

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

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<sup>4</sup> **Abstract**

OLD OUTDATED IEW-EXTENDED-ABSTRACT. The European Union (EU) aims to achieve climate-neutrality by 2050, with ambitious 2030 target, such as 55 % greenhouse gas emissions reduction compared to 1990 levels, 10 Mt p.a. of a domestic green H<sub>2</sub> production, and 50 Mt p.a. of CO<sub>2</sub> injection capacity, which should be sequestered within the EU. The European Commission selects so-called Projects of Common Interest (PCI) and Projects of Mutual Interest (PMI)—a large infrastructure projects for electricity, hydrogen and CO<sub>2</sub> transport, and storage—that are of transnational importance as they link the energy systems of European countries. In this work, we evaluate the impact of PCI-PMI projects for the European energy system and EU energy policies. To achieve this, we investigate how delays in these projects could affect the EU's policy targets and examine potential conflicts between various policy objectives and the overarching greenhouse gas reduction goal. Our preliminary results for 2030 indicate that policy targets can be met even without PCI-PMI projects; however, these projects offer additional benefits: (i) H<sub>2</sub> pipelines enhance the affordability and distribution of green H<sub>2</sub>, thereby jumpstarting the hydrogen economy, and (ii) CO<sub>2</sub> transport projects connect major industrial emissions to offshore sequestration sites in the North Sea. In our future work, we will analyse long-term pathway effects up to 2050, and incorporate hybrid interconnectors and CO<sub>2</sub> shipping routes from the PCI-PMI list. Overall, our findings highlight the critical interplay between cross-border cooperation, infrastructure investments, and policy targets in the European energy transition across all sectors.

<sup>5</sup> *Keywords:* energy system modelling, policy targets, infrastructure,  
<sup>6</sup> resilience, hydrogen, carbon, Europe

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7 **List of abbreviations**

- 8   **AC** Alternating Current  
9   **API** Application Programming Interface  
10   **CC** Carbon Capture  
11   **CU** Carbon Utilisation  
12   **CS** Carbon Storage  
13   **CCUS** Carbon Capture, Utilisation, and Storage  
14   **DAC** Direct Air Capture  
15   **DC** Direct Current  
16   **EU** European Union  
17   **GHG** Greenhouse gas  
18   **NEP** Netzentwicklungsplan (German grid development plan)  
19   **NUTS** Nomenclature of Territorial Units for Statistics  
20   **PCI** Projects of Common Interest  
21   **PMI** Projects of Mutual Interest  
22   **REST** Representational State Transfer  
23   **tsam** Time Series Aggregation Module  
24   **TYNDP** Ten-Year Network Development Plan  
25   **WACC** Weighted Average Cost of Capital

26 **1. Introduction**

27   WORK-IN-PROGRESS-INCOMPLETE. On the pathway to a climate-  
28   neutral Europe by 2050, the European Union (EU) has set ambitious targets  
29   for 2030. These targets include a reduction of 55 % in greenhouse gas emis-  
30   sions compared to 1990 levels [1], 10 Mt p.a. domestic green H<sub>2</sub> production  
31   [2], and 50 Mt p.a. of CO<sub>2</sub> injection capacity with sequestration in within  
32   the EU [3].

33   To support reaching these targets, the European Commission bi-annually  
34   identifies a list of Projects of Common Interest (PCI), which are key cross-  
35   border infrastructure projects that link the energy systems of the EU mem-  
36   bers, including transmission and storage projects for electricity, hydrogen and  
37   CO<sub>2</sub> [4]. The pool of project suitable for PCI status is based on projects sub-  
38   mitted by transmission system operators, consortia, or third parties. Projects  
39   of Mutual Interest (PMI) further include cooperations with countries outside  
40   the EU, such as Norway or the United Kingdom. With a PCI-PMI status,  
41   project awardees receive strong political support and are, amongst others,

42 eligible for financial support (e.g. through funding of the Connecting Eu-  
43 rope Facility) and see accelerated permitting processes. On the other hand,  
44 project promoters are obliged to undergo comprehensive reporting and mon-  
45 itoring processes. In order for projects to be eligible for PCI-PMI status,  
46 their *potential benefits need to outweigh their costs* [4]. Given the political  
47 and lighthouse character, these projects are highly likely to be implemented.  
48 However, any large infrastructure project, including PCI-PMI projects, com-  
49 monly face delays due to permitting, financing, procurement bottlenecks, etc.  
50 [5].

- 51 • Net zero law by 2050 (**author?**) [3]

52 1.1. *Fuels, carriers, targets*

53 *Hydrogen (H<sub>2</sub>).*

- 54 • "net zero systems: H<sub>2</sub> feedstock for synthetic fuels, fuel transportation  
55 sector, feedstock and heat source in industry," [6], [7]

56 1.2. *Projects of Common/Mutual Interest*

57    **2. Literature review**

58    We structure the literature review into three main sections: (i) the value  
59    of CO<sub>2</sub> and H<sub>2</sub> in low-carbon energy systems, (ii) transporting CO<sub>2</sub> and H<sub>2</sub>  
60    through pipelines, and (iii) addressing uncertainty in energy system models.  
61    Based on this review, identify research gaps and position our work as a novel  
62    contribution to the current state of the art (iv).

63    *2.1. The value of CO<sub>2</sub> and H<sub>2</sub> in low-carbon energy systems*

64    A growing body of literature has been investigating the long-term role  
65    of H<sub>2</sub> and CO<sub>2</sub> in low-carbon or net-zero energy systems. Both carriers see  
66    their primary value outside the electricity sector, i.e., in the decarbonisation  
67    of hard-to-abate sectors such as industry, transport, shipping, and aviation  
68    [8]. While there are direct use cases for H<sub>2</sub> in the industry sector such as  
69    steel production, it is primarily expected to serve as a precursor for synthetic  
70    fuels, including methanol, Fischer-Tropsch fuels (e.g. synthetic kerosene and  
71    naphta) and methane. The demand for these fuels is driven by the aviation,  
72    shipping, industry, and agriculture sectors [9]. To produce these carbona-  
73    ceous fuels, CO<sub>2</sub> is required as a feedstock (Carbon Utilisation — CU). This  
74    CO<sub>2</sub> can be captured from the atmosphere via Direct Air Capture (DAC) or  
75    from industrial and process emissions (e.g. cement, steel, ammonia produc-  
76    tion) in combination with Carbon Capture (CC) units.

77    Van Greevenbroek et al. [6]: Look at near optimal solution space by  
78    assessing a wide range. Derived from a wide set of literature, modelling  
79    hydrogen and CS, CU [7, 9–16]

80    Range of assessed CO<sub>2</sub> sequestration potential from 275 Mt p.a., 550 Mt  
81    p.a., up to 1100 Mt p.a. Range of green hydrogen production in 2050 goes  
82    up to 90 Mt p.a. Page 3: Europe has little to loose by committing to targets  
83    like 25 Mt pa H<sub>2</sub> production by 2040, moderate target, feasible.

84    "Cost optimal modelling results with a central planning approach may  
85    not capture system designs that are politically more viable but slightly more  
86    costly." from Koens paper, [17]

87    *2.2. Transporting H<sub>2</sub> and CO<sub>2</sub> through pipelines*

88    Recent publications show that transporting CO<sub>2</sub> and H<sub>2</sub> via dedicated  
89    pipeline infrastructure can unlock additional benefits and net cost-savings in  
90    a sector-coupled energy system. Victoria et al. [?] ... TODO

91 Neumann et al. [9] examine the interaction between electricity grid ex-  
92 pansion and a European-wide deployment of hydrogen pipelines in a net-zero  
93 system (new and retrofitting of existing gas pipelines). While H<sub>2</sub> pipelines are  
94 not essential, their build-out can significantly reduce system costs by up to 26  
95 bn. € p.a. (3.4 % of annual CAPEX and OPEX) by connecting regions with  
96 excessive renewable potential to storage sites and load centres. Extending  
97 their previous work, Neumann et al. [18] investigate the trade-off between  
98 relying on different energy import strategies and domestic infrastructure  
99 build-out. By coupling the global energy supply chain model TRACE [19]  
100 and the sector-coupled PyPSA-Eur model, they assess different energy vector  
101 import combinations (e.g. electricity, H<sub>2</sub> or H<sub>2</sub> derivatives) and their impact  
102 on Europe's infrastructural needs. Depending on the import costs, they ob-  
103 serve up to 14 % in system cost savings. Further, with an increasing share of  
104 H<sub>2</sub> imports, the need for domestic H<sub>2</sub> pipelines would decrease.

105 In a study by Kontouris et al. [16], the authors explore pathways for a po-  
106 tential integrated hydrogen infrastructure in Europe while considering sector-  
107 coupling and energy imports. Using the European energy system model Bal-  
108 morel [20], the authors implement three scenarios varying between domes-  
109 tic and imported H<sub>2</sub> levels as well as H<sub>2</sub> production technologies. In their  
110 findings they identify main H<sub>2</sub> transport corridors from Spain and France,  
111 Ireland and the United Kingdom, Italy, and Southeastern Europe. When  
112 synergies through sector-coupling are exploited, domestic H<sub>2</sub> production can  
113 be competitive, seeing an increase in up to 3 % in system costs.

114 Fleiter et al. [10] use a mixed simulation and optimisation method to  
115 model H<sub>2</sub> uptake and transport by coupling three models, (i) FORECAST  
116 for buildings and industry, (ii) ALADIN for transport together with (iii) the  
117 European energy system model Enertile. Total demand for H<sub>2</sub> ranges from  
118 690 TWh to 2800 TWh in 2050, 600 TWh to 1400 TWh for synthetic fuels.  
119 In their study, the chemical and steel industry in Northwest Europe (incl.  
120 western regions of Germany, Netherlands and northern regions of Belgium),  
121 display a demand of more than 100 TWh each. With regard to crossborder  
122 transport, they mainly observe hydrogen flows from Norway, UK and Ireland to  
123 continental Europe (around 53 TWh to 72 TWh). Depending on the scenario,  
124 the Iberian Peninsula exports around 72 TWh to 235 TWh via and to France.

125 On the carbon networks side, [21]

126 Doing both: Hofmann et al. [22] address previous research gap in as-  
127 sessing the interaction between H<sub>2</sub> and CO<sub>2</sub> infrastructure, including their  
128 production, transport, storage, utilisation, and sequestration. They find that

<sup>129</sup> ... WORK-IN-PROGRESS-INCOMPLETE.

<sup>130</sup> *2.3. Addressing uncertainty in energy system models*

<sup>131</sup> WORK-IN-PROGRESS-INCOMPLETE.

<sup>132</sup> • Regret analysis common in economics, also in energy system modelling

<sup>133</sup> • Carbon networks

<sup>134</sup> • Regret

<sup>135</sup> • Cite Hobbs, Iegor, Möbius and Riepin two-stage, stochastic, regret ap-  
<sup>136</sup> proach [? ] PCI projects gas

### <sup>137</sup> 3. Research gaps and our contribution

<sup>138</sup> TODO NOVELTIES:

<sup>139</sup> • basically mega PINT CBA, which was not done before, neither for PCI  
<sup>140</sup> projects nor for the sectors

<sup>141</sup> • Chicken and egg problem. Assess real planned projects

<sup>142</sup> • high spatial and temporal resolution

<sup>143</sup> • regret matrix approach

<sup>144</sup> • Time, myopic, iterative dimension, usually studies look directly at the  
<sup>145</sup> target 2050, yielding overly optimistic results (overnight 2050 optimi-  
<sup>146</sup> sation will yield different result than pathway-dependent solutions)

<sup>147</sup> This paper aims to evaluate the impact of PCI-PMI projects on the Eu-  
<sup>148</sup> ropean energy system and EU energy policies. We focus on the following key  
<sup>149</sup> research questions:

<sup>150</sup> 1. What is the impact of delay in PCI-PMI projects' realisation on the  
<sup>151</sup> EU's policy targets for 2030?

<sup>152</sup> 2. What are the costs associated with adhering to the EU policy targets,  
<sup>153</sup> even if PCI-PMI projects are delayed?

<sup>154</sup>        3. Do the green hydrogen production and carbon sequestration targets  
<sup>155</sup> conflict with the cost-effective achievement of the greenhouse gas emis-  
<sup>156</sup> sion reduction goals?

<sup>157</sup>        Key motivations for the questions as the EU targets especially for 2030  
<sup>158</sup> have have been criticised as unrealistic, primarily politically motivated. [6,  
<sup>159</sup> 23]

160 **4. Methodology**

161 We build on the open-source, sector-coupled energy system model PyPSA-  
162 Eur [9, 24–26] to optimise investment and dispatch decisions in the European  
163 energy system. The model’s endogenous decisions include the expansion and  
164 dispatch of renewable energy sources, dispatchable power plants, electricity  
165 storage, power-to-X conversion capacities, and transmission infrastructure  
166 for power, hydrogen, and CO<sub>2</sub>. It also encompasses heating technologies  
167 and various hydrogen production methods (gray, blue, green). PyPSA-Eur  
168 integrates multiple energy carriers (e.g., electricity, heat, hydrogen, CO<sub>2</sub>,  
169 methane, methanol, liquid hydrocarbons, and biomass) with corresponding  
170 conversion technologies across multiple sectors (i.e., electricity, trans-  
171 port, heating, biomass, industry, shipping, aviation, agriculture and fossil  
172 fuel feedstock). The model features high spatial and temporal resolution  
173 across Europe, incorporating existing power plant stocks [27], renewable po-  
174 tentials, and availability time series [28]. It includes the current high-voltage  
175 transmission grid (AC 220 kV to 750 kV and DC 150 kV and above) [29].  
176 Furthermore, electricity transmission projects from the TYNDP (SOURCE)  
177 and German Netzentwicklungsplan (SOURCE) are also enabled.

178 *4.1. Model setup*

179 *Temporal resolution.* To assess the long-term impact of PCI-PMI projects  
180 on European policy targets across all sectors, we optimise the sector-coupled  
181 network for three key planning horizons 2030, 2040, and 2050, myopically.  
182 The myopic approach ensures that investment decisions across all planning  
183 horizons are coherent and build on top of the previous planning horizon. We  
184 use the built-in Time Series Aggregation Module (tsam) to solve the model  
185 for 2190 time steps, yielding an average resolution of four hours. tsam is  
186 a Python package developed by Kotzur et al. [30] to aggregate time series  
187 data into representative time slices to reduce computational complexity while  
188 maintaining their specific intertemporal characteristics, such as renewable  
189 infeed variability, demand fluctuations, and seasonal storage needs.

190 *Geographical scope.* We model 34 European countries, including 25 of the  
191 EU27 member states (excluding Cyprus and Malta), as well as Norway,  
192 Switzerland, the United Kingdom, Albania, Bosnia and Herzegovina, Mon-  
193 tenegro, North Macedonia, Serbia, and Kosovo. Regional clustering is based  
194 on administrative NUTS boundaries, with higher spatial resolution applied

195 to regions hosting planned PCI-PMI infrastructure, producing 99 onshore re-  
196 gions (see Table A.4). Depending on the scenario, additional offshore buses  
197 are introduced to appropriately represent offshore sequestration sites and  
198 PCI-PMI projects. To isolate the effect of PCI-PMI projects, Europe is self-  
199 sufficient in our study, i.e., we do not allow any imports or exports of the  
200 assessed carriers like electricity, H<sub>2</sub>, or CO<sub>2</sub>.

201 *Technology assumptions.* As part of the PyPSA-Eur model, we source all  
202 technology-specific assumptions including lifetime, efficiency, investment and  
203 operational costs from the public *Energy System Technology Data* repository,  
204 v.0.10.1 [31]. We use values projected for 2030 and apply a discount rate of  
205 7 %, reflecting the weighted average cost of capital (WACC). We assume CO<sub>2</sub>  
206 sequestration costs of 15 €/tCO<sub>2</sub> which can be considered in the mid-range  
207 of the cost spectrum (cf. TODO SOURCE 1 and 10 €/tCO<sub>2</sub> [22])

208 *Demand and CO<sub>2</sub> emissions.* Energy and fuel carrier demand in the mod-  
209 elled sectors, as well as non-abatable CO<sub>2</sub> process emissions are taken from  
210 various sources [32–36]. Regionally and temporally resolved demand includes  
211 electricity, heat, gas, biomass and transport. Internal combustion engine ve-  
212 hicles in land transport are expected to fully phase out in favour of electric  
213 vehicles by 2050 [37]. Demand for hydrocarbons, including methanol and  
214 kerosene are primarily driven by the shipping, aviation and industry sector  
215 and are not spatially resolved. To reach net-zero CO<sub>2</sub> emissions by 2050,  
216 the yearly emission budget follows the EU’s 2030 (−55 %) and 2040 (−90 %)  
217 targets [1, 38], translating into a carbon budget of 2072 Mt p.a. in 2030 and  
218 460 Mt p.a. in 2040, respectively (see Table 2).

219 *PCI-PMI projects implementation.* We implement all PCI-PMI projects of  
220 the electricity, CO<sub>2</sub> and H<sub>2</sub> sectors (excl. offshore energy islands and hy-  
221 brid interconnectors, as they are not the focus of our research) by accessing  
222 the REST API of the PCI-PMI Transparency Platform and associated pub-  
223 lic project sheets provided by the European Commission [39]. We add all  
224 CO<sub>2</sub> sequestration sites and connected pipelines, H<sub>2</sub> pipelines and storage  
225 sites, as well as proposed pumped-hydro storages and transmission lines (AC  
226 and DC) to the PyPSA-Eur model. We consider the exact geographic in-  
227 formation, build year, as well as available static technical parameters when  
228 adding individual assets to the respective modelling year. An overview of the  
229 implemented PCI-PMI projects is provided in Figure 1.

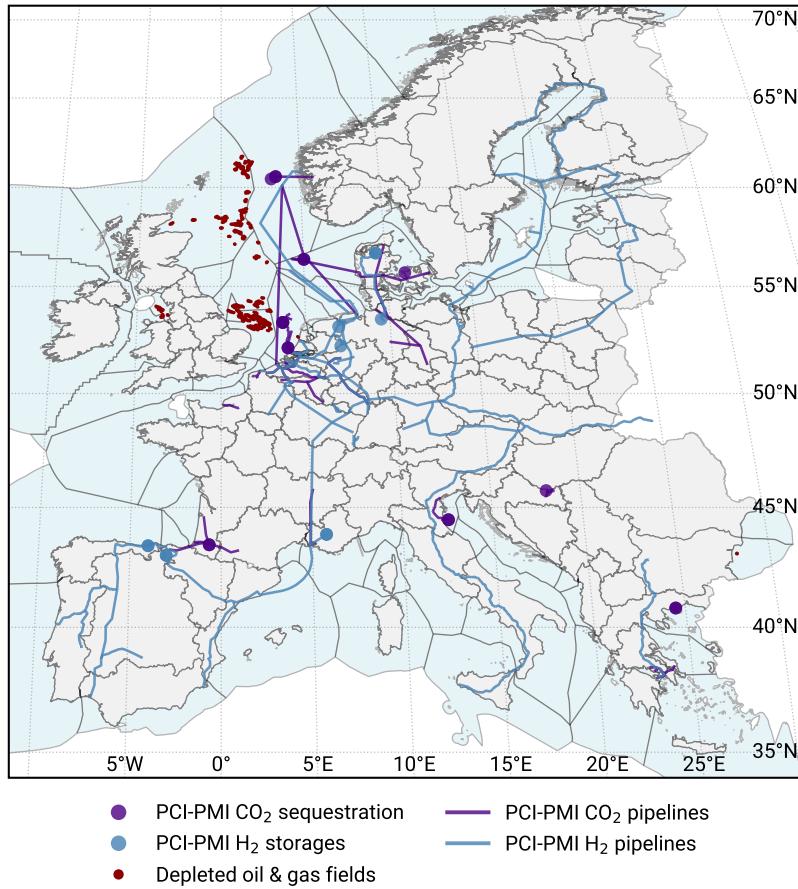


Figure 1: Map of the regional scope including clustered onshore (grey) and offshore regions (blue), as well as PCI-PMI CO<sub>2</sub> and H<sub>2</sub> pipelines, storage and sequestration sites. Depleted offshore oil and gas fields (red) provide additional CO<sub>2</sub> sequestration potential [22].

230 Our implementation can adapt to the needs and configuration of the  
231 model, including selected technologies, geographical and temporal resolu-  
232 tion, as well as the level of sector-coupling. Here, all projects are mapped to  
233 the 99 NUTS regions, in this process, pipelines are aggregated and con-  
234 nect all overpassing regions. Similar to how all electricity lines and carrier  
235 links are modelled in PyPSA-Eur, lengths are calculated using the havers-  
236 sine formula multiplied by a factor of 1.25 to account for the non-straight  
237 shape of pipelines. We apply standardised cost assumptions [31] across all  
238 existing brownfield assets, model-endogenously selected projects, and exoge-  
239 nously specified PCI-PMI projects, equally. Our approach is motivated by  
240 two key considerations: (i) cost data submitted by project promoters are of-  
241 ten incomplete and may differ in terms of included components, underlying  
242 assumptions, and risk margins; and (ii) applying uniform cost assumptions  
243 ensures comparability and a level playing field across all potential invest-  
244 ments, including both PCI-PMI and model-endogenous options.

245 *CO<sub>2</sub> sequestration sites.* Beyond CO<sub>2</sub> sequestration site projects included in  
246 the latest PCI-PMI list (around 114 Mt p.a.), we consider additional technical  
247 potential from the European CO<sub>2</sub> storage database [22, 40]. While social and  
248 commercial acceptance of CO<sub>2</sub> storage has been increasing in recent years,  
249 however, concerns still exist regarding its long-term purpose and safety [41].  
250 For this reason, we only consider conservative estimates from depleted oil and  
251 gas fields, which are primarily located offshore in the British, Norwegian, and  
252 Dutch North Sea (see Figure 1), yielding a total sequestration potential of  
253 7164 Mt. Spread over a lifetime of 25 years, this translates into an annual  
254 sequestration potential of up to 286 Mt p.a. We then cluster all offshore  
255 potential within a buffer radius of 50 km per offshore bus region in each  
256 modelled NUTS region and connect them through offshore CO<sub>2</sub> pipelines  
257 to the closest onshore bus (TODO: add reference to cost assumptions in  
258 appendix).

259 *4.2. Scenario setup and regret matrix*

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

265 *4.2.1. Long-term scenarios*

266 *Scenario definition.* We define the long-term scenarios based on the degree  
 267 of CO<sub>2</sub> and H<sub>2</sub> infrastructure build-out, including the roll-out of PCI-PMI  
 268 projects as well additional pipeline investments. In total, we implement  
 269 five long-term scenarios, (i) a pessimistic scenario (Decentral Islands — DI)  
 270 without any H<sub>2</sub> pipeline and onshore CO<sub>2</sub> pipeline infrastructure, (ii) a sce-  
 271 nario that considers the on-time commissioning of all PCI-PMI CO<sub>2</sub> and H<sub>2</sub>  
 272 projects (PCI-PMI — PCI) only, (iii) more ambitious scenarios that further  
 273 allow investments into national and (iv) international pipelines (PCI-PMI  
 274 nat. — PCI-n and PCI-PMI internat. — PCI-in), and (v) a scenario that  
 275 does not assume any fixed PCI-PMI infrastructure but allows for a cen-  
 276 tralised, purely needs-based build-out of CO<sub>2</sub> and H<sub>2</sub> pipelines (Centralised  
 277 Planning — CP). An overview of the long-term scenarios and their associated  
 278 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
<b>CO<sub>2</sub> sequestration</b>					
Depleted oil & gas fields*	■	■	■	■	■
PCI-PMI seq. sites**	—	■	■	■	■
<b>H<sub>2</sub> storage</b>					
Endogenous build-out	■	■	■	■	■
PCI-PMI storage sites	—	■	■	■	■
<b>CO<sub>2</sub> pipelines</b>					
to depleted oil & gas fields	■	■	■	■	■
to PCI-PMI seq. sites	—	■	■	■	■
<b>CO<sub>2</sub> and H<sub>2</sub> pipelines</b>					
PCI-PMI	—	■	■	■	■
National build-out	—	■	■	■	■
International build-out	—	—	—	■	■
PCI-PMI extendable	—	—	—	—	■

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

279 *Targets.* In all long-term scenarios, emission, technology, sequestration and  
 280 production targets have to be met for each planning horizon (see Table 2).  
 281 For the year 2030, these targets are directly derived from the EU’s policy  
 282 targets, including a 55 % reduction in greenhouse gas emissions compared to  
 283 1990 levels [1], 10 Mt p.a. of domestic green H<sub>2</sub> production [2] and 40 GW  
 284 [42], and 50 Mt p.a. of CO<sub>2</sub> sequestration capacity [3]. For 2050, the CO<sub>2</sub>

285 sequestration target is derived from impact assessment, modelling for Euro-  
 286 pean Commission’s 2024 industrial carbon management strategy, in which  
 287 250 Mt p.a. out of 450 Mt p.a. (Carbon Capture Utilisation and Storage) is  
 288 sequestered [43]. H<sub>2</sub> production targets for 2050 are based on the European  
 289 Commission’s METIS 3 study S5 [44], modelling possible pathways for indus-  
 290 try decarbonisations until 2040. For 2040, we interpolate linearly between  
 291 the 2030 and 2050 targets. The electrolyser capacities for 2040 and 2050 are  
 292 scaled by the ratio of H<sub>2</sub> production to electrolyser capacity in 2030. An  
 293 overview of the targets and their values is provided in Table 2. Note that  
 294 we implement the green H<sub>2</sub> production target as a minimum H<sub>2</sub> production  
 295 constraint from electrolyzers, hence we will refer to this H<sub>2</sub> as electrolytic H<sub>2</sub>  
 296 within the scope of this paper.

Table 2: Pathway for implemented targets.

Planning horizon	2030	2040	2050
<b>Targets</b>			
GHG emission reduction	–55 %	–90 %	–100 %
CO <sub>2</sub> sequestration	50 Mt p.a.	150 Mt p.a.	250 Mt p.a.
Electrolytic H <sub>2</sub> production	10 Mt p.a.	27.5 Mt p.a.	45 Mt p.a.
H <sub>2</sub> electrolyser capacity	40 GW	110 GW	180 GW

Model targets based on [1–3, 43, 44]

### 297 4.3. Short-term scenarios

298 In a second step, we assess the impact of three short-term scenarios on  
 299 the long-term scenarios, by fixing or removing pipeline capacities (depend-  
 300 ing on the scenario). Further, the model can still react by investing into  
 301 additional generation, storage, or conversion, or carbon-removal technologies  
 302 in the short-term, assuming the technical potential was not exceeded in the  
 303 long-term optimisation. In *Reduced targets*, we remove all of the long-term  
 304 targets (Table 2) except for the GHG emission reduction targets to assess  
 305 the value of the CO<sub>2</sub> and H<sub>2</sub> infrastructure in a less ambitious policy envi-  
 306 ronment. In *Delayed pipelines*, we assume that all PCI-PMI and endogenous  
 307 pipelines are delayed by one period, i.e., the commissioning of the project is  
 308 shifted to the next planning horizon. Lastly, we remove all pipeline capacities  
 309 in *No pipelines*, including the PCI-PMI projects, allowing us to evaluate the  
 310 impact of a complete lack of planned infrastructure.

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

Table 3: Regret matrix setup: Long-term and short-term scenarios.

Short-term	Reduced targets	Delayed pipelines	No pipelines
<b>Long-term scenarios</b>			
Decentral Islands ( <b>DI</b> )	■	—	—
PCI-PMI ( <b>PCI</b> )	■	■	■
PCI-PMI nat. ( <b>PCI-n</b> )	■	■	■
PCI-PMI internat. ( <b>PCI-in</b> )	■	■	■
Central Planning ( <b>CP</b> )	■	■	■
<b>Targets</b>			
GHG emission reduction	■	■	■
CO <sub>2</sub> sequestration	—	■	■
Electrolytic H <sub>2</sub> production	—	■	■
H <sub>2</sub> electrolyzers	—	■	■
<b>CO<sub>2</sub> + H<sub>2</sub> infrastructure</b>			
CO <sub>2</sub> sequestration sites	■	■	■
CO <sub>2</sub> pipelines to seq. site	■	■	■
CO <sub>2</sub> pipelines	■	□	—
H <sub>2</sub> pipelines	■	□	—

■ enabled    □ delayed by one period    — disabled

## 319 5. Results and discussion

320 We structure the results and discussion into three main sections. First, we  
 321 present the results of the long-term scenarios. Then, we look at the impact  
 322 of the short-term scenarios on the long-term scenarios, by comparing the  
 323 economic regret and impacts on CO<sub>2</sub> and H<sub>2</sub> balances. Finally, we assess the  
 324 benefits of the PCI-PMI projects with regard to reduced system costs and  
 325 discuss the implications of our findings for the European energy system and  
 326 its policy targets.

327 *5.1. Long-term scenarios*

328 In all long-term runs, we observe the highest total annual system costs in  
 329 the planning horizon 2040, ranging from 912 to 968 bn. € p.a. (Figure 2),  
 330 driven by high investments. This can be primarily attributed to the strict  
 331 exogenously given GHG emission reduction pathway, facing the largest net  
 332 change from 2030 to 2040 — a carbon budget reduction of more than 1600  
 333 Mt p.a. as opposed to the remaining 460 Mt p.a. in the last decade. In 2030,  
 334 total system costs are lowest in the *DI* and *CP* scenario, as the model does  
 335 not see the need for large-scale investments into H<sub>2</sub> and CO<sub>2</sub> infrastructure  
 336 yet. With only CO<sub>2</sub> pipelines to the depleted offshore oil and gas fields, the  
 337 policy targets, incl. CO<sub>2</sub> sequestration can be achieved at a total of 865 bn.  
 338 € p.a. Adding PCI-PMI projects in 2030 increases costs by less than 1%.

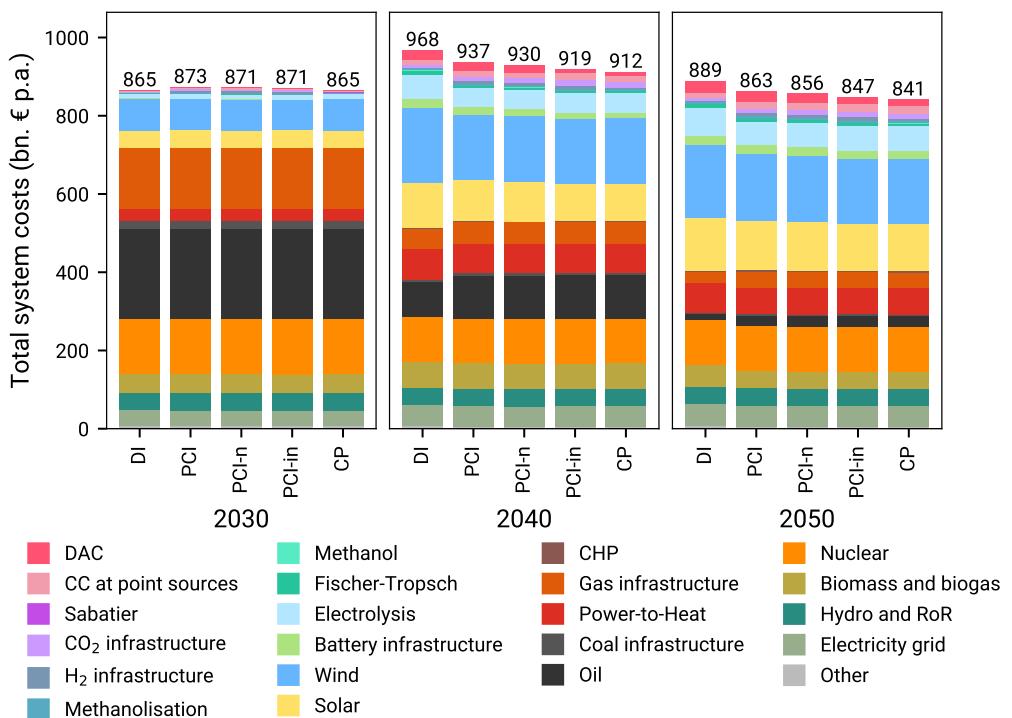


Figure 2: Total annual system costs (CAPEX + OPEX) by technology group.

339 Starting in 2040, all scenarios with PCI-PMI and endogenous pipeline  
 340 investments unlock significant cost savings, ranging from more than 30 bn.  
 341 € p.a. in the *PCI* up to 50 bn. € p.a. in the *PCI-in* scenario. By giving

342 the model complete freedom in pipeline expansions, additional annual cost  
343 savings of 6 to 7 bn. € are unlocked by investing in fewer, but more optimally  
344 located CO<sub>2</sub> pipelines and H<sub>2</sub> (see *PCI-in* pipeline utilisation in Figures 7 to  
345 9 compared to *CP* pipeline utilisation in Figures B.22 to B.24). This effect  
346 is slightly less pronounced in the 2050 model results, system costs can be  
347 reduced by 26 to 41 bn. € p.a. with PCI-PMI and endogenous pipeline  
348 investments.

349 *Base scenario.* Figure ?? shows the regional distribution of the H<sub>2</sub> and CO<sub>2</sub>  
350 value chain in the Base scenario. Note that for the specific year of 2030, a  
351 disconnect in H<sub>2</sub> infrastructure between central and southeastern Europe can  
352 be observed, due to the delay in commissioning of the project connecting the  
353 two networks. Within the two interconnected regions, almost homogenous  
354 average marginal prices for H<sub>2</sub> can be observed. Note that Figure ?? shows  
355 the cost of all H<sub>2</sub> produced, weighted by the respective regional demand  
356 at a certain point in time. CO<sub>2</sub> prices are higher in demand regions for  
357 industry processes and methanolisation located in northwestern Europe —  
358 primarily Norway and the United Kingdom (Figure ??). Negative CO<sub>2</sub> prices  
359 in southeastern Europe indicate a lack of demand and missing economic  
360 value.

361 Utilisation of H<sub>2</sub> pipelines vary strongly across the PCI-PMI projects.  
362 In most of the times, pipelines serve the purpose of transporting H<sub>2</sub> in a  
363 single direction only, i.e. from high renewable potential regions to H<sub>2</sub> con-  
364 sumption sites, where it serves as a precursor for methanolisation or direct  
365 use in industry and shipping (see Figure ??). Prominent PCI-PMI projects  
366 with particularly high full-load hours include P9.9.2 *Hydrogen Interconnec-*  
367 *tor Denmark-Germany* (6937 h) and P11.2 *Nordic-Baltic Hydrogen Corridor*  
368 (2295 h), followed by projects connecting major steel-industrial and chemical  
369 sites of Germany (southwest) with Belgium (P9.4 *H2ercules West*, 1634 h),  
370 the Netherlands (P9.6 *Netherlands National Hydrogen Backbone*, 1967 h and  
371 P9.7.3 *Delta Rhine Corridor H2*, 1510 h), and France (P9.2.2 *MosaHYyc*,  
372 4662 h). PCI project P13.8 *EU2NSEA* connects CO<sub>2</sub> from process emissions  
373 in Germany, Belgium and the Netherlands to major geological sequestra-  
374 tion sinks close to the Norwegian shore *Smeaheia* and *Luna* with an annual  
375 injection potential of 20 Mt p.a. and 5Mt p.a., respectively.

- 376 • Regarding DAC Figure 5  
377 • No DAC in 2030 yet, primarily from CC from point sources

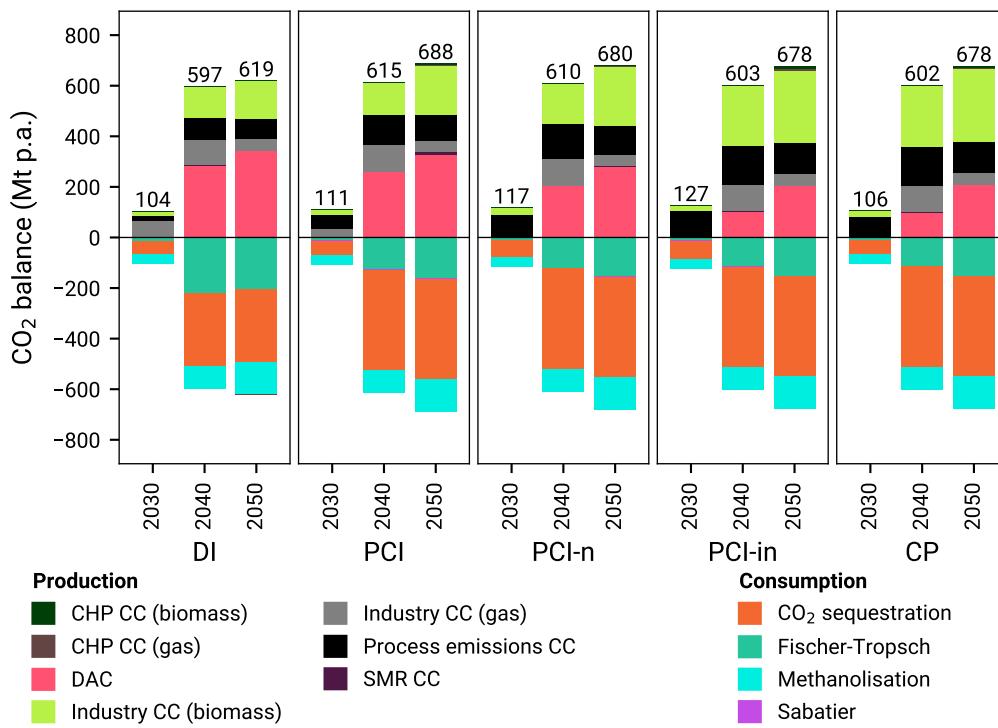


Figure 3: CO<sub>2</sub> balances in long-term scenarios.

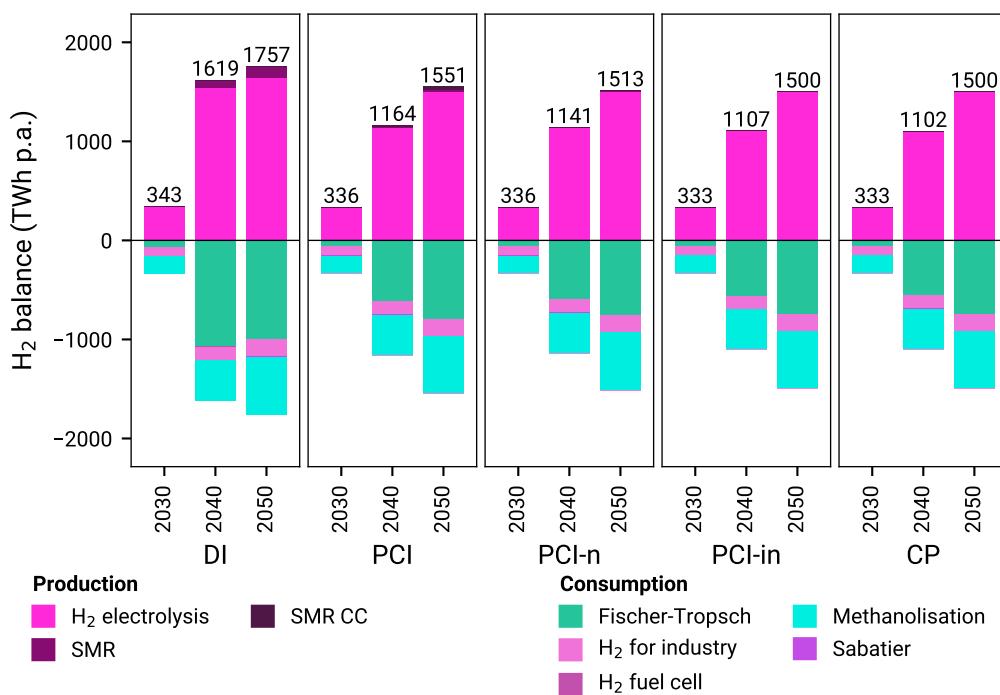


Figure 4: H<sub>2</sub> balances in long-term scenarios.

- 378     • 2040 sees strong effect in short-term runs, delaying the pipelines means  
 379        a much higher utilisation in DAC to compensate for missing pipelines

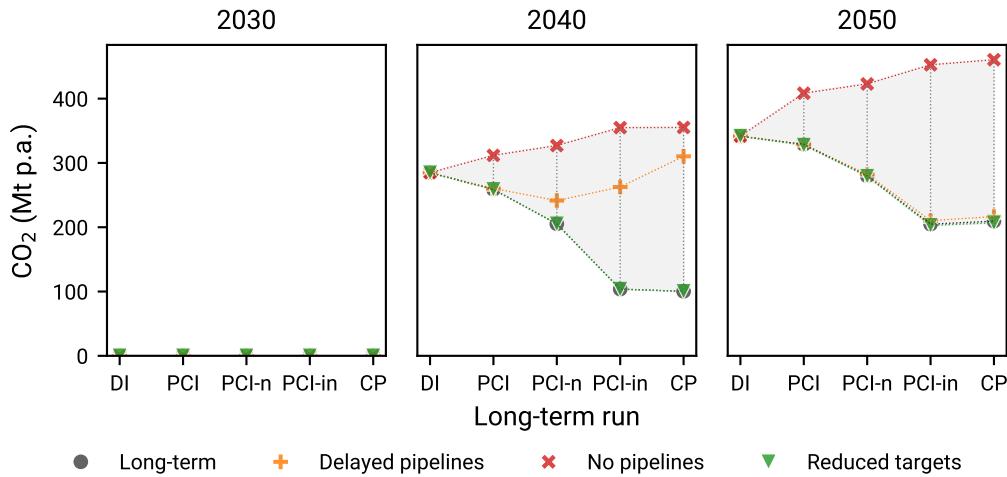


Figure 5: Delta balances — CO<sub>2</sub> from Direct Air Capture.

380 *Scenario A compared to Base.* PCI-PMI infrastructure account for a total  
 381 of around 30 bn. € p.a. in additional total system costs, indicating that  
 382 for the target year 2030, the projects are not cost-optimal. With a delay of  
 383 PCI-PMI projects in scenario A, Europe's policy targets can still be achieved  
 384 at significantly lower cost. However, this comes at the expense of a less in-  
 385 terconnected energy system, which may lead to higher costs in the long run.  
 386 Further, H<sub>2</sub> prices vary more strongly across regions, seeing higher costs in  
 387 southeastern Europe due to industrial demand and lower renewable poten-  
 388 tials (Figure ??). We make similar observations for CO<sub>2</sub> — a lack of pipeline  
 389 infrastructure increases spread of CO<sub>2</sub> prices, seeing higher values for CO<sub>2</sub> in  
 390 regions with high demand (e.g. for industrial processes or methanolisation).

391 *Scenario B compared to Base.* By omitting a green H<sub>2</sub> target, almost no elec-  
 392 trolysers are installed. Around 8 Mt are still produced to cover industrial H<sub>2</sub>  
 393 and methanol (primarily shipping) demand (Figures ?? and ??). However,  
 394 this demand is met by decentral steam methane reforming instead of elec-  
 395 trolysers (Figure ??). Without specifying a CO<sub>2</sub> sequestration target, the

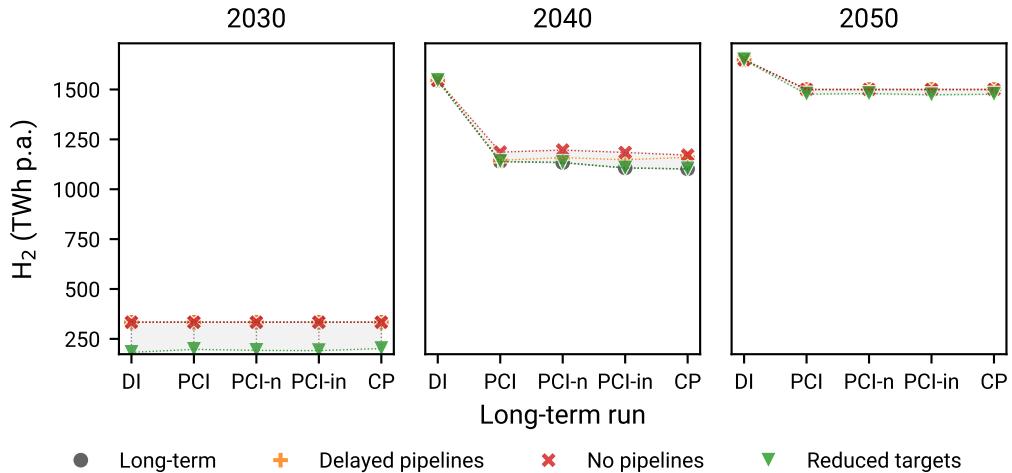


Figure 6: Delta balances — Electrolytic H<sub>2</sub> production

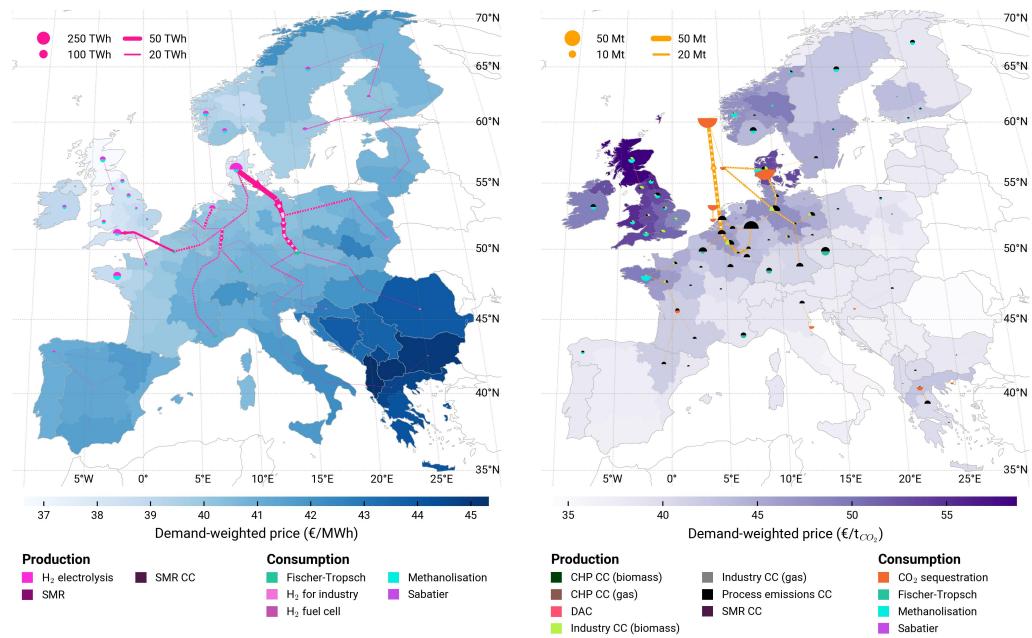


Figure 7: *PCI-in long-term* scenario (2030) — Regional distribution of H<sub>2</sub> and CO<sub>2</sub> production, utilisation, storage, and transport.

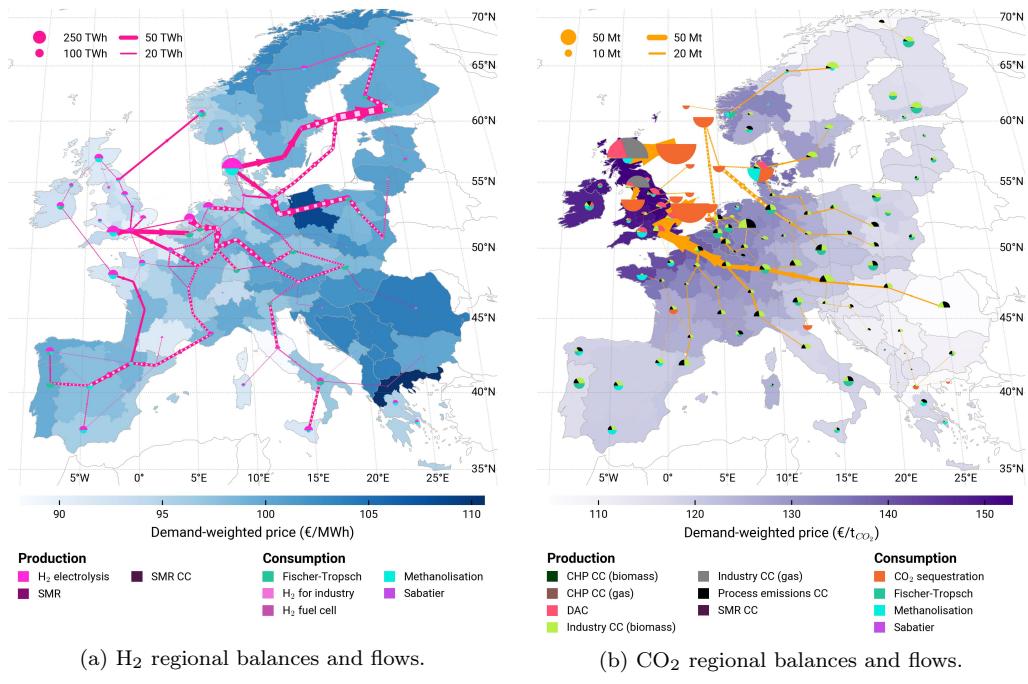


Figure 8: *PCI-in long-term scenario (2040)* — Regional distribution of H<sub>2</sub> and CO<sub>2</sub> production, utilisation, storage, and transport.

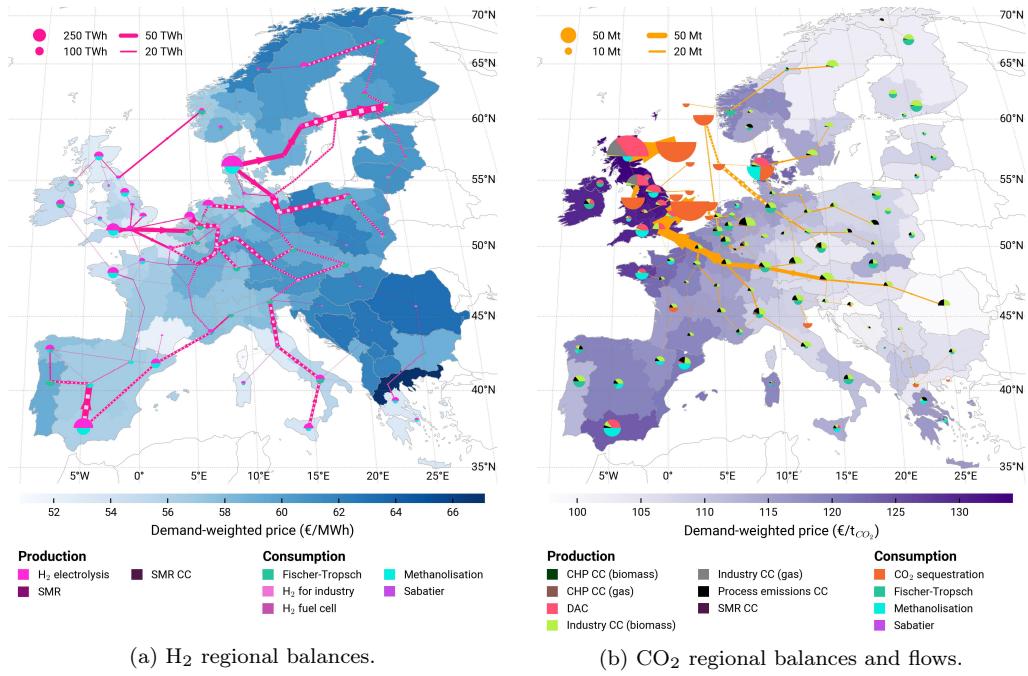


Figure 9: *PCI-in long-term* scenario (2050) — Regional distribution of H<sub>2</sub> and CO<sub>2</sub> production, utilisation, storage, and transport.

396 system still collects around 21 Mt of CO<sub>2</sub> p.a. primarily from process emissions  
 397 in the industry sector and sequesters it in carbon sinks near industrial  
 398 sites where a sequestration potential is identified (see Figure 1) [22]. This  
 399 carbon sequestration is incentivised by the emission constraint for 2030. As  
 400 no pipeline infrastructure is built in these scenarios, the chosen locations differ  
 401 in the delay scenarios — this can be observed for regions near the coast,  
 402 such as the United Kingdom and Norway (see Figure 1). Given the lack of  
 403 infrastructure, both the average cost for H<sub>2</sub> and CO<sub>2</sub> are higher in scenario  
 404 *B* compared to the Base scenario (Figures ?? and ??).

405 Overall, the results for the modelling year 2030 show that reaching the  
 406 EU’s 2030 H<sub>2</sub> production and CO<sub>2</sub> sequestration targets translates into around  
 407 20 bn. € p.a. in total system costs for all included sectors (Figure ??). This  
 408 is true for both comparing scenario *A* and *Base* scenario with scenario *B*,  
 409 respectively, deducting the cost of the PCI-PMI projects.

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

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

410 5.2. Limitations of our study

- 411 • Haversine distance for level playing field
- 412 • No discretisation of pipelines
- 413 • Regional resolution for computational reasons

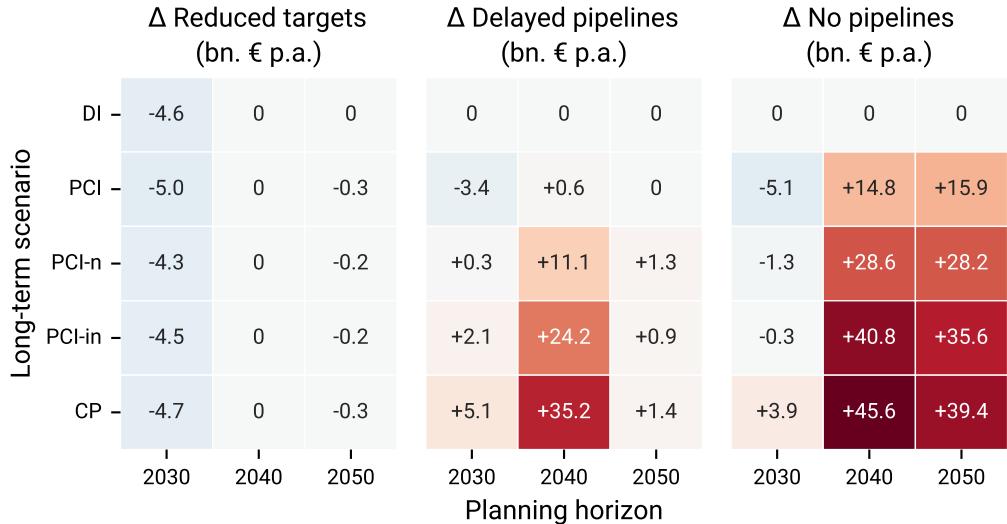


Figure 11: Regret matrix. Calculating regret terms by subtracting system costs of long-term scenarios (columns) from short-term scenarios (rows). Positive values reflect higher costs in the short-term scenarios compared to the long-term ones.

414      • ...

415      Our study focuses primarily on the effects on real, planned infrastructure  
 416      in the European energy system. Most final energy demand is given exoge-  
 417      nously, naturally a key driver of infrastructure utilisation. We somewhat  
 418      reduce the impact with the reduced targets scenario where at least the key  
 419      carriers H2 and CO2 are freely optimised.

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

421      ...

422 **6. Conclusion**

423 We conclude that although all three EU policy targets for 2030 can be  
424 achieved without PCI-PMI infrastructure, they bring additional benefits: i)  
425 H<sub>2</sub> pipelines projects help distribute more affordable green H<sub>2</sub> from northern  
426 and south-western Europe to high-demand regions in central Europe; ii) CO<sub>2</sub>  
427 transport and storage projects help decarbonising the industry by connecting  
428 major industrial sites and their process emissions to offshore sequestration  
429 sites in the North Sea (Denmark, Norway, and the Netherlands). Preliminary  
430 results have further shown that most PCI-PMI projects seem to be over-  
431 dimensioned and are not cost-optimal, as very few projects show utilisation  
432 above 1000 full-load hours. However, to adequately assess the value of PCI-  
433 PMI projects, we need to assess their benefits in future target years. Further,  
434 policy targets for 2030 are not cost-effective, although needed in the long run  
435 to reach net-zero emissions by 2050.

436 *Research outlook.* Next steps include the implementation of remaining PCI-  
437 PMI projects, such as hybrid offshore interconnectors (energy islands), elec-  
438 tricity storages, and CO<sub>2</sub> shipping routes. To evaluate the long-term value of  
439 PCI-PMI projects in a sector-coupled European energy system, we will model  
440 pathway dependencies towards 2050. We will also assess the sensitivity of  
441 the infrastructure to technology-specific build-out rates.

442 **CRediT authorship contribution statement**

443 **Bobby Xiong:** Conceptualisation, Methodology, Software, Validation,  
444 Investigation, Data Curation, Writing — Original Draft, Review & Editing,  
445 Visualisation. **Iegor Riepin:** Conceptualisation, Methodology, Investiga-  
446 tion, Writing — Review & Editing, Project Administration, Funding acqui-  
447 sition. **Tom Brown:** Investigation, Resources, Writing — Review & Editing,  
448 Supervision, Funding acquisition.

449 **Declaration of competing interest**

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

453 **Data and code availability**

454 All results, including solved PyPSA networks and summaries in .csv for-  
455 mat are published on Zenodo:  
456 <https://doi.org/XX.YYYY/zenodo.10000000>

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

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

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464 Affairs and Climate Action (BMWK) under Grant No. 03EI4083A (RE-  
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467 project has received funding from the European Union’s Horizon Europe  
468 research and innovation programme under grant agreement no. 101069750.

<sup>469</sup> **Appendix A. Supplementary material — Methodology**

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

Country		Buses
Administrative level	$\Sigma$	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
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

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

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

	<b>Unit</b>	<b>2030</b>	<b>2040</b>	<b>2050</b>
<b>Technology</b>				
CO2 pipelines	XX	1000	1000	1000
Onshore, offshore	XX	1000	1000	1000
Electrolysers	XX	1000	1000	1000

470 **Appendix B. Supplementary material — Results and discussion**

471 *Appendix B.1. Delta system costs*

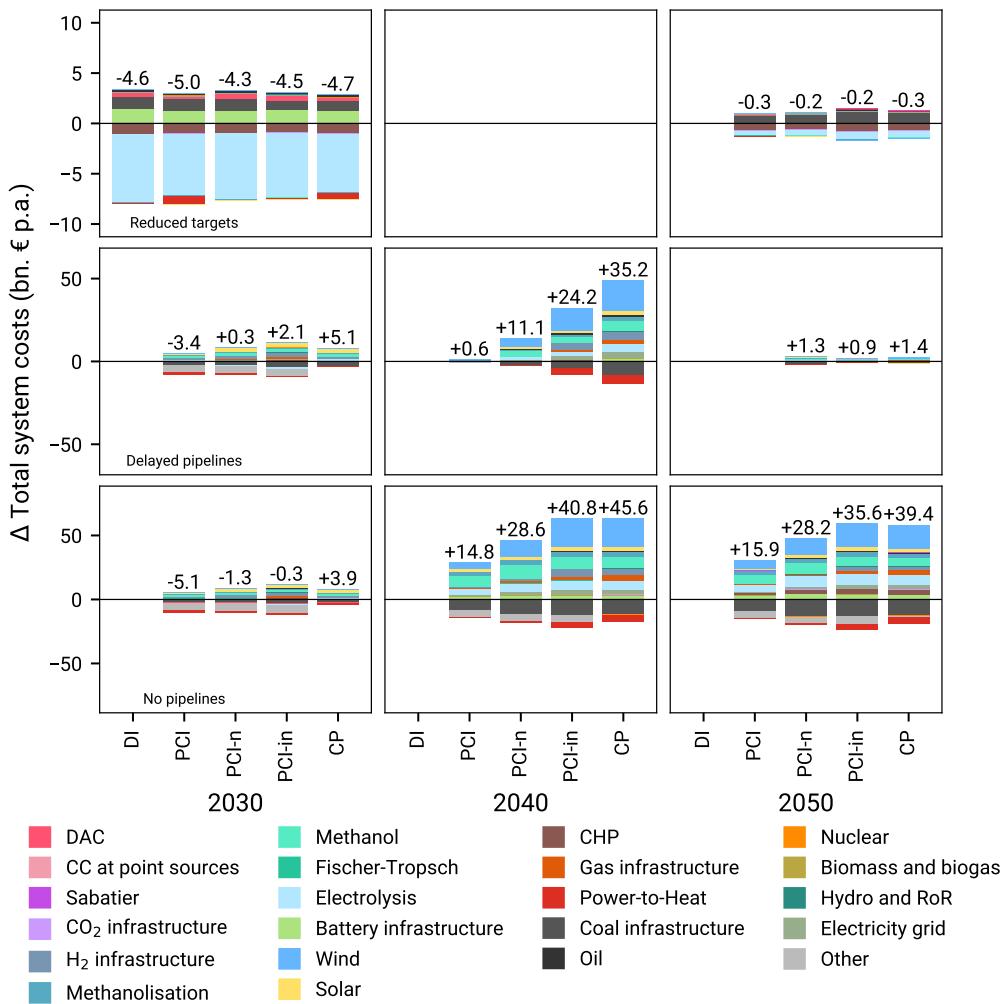


Figure B.12: Delta system costs — Short-term minus long-term runs.

<sup>472</sup> Appendix B.2. Delta balances

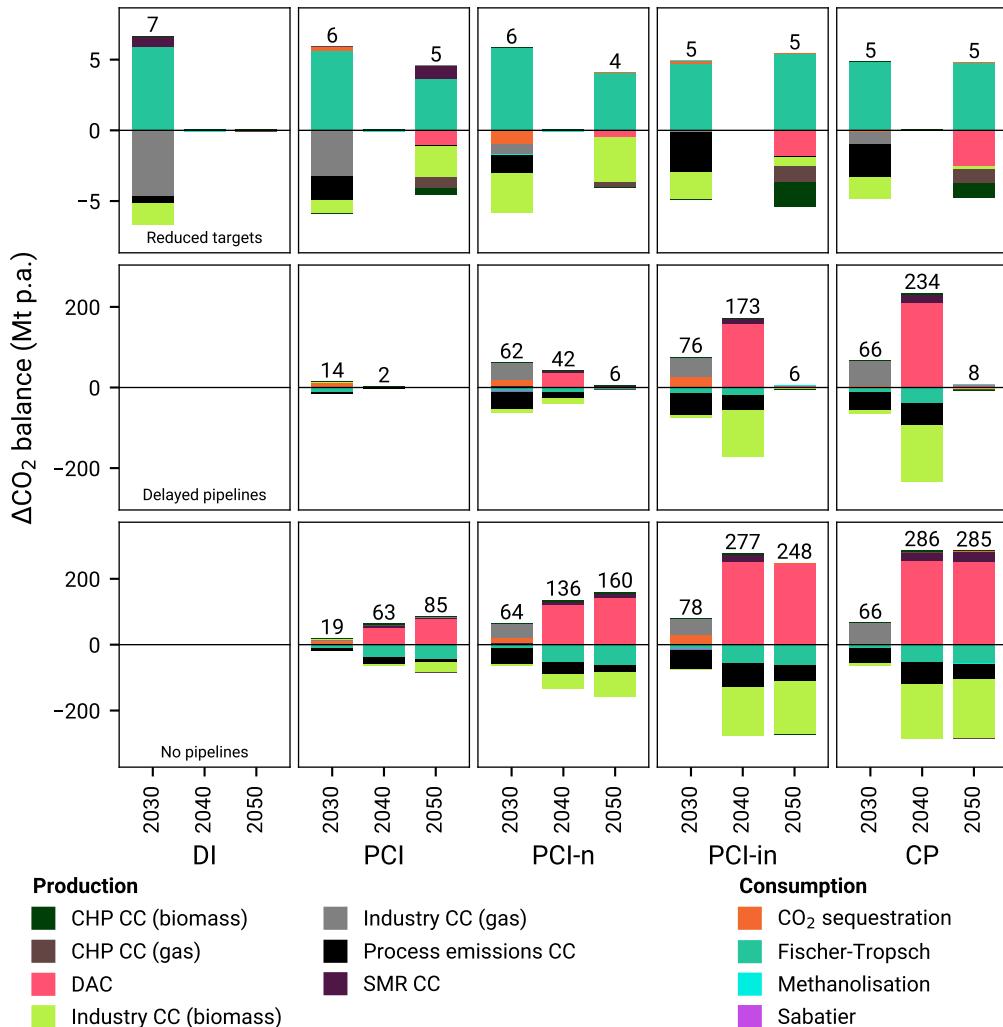


Figure B.13:  $\Delta\text{CO}_2$  balances — Short-term minus long-term runs.

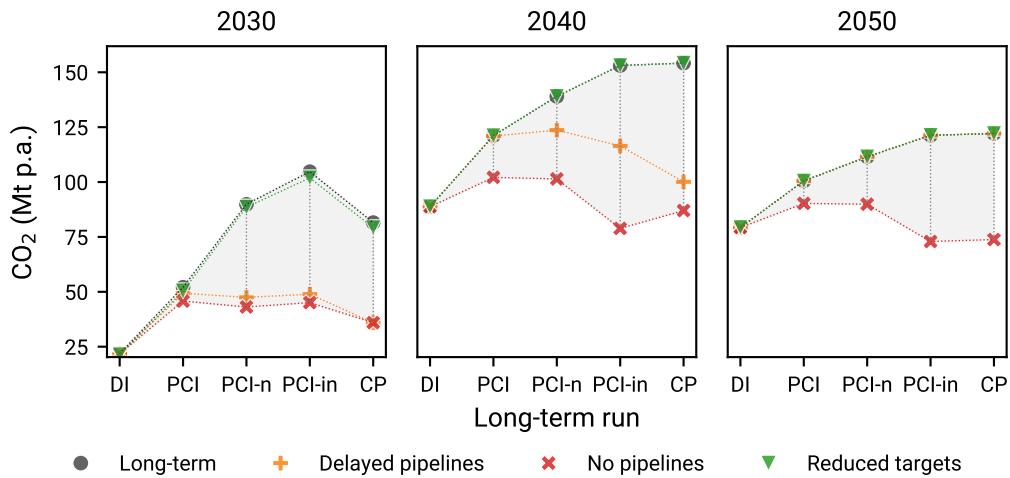


Figure B.14: ΔCO<sub>2</sub> balances — Process emissions including Carbon Capture.

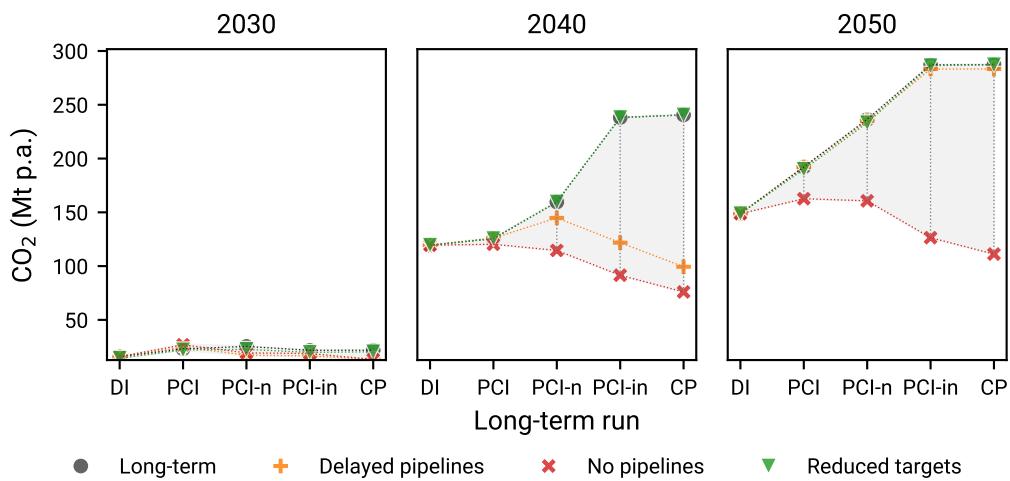


Figure B.15: ΔCO<sub>2</sub> balances — Carbon capture from solid biomass for industry point sources.

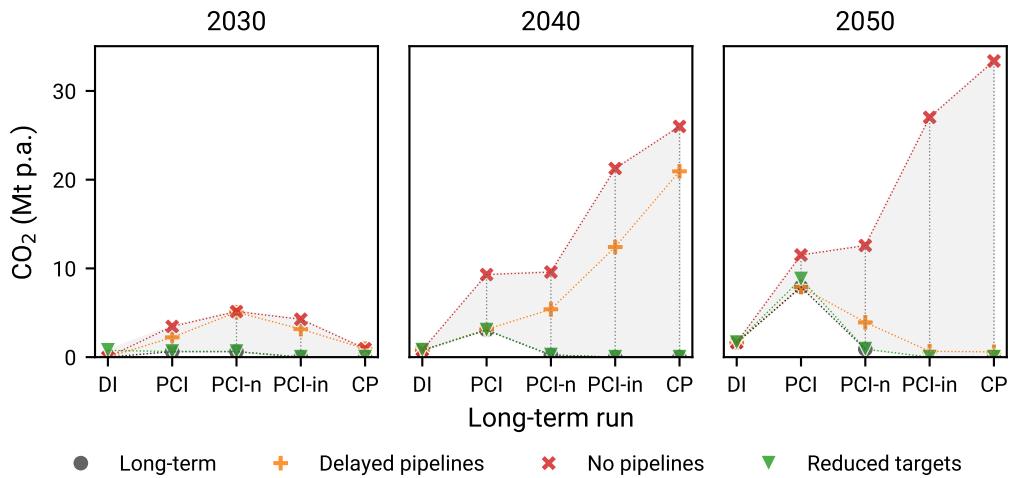


Figure B.16:  $\Delta\text{CO}_2$  balances — Carbon capture from steam methane reforming point sources.

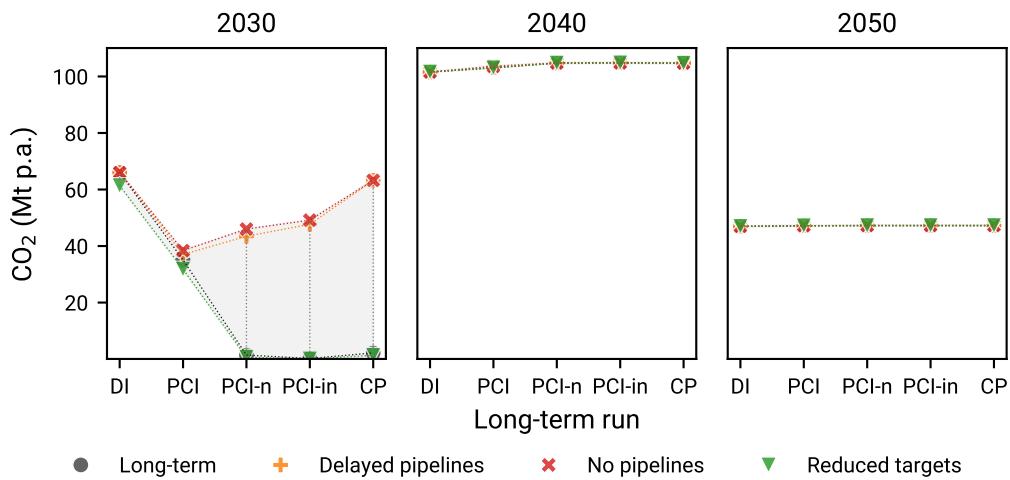


Figure B.17:  $\Delta\text{CO}_2$  balances — Carbon captured from gas for industry point sources.

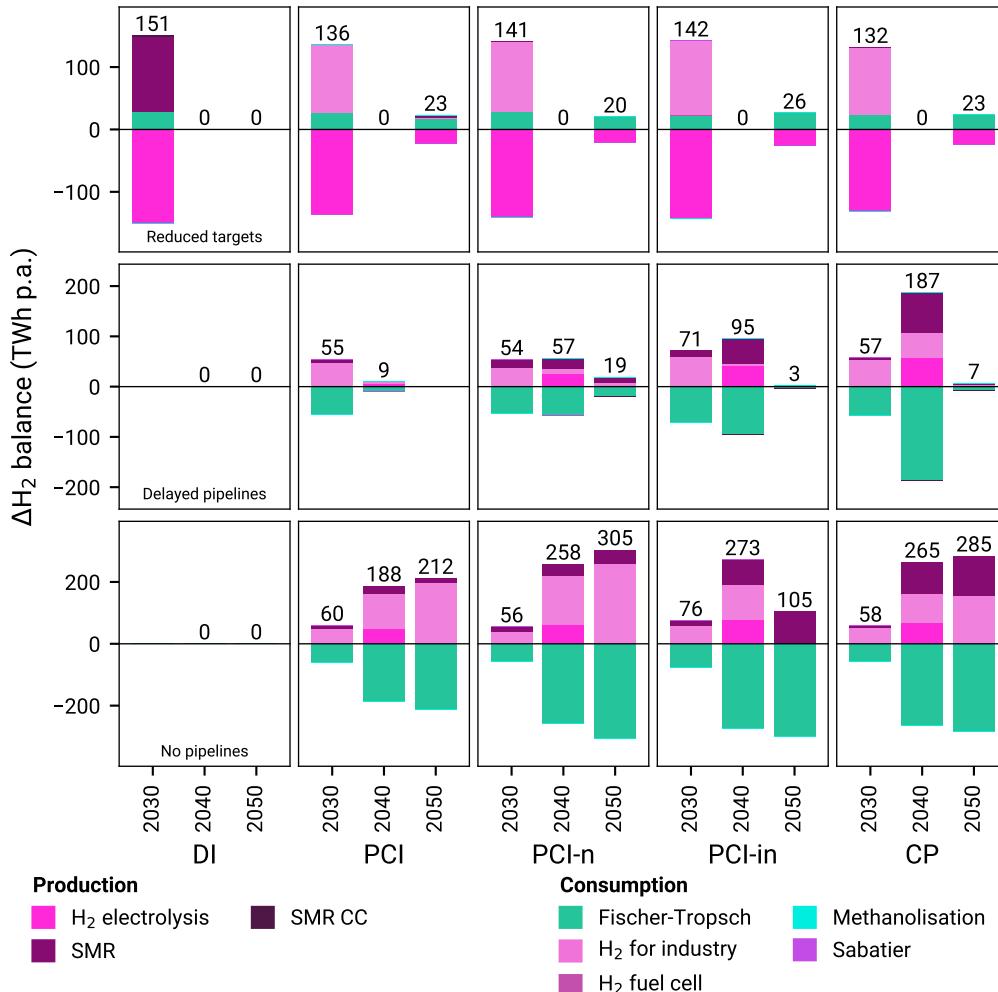


Figure B.18:  $\Delta H_2$  balances — Short-term minus long-term runs.

473 *Appendix B.3. Maps*

474 *Appendix B.3.1. Decentral Islands*

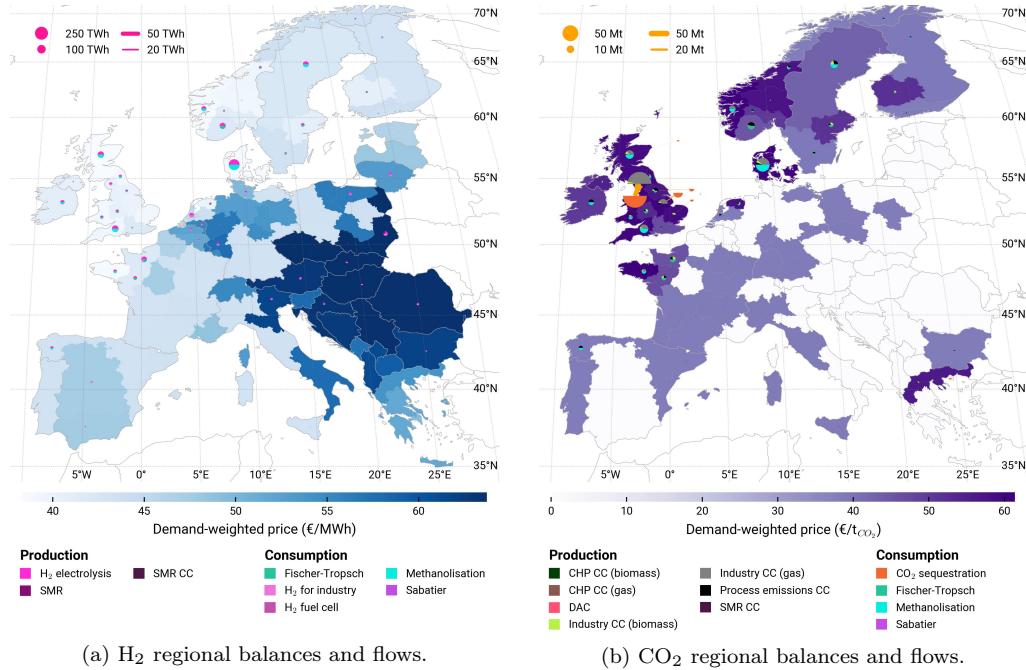


Figure B.19: *Decentral Islands* scenario (2030) — Regional distribution of H<sub>2</sub> and CO<sub>2</sub> production, utilisation, storage, and transport.

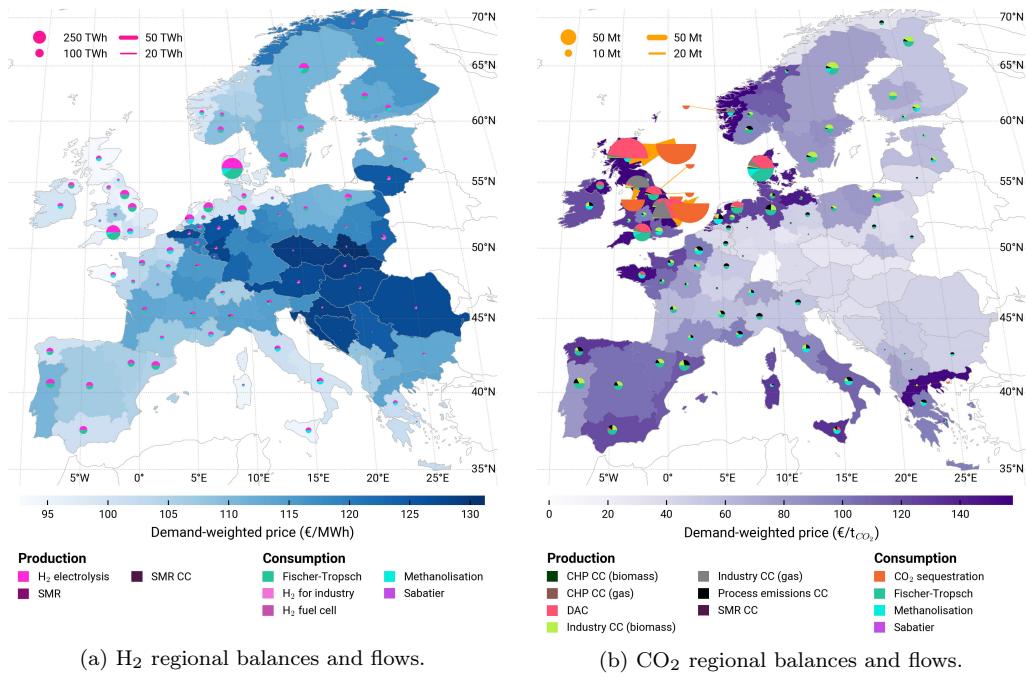


Figure B.20: *Decentral Islands* scenario (2040) — Regional distribution of H<sub>2</sub> and CO<sub>2</sub> production, utilisation, storage, and transport.

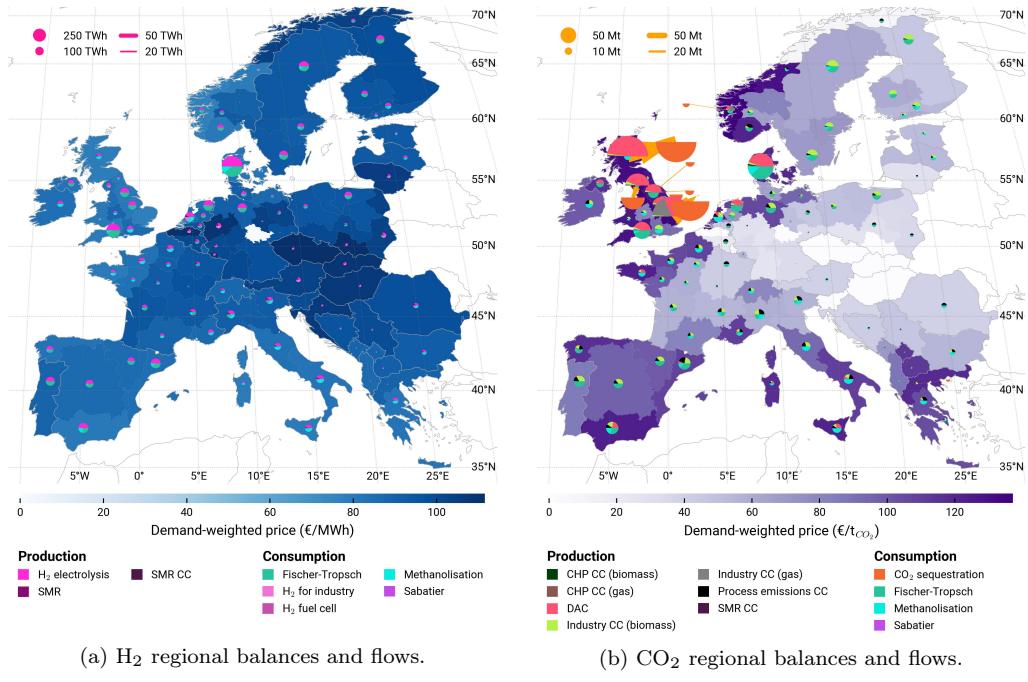


Figure B.21: *Decentral Islands* scenario (2050) — Regional distribution of H<sub>2</sub> and CO<sub>2</sub> production, utilisation, storage, and transport.

475 *Appendix B.3.2. Central Planning*

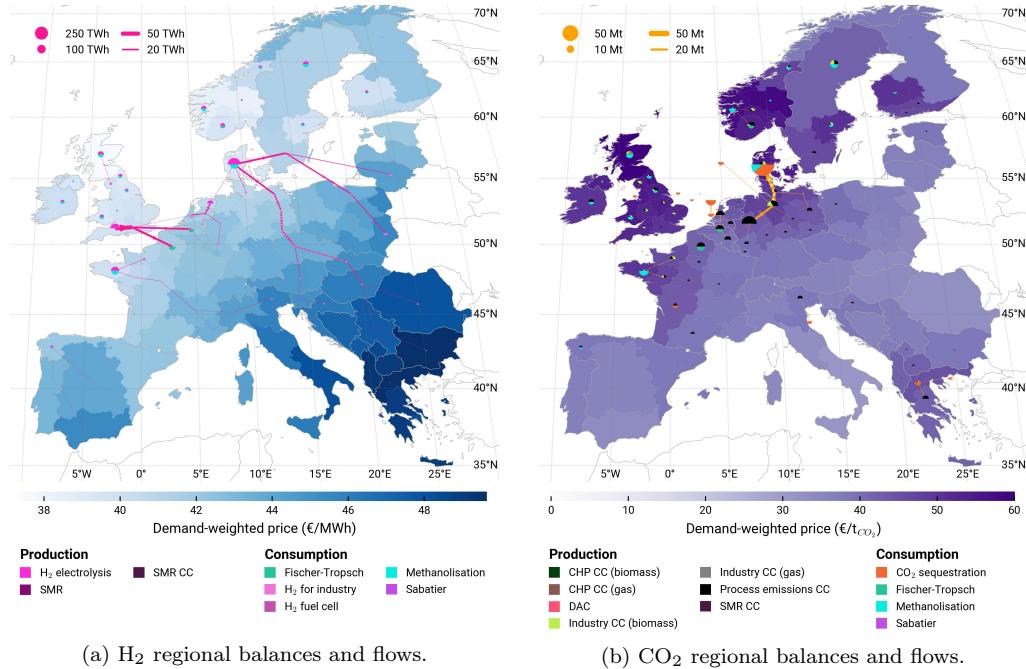


Figure B.22: *Central Planning* scenario (2030) — Regional distribution of H<sub>2</sub> and CO<sub>2</sub> production, utilisation, storage, and transport.

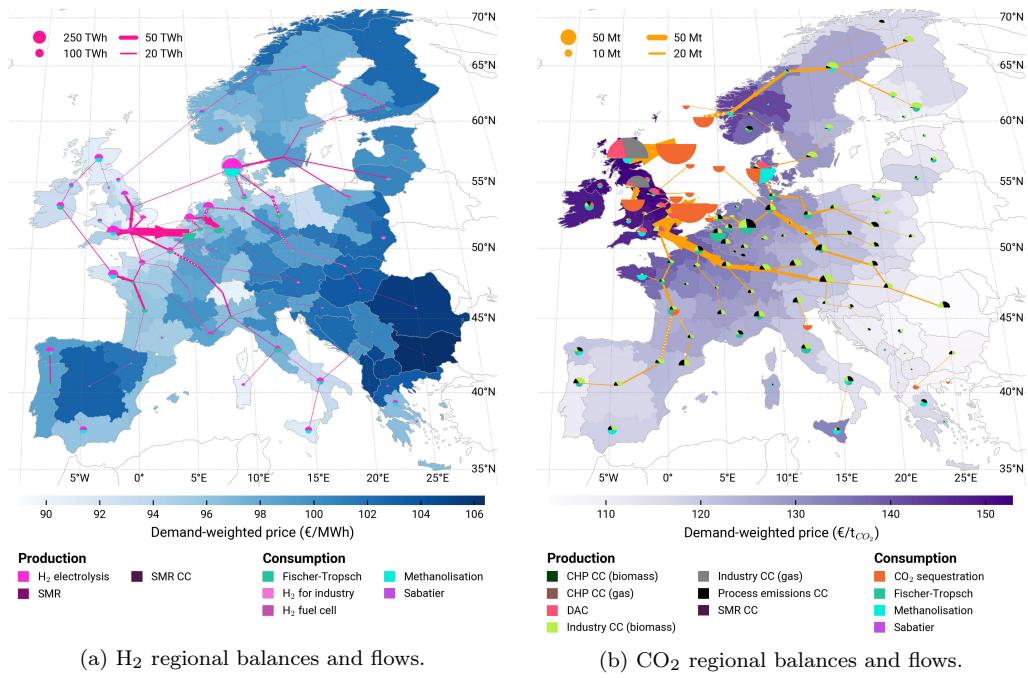


Figure B.23: *Central Planning* scenario (2040) — Regional distribution of H<sub>2</sub> and CO<sub>2</sub> production, utilisation, storage, and transport.

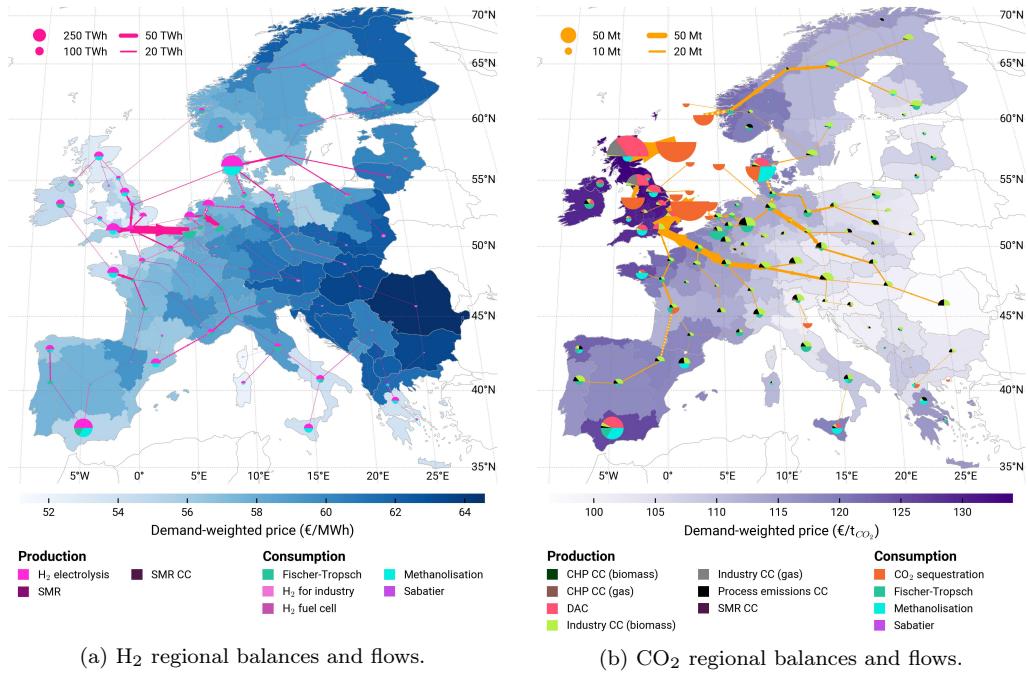


Figure B.24: *Central Planning* scenario (2050) — Regional distribution of H<sub>2</sub> and CO<sub>2</sub> production, utilisation, storage, and transport.

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