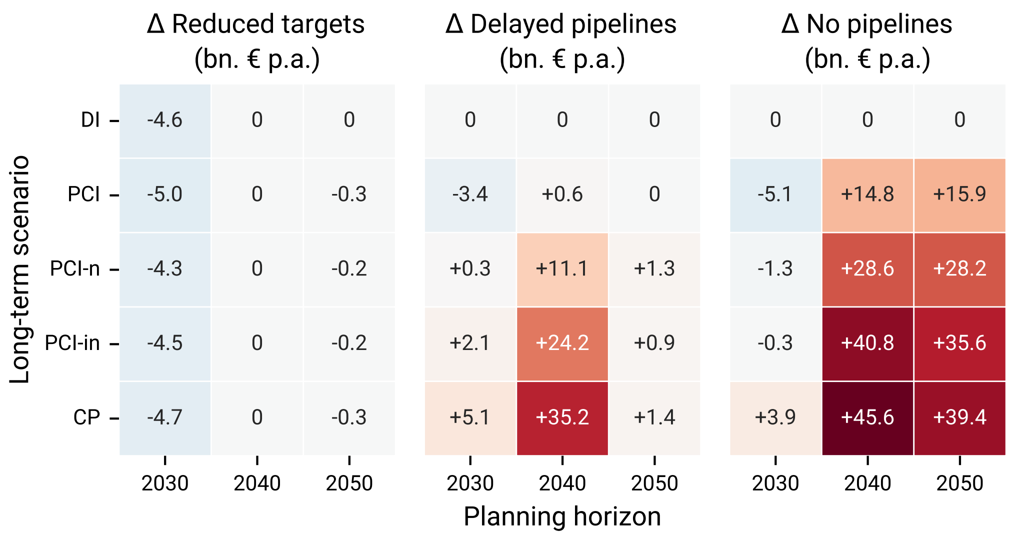


Figure 6: Regret matrix. Calculating regret terms by subtracting system costs of long-term scenarios (rows) from short-term scenarios (columns). Positive values reflect higher costs in the short-term scenarios compared to the long-term ones.

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 is not 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.28), 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 storage) 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. 2050 regrets are lower than 2040 regrets, as almost all PCI-PMI 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.

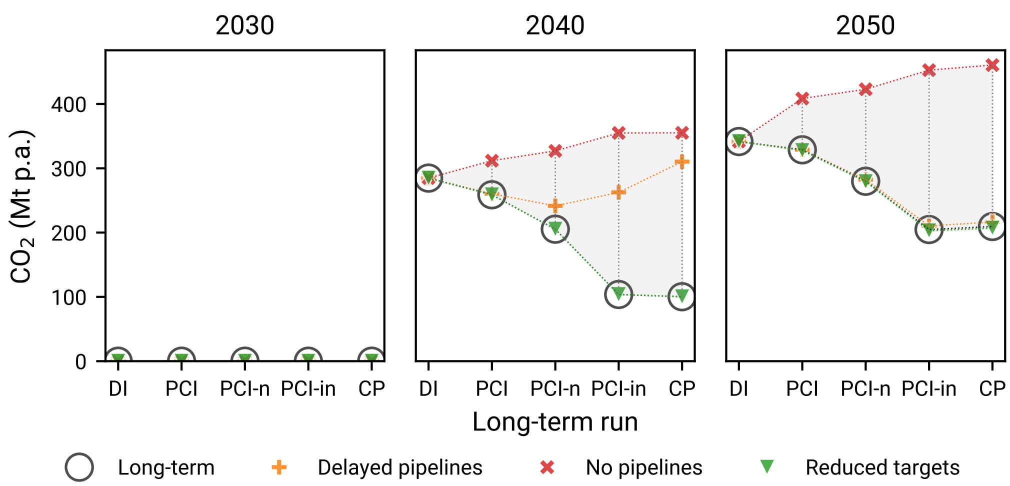


Figure 7: Delta balances — CO_2 from Direct Air Capture.

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 shows the total system costs (TOTEX) p.a. split into CAPEX and OPEX p.a., as well as the net present value of total system costs (NPV) until 2060, discounted at an interest rate of 7 % p.a. 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 of 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.

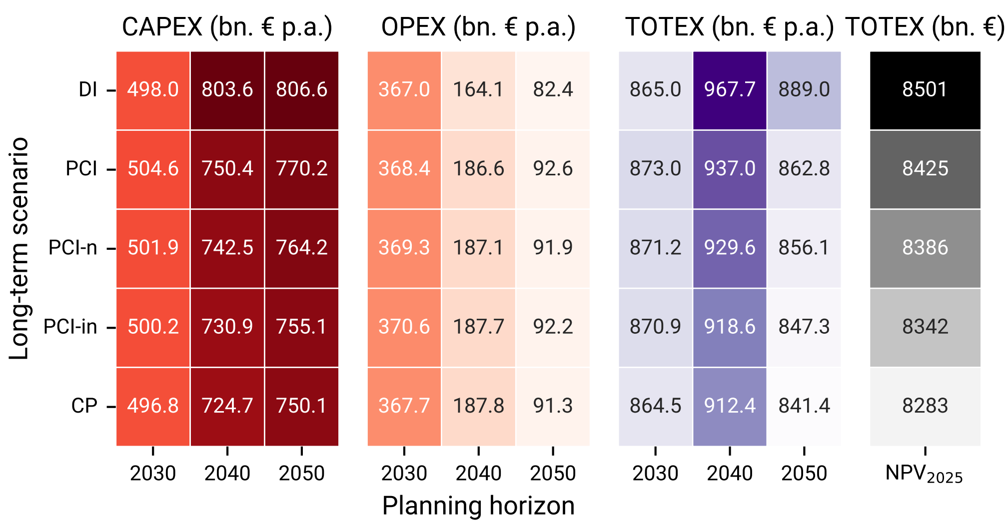


Figure 8: Annual system costs by long-term scenario and planning horizon.

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 endogenously built 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

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

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

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

Technology and risk diversification. The build-out of pipelines serves as an essential risk hedging mechanism against overbuilding solar and wind generation capacities while reducing excessive reliance on single carbon capture technologies such as direct air capture (DAC) and point-source carbon capture, confirming the findings of [4]. This diversification further enhances system resilience towards uncertainties involved with technologies that are not yet commercially available at scale, such as DAC.

Political support and public acceptance. While PCI-PMI may not achieve perfect cost-optimality in their entirety compared to a theoretically centrally planned system, they possess benefits beyond pure economic viability. The success of large-scale infrastructure investments highly depend on continuous political support and public acceptance — factors that are particularly favourable for PCI-PMI projects. Being directly supported by the European Commission, PCI-PMI projects see stronger political backing, institutional support structures with regard to financing, access to grants, acceleration in permitting processes. Being required to frequent and transparent progress reports, PCI-PMI projects are more likely to be accepted by the public.

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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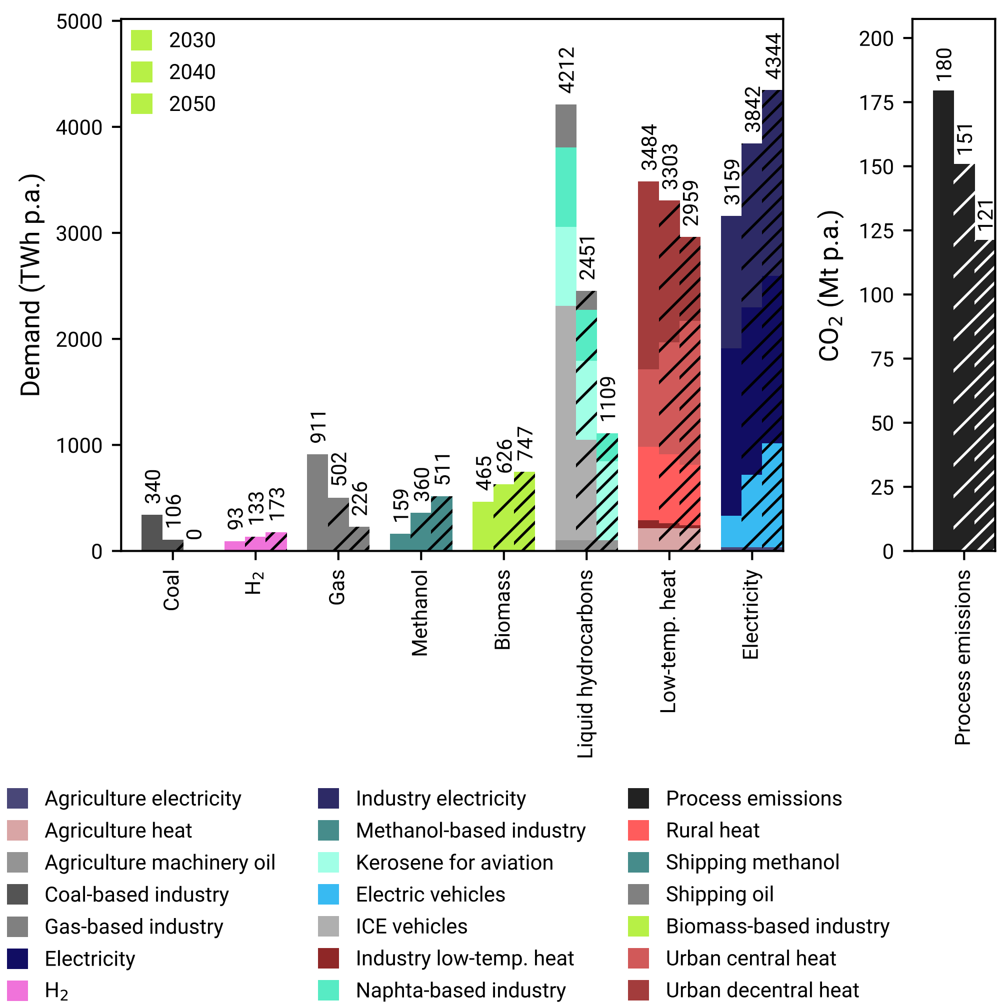


Figure A.9: Exogenous demand.

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

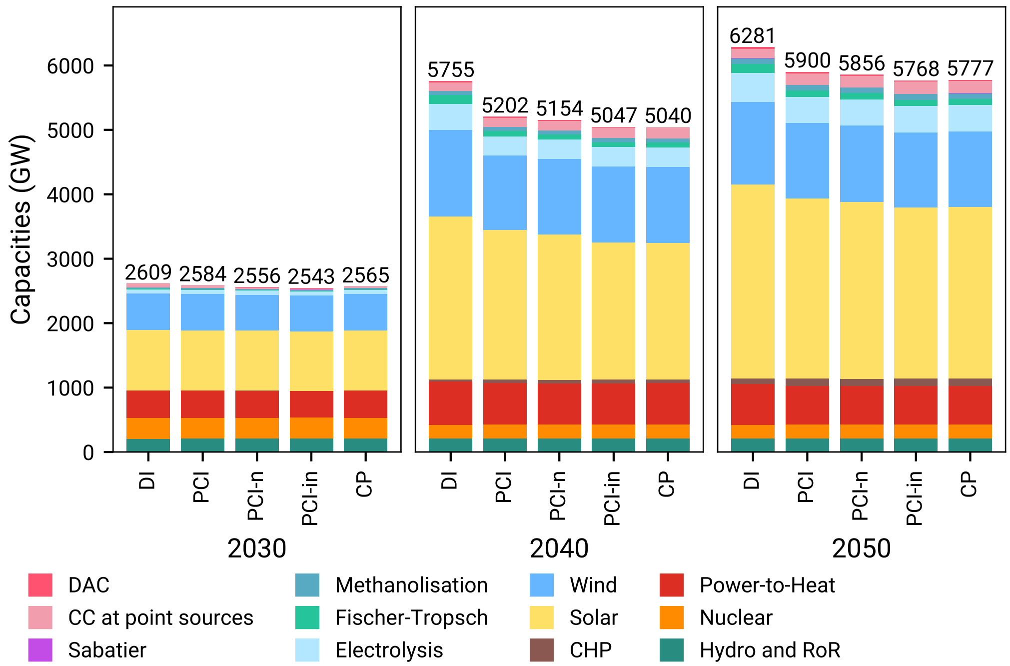


Figure C.10: Installed capacities in long-term scenarios.

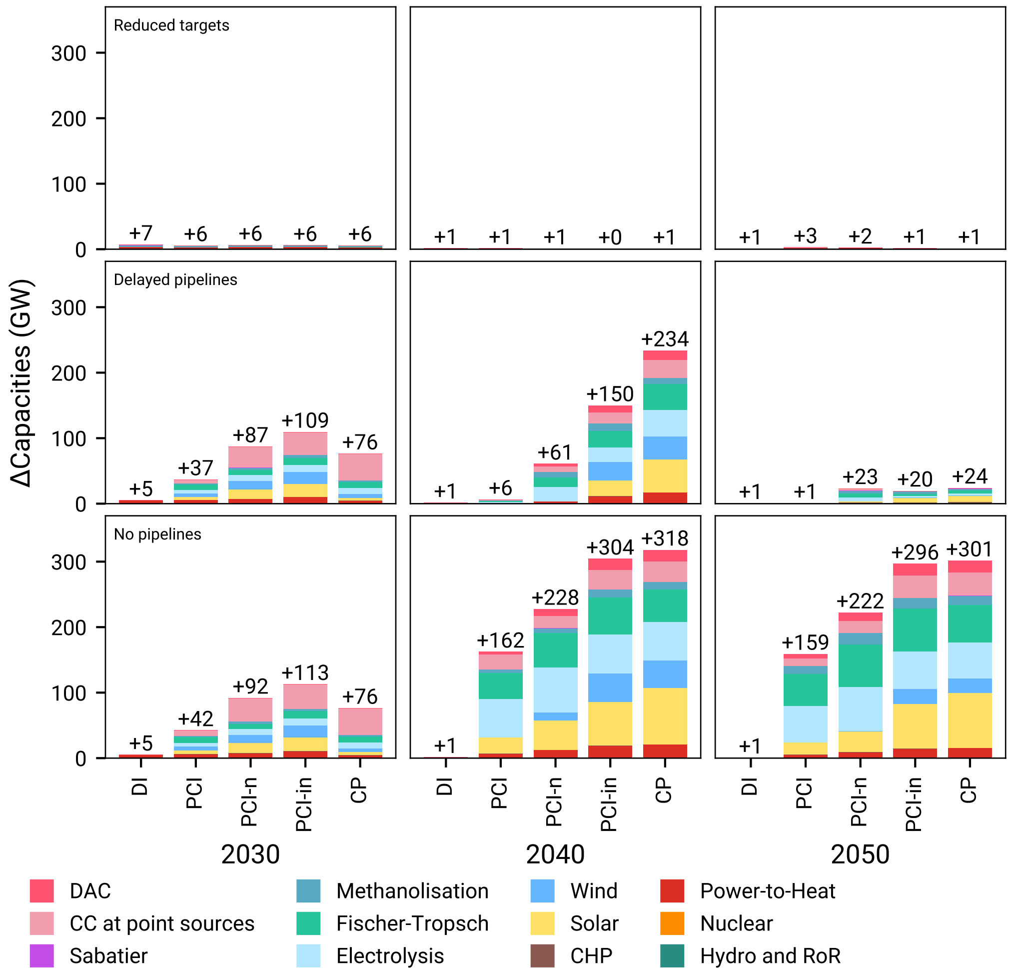


Figure C.11: ΔCapacities — Short-term minus long-term runs.

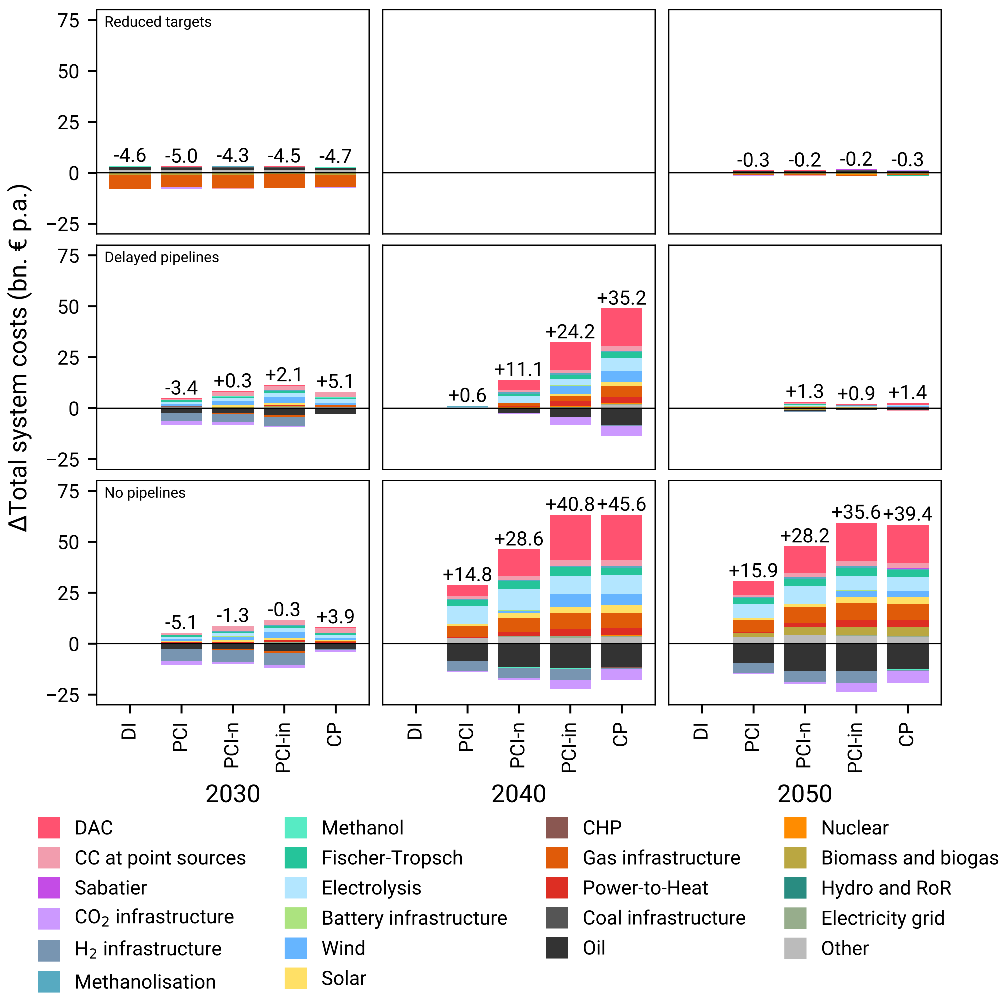


Figure C.12: ΔSystem costs — Short-term minus long-term runs.

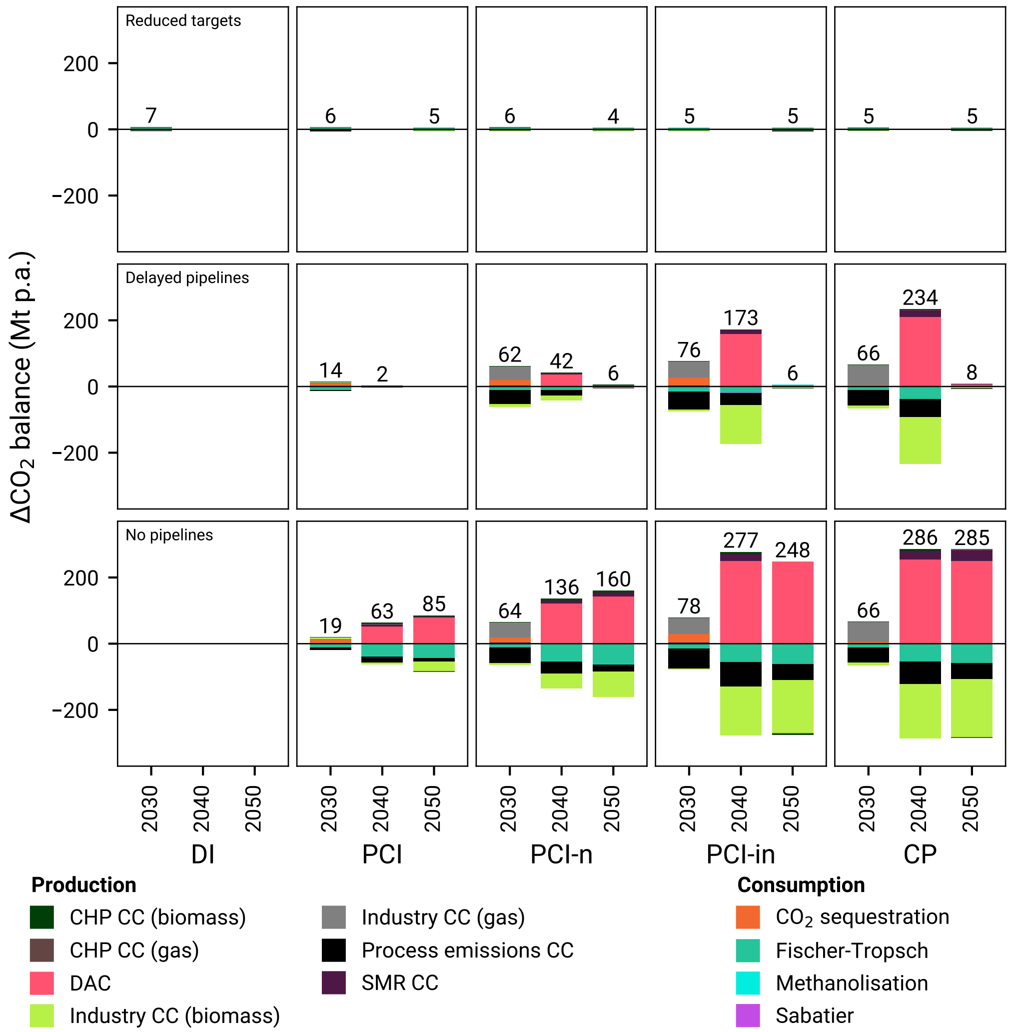


Figure C.13: ΔCO_2 balances — Short-term minus long-term runs.

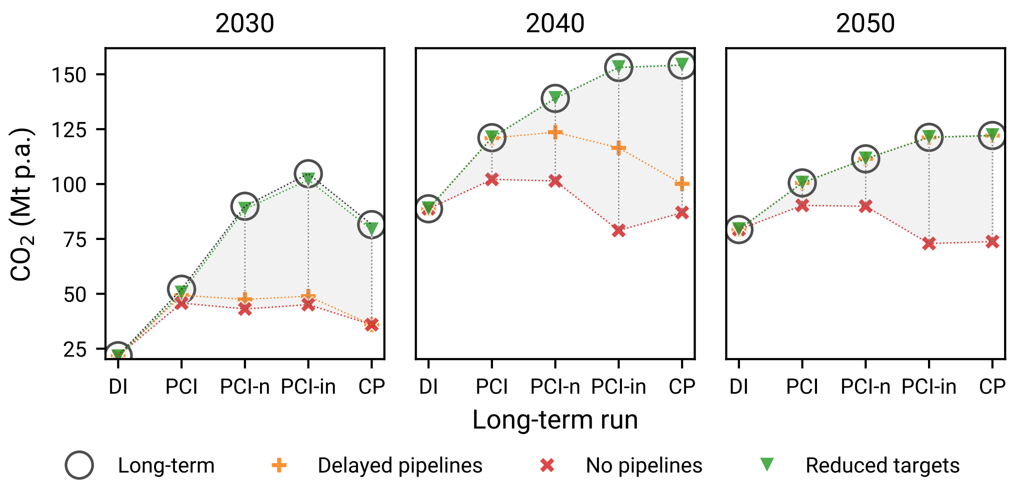


Figure C.14: ΔCO_2 balances — Process emissions including Carbon Capture.

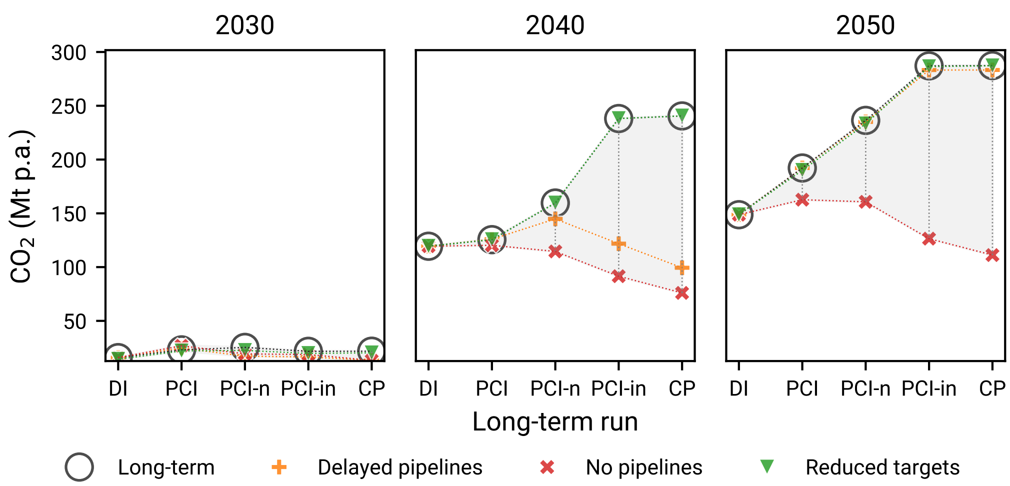


Figure C.15: ΔCO_2 balances — Carbon capture from solid biomass for industry point sources.

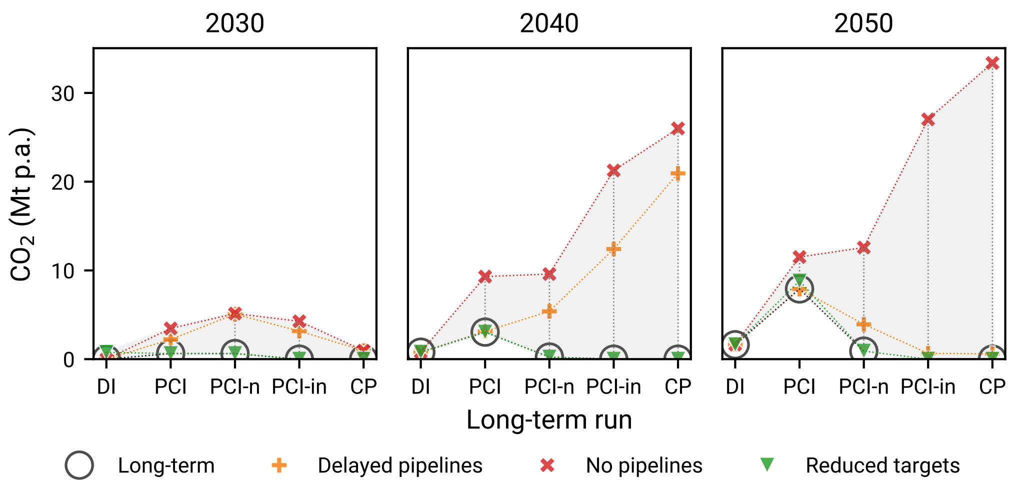


Figure C.16: ΔCO_2 balances — Carbon capture from steam methane reforming point sources.

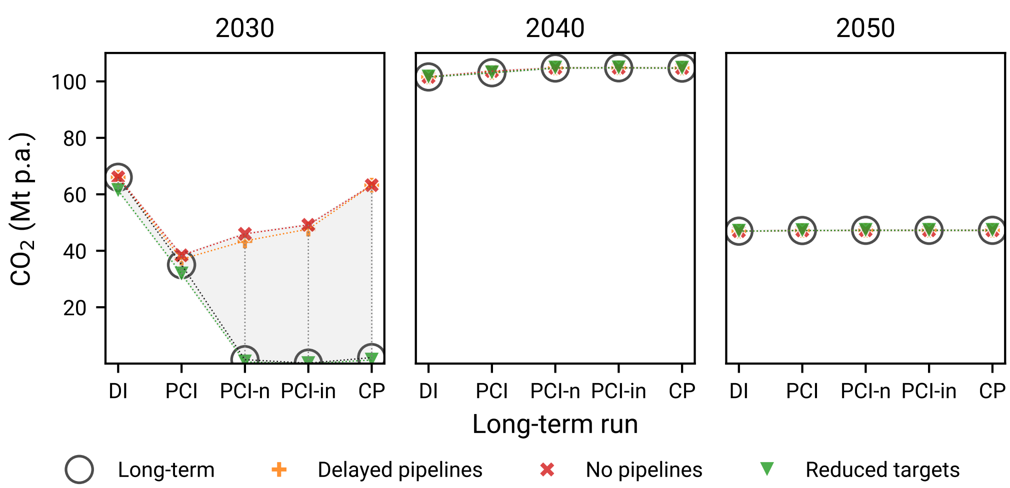


Figure C.17: ΔCO_2 balances — Carbon captured from gas for industry point sources.

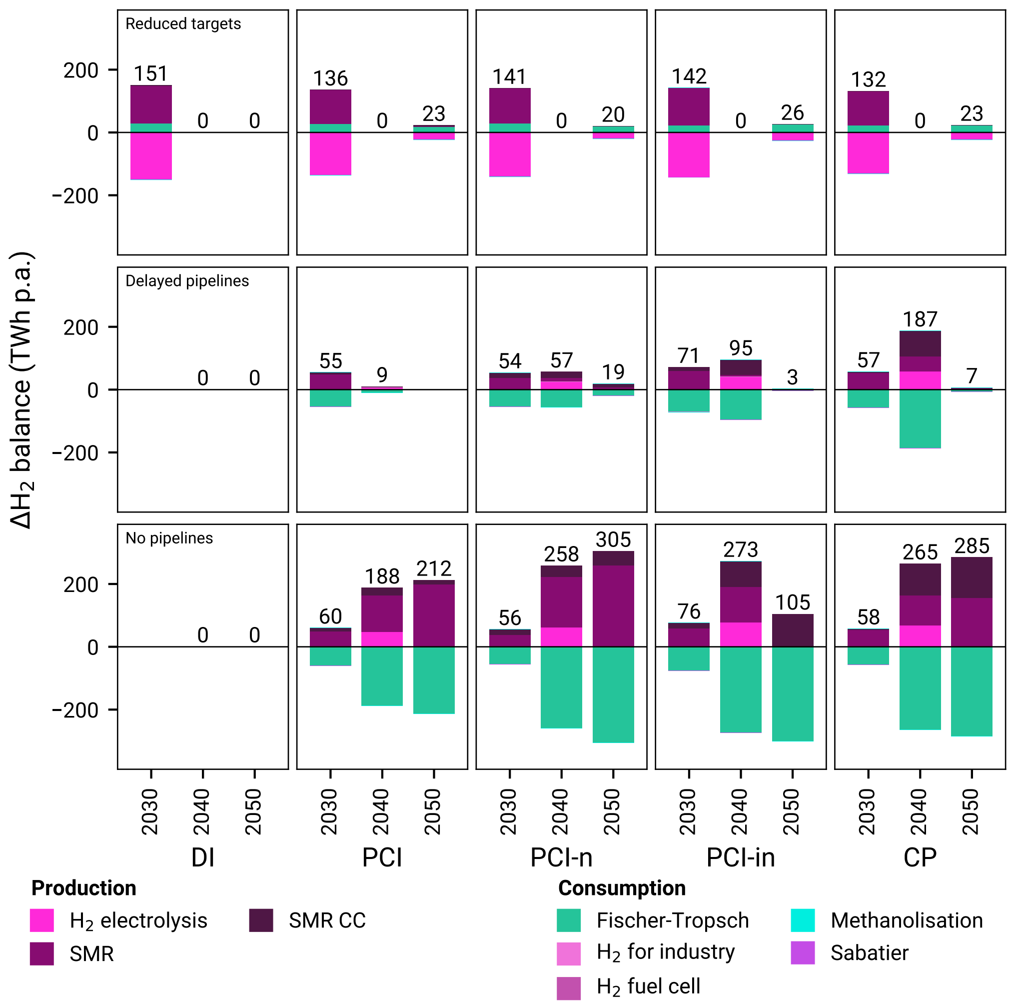


Figure C.18: ΔH_2 balances — Short-term minus long-term runs.

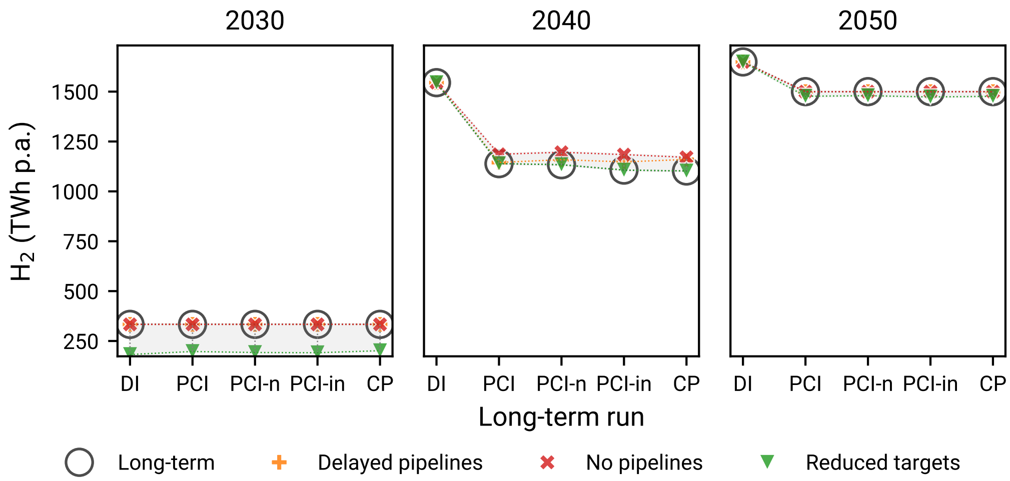


Figure C.19: Delta balances — Electrolytic H_2 production

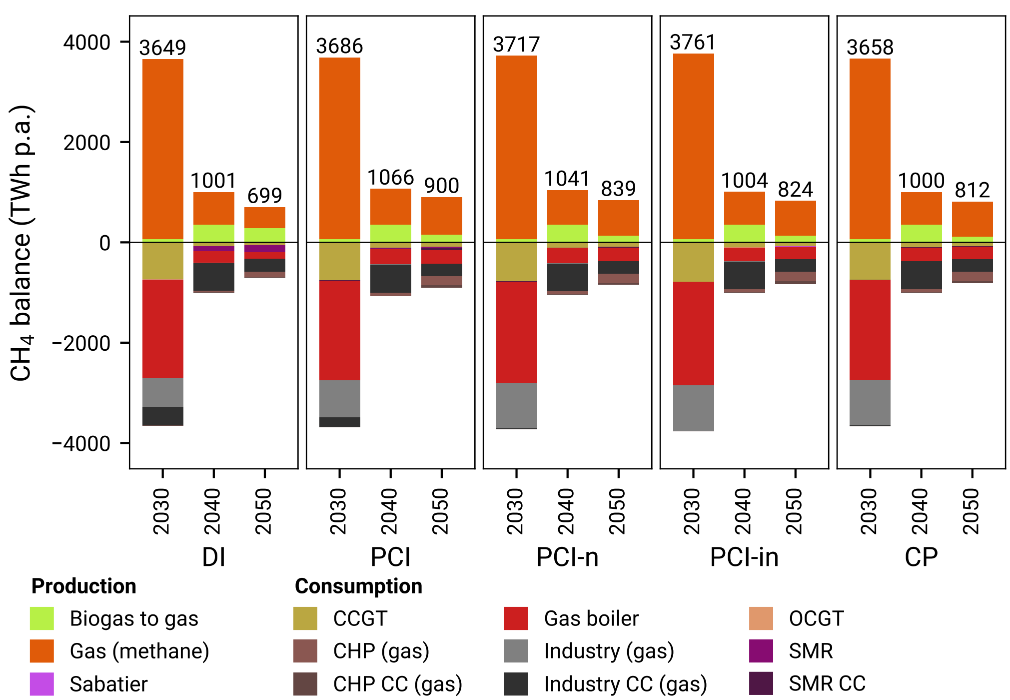


Figure C.20: CH_4 balances in long-term scenarios.

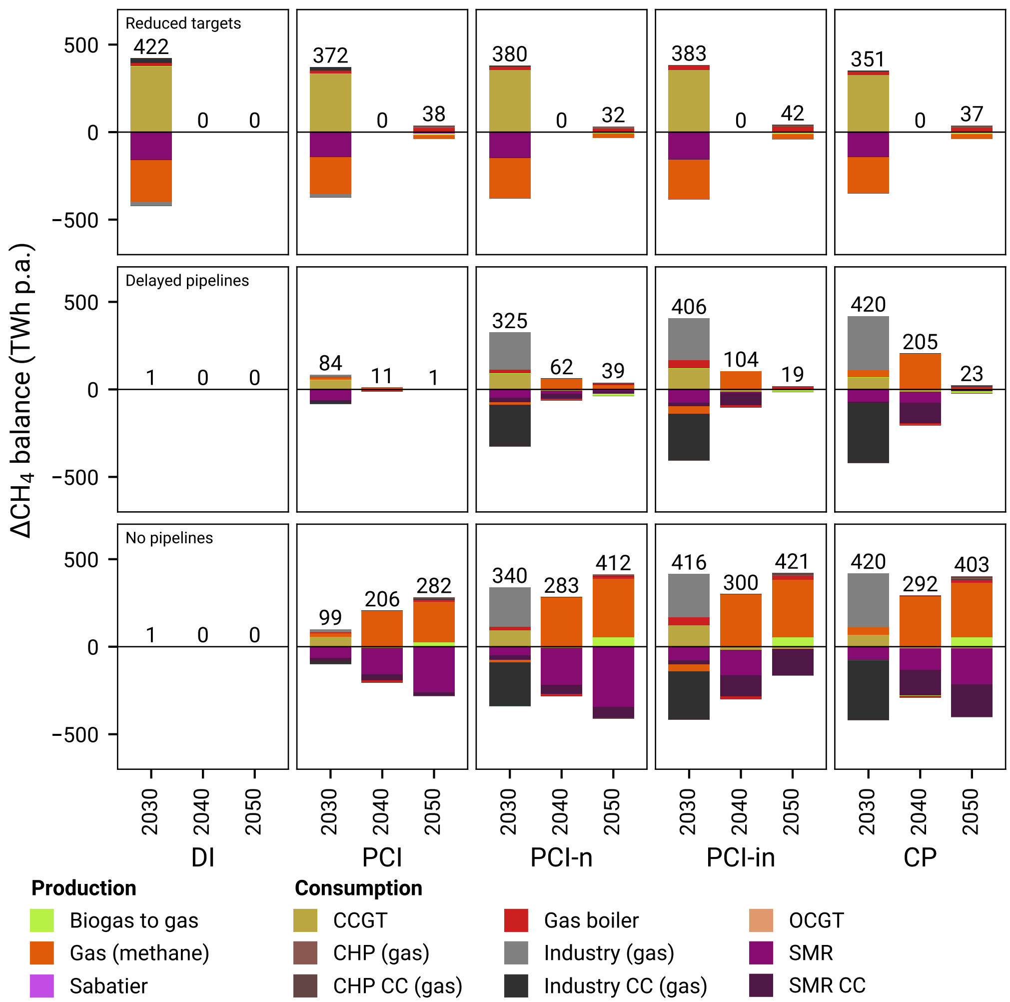
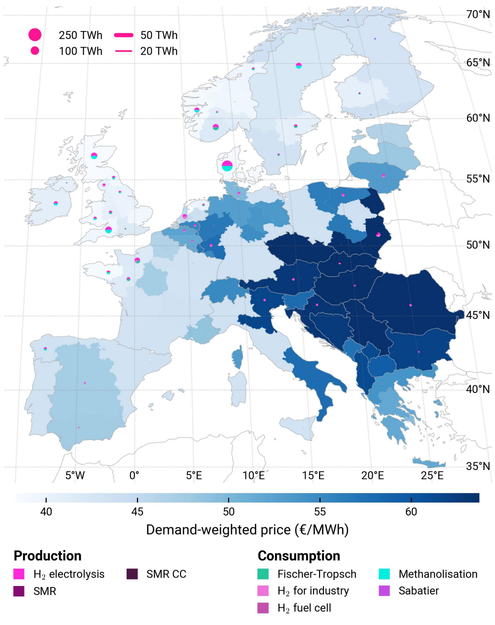


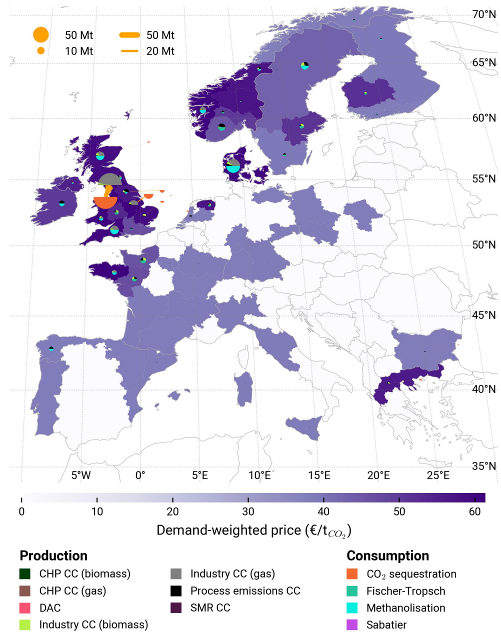
Figure C.21: ΔCH_4 balances — Short-term minus long-term runs.

Appendix C.5. Maps

Appendix C.5.1. Decentral Islands

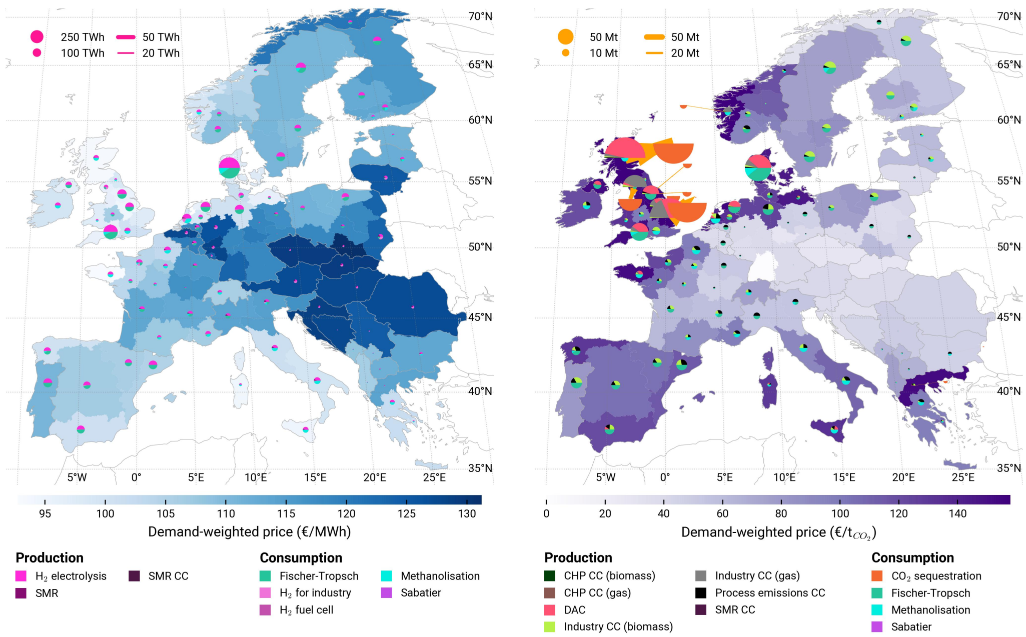


(a) H_2 regional balances and flows.



(b) CO_2 regional balances and flows.

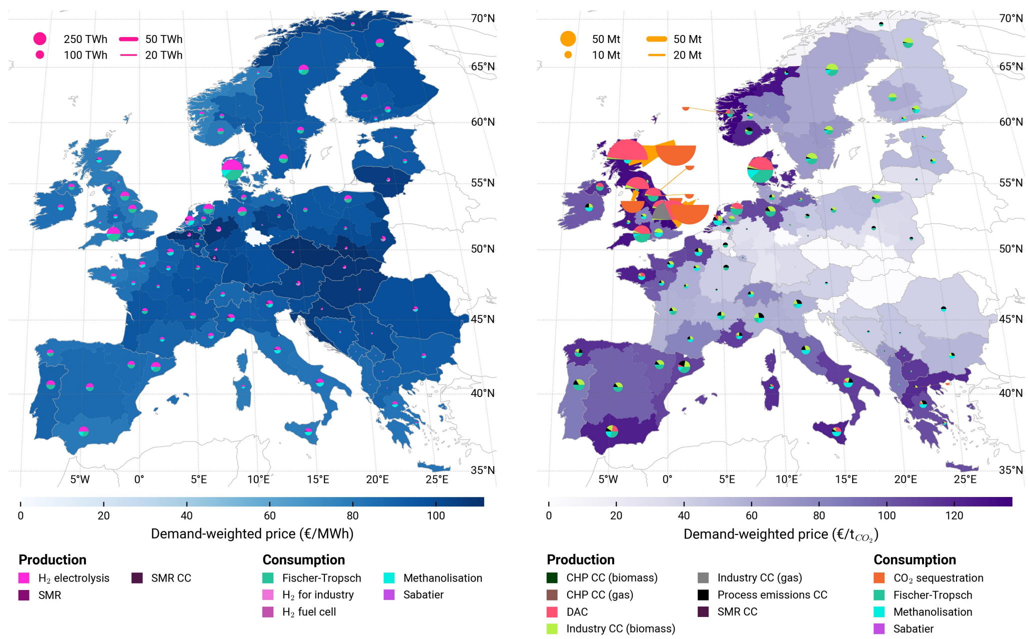
Figure C.22: *Decentral Islands* long-term scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

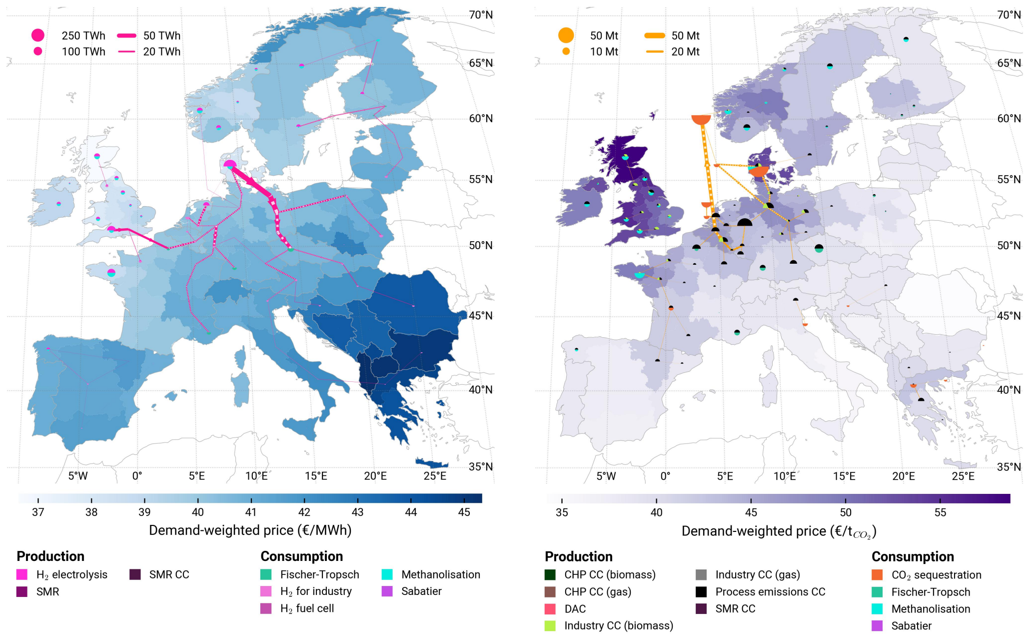
Figure C.23: *Decentral Islands* long-term scenario (2040) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

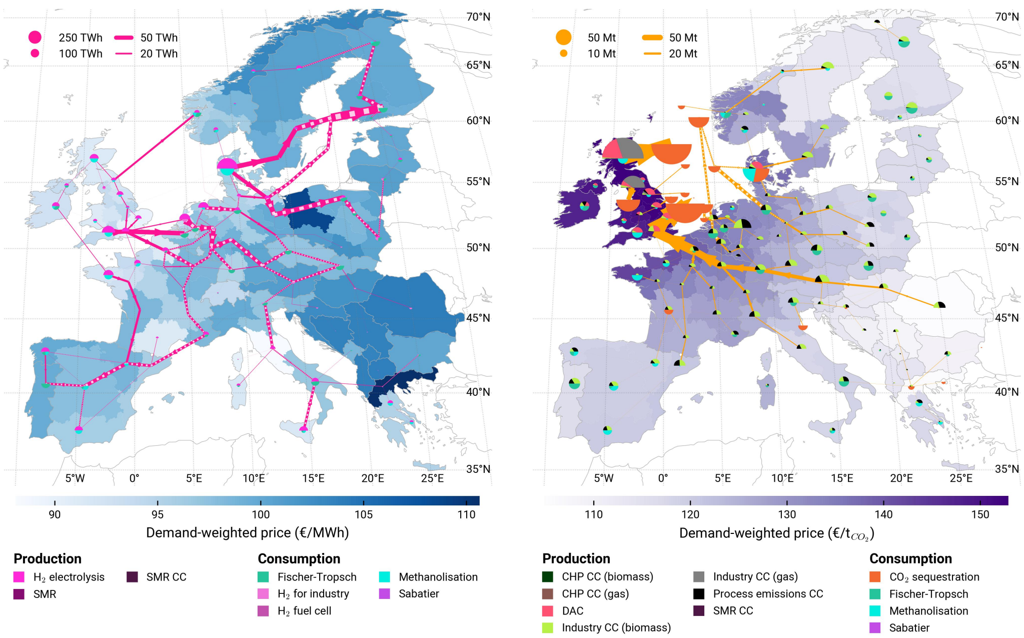
Figure C.24: *Decentral Islands* long-term scenario (2050) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

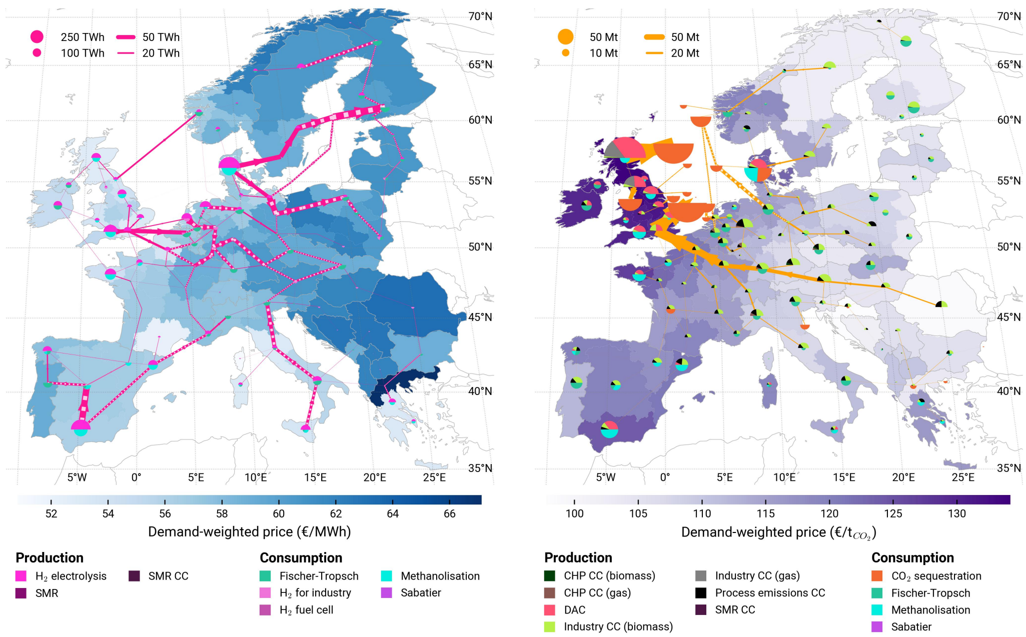
Figure C.25: *PCI* long-term scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport. Dotted white lines represent PCI-PMI projects.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

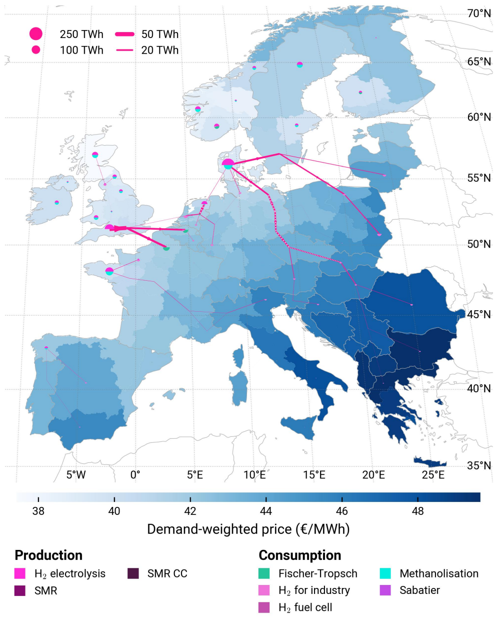
Figure C.26: *PCI-in* long-term scenario (2040) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport. Dotted white lines represent PCI-PMI projects.



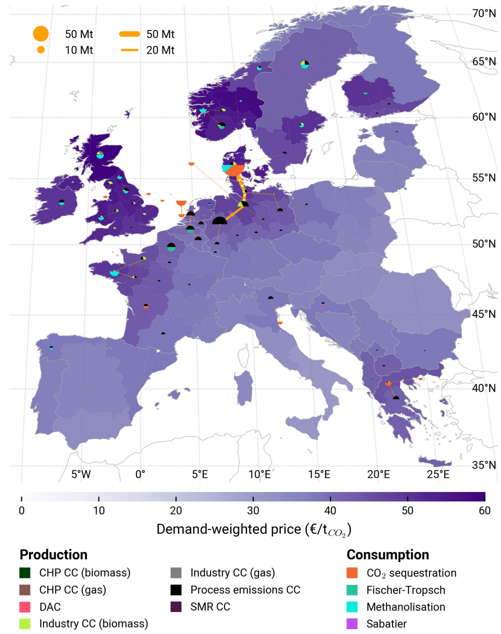
(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

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

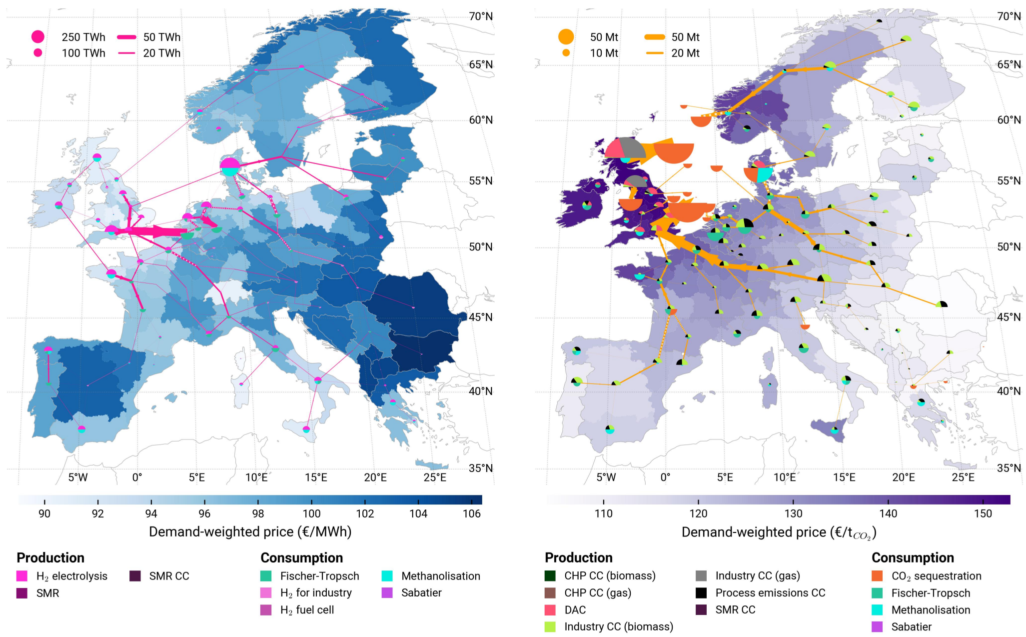


(a) H_2 regional balances and flows.



(b) CO_2 regional balances and flows.

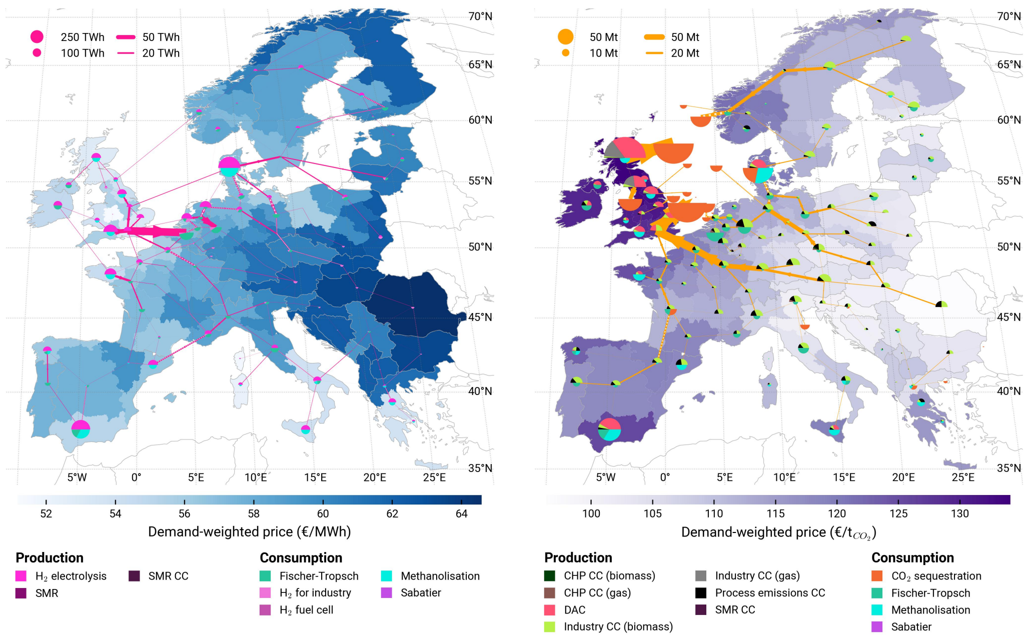
Figure C.28: *Central Planning* long-term scenario (2030) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.



(a) H_2 regional balances and flows.

(b) CO_2 regional balances and flows.

Figure C.29: *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.30: *Central Planning* long-term scenario (2050) — Regional distribution of H_2 and CO_2 production, utilisation, storage, and transport.

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