

¹ The role of Projects of Common Interest in reaching
² Europe's energy policy targets

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⁴ **Abstract**

⁵ The European Union (EU) aims to achieve climate-neutrality by 2050, with
⁶ interim 2030 targets including 55 % greenhouse gas emissions reduction com-
⁷ pared to 1990 levels, 10 Mt p.a. of a domestic green H₂ production, and 50 Mt
⁸ p.a. of domestic CO₂ injection capacity. To support these targets, Projects
⁹ of Common and Mutual Interest (PCI-PMI) — large infrastructure projects
¹⁰ for electricity, hydrogen and CO₂ transport, and storage — are identified by
¹¹ the European Commission. This study focuses on PCI-PMI projects related
¹² to hydrogen and carbon value chains, assessing their long-term system value
¹³ and the impact of policy delays or relaxations using a myopic, deterministic
¹⁴ 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 CO₂ 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 CO₂ removal.

¹⁵ *Keywords:* energy system modelling, policy targets, infrastructure,
¹⁶ resilience, hydrogen, carbon, Europe

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17 **List of abbreviations**

- 18 **AC** Alternating Current
19 **API** Application Programming Interface
20 **CC** Carbon Capture
21 **CU** Carbon Utilisation
22 **CS** Carbon Storage
23 **CCUS** Carbon Capture, Utilisation, and Storage
24 **DAC** Direct Air Capture
25 **DC** Direct Current
26 **EU** European Union
27 **GHG** Greenhouse gas
28 **NEP** Netzentwicklungsplan (German grid development plan)
29 **NUTS** Nomenclature of Territorial Units for Statistics
30 **PCI** Projects of Common Interest
31 **PMI** Projects of Mutual Interest
32 **REST** Representational State Transfer
33 **tsam** Time Series Aggregation Module
34 **TYNDP** Ten-Year Network Development Plan
35 **WACC** Weighted Average Cost of Capital

36 **1. Introduction**

37 On the pathway to a climate-neutral Europe by 2050, the European Union
38 (EU) has set ambitious targets for 2030. These targets include a reduction
39 of 55 % in greenhouse gas emissions compared to 1990 levels [1], 10 Mt p.a.
40 domestic green H₂ production [2], and 50 Mt p.a. of CO₂ injection capacity
41 with sequestration in within the EU [3]. For the long-term planning horizon,
42 e.g. 2050, concrete targets for H₂ and CO₂ are still missing beyond reaching a
43 net-zero GHG emissions. Recent studies [4–6] agree that a mixture of invest-
44 ments into H₂ and CO₂ infrastructure including carbon removal technologies
45 are cost-optimal and needed for a net-zero energy system, especially in the
46 hard-to-abate sectors, such as industry, aviation, and shipping.

47 Add two paragraphs on H₂ and CO₂ use

48 To meet the regionally distributed need for H₂ and CO₂, significant invest-
49 ments into its transport and storage/sequestration investment are needed.
50 A recent report by the European Commission [7] confirms that investment
51 needs into the EU's energy infrastructure will grow continuously, with the

52 largest share (around 1200 bn. €) of the investment volume going into elec-
53 tricity distribution and transmission by 2040. Beyond the electricity sector,
54 the report also emphasises on significant investments into H₂ and CO₂ in-
55 frastructure, expecting around 170 bn. € and up to 20 bn. € p.a. by 2040,
56 respectively. Their findings also highlight the higher uncertainty and risks
57 involved with investments into H₂ and CO₂ infrastructure, as these sectors
58 are still in their infancy.

59 To support storing and distributing electricity, CO₂ and H₂ efficiently,
60 the European Commission bi-annually identifies a list of Projects of Com-
61 mon Interest (PCI), which are key cross-border (and national) infrastructure
62 projects that link the energy systems of the EU members [8]. Projects suit-
63 able for PCI-PMI status are based on candidates submitted by transmission
64 system operators, consortia, or third parties. Projects of Mutual Interest
65 (PMI) further include cooperations with countries outside the EU, such as
66 Norway or the United Kingdom. With a PCI-PMI status, project awardees
67 receive strong political support and are, amongst others, eligible for financial
68 support (e.g. through funding of the Connecting Europe Facility) and see
69 accelerated permitting processes. On the other hand, project promoters are
70 obliged to undergo comprehensive reporting and monitoring processes. In
71 order for projects to be eligible for PCI-PMI status, their *potential benefits*
72 *need to outweigh their costs* [8]. Given the political and lighthouse charac-
73 ter, these projects are highly likely to be implemented [7]. At the same time,
74 any large infrastructure project, including PCI-PMI projects, commonly face
75 delays due to permitting, financing, procurement bottlenecks, etc. [9].

76 **2. Literature review**

77 We structure the literature review into three main sections: (i) the value
78 of CO₂ and H₂ in low-carbon energy systems and (iii) addressing uncertainty
79 in energy system models. Based on this review, identify research gaps and
80 position our work as a novel contribution to the current state of the art (iii).

81 *2.1. The value of CO₂ and H₂ in low-carbon energy systems*

82 A growing body of literature has been investigating the long-term role
83 of H₂ and CO₂ in low-carbon or net-zero energy systems. Both carriers see
84 their primary value outside the electricity sector, i.e., in the decarbonisation
85 of hard-to-abate sectors such as industry, transport, shipping, and aviation
86 [10]. While there are direct use cases for H₂ in the industry sector such as
87 steel production, it is primarily expected to serve as a precursor for synthetic
88 fuels, including methanol, Fischer-Tropsch fuels (e.g. synthetic kerosene and
89 naphta) and methane. The demand for these fuels is driven by the aviation,
90 shipping, industry, and agriculture sectors [5]. To produce these carbona-
91 ceous fuels, CO₂ is required as a feedstock (Carbon Utilisation — CU). This
92 CO₂ can be captured from the atmosphere via Direct Air Capture (DAC) or
93 from industrial and process emissions (e.g. cement, steel, ammonia produc-
94 tion) in combination with Carbon Capture (CC) units.

95 Béres et al. [11] evaluate the interaction between electricity, H₂, and syn-
96 synthetic fuel demand by linking the JRC-EU-TIMES long-term energy system
97 model with PLEXOS. In their findings, H₂ production varies between 42
98 (1400 TWh) and 66 Mt (2200 TWh) p.a. in 2050.

99 Van Greevenbroek et al. [12] investigate the cost-optimal development
100 of green H₂ by assessing the near-optimal space of an extensive scenario
101 set. They find a moderate level of green H₂ production is cost-optimal, with
102 production levels depending primarily on the availability of green fuel imports
103 and carbon, capture, and storage. Eliminating green H₂ entirely would come
104 at a total system cost increase of 2 %.

105 By including H₂ and CO₂ transport infrastructure, additional benefits
106 and net cost-savings can be unlocked in a sector-coupled system.

107 Neumann et al. [5] examine the interaction between electricity grid ex-
108 pansion and a European-wide deployment of hydrogen pipelines in a net-zero
109 system (new and retrofitting of existing gas pipelines). While H₂ pipelines are
110 not essential, their build-out can significantly reduce system costs by up to 26
111 bn. € p.a. (3.4 % of annual CAPEX and OPEX) by connecting regions with

112 excessive renewable potential to storage sites and load centres. Extending
113 their previous work, Neumann et al. [13] investigate the trade-off between
114 relying on different energy import strategies and domestic infrastructure
115 build-out. By coupling the global energy supply chain model TRACE [14]
116 and the sector-coupled PyPSA-Eur model, they assess different energy vector
117 import combinations (e.g. electricity, H₂ or H₂ derivatives) and their impact
118 on Europe's infrastructural needs. Depending on the import costs, they ob-
119 serve up to 14 % in system cost savings. Further, with an increasing share of
120 H₂ imports, the need for domestic H₂ pipelines would decrease.

121 In a study by Kontouris et al. [15], the authors explore pathways for a po-
122 tential integrated hydrogen infrastructure in Europe while considering sector-
123 coupling and energy imports. Using the European energy system model Bal-
124 morel [16], the authors implement three scenarios varying between domes-
125 tic and imported H₂ levels as well as H₂ production technologies. In their
126 findings they identify main H₂ transport corridors from Spain and France,
127 Ireland and the United Kingdom, Italy, and Southeastern Europe. When
128 synergies through sector-coupling are exploited, domestic H₂ production can
129 be competitive, seeing an increase in up to 3 % in system costs.

130 Fleiter et al. [4] use a mixed simulation and optimisation method to
131 model H₂ uptake and transport by coupling three models, (i) FORECAST
132 for buildings and industry, (ii) ALADIN for transport together with (iii) the
133 European energy system model Enertile. Total demand for H₂ ranges from
134 690 TWh to 2800 TWh in 2050, 600 TWh to 1400 TWh for synthetic fuels.
135 In their study, the chemical and steel industry in Northwest Europe (incl.
136 western regions of Germany, Netherlands and northern regions of Belgium),
137 display a demand of more than 100 TWh each. With regard to crossborder
138 transport, they mainly observe hydrogen flows from Norway, UK and Ireland to
139 continental Europe (around 53 TWh to 72 TWh). Depending on the scenario,
140 the Iberian Peninsula exports around 72 TWh to 235 TWh via and to France.

141 On the carbon networks side, Bakken and Velken [17] formulate linear
142 models for the optimisation of CO₂ infrastructure, including pipelines, ship-
143 ping, CO₂ capture, and storage and demonstrate the applicability in a re-
144 gional case study for Norway. Hofmann et al. [6] address previous research
145 gap in assessing the interaction between H₂ and CO₂ infrastructure, by com-
146 bining the production, transport, storage, and utilisation of both H₂, CO₂
147 and their products. They specifically raise the question whether H₂ should
148 be transported to CO₂ point sources or vice versa. They find that most cost
149 savings can be achieved in a hybrid setup where both networks are present, as

150 the CO₂ network complements the H₂ network by promoting carbon capture
151 from point sources and reducing reliance on Direct Air Capture (DAC).

152 *2.2. Addressing uncertainty in energy system models*

153 While the previous section have examined the value of CO₂ and H₂ in low-
154 carbon energy systems, they do not take into account potential uncertainties
155 regarding future policy targets or infrastructure build-outs. Energy system
156 models can address such uncertainties through a range of approaches, in-
157 cluding scenario analysis, sensitivity analysis, stochastic programming, and
158 regret-based methods. Within the scope of this research, we focus on the
159 (deterministic) scenario analysis and regret-based methods, as they are par-
160 ticularly suitable for complex, large-scale, sector-coupled system models.

161 *Regret analysis.* A regret analysis is a common and widely established ap-
162 proach in economics that systematically evaluates the regret, i.e., additional
163 system costs, incurred by not having made the optimal decision in hindsight.
164 Usually, a regret-analysis is designed in two steps, first, a set of scenarios is
165 defined, which represent different future developments, such as policy targets,
166 infrastructure build-out, or technology costs. In a second step, the perfor-
167 mance of first-stage investment is evaluated under the realisation of second-
168 stage or short-term realisations of the future [18]. It is particularly useful in
169 energy system modelling, where future uncertainties can significantly impact
170 the performance of investments in infrastructure and technologies.

171 Möbius and Riepin [19] investigate the regret of investment decisions into
172 electricity generation capacities, by developing a two-stage, stochastic cost-
173 minimisation model of the European electricity and gas markets. In the first
174 stage, the model determines optimal investment decisions, accounting for
175 three TYNDP scenarios, while the second step solves the optimal dispatch for
176 all assets in the electricity and gas sector. They find that ignoring uncertainty
177 may result in investment decisions that lead to higher costs and regrets.

178 Van der Weijde and Hobbes [20] demonstrate the importance of consid-
179 ering uncertainty in energy system models, by applying a two-stage opti-
180 misation model to evaluate grid reinforcements in Great Britain. Including
181 the status quo scenario, they consider six scenarios, which represent different
182 future developments of electricity demand, generation, fuel, and CO₂ prices.
183 As part of their study, they calculate the regret for given first-stage trans-
184 mission decisions under the realisation of second-stage scenarios. Note that

185 the regret matrix is symmetric, i.e., the regret of each first-stage decision is
186 evaluated under all second-stage scenarios.

187 **3. Research gaps and our contribution**

188 Based on the literature review, we have identified that there is still a lack
189 of comprehensive studies that assess the complex interaction of CO₂ and H₂
190 infrastructure in a large-scale, sector-coupled energy system model. Further,
191 not many studies have considered real planned projects, such as PCI-PMI
192 projects, potentially neglecting investment options that may not be perfectly
193 cost-optimal, but are politically supported and have a high likelihood of being
194 implemented [12, 21]. To the best of our knowledge, the performance of PCI-
195 PMI projects has not yet been evaluated in a sector-coupled energy system
196 model. Given the variety of project promoters involved, the complexity and
197 the high cost of these projects, we believe it is crucial to transparently assess
198 the impact of these projects on the European energy system and key EU
199 policy targets.

200 Our study aims to fill this gap by evaluating different build-out levels
201 of CO₂ and H₂ infrastructure, including PCI-PMI projects and their per-
202 formance under a chosen set of short-term scenarios. By using a myopic
203 and hence, iterative modelling approach, we consider long-term pathway ef-
204 fects. This also reduces the risk of overly optimistic results that are often
205 observed in studies that look directly at the target year 2050. We implement
206 a deterministic, two-stage regret matrix approach to assess the performance
207 of different scenarios under three short-term occurrences for each planning
208 horizon, individually. This allows us to consider future uncertainties, includ-
209 ing changes in policy ambitions and infrastructure delays. By limiting the
210 analysis to a discrete set of scenarios, the regret analysis is manageable and
211 computationally feasible. We deliberately keep a deterministic approach, as
212 this would increase the complexity of the model and the computational time
213 significantly.

214 With this study, we also bring more certainty into the chicken-and-egg
215 problem of investing into CO₂ and H₂ infrastructure first vs. waiting for their
216 demand to materialise.

217 Our paper aims in particular to address the following research questions:

218
219

Maybe rephrase/fine tune RQs a bit?

- 220 1. What are the benefits of PCI-PMI projects for the European energy
221 system, especially concerning reaching European policies

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

224 **4. Methodology**

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

228 We build on the open-source, sector-coupled energy system model PyPSA-
229 Eur [5, 22–24] to optimise investment and dispatch decisions in the European
230 energy system. The model’s endogenous decisions include the expansion and
231 dispatch of renewable energy sources, dispatchable power plants, electricity
232 storage, power-to-X conversion capacities, and transmission infrastructure
233 for power, hydrogen, and CO₂. It also encompasses heating technologies
234 and various hydrogen production methods (gray, blue, green). PyPSA-Eur
235 integrates multiple energy carriers (e.g., electricity, heat, hydrogen, CO₂,
236 methane, methanol, liquid hydrocarbons, and biomass) with correspond-
237 ing conversion technologies across multiple sectors (i.e., electricity, trans-
238 port, heating, biomass, industry, shipping, aviation, agriculture and fossil
239 fuel feedstock). The model features high spatial and temporal resolution
240 across Europe, incorporating existing power plant stocks [25], renewable po-
241 tentials, and availability time series [26]. It includes the current high-voltage
242 transmission grid (AC 220 kV to 750 kV and DC 150 kV and above) [27].
243 Furthermore, electricity transmission projects from the TYNNDP (SOURCE)
244 and German Netzentwicklungsplan (SOURCE) are also enabled.

245 *4.1. Model setup*

246 *Temporal resolution.* To assess the long-term impact of PCI-PMI projects
247 on European policy targets across all sectors, we optimise the sector-coupled
248 network for three key planning horizons 2030, 2040, and 2050, myopically.
249 The myopic approach ensures that investment decisions across all planning
250 horizons are coherent and build on top of the previous planning horizon. We
251 use the built-in Time Series Aggregation Module (tsam) to solve the model
252 for 2190 time steps, yielding an average resolution of four hours. tsam is
253 a Python package developed by Kotzur et al. [28] to aggregate time series

254 data into representative time slices to reduce computational complexity while
255 maintaining their specific intertemporal characteristics, such as renewable
256 infeed variability, demand fluctuations, and seasonal storage needs.

257 *Geographical scope.* We model 34 European countries, including 25 of the
258 EU27 member states (excluding Cyprus and Malta), as well as Norway,
259 Switzerland, the United Kingdom, Albania, Bosnia and Herzegovina, Mon-
260 tenegro, North Macedonia, Serbia, and Kosovo. Regional clustering is based
261 on administrative NUTS boundaries, with higher spatial resolution applied
262 to regions hosting planned PCI-PMI infrastructure, producing 99 onshore re-
263 gions (see Table B.4). Depending on the scenario, additional offshore buses
264 are introduced to appropriately represent offshore sequestration sites and
265 PCI-PMI projects. To isolate the effect of PCI-PMI projects, Europe is self-
266 sufficient in our study, i.e., we do not allow any imports or exports of the
267 assessed carriers like electricity, H₂, or CO₂.

268 *Technology assumptions.* As part of the PyPSA-Eur model, we source all
269 technology-specific assumptions including lifetime, efficiency, investment and
270 operational costs from the public *Energy System Technology Data* repository,
271 v.0.10.1 [29]. We use values projected for 2030 and apply a discount rate of
272 7 %, reflecting the weighted average cost of capital (WACC). We assume CO₂
273 sequestration costs of 15 €/tCO₂ which can be considered in the mid-range
274 of the cost spectrum (cf. TODO SOURCE 1 and 10 €/tCO₂ [6])

275 *Demand and CO₂ emissions.* Energy and fuel carrier demand in the modelled
276 sectors, as well as non-abatable CO₂ process emissions are taken from various
277 sources [30–34] and are shown in Figure A.9. Regionally and temporally
278 resolved demand includes electricity, heat, gas, biomass and transport.

279 Gas (methane/CH₄) demand includes direct use in gas-based industrial
280 processes, as well as fuel in the electricity and heating sector. Note that we
281 do not explicitly enable the gas transmission grid as opposed to the CO₂
282 and H₂ infrastructure. We do this for different reasons: (i) the modelled
283 PCI-PMI projects overlap in some parts with the gas grid, i.e., include CH₄
284 pipelines that will be retrofitted to H₂ pipelines, however, input data is not
285 always clear; (ii) we do not assume the gas transport to be bottlenecked by
286 the existing gas grid, as such, gas transport is assumed to be copper plated;
287 and (iii) the computational complexity is already high due to the geospatial
288 and temporal resolution, as well as the number of components. Instead, given
289 the focus on the CO₂ and H₂ 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 [35]. 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 CO₂ emissions by 2050, the yearly emission budget follows the EU's 2030 (−55 %) and 2040 (−90 %) targets [1, 36], 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, CO₂ and H₂ 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 [37]. We add all CO₂ sequestration sites and connected pipelines, H₂ 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 the 99 NUTS regions, in this process, pipelines 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 [29] 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.

CO₂ sequestration and H₂ storage sites. Beyond CO₂ sequestration site projects included in the latest PCI-PMI list (around 114 Mt p.a.), we consider additional technical potential from the European CO₂ storage database [6, 38].

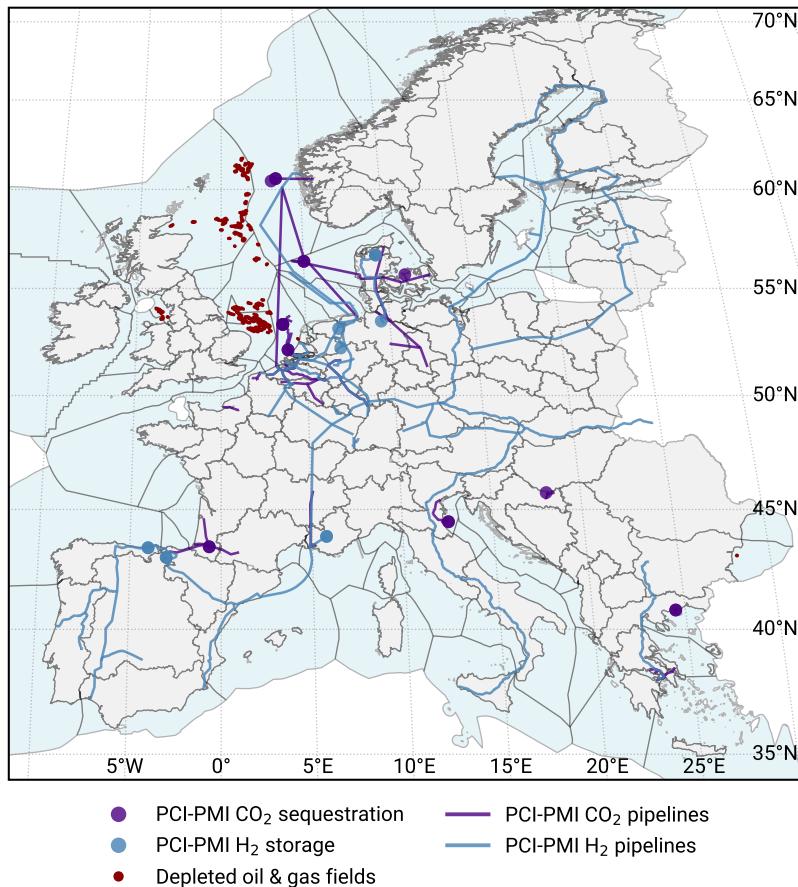


Figure 1: Map of the regional scope including clustered onshore (grey) and offshore regions (blue), as well as PCI-PMI CO₂ and H₂ pipelines, storage and sequestration sites. Depleted offshore oil and gas fields (red) provide additional CO₂ sequestration potential [6].

327 The dataset includes storage potential from depleted oil and gas fields as well
328 as saline aquifers. While social and commercial acceptance of CO₂ storage
329 has been increasing in recent years, concerns still exist regarding its long-
330 term purpose and safety [39]. We only consider conservative estimates from
331 depleted oil and gas fields, which are primarily located offshore in the British,
332 Norwegian, and Dutch North Sea (see Figure 1), yielding a total sequestra-
333 tion potential of 7164 Mt. Our focus is motivated by the following reasons:
334 (i) infrastructure such as wells, platforms, and pipelines already exist for de-
335 pleted oil and gas fields and can be repurposed, significantly lowering costs
336 and project risk; (ii) depleted fields are generally better understood geologi-
337 cally and have demonstrated sealing capacities, further reducing uncertainty;
338 and (iii) repurposing former production sites is often more publicly and po-
339 litically acceptable than developing entirely new storage locations, entirely.
340 In contrast, while saline aquifers represent a substantial share of the total
341 technical potential, they carry higher development costs and risks and are
342 less likely to be advanced without strong policy and financial support [38].
343 Note that the PCI-PMI project list includes some aquifer-based sequestra-
344 tion projects, however, their inclusion as PCI-PMI project indicates a higher
345 likelihood of development.

346 Spread over a lifetime of 25 years, the selected depleted oil and gas fields
347 translate into an annual sequestration potential of up to 286 Mt p.a. We
348 then cluster all offshore potential within a buffer radius of 50 km per offshore
349 bus region in each modelled NUTS region and connect them through off-
350 shore CO₂ pipelines to the closest onshore bus (TODO: add reference to cost
351 assumptions in appendix).

352 The model also includes H₂ storage sites from the PCI-PMI list and allows
353 for endogenous build-out of additional storage capacities by repurposing salt
354 caverns [5].

355 4.2. Scenario setup and regret matrix

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

361 4.2.1. Long-term scenarios

362 *Scenario definition.* We define the long-term scenarios based on the degree
 363 of CO₂ and H₂ infrastructure build-out, including the roll-out of PCI-PMI
 364 projects as well additional pipeline investments. In total, we implement
 365 five long-term scenarios, (i) a pessimistic scenario (Decentral Islands — DI)
 366 without any H₂ pipeline and onshore CO₂ pipeline infrastructure, (ii) a sce-
 367 nario that considers the on-time commissioning of all PCI-PMI CO₂ and H₂
 368 projects (PCI-PMI — PCI) only, (iii) more ambitious scenarios that further
 369 allow investments into national and (iv) international pipelines (PCI-PMI
 370 nat. — PCI-n and PCI-PMI internat. — PCI-in), and (v) a scenario that
 371 does not assume any fixed PCI-PMI infrastructure but allows for a cen-
 372 tralised, purely needs-based build-out of CO₂ and H₂ pipelines (Centralised
 373 Planning — CP). An overview of the long-term scenarios and their associated
 374 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 |
|---|----|-----|-------|--------|----|
| CO₂ sequestration | | | | | |
| Depleted oil & gas fields* | ■ | ■ | ■ | ■ | ■ |
| PCI-PMI seq. sites** | — | ■ | ■ | ■ | ■ |
| H₂ storage | | | | | |
| Endogenous build-out | ■ | ■ | ■ | ■ | ■ |
| PCI-PMI storage sites | — | ■ | ■ | ■ | ■ |
| CO₂ pipelines | | | | | |
| to depleted oil & gas fields | ■ | ■ | ■ | ■ | ■ |
| to PCI-PMI seq. sites | — | ■ | ■ | ■ | ■ |
| CO₂ and H₂ pipelines | | | | | |
| PCI-PMI | — | ■ | ■ | ■ | ■ |
| National build-out | — | ■ | ■ | ■ | ■ |
| International build-out | — | — | — | ■ | ■ |
| PCI-PMI extendable | — | — | — | — | ■ |

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

375 *Targets.* In all long-term scenarios, emission, technology, sequestration and
 376 production targets have to be met for each planning horizon (see Table 2).
 377 For the year 2030, these targets are directly derived from the EU's policy
 378 targets, including a 55 % reduction in greenhouse gas emissions compared to
 379 1990 levels [1], 10 Mt p.a. of domestic green H₂ production [2] and 40 GW of
 380 electrolyser capacity [40], and 50 Mt p.a. of CO₂ sequestration capacity [3].

381 For 2050, the CO₂ are based on the modelling the impact assessment for the
 382 EU's 2040 climate targets, in 250 Mt p.a. need to be sequestered [41]. H₂
 383 production targets for 2050 are based on the European Commission's METIS
 384 3 study S5 [42], modelling possible pathways for industry decarbonisation
 385 until 2040. For 2040, we interpolate linearly between the 2030 and 2050
 386 targets. The electrolyser capacities for 2040 and 2050 are scaled by the
 387 ratio of H₂ production to electrolyser capacity in 2030. An overview of the
 388 targets and their values is provided in Table 2. Note that we implement
 389 the green H₂ production target as a minimum H₂ production constraint from
 390 electrolysis , hence we will refer to this H₂ as electrolytic H₂ within the scope
 391 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, 41, 42]

392 4.2.2. Short-term scenarios

393 In a second step, we assess the impact of three short-term scenarios on
 394 the long-term scenarios, i.e., the CO₂ and H₂ pipeline capacities built in
 395 the long-term scenarios are either frozen or removed. Further, the model
 396 can still react by investing into additional generation, storage, or conversion,
 397 or carbon-removal technologies in the short-term, assuming the technical
 398 potential was not exceeded in the long-term optimisation. In *Reduced targets*,
 399 we remove all of the long-term targets (Table 2) except for the GHG emission
 400 reduction targets to assess the value of the CO₂ and H₂ infrastructure in a
 401 less ambitious policy environment [43]. In *Delayed pipelines*, we assume that
 402 all PCI-PMI and endogenous pipelines are delayed by one period, i.e., the
 403 commissioning of the project is shifted to the next planning horizon. Lastly,
 404 we remove all pipeline capacities in *No pipelines*, including the PCI-PMI
 405 projects, allowing us to evaluate the impact of a complete lack of planned
 406 infrastructure.

407 Table 3 gives an overview of this regret-analysis and their individual as-
 408 sumptions, where the long-term scenario serves as the *planned* or *anticipated*

409 and the short-term scenario serves as the hypothetically *realised* outcome.
 410 A regret matrix provides a decision-making framework that evaluates the
 411 potential loss (*regret*) associated with choosing one strategy over the other
 412 by comparing the outcomes, i.e., the total system costs. Here, the regret is
 413 quantified as the difference between system costs of the short-term scenario
 414 and the long-term (anticipated) scenario for each scenario. In total, we run
 415 60 optimisations on a cluster, taking up to 160 GB of RAM and 8 to 16
 416 hours each to solve: $(n_{LT} \times n_{planning\ horizons}) \times (1 + n_{ST}) = 60$. The models
 417 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 electrolyzers | – | ■ | ■ |
| CO₂ + H₂ infrastructure | | | |
| CO ₂ sequestration sites | ■ | ■ | ■ |
| CO ₂ pipelines to seq. site | ■ | ■ | ■ |
| CO ₂ pipelines | ■ | □ | – |
| H ₂ pipelines | ■ | □ | – |

■ enabled □ delayed by one period – disabled

418 5. Results and discussion

419 We structure the results and discussion into three main sections. First, we
 420 present the results of the long-term scenarios. Then, we look at the impact
 421 of the short-term scenarios on the long-term scenarios, by comparing the
 422 economic regret and impacts on CO₂ and H₂ balances. Finally, we assess the
 423 benefits of the PCI-PMI projects with regard to reduced system costs and
 424 discuss the implications of our findings for the European energy system and
 425 its policy targets.

426 *5.1. Long-term scenarios*

427 In all long-term runs, we observe the highest total annual system costs in
 428 the planning horizon 2040, ranging from 912 to 968 bn. € p.a. (Figure 2),
 429 driven by high investments. This can be primarily attributed to the strict
 430 exogenously given GHG emission reduction pathway, facing the largest net
 431 change from 2030 to 2040 — a carbon budget reduction of more than 1600
 432 Mt p.a. as opposed to the remaining 460 Mt p.a. in the last decade. In 2030,
 433 total system costs are lowest in the *DI* and *CP* scenario, as the model does
 434 not see the need for large-scale investments into H₂ and CO₂ infrastructure
 435 yet. With CO₂ pipelines connecting depleted offshore oil and gas fields to
 436 their closest onshore region, the policy targets, incl. CO₂ sequestration can
 437 be achieved at a total of 865 bn. € p.a. Adding PCI-PMI projects in 2030
 438 increases costs by less than 1%.

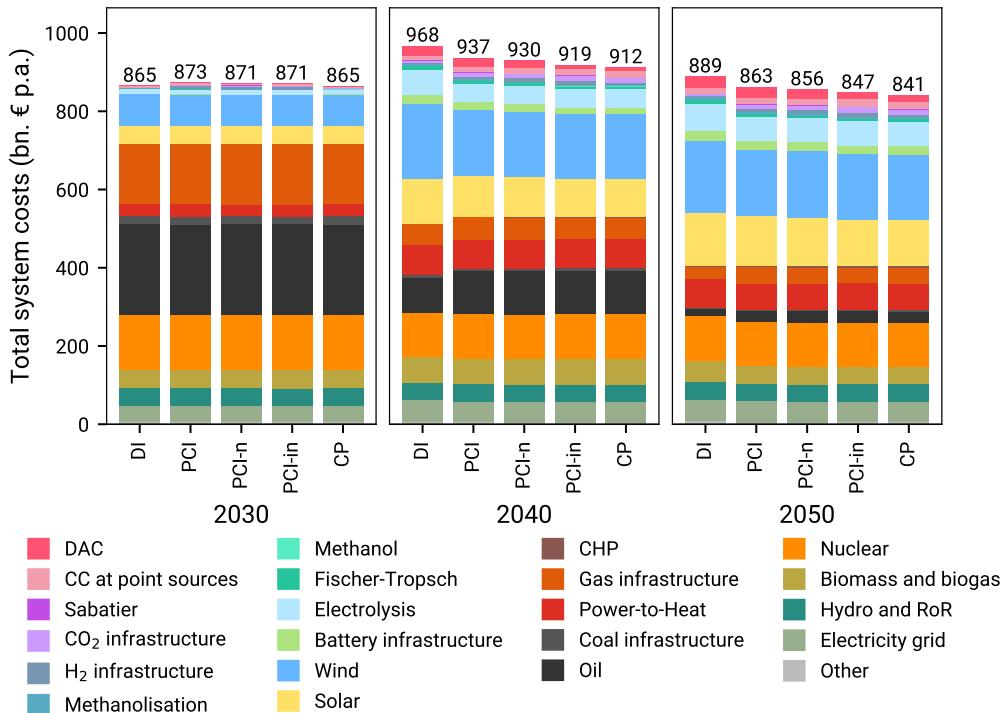


Figure 2: Total annual system costs (CAPEX + OPEX) by technology group.

439 Starting in 2040, all scenarios with PCI-PMI and endogenous pipeline
 440 investments unlock significant cost savings, from more than 30 bn. € p.a. in

441 the *PCI* up to 50 bn. € p.a. in the *PCI-in* scenario. By giving the model
 442 complete freedom in pipeline expansions, additional annual cost savings of 6
 443 to 7 bn. € are unlocked by investing in fewer, but more optimally located CO₂
 444 and H₂ pipelines from a systemic perspective (see *PCI-in* pipeline utilisation
 445 in Figures C.25 to C.27 compared to *CP* pipeline utilisation in Figures C.28
 446 to C.30). Further, this reduces the reliance on larger investments into wind
 447 generation and more expensive Direct Air Capture (DAC) technologies near
 448 the sequestration sites. These effects are slightly less pronounced in the 2050
 449 model results, system costs can be reduced by 26 to 41 bn. € p.a. with
 450 PCI-PMI and endogenous pipeline investments.

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

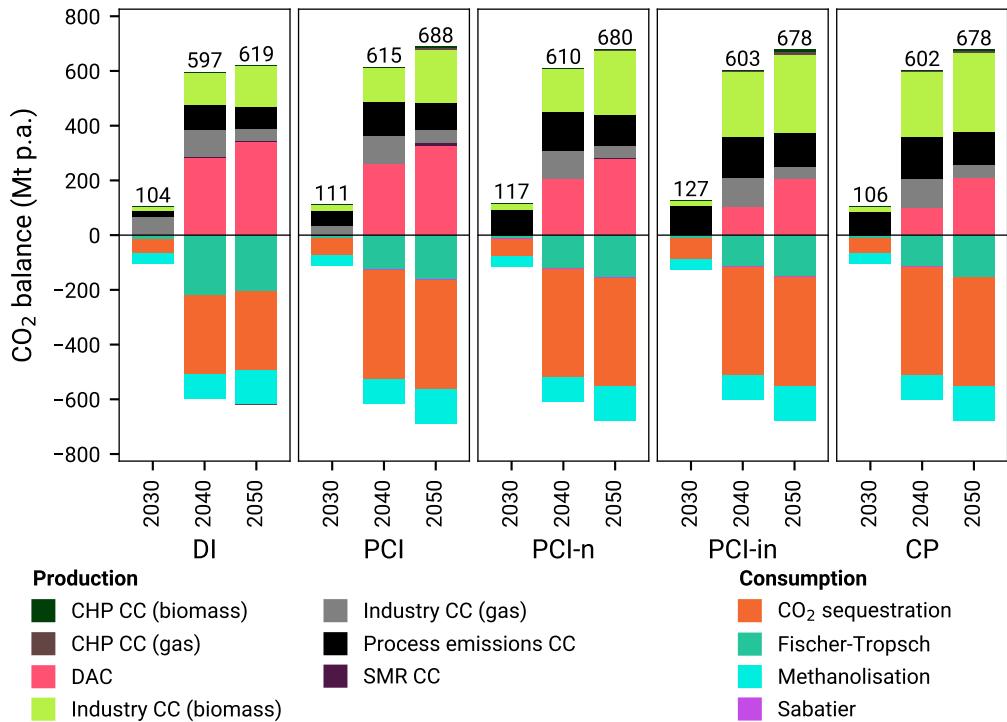


Figure 3: CO₂ balances in long-term scenarios.

452 *Carbon capture, utilisation, and storage.* We find that most of the differences
 453 in system cost and savings can be attributed to the production and utilisation

454 of CO₂, as shown in Figure 3. Lacking the option to transport CO₂ from
455 industry and other point sources to the offshore sequestration sites, the model
456 has to invest in expensive DAC technologies in the *DI* scenario. While the
457 sequestration target of 50 Mt p.a. in 2030 is binding for the *DI* scenario, all
458 other scenarios sequester more CO₂, the higher their CO₂ pipeline build-out.
459 The 53.9 Mt p.a. CO₂ sequestered in the *CP* serve as an indicator for what
460 would be a cost-optimal amount for 2030 with perfectly located pipelines.
461 With the inclusion of PCI-PMI projects, CO₂ sequestration ranges from 58.7
462 Mt p.a. in the *PCI* to 75 Mt p.a. in the *PCI-in* scenario. Looking at
463 2040 and 2050, in place of expensive DAC in the *DI* scenario, the model
464 equips biomass-based industrial processes primarily located in Belgium, the
465 Netherlands and Western regions of Germany (see Figures 4b, 4d, and 4f).

466 In 2040 and 2050, all sequestration targets (Table 2) are overachieved, as
467 the full combined CO₂ sequestration potential of 398 Mt p.a. is exploited in
468 all scenarios where PCI-PMI projects are included (*PCI* to *CP*). Emissions
469 are captured from industrial processes equipped with carbon capture units,
470 with biomass-based industry providing the largest share in carbon capture
471 from point sources, ranging from 119 to 241 Mt p.a. in 2040 and 149 to 287
472 Mt p.a. in 2050, increasing with the build-out of CO₂ infrastructure (from
473 left to right, see Figure 3). Being the most expensive carbon capture option,
474 only up to 8 Mt p.a. of CO₂ is captured from SMR CC processes in the *PCI*
475 scenario in 2050. With a lower sequestration potential of 286 Mt p.a. in *DI*
476 scenario, more CO₂ is used as a precursor for the synthesis of Fischer-Tropsch
477 fuels instead — 221 Mt p.a. vs. 115-127 Mt p.a. (2040) and 206 Mt p.a.
478 vs 153-163 Mt p.a. (2050), to meet the emission reduction targets for 2040
479 and 2050, respectively. Given the fixed exogenous demand for (shipping)
480 methanol (Figure A.9), CO₂ demand for methanolisation is constant across
481 all scenarios (39 Mt p.a. in 2030, 89 Mt p.a. in 2040, and 127 Mt p.a. in
482 2050).

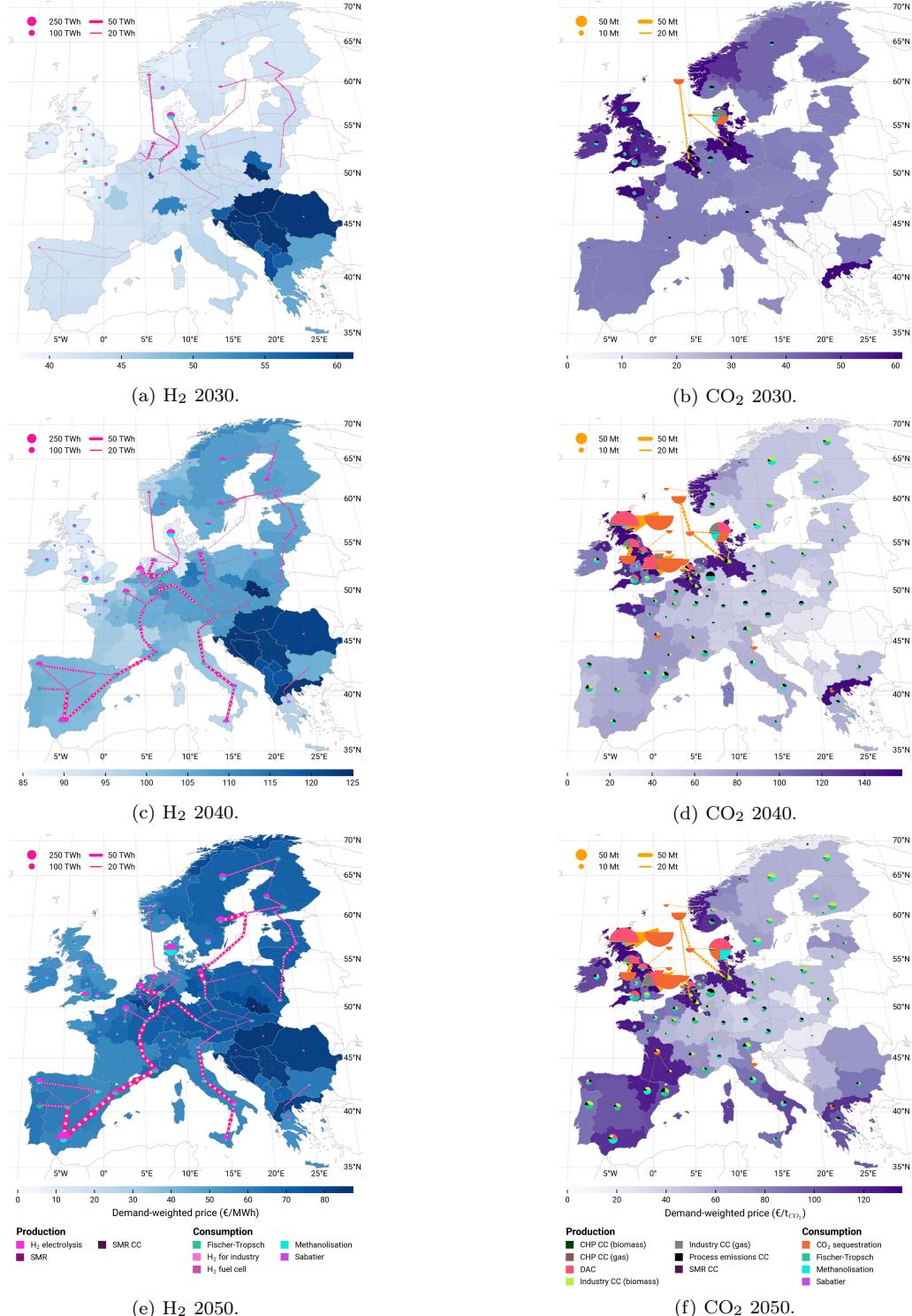


Figure 4: PCI long-term scenario — Regional distribution of H₂ and CO₂ production, utilisation, storage, and transport. ¹⁹

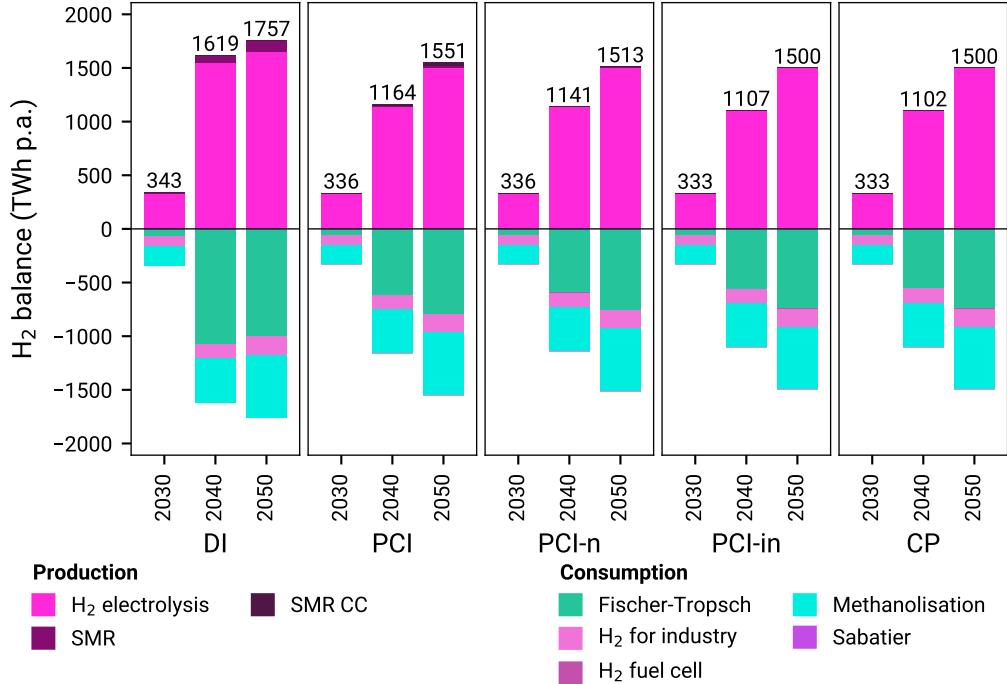


Figure 5: H₂ balances in long-term scenarios.

483 *Hydrogen production and utilisation.* H₂ production in the model is primarily
 484 driven by the demand for Fischer-Tropsch fuels and methanol. In 2030
 485 and 2050, the electrolytic H₂ production target of 10 and 45 Mt p.a. is
 486 binding, equivalent to 333 and 1500 TWh p.a. (at a lower heating value of
 487 33.33 kWh/kg for H₂). Only in 2040, the H₂ production target of 27.5 Mt
 488 p.a. (917 TWh p.a.) is overachieved by 185-247 TWh p.a. in the PCI to
 489 CP scenarios. H₂ production in the DI is significantly higher, given its need
 490 for additional Fischer-Tropsch synthesis to bind CO₂ as an alternative to
 491 sequestration, as described in the previous section. In 2050, Fischer-Tropsch
 492 fuels are primarily used to satisfy the demand for kerosene in aviation and
 493 naphta for industrial processes (see Table A.9). Only about 93 to 173
 494 TWh p.a. of H₂ is directly used in the industry. Throughout all long-term
 495 scenarios, H₂ is almost exclusively produced via electrolysis. Only without
 496 any H₂ pipeline infrastructure in the DI, the model reverts to steam methane
 497 reforming (SMR) to produce 71 to 102 TWh p.a. of H₂ in 2040 and 2050,
 498 respectively. Regionally, H₂ production is concentrated in regions with high

499 solar PV potential such as the Iberian and Italian Peninsula, as well as high
500 wind infeed regions including Denmark, the Netherlands and Belgium. The
501 produced H₂ is then transported via H₂ pipelines including PCI-PMI projects
502 to carbon point sources in central, continental Europe where it is used as a
503 precursor for Fischer-Tropsch fuels. Onsite H₂ production and consumption
504 primarily occurs in conjunction with methanolisation processes. Figures 4a,
505 4c, and 4e provide a map of the regional distribution of H₂ production, util-
506 isation, and transport in the *PCI* scenario. Additional maps are provided in
507 Appendix C.5. Note that PCI-PMI projects or candidates (in *CP* scenario)
508 are plotted in dotted white lines.

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

510 5.2. Performance in short-term scenarios

511 In this section, we assess the impact of the short-term scenarios on the
512 long-term scenarios, by comparing the economic regret, as well as the impact
513 on CO₂ utilisation and sequestration, H₂ production.

514 *Regret analysis.* We calculate the regret terms by subtracting the annual to-
515 tal system costs of the long-term scenarios (row) from the short-term scenar-
516 ios (columns). Positive values reflect higher costs in the short-term scenarios
517 compared to the long-term ones. Figure 6 shows the regret matrix for all sce-
518 narios and planning horizons. From left to right, the first column shows the
519 regret terms for the *Reduced targets* scenario, where all long-term targets are
520 removed except for the GHG emission reduction target. The second column
521 shows the regret terms for the *Delayed pipelines* scenario, where all PCI-PMI
522 and endogenous pipelines are delayed by one period. The third column shows
523 the regret terms for the *No pipelines* scenario, where all pipeline capacities
524 are removed.

525 In the *Reduced targets* scenario, system costs barely change through the
526 relaxation of the targets. The long-term results have shown that the model
527 was overachieving the H₂ production targets in 2040. As for the CO₂ se-
528 questration targets, the model is still incentivised by GHG emission targets,
529 especially in 2040 and 2050. Only in 2030, we see minimal changes in total
530 system costs, as the 2030 targets are not cost-optimal. However, they are
531 required to stimulate the build-out necessary to reach 2040 and 2050 targets.
532 In all of the long-term scenarios, we have observed that in 2030 that espe-
533 cially CO₂ pipeline infrastructure is not essential yet (see Figure C.28b). As

534 for H₂ pipeline infrastructure, the solution space seems to be quite flat, as
 535 the costs for the *DI* scenario without any pipelines (Figure C.22b) and the
 536 *CP* scenario (Figure C.28b) with notable pipeline investments are almost
 537 identical. By removing the H₂ production and CO₂ sequestration targets,
 538 pipelines become even less relevant, although the cost savings due to the
 539 dropped targets are minimal, ranging from 4.3 to 5 bn. € p.a. in 2030 and
 540 2040.

| | Δ Reduced targets (bn. € p.a.) | | | Δ Delayed pipelines (bn. € p.a.) | | | Δ No pipelines (bn. € p.a.) | | |
|--------------------|--|------|------|--|------|-------|---------------------------------------|------|-------|
| | 2030 | 2040 | 2050 | 2030 | 2040 | 2050 | 2030 | 2040 | 2050 |
| Long-term scenario | DI - | -4.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | PCI - | -5.0 | 0 | -0.3 | -3.4 | +0.6 | 0 | -5.1 | +14.8 |
| | PCI-n - | -4.3 | 0 | -0.2 | +0.3 | +11.1 | +1.3 | -1.3 | +28.6 |
| | PCI-in - | -4.5 | 0 | -0.2 | +2.1 | +24.2 | +0.9 | -0.3 | +40.8 |
| | CP - | -4.7 | 0 | -0.3 | +5.1 | +35.2 | +1.4 | +3.9 | +45.6 |
| Planning horizon | | | | | | | | | |

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.

541 For the same reasons, the 2030 results for the *Delayed pipelines* and *No*
 542 *pipelines* scenarios show only minor differences in system costs compared to
 543 the long-term scenarios. Cost savings of 3.4 to 5.1 bn. € p.a. in the *PCI*
 544 long-term scenario indicate that for 2030, forcing in PCI-PMI projects is not
 545 cost- and topologically optimal in the short run. Whereas slight regret/cost
 546 increase of 3.9 to 5.1 bn € p.a. in the *CP* shows a small dependency on the
 547 invested pipeline infrastructure (Figure C.28), being the most cost-optimal
 548 solution.

549 When looking at the more long-term perspective, we see significant re-
 550 grets in the *Delayed pipelines* and *No pipelines* scenarios. Having originally
 551 planned the energy system layout (incl. generation, transport, conversion

552 technologies and storage) in the long-term scenario with PCI-PMI projects
553 and/or endogenous pipelines, the model has to find alternative investments
554 to still meet all targets, as the pipelines now materialise one period later or
555 not at all. Regrets peak in 2040, where a delay of pipelines costs the sys-
556 tem between 0.6 to 24.2 bn. € p.a. in the scenarios with PCI-PMI projects
557 and up to 35.2 bn. € p.a. in the *CP* scenario. 2050 regrets are lower than
558 2040 regrets, as almost all PCI-PMI pipelines are originally commissioned
559 by 2030. So a delay of projects from 2040 to 2050 only mildly impacts the
560 system costs by 0.6 bn. € p.a. The more pipelines invested beyond those of
561 PCI-PMI projects, the higher the regret if they are delayed. In 2050, very
562 few additional CO₂ and H₂ pipelines are built, as such, a delay only increases
563 system costs by 0.9 to 1.4 bn. € p.a. The short-term scenario *No pipelines*
564 shows the highest regrets, ranging from 14.8 to 45.6 bn. € p.a. in 2040 and
565 15.9 to 39.4 bn. € p.a. in 2050. Note that this scenario serves more of a
566 hypothetical worst case as it is not likely to build out an energy system with
567 pipelines in mind but none materialising at all.

568 Consistently throughout all short-term scenarios, most of the additional
569 cost stem from the need to invest into additional carbon capture, renewable
570 generation, and conversion technologies (see Figure C.11). Additional renew-
571 able generation capacities are made up of solar PV and wind. A significant
572 higher amount of electrolyser capacity of more than 50 GW is needed in 2040
573 if pipelines are delayed.

574 *Carbon capture.* Further, the model has to invest in more than 28 GW of
575 carbon capture units at point sources and an additional 14 GW in DAC
576 technologies to meet the sequestration and emission reduction targets. Cost-
577 wise, the short-term investments into DAC technologies make up to a half
578 of the of the additional system costs in both the *Delayed pipelines* and *No*
579 *pipelines* scenarios (see Figure C.12). DAC utilisation can increase from 40
580 Mt p.a. in the *PCI-n* to more than 200 Mt p.a. in the *CP* scenario when
581 pipelines are delayed (see Figure C.13). If pipelines are not built at all,
582 additional 60 Mt p.a. in the *PCI* up to 250 Mt p.a. in the *CP* scenario are
583 captured from DAC, substituting a large share of CO₂ previously captured
584 from point sources equipped with carbon capture (biomass-based industry
585 processes and non-abatable process emissions).

586 Note that a clear trade-off between the reliance on pipeline infrastructure
587 and the need for DAC technologies can be observed in Figure 7. While the
588 reliance on DAC decreases with the build-out of pipeline infrastructure, the

589 model in return has to invest in more DAC if pipelines are delayed or not
 590 built at all. There is a risk involved, that the need for DAC is even higher
 591 in the scenarios with pipeline infrastructure compared to the *DI* scenario,
 592 especially in later years (2040 and 2050), if the pipelines do not materialise
 593 at all, seeing a potential increase of 50 Mt p.a. in 2040 and 80 Mt p.a. in
 594 2050 in the *PCI* scenario.

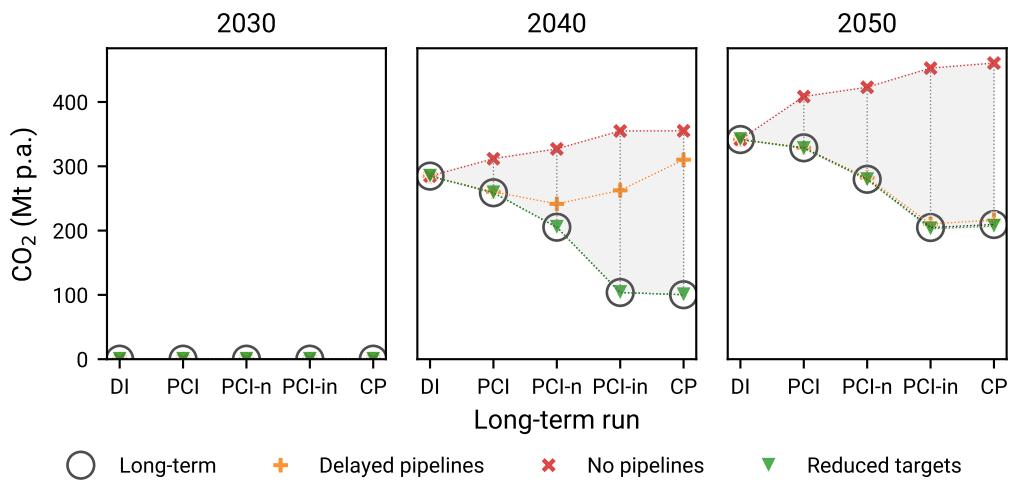


Figure 7: Delta balances — CO₂ from Direct Air Capture.

595 *H₂ production.* On the H₂ side, we find that the electrolytic H₂ production
 596 target of 10 Mt p.a. (333 TWh p.a.) in 2030 is overly ambitious. Figure
 597 C.18 shows that in the *Reduced targets* scenario, 132 to 151 TWh p.a. of
 598 H₂, corresponding to almost half of the target is produced from SMR instead
 599 of electrolysis. When pipelines are delayed, the model has to fall back to
 600 more decentral H₂ production of an additional 55 to 187 TWh p.a. of H₂
 601 from electrolysis, SMR and SMR with carbon capture (the latter being the
 602 most expensive option). In the *No pipelines* scenario, this additional H₂
 603 production increases to up to 305 TWh p.a (see Figure C.18).

604 5.3. Value of PCI-PMI projects

605 Looking at long-run we find that PCI-PMI projects, while not completely
 606 cost-optimal compared to a centrally planned system, are still cost-beneficial.
 607 Compared to a complete lack of H₂ and CO₂ pipeline infrastructure as well

608 as lower CO₂ sequestration potential, the *PCI* scenario unlocks annual cost
 609 savings in up to 30.7 bn. € p.a. Figure 8 shows the total system costs (TO-
 610 TEX) p.a. split into CAPEX and OPEX p.a., as well as the net present value
 611 of total system costs (NPV) until 2060, discounted at an interest rate of 7%
 612 p.a. Even when accounting for the additional costs of 0.6 bn. € faced in the
 613 *Delayed pipelines* and up to 15.9 bn. € p.a. in the *No pipelines* scenario, a
 614 net positive is achieved, indicating that investing into the PCI-PMI infras-
 615 tructure is a no-regret option. By connecting further H₂ production sites
 616 and CO₂ point sources to the pipeline network. additional cost savings of
 617 up to 18.4 bn. € p.a. can be achieved in the *PCI-in* scenario. The *CP* sce-
 618 nario serves as a theoretical benchmark, allowing the model to invest freely,
 619 not bound by *forced* PCI-PMI projects. The model can invest in fewer, but
 620 more optimally located CO₂ and H₂ pipelines from a systemic perspective.
 621 Economic benefits of all pipeline investments materialise after 2030, yielding
 622 lower net present values (NPV) of total system costs of potentially at least
 623 75 bn. € over the course of the assets' lifetime.

| | CAPEX (bn. € p.a.) | | | OPEX (bn. € p.a.) | | | TOTEX (bn. € p.a.) | | | TOTEX (bn. €) |
|--------------------|--------------------|-------|-------|-------------------|-------|-------|--------------------|-------|--------|---------------------|
| Long-term scenario | DI | PCI | PCI-n | PCI-in | CP | DI | PCI | PCI-n | PCI-in | CP |
| 2030 | 498.0 | 504.6 | 501.9 | 500.2 | 496.8 | 367.0 | 368.4 | 369.3 | 370.6 | 367.7 |
| 2040 | 803.6 | 750.4 | 742.5 | 730.9 | 724.7 | 164.1 | 186.6 | 187.1 | 187.7 | 187.8 |
| 2050 | 806.6 | 770.2 | 764.2 | 755.1 | 750.1 | 82.4 | 92.6 | 91.9 | 92.2 | 91.3 |
| | | | | | | 865.0 | 873.0 | 871.2 | 870.9 | 864.5 |
| | | | | | | 967.7 | 937.0 | 929.6 | 918.6 | 912.4 |
| | | | | | | 889.0 | 862.8 | 856.1 | 847.3 | 841.4 |
| | | | | | | | | | | 8501 |
| | | | | | | | | | | 8425 |
| | | | | | | | | | | 8386 |
| | | | | | | | | | | 8342 |
| | | | | | | | | | | 8283 |
| | | | | | | | | | | NPV ₂₀₂₅ |
| Planning horizon | | | | | | | | | | |

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

624 *5.4. Limitations of our study*

625 While our study assesses a variety of topologies, planning horizons, and
626 potential regret scenarios, it is not exhaustive and comes with limitations. As
627 we focus on the impact of continental European PCI-PMI infrastructure, we
628 neglect fuel and energy imports from outside Europe. H₂ and CO₂ demand
629 is directly driven by fixed, exogenous demands for the respective carrier or
630 their derivatives.

631 Regarding the modelling of both H₂ and CO₂ pipelines, we assume a level
632 playing field for all pipeline projects through standardised costs and applying
633 haversine distance, i.e., no discrimination between PCI-PMI projects and
634 other projects, this is a simplification as real costs may differ. We also do
635 not discretise the endogenously built pipelines (due to computational com-
636 plexity) and allow any capacity to be built. This assumption can lead to
637 underestimation of the true costs of pipeline investments.

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

641 **6. Conclusion**

642 In this study, we have assessed the impact of PCI-PMI projects on reaching
643 European climate targets on its path to net-zero by 2050. We have
644 modelled the European energy system with a focus on H₂ and CO₂ infrastruc-
645 ture, and evaluated the performance of different levels of pipeline roll-out
646 under three short-term scenarios.

647 *Economic viability and policy targets.* Our findings demonstrate that PCI-
648 PMI CO₂ and H₂ infrastructure generate a net positive impact on total sys-
649 tem costs, even when accounting for potential additional costs involved with
650 the delay of pipelines. This positions PCI-PMI projects as a no-regret in-
651 vestment option for the European energy system. Their economic benefit
652 increases considerably when strategic pipeline extensions are implemented,
653 connecting additional H₂ production sites and CO₂ point sources to the
654 pipeline network. Compared to a system without any pipeline infrastruc-
655 ture, PCI-PMI projects help to achieve the EU's ambitious policy targets,
656 including net-zero emissions, H₂ production and CO₂ sequestration targets,
657 while reducing system costs and technology dependencies.

658 *CCUS and hydrogen utilisation.* The pipeline infrastructure serves dual pur-
659 poses in Europe’s decarbonisation strategy, H₂ pipelines facilitate the distri-
660 bution of more affordable green H₂ from northern and south-western regions
661 rich in renewable energy potential to high-demand regions in central Europe.
662 Complementarily, CO₂ transport and offshore sequestration sites enable in-
663 dustrial decarbonisation by linking major industrial sites and their process
664 emissions to offshore sequestration sites in the North Sea, particularly in
665 Denmark, Norway, and the Netherlands.

666 *Technology diversification.* The build-out of pipelines serves as an essen-
667 tial risk hedging mechanism against overbuilding solar and wind generation
668 capacities while reducing excessive reliance on single carbon capture tech-
669 nologies such as direct air capture (DAC) and point-source carbon capture,
670 confirming the findings of [6]. This diversification further enhances system
671 resilience towards uncertainties involved with technologies that are not yet
672 commercially available at scale, such as DAC.

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

683 **CRediT authorship contribution statement**

684 **Bobby Xiong:** Conceptualisation, Methodology, Software, Validation,
685 Investigation, Data Curation, Writing — Original Draft, Review & Editing,
686 Visualisation. **Iegor Riepin:** Conceptualisation, Methodology, Investiga-
687 tion, Writing — Review & Editing, Project Administration, Funding acqui-
688 sition. **Tom Brown:** Investigation, Resources, Writing — Review & Editing,
689 Supervision, Funding acquisition.

690 **Declaration of competing interest**

691 The authors declare that they have no known competing financial inter-
692 ests or personal relationships that could have appeared to influence the work
693 reported in this paper.

694 **Data and code availability**

695 All results, including solved PyPSA networks and summaries in .csv for-
696 mat are published on Zenodo:

697 <https://doi.org/XX.YYYY/zenodo.10000000>

698 The entire workflow, including the custom model based on PyPSA-Eur
699 v2025.01.0, PCI-PMI project implementation, regret-matrix setup, postpro-
700 cessing and visualisation routines can be completely reproduced from the
701 GitHub repository:

702 <https://github.com/bobbyxng/pcipmi-policy-targets>

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709 research and innovation programme under grant agreement no. 101069750.

⁷¹⁰ Appendix A. Supplementary material — Data

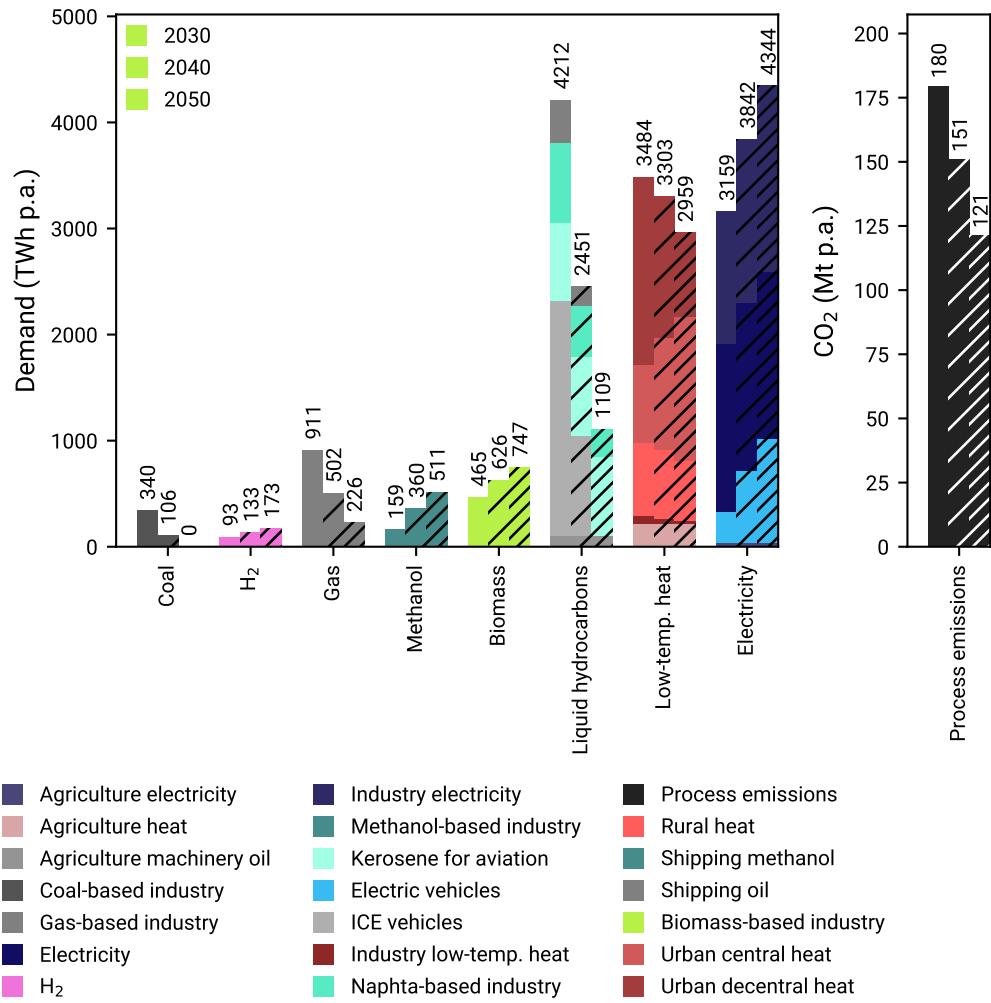


Figure A.9: Exogenous demand.

711 **Appendix B. Supplementary material — Methodology**

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

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

712 **Appendix C. Supplementary material — Results and discussion**

713 *Appendix C.1. Installed capacities*

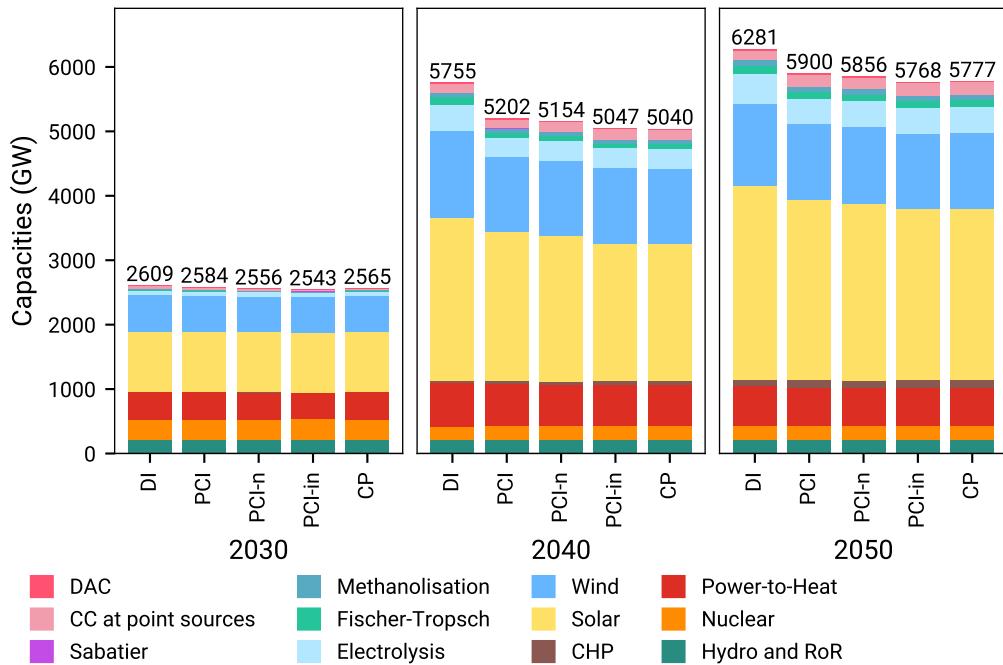


Figure C.10: Installed capacities in long-term scenarios.

⁷¹⁴ Appendix C.2. Delta capacities

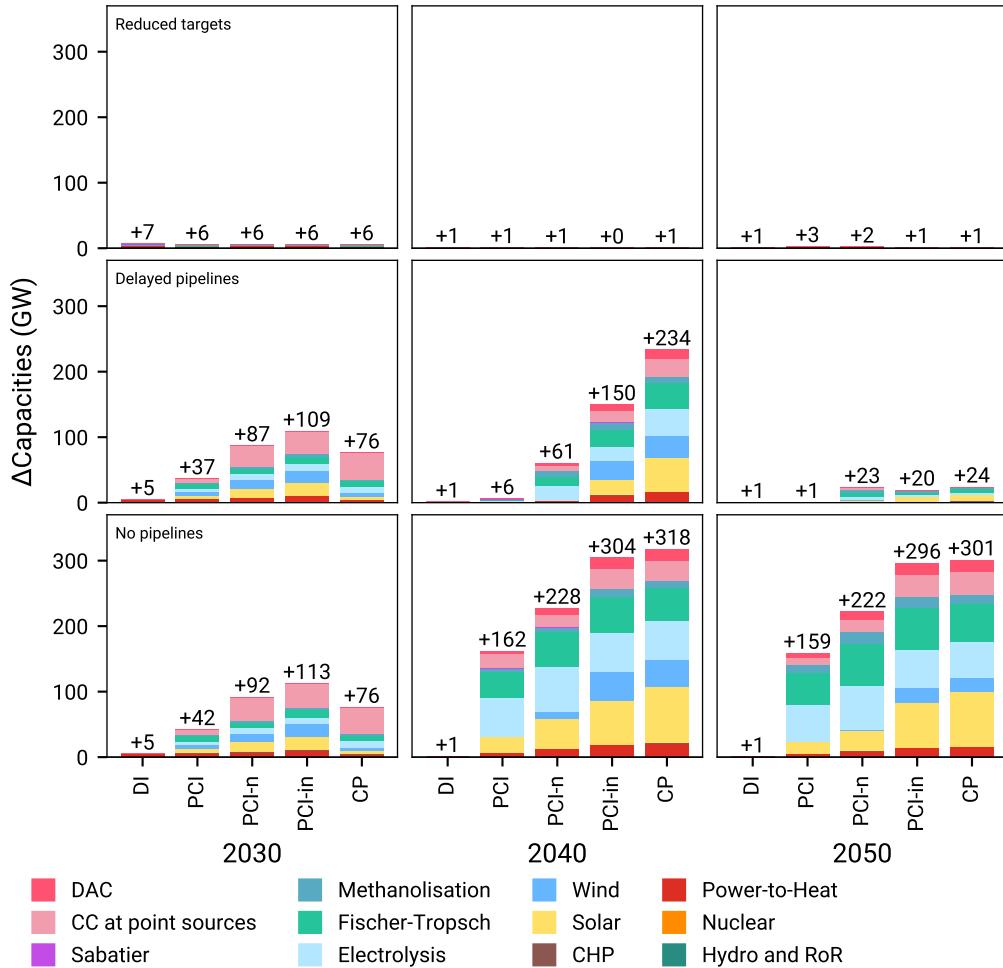


Figure C.11: Δ Capacities — Short-term minus long-term runs.

715 *Appendix C.3. Delta system costs*

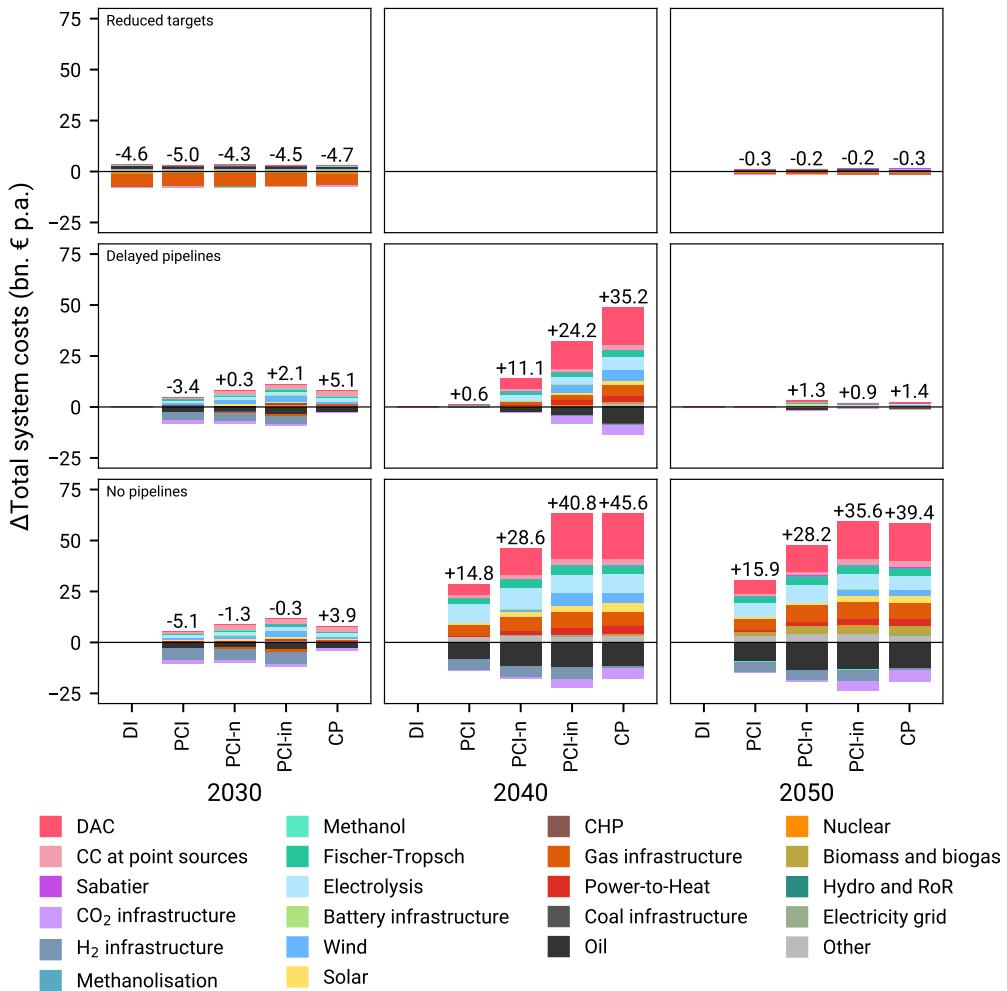


Figure C.12: Δ System costs — Short-term minus long-term runs.

⁷¹⁶ Appendix C.4. Delta balances

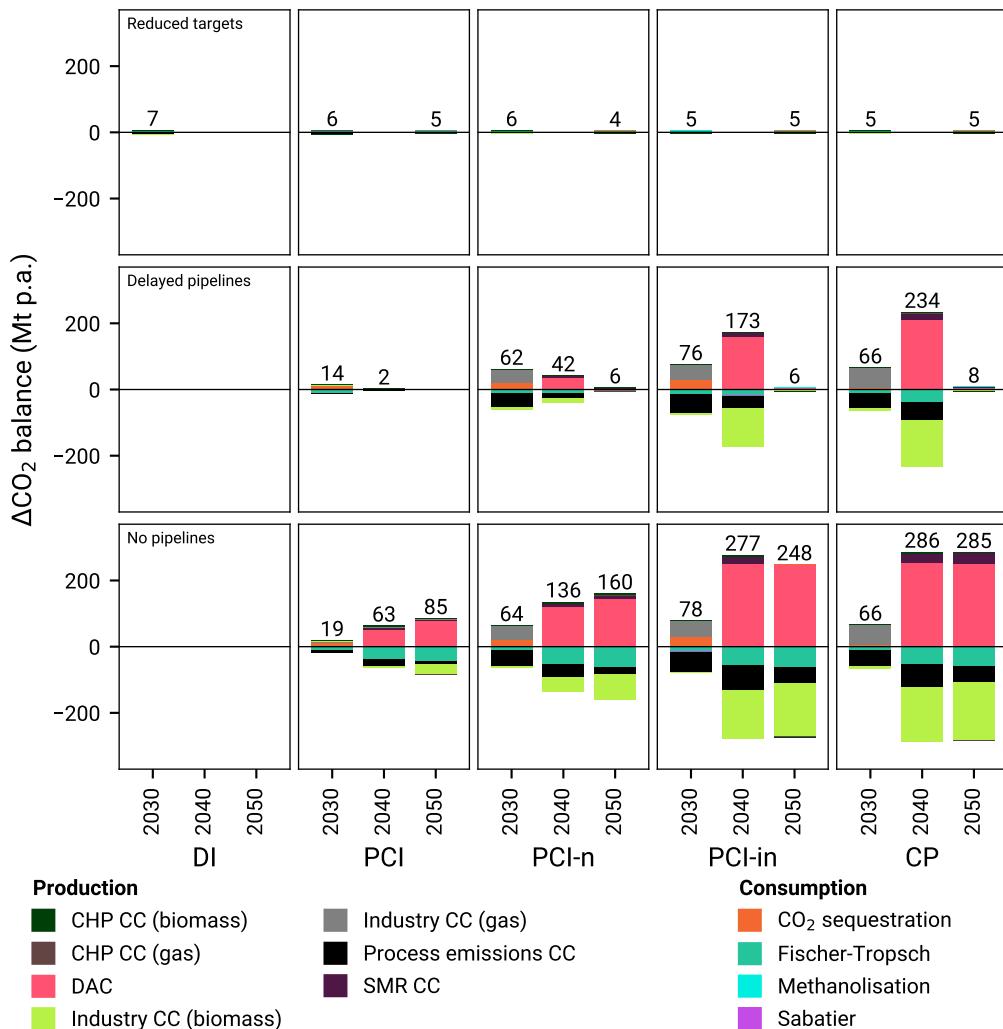


Figure C.13: ΔCO_2 balances — Short-term minus long-term runs.

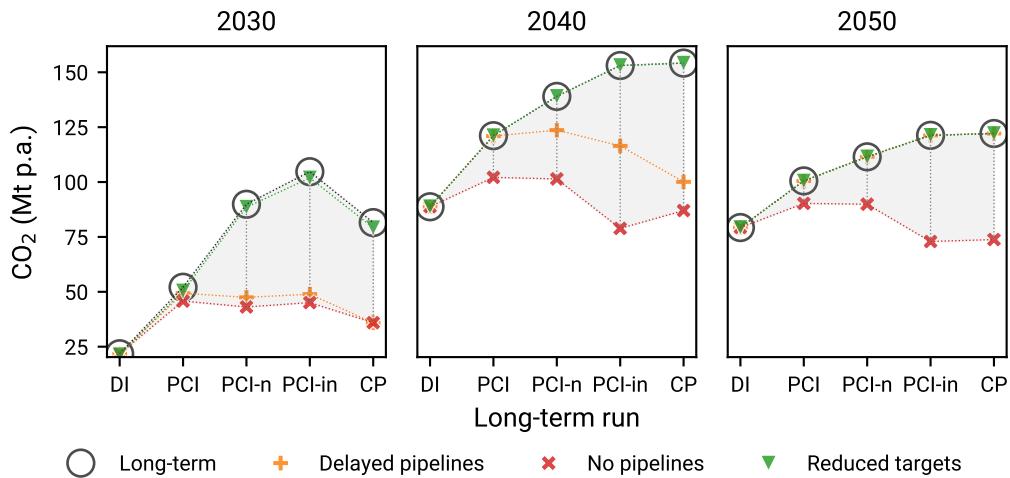


Figure C.14: ΔCO_2 balances — Process emissions including Carbon Capture.

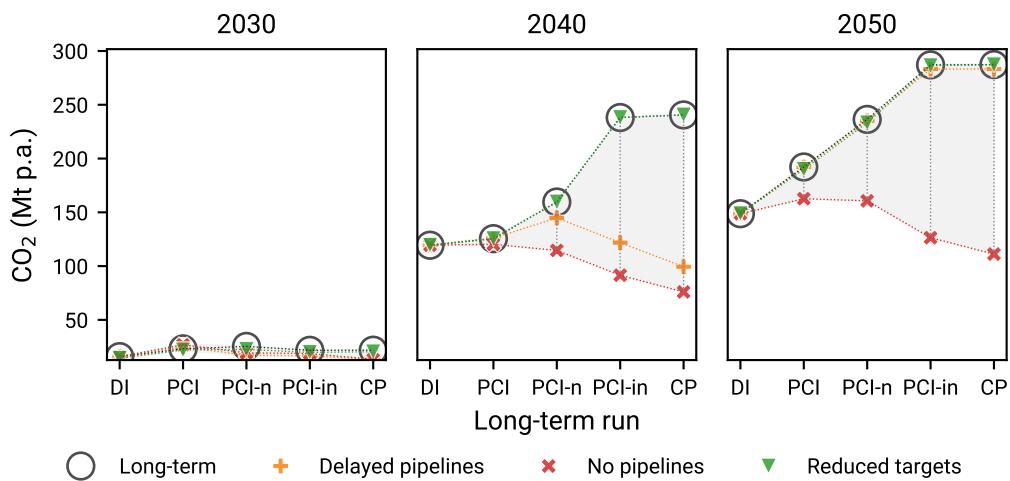


Figure C.15: ΔCO_2 balances — Carbon capture from solid biomass for industry point sources.

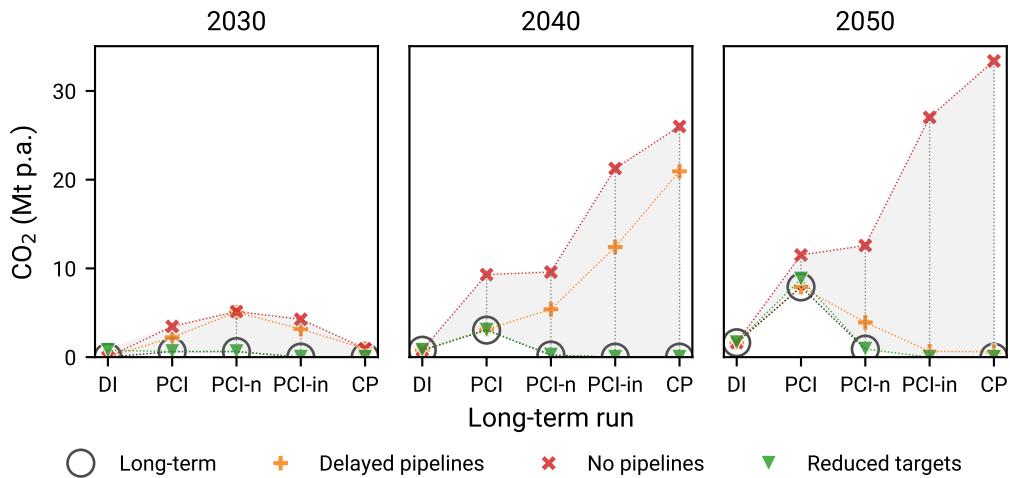


Figure C.16: ΔCO_2 balances — Carbon capture from steam methane reforming point sources.

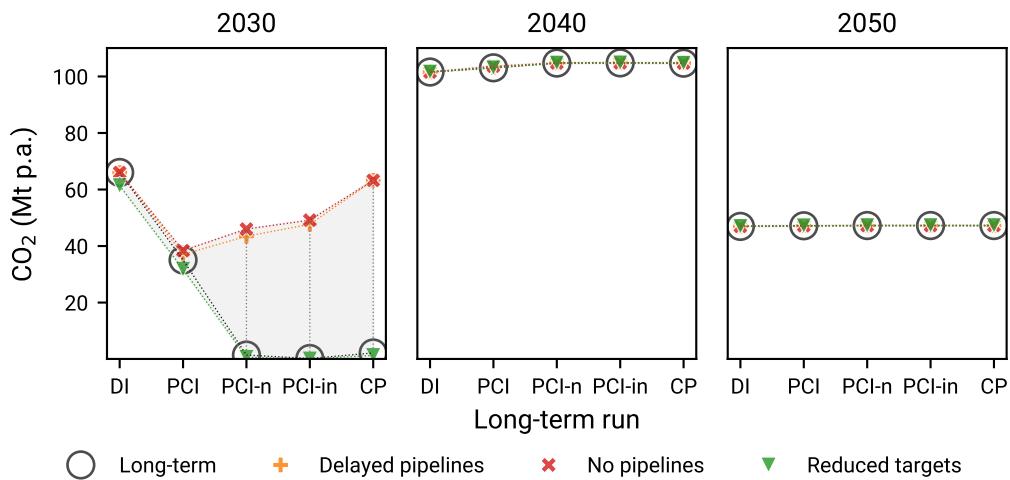


Figure C.17: ΔCO_2 balances — Carbon captured from gas for industry point sources.

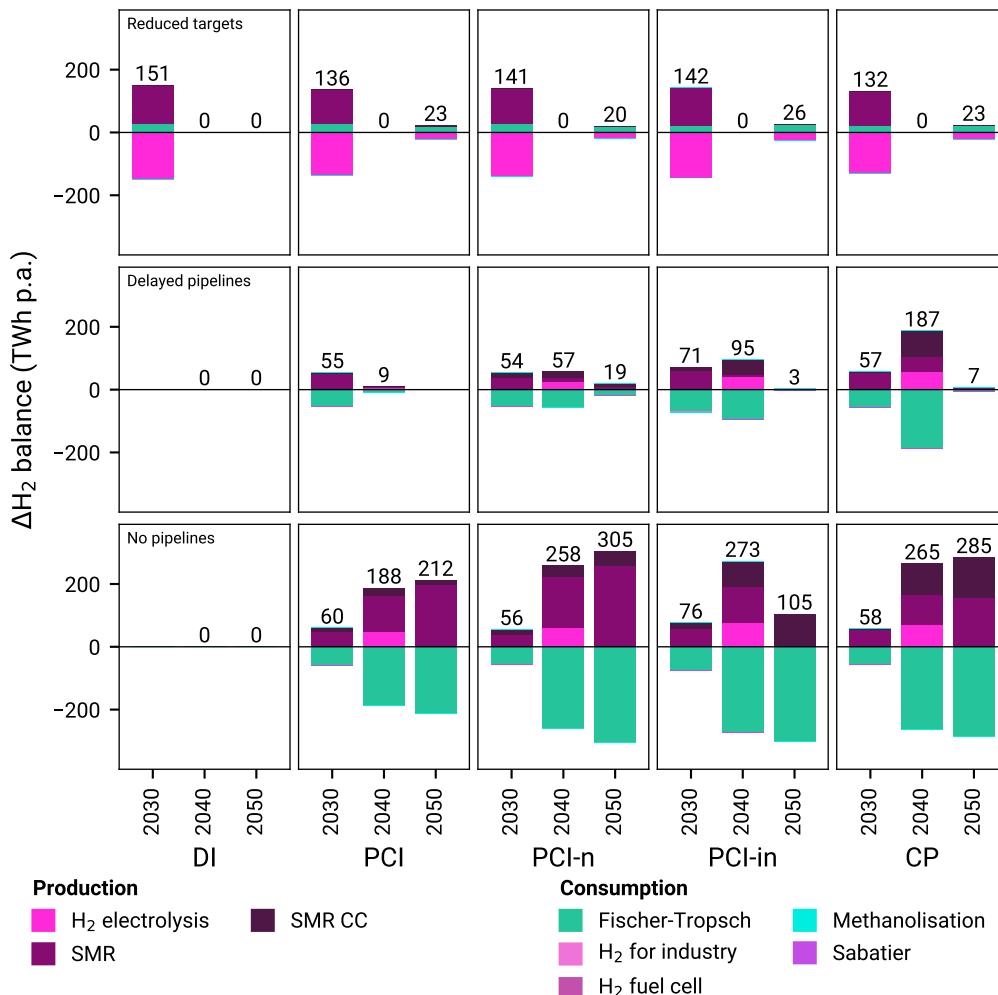


Figure C.18: ΔH_2 balances — Short-term minus long-term runs.

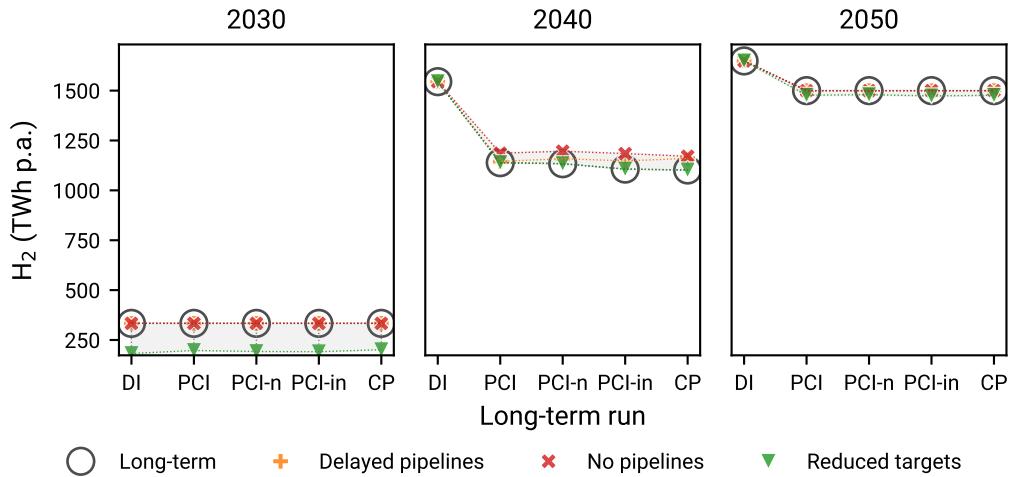


Figure C.19: Delta balances — Electrolytic H₂ production

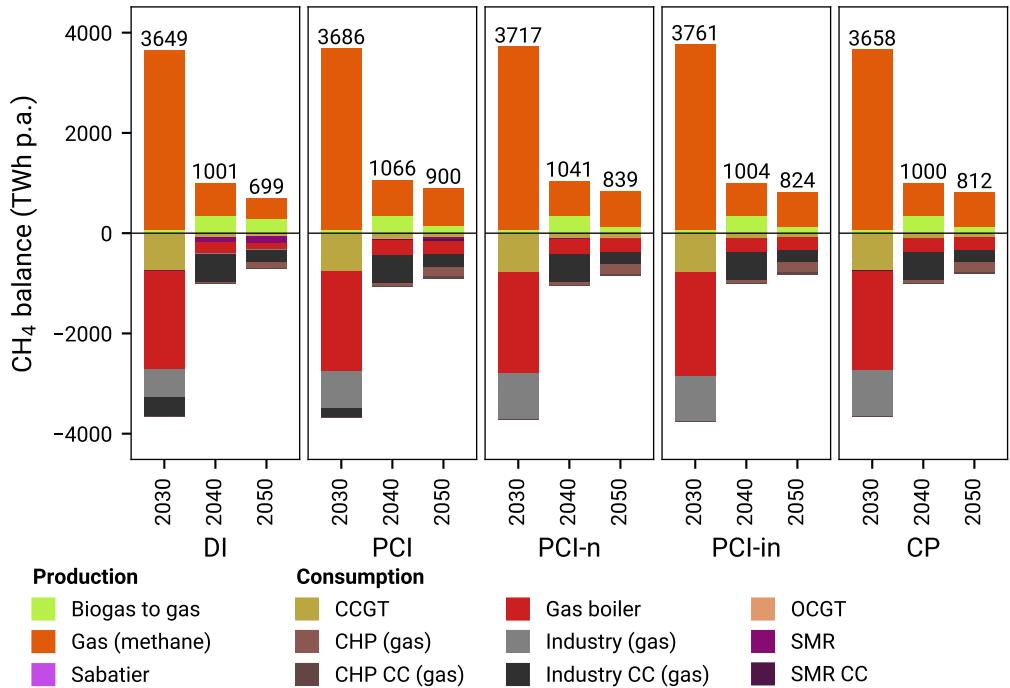


Figure C.20: CH₄ balances in long-term scenarios.

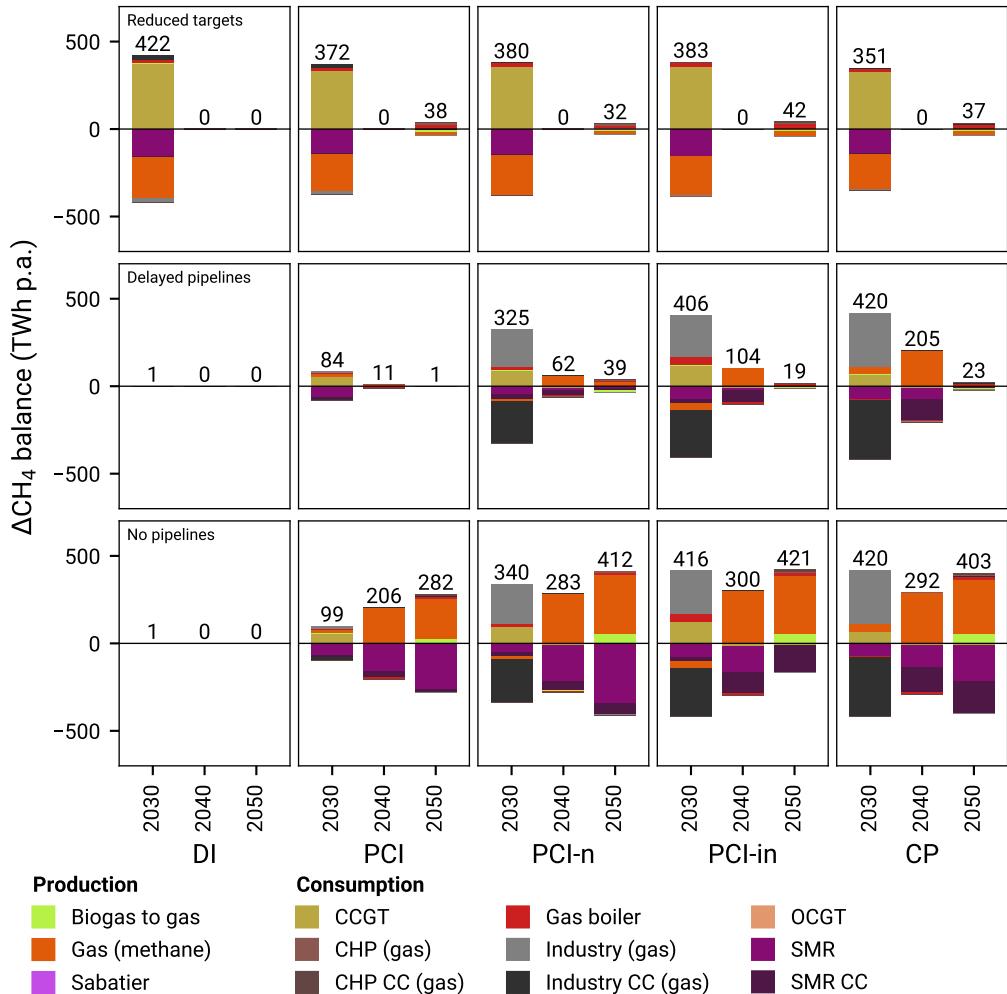


Figure C.21: ΔCH_4 balances — Short-term minus long-term runs.

717 *Appendix C.5. Maps*

718 *Appendix C.5.1. Decentral Islands*

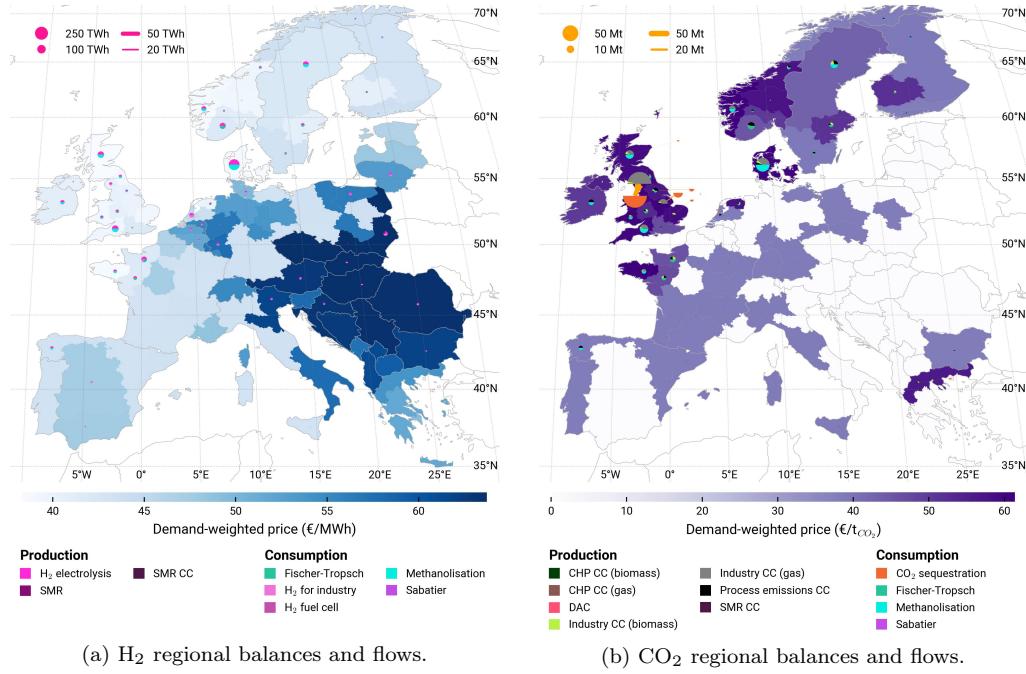


Figure C.22: *Decentral Islands* long-term scenario (2030) — Regional distribution of H₂ and CO₂ production, utilisation, storage, and transport.

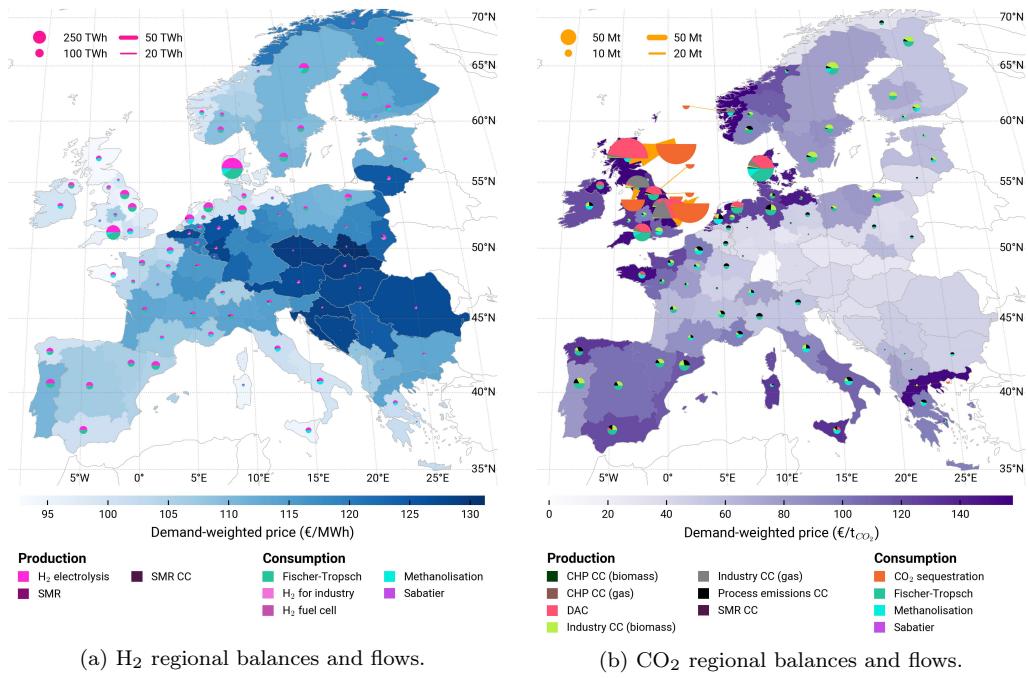


Figure C.23: *Decentral Islands* long-term scenario (2040) — Regional distribution of H₂ and CO₂ production, utilisation, storage, and transport.

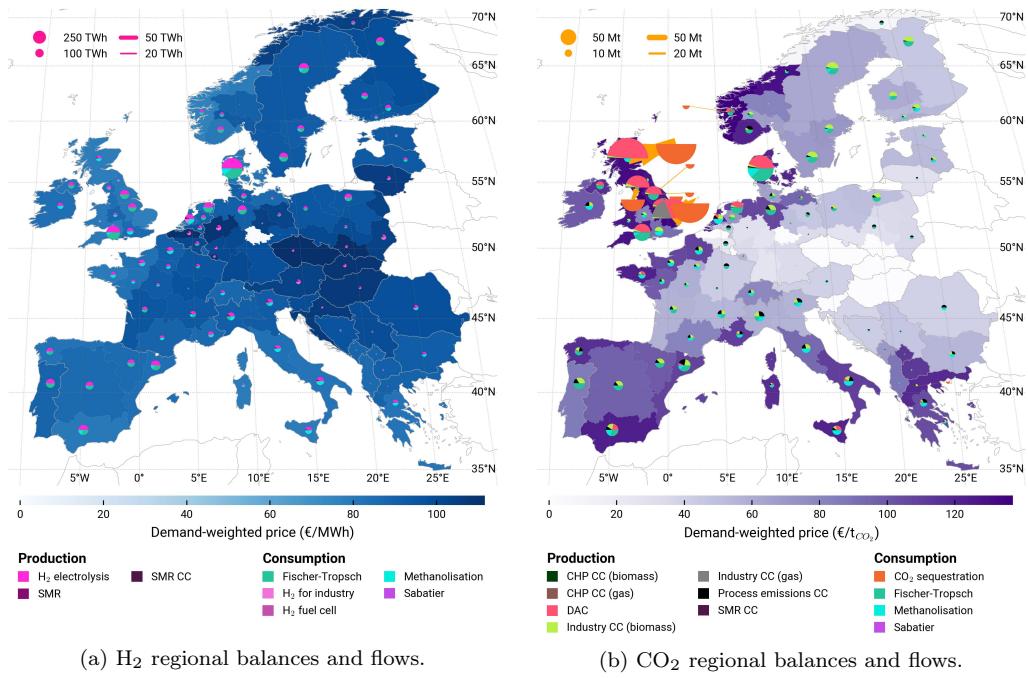


Figure C.24: *Decentral Islands* long-term scenario (2050) — Regional distribution of H₂ and CO₂ production, utilisation, storage, and transport.

719 *Appendix C.6. PCI international*

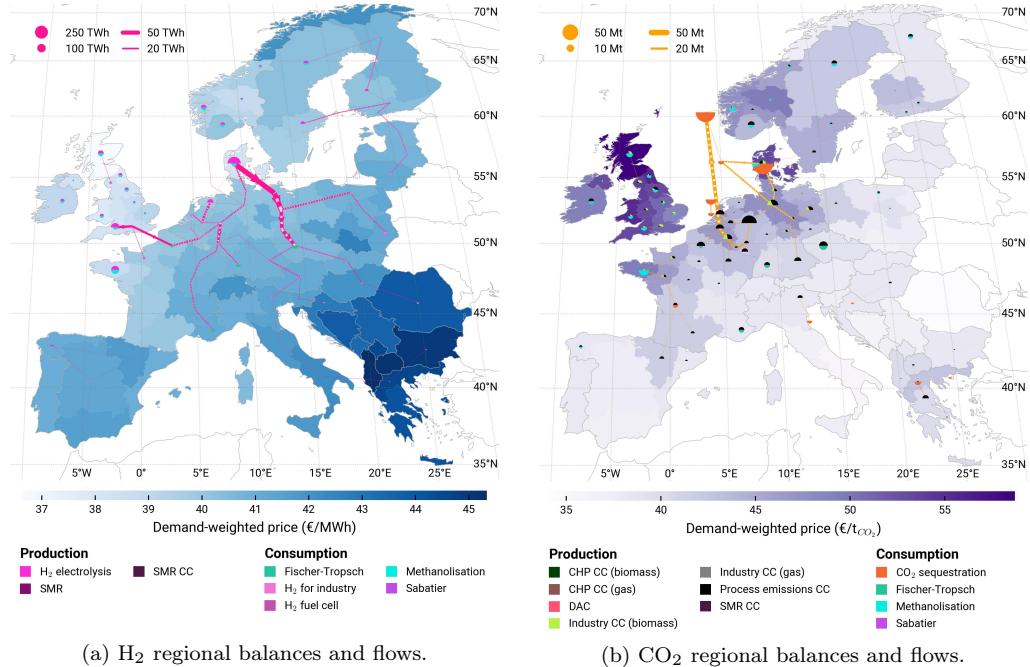


Figure C.25: *PCI* long-term scenario (2030) — Regional distribution of H₂ and CO₂ production, utilisation, storage, and transport. Dotted white lines represent PCI-PMI projects.

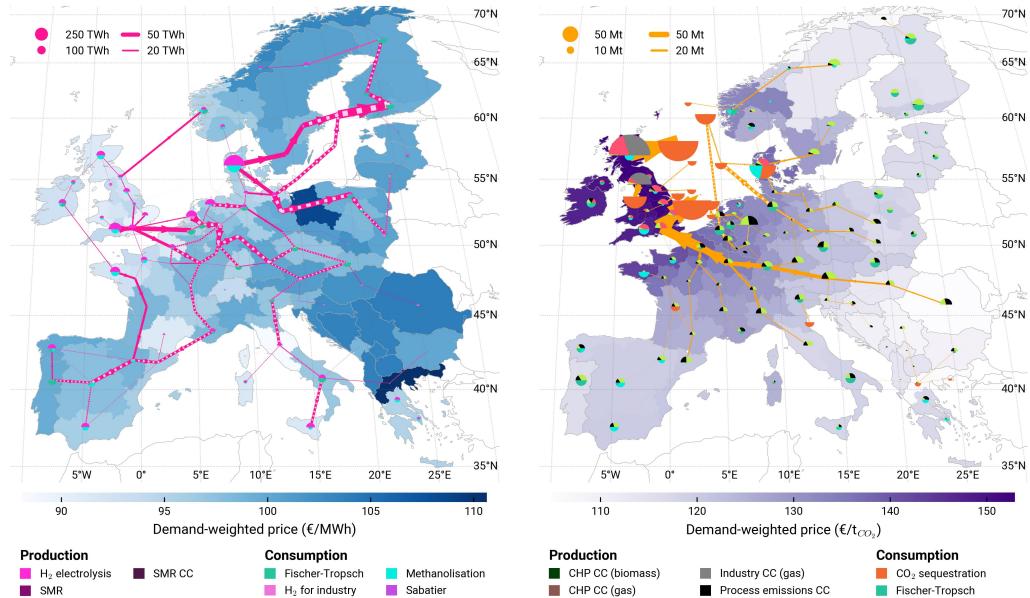


Figure C.26: *PCI-in* long-term scenario (2040) — Regional distribution of H₂ and CO₂ production, utilisation, storage, and transport. Dotted white lines represent PCI-PMI projects.

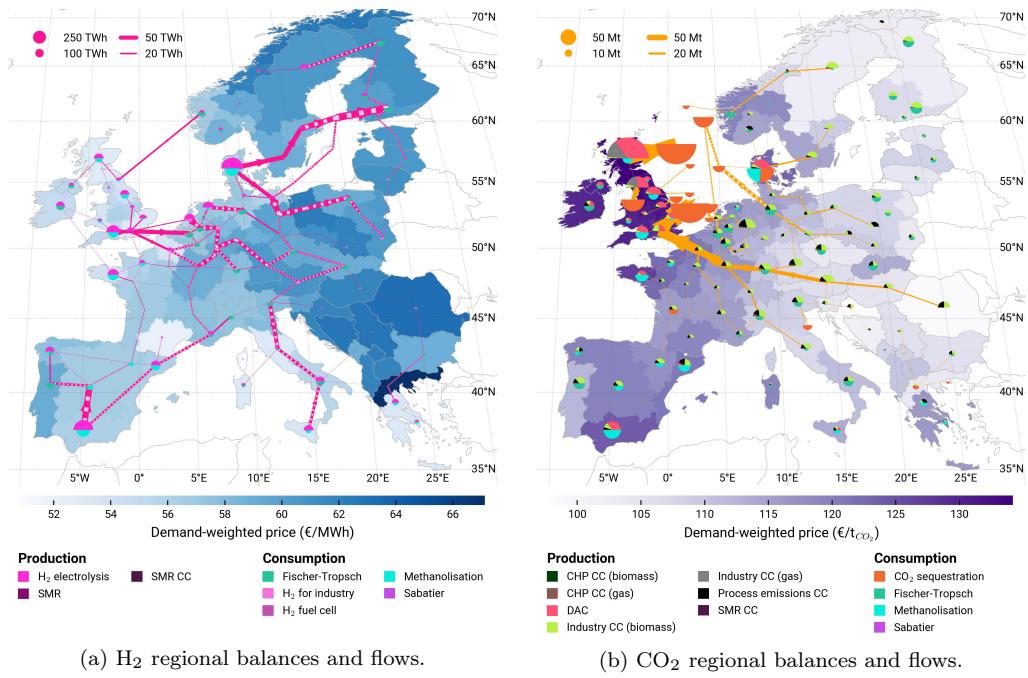


Figure C.27: *PCI-in* long-term scenario (2050) — Regional distribution of H₂ and CO₂ production, utilisation, storage, and transport.

720 *Appendix C.6.1. Central Planning*

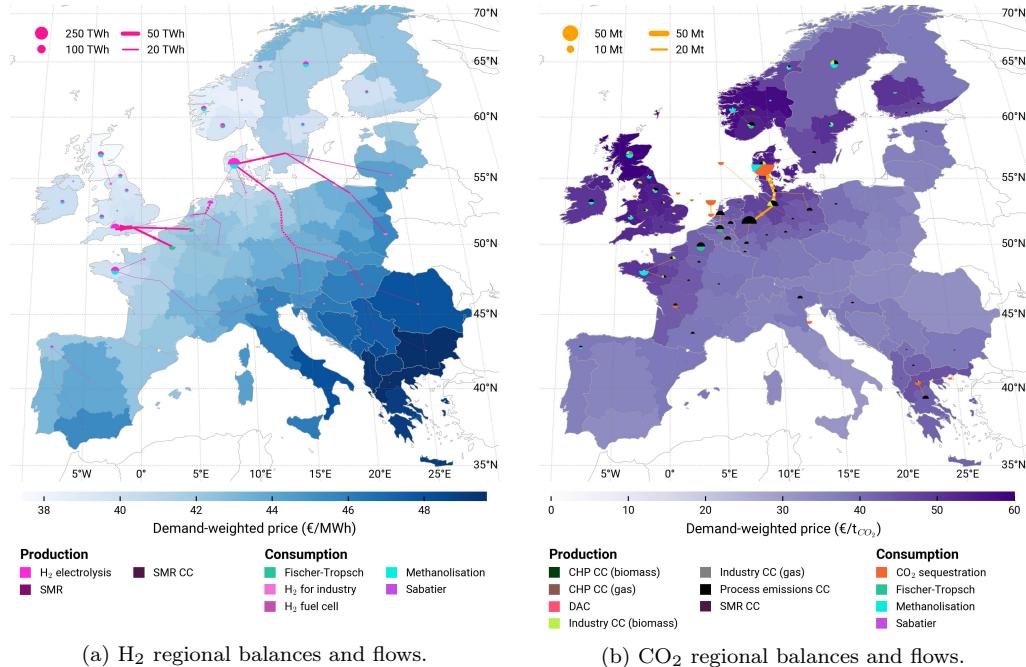


Figure C.28: *Central Planning* long-term scenario (2030) — Regional distribution of H₂ and CO₂ production, utilisation, storage, and transport.

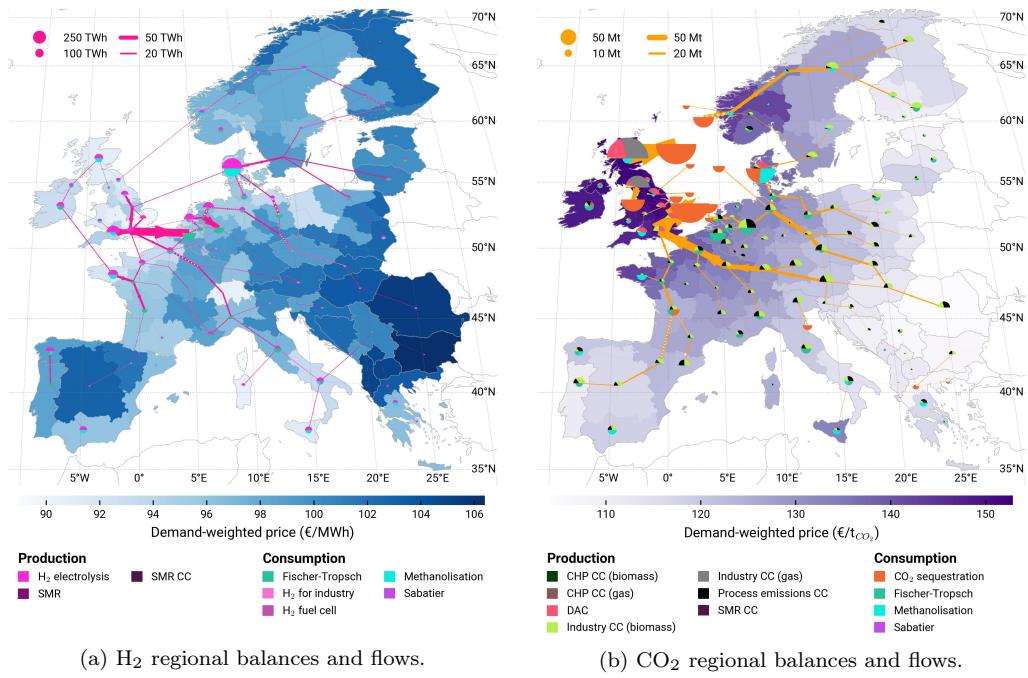


Figure C.29: *Central Planning* long-term scenario (2040) — Regional distribution of H₂ and CO₂ production, utilisation, storage, and transport.

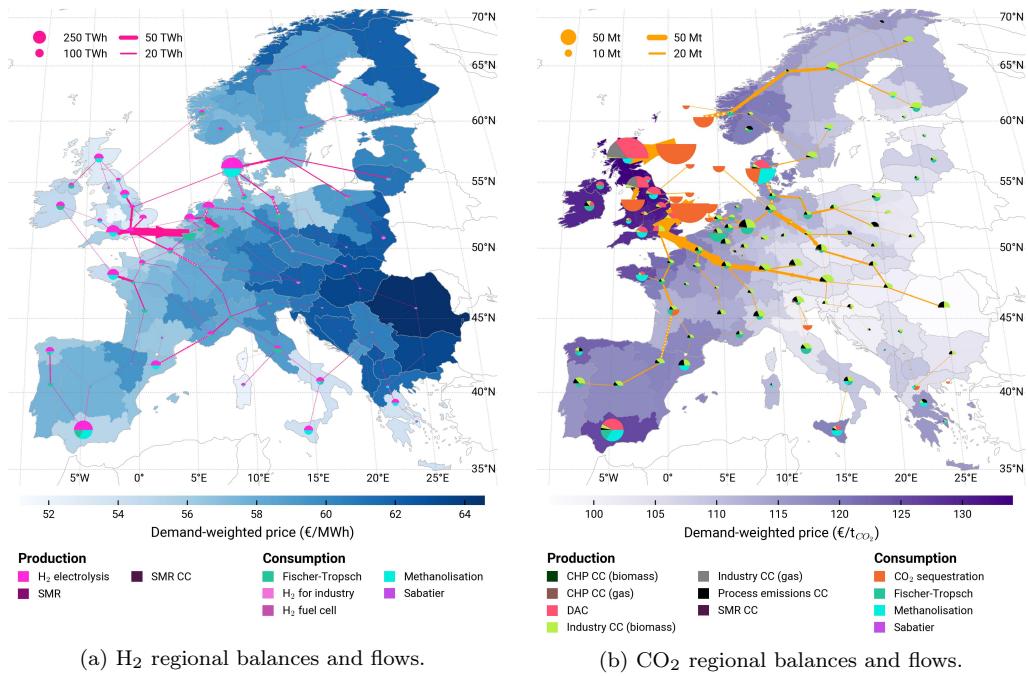


Figure C.30: *Central Planning* long-term scenario (2050) — Regional distribution of H₂ and CO₂ production, utilisation, storage, and transport.

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