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Electricity- and hydrogen-driven energy system sector-coupling in net-zero CO_2 emission pathways

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Electricity- and hydrogen-based sector coupling contributes to realizing the transition towards greenhouse gas neutrality in the European energy system. Energy system and integrated assessment models show that, to follow pathways compatible with the European policy target of net-zero greenhouse gas emissions by 2050, large amounts of renewable electricity and H_2 need to be generated, mostly by scaling-up wind and solar energy production capacity. With a set of such models, under jointly adopted deep decarbonisation scenario assumptions, we here show that the ensuing direct penetration of electricity and H_2 in final energy consumption may rise to average shares of around 60% and 6%, respectively, by 2050. We demonstrate that electrification proves the most cost-efficient decarbonisation route in all economic sectors, while the direct use of H_2 in final energy consumption provides a relatively small, though essential, contribution to deep decarbonisation. We conclude that the variance observed across results from different models reflects the uncertainties that abound in the shape of deep decarbonisation pathways, in particular with regard to the role of H_2.

It is necessary to achieve a net-zero CO_2 emitting global economy by the middle of the century to mitigate climate change in line with the 1.5 °C temperature target of the Paris Agreement[1,2]. Scenario analysis using energy system and integrated assessment models forms a key method to explore the pathways towards the goal of net-zero emissions[3]. These models allow for studying the emission abatement options and technologies required across sectors and countries to meet the goals of the Paris Agreement. In Europe, they are employed to investigate the implications of the European Green Deal, the Fit-for-55 package, and the Climate Law. These policy packages form the legal backbone for the European Union (EU) to not only achieve its climate change mitigation ambitions, but also improve its energy security and supply diversification, and reduce its dependence on fossil fuels, notably those imported from Russia[4,5].

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The European Climate and Energy Modelling Forum (ECEMF) is a multi-institution collaborative research project, whose aim is to establish a European forum for energy-climate researchers, stakeholders, and policymakers to analyze and discuss how to achieve greenhouse gas (GHG) neutrality by 2050[6]. The intention of ECEMF is to create a closer and stronger European modeling community and enhance collaboration beyond Europe, and to expand the interactions between global energy analysts and the European climate policy scene. It does so by informing energy and climate policy-making at both the European and EU member state level, and presenting a more coherent and unified evidence base that forms a scientific starting point for action by policymakers. One central activity of ECEMF is to compare model outcomes, in order to study GHG abatement pathways leading to a net-zero emission European energy system by 2050. This supports the EU in making its contribution to the global goal of staying well below 2 °C average surface temperature increase and pursue efforts to limit the increase to 1.5 °C.

So far, a number of studies have been produced in the context of ECEMF. Dekker et al.[7] attempt to introduce and systematically apply diagnostic indicators in the emissions mitigation literature, to identify and interpret the way in which the models used in ECEMF vary in terms of structure, objectives, parameterization, and level of detail, as a result of which differences ensue in computed climate change control scenarios. In Henke et al.[8] a methodology is developed for comparing integrated assessment models with energy system models in their use to inform decarbonization policy-making; the authors observe that both model types cover in detail the energy sector, but that benefits and hurdles arise when comparing scenarios developed by these two types of models. An analysis by Pietzcker et al.[9] provides insight on both overarching and sectoral transformation milestones to be reached by 2040 in European pathways towards GHG neutrality in 2050, against the background that the EU Climate Law sets a legally binding target to reduce the EU's GHG emissions by 55% in 2030 and 100% in 2050, but currently has no such target for 2040.

Here we ask to what extent net-zero CO_2 emission pathways call for sector coupling within the European energy system until the middle of the century. Coupling or integration between economic sectors that are responsible for large shares of energy supply and demand is already observed in the energy transitions of many countries, such as between the power and transportation sectors. It has also been reported in various leading energy policy and climate change mitigation publications from renowned organizations such as the International Energy Agency, the International Renewable Energy Agency, and the Intergovernmental Panel on Climate Change (IPCC)[2,3,10–13]. Therefore, we can conclude that policymakers are interested in utilizing sector coupling, to help achieve the transition towards a sustainable world economy. In the academic literature, scholars have studied sector coupling from various angles, and following diverse approaches. For example, many publications based on studies performed with market models specifically zoom into the sector-integration role played by energy carriers such as electricity, hydrogen, and power-to-liquids (see e.g., refs. 14–19). In addition to this approach, other articles are dedicated to sector integration in specific countries (see for an overview of national models, ref. 20; for other country-specific studies see, for instance, refs. 21,22,). Furthermore, other authors have focused their research on specific regions, such as the North Sea region (in refs. 16,23). Finally, other papers on the subject proffer a continental perspective (for Europe, see e.g., refs. 17,22,24,25). After studying the aforementioned literature, it becomes evident that sector coupling is a multi-faceted topic, providing the opportunity to explore various aspects of the global energy system, and efforts to reduce GHG emissions. It also becomes clear that sector coupling has not been much studied through energy system and integrated assessment modeling, which is the research gap that this paper intends to fill.

Table 1 | Representation of direct H_2 use per model and sector

	Industry	Transportation	Buildings
Euro-Calliope 2.0	✓		
IMAGE 3.2		✓	✓
MESSAGEix-GLOBIOM 1.2	✓	✓	✓
PRIMES 2022	✓	✓	✓
PROMETHEUS 1.2	✓	✓	✓
REMIND 2.1	✓	✓	✓
TIAM-ECN 1.2	✓	✓	✓
WITCH 5.1		✓	

Indicated are the three main sectors into which H_2 may be deployed and whether our eight models allow for such deployment.

While sector coupling is relevant across the world, and can be researched through various types of modeling tools, in this work we aim at answering two Europe-focused questions using cost-minimization models. First, how might sector coupling be implemented over the medium- to long-term in Europe? Second, how much of it could be direct electricity-based, respectively, hydrogen-based in final energy consumption (FEC) in different European sectors? Because we use cost-minimization models, we implicitly also examine which of these two sector-coupling drivers is the most cost-efficient decarbonization route. Finally, we want to quantify the extent to which, again under the assumption of minimizing costs, a "hydrogen economy" would come into being based on the direct penetration of hydrogen into final energy demand, thus giving more precise meaning to this rather imprecise concept (see e.g., refs. 26,27). To address these questions, we compare the outcomes from multiple well-established energy system and integrated assessment models across a uniform set of scenarios, which differ as to the degree of decarbonization ambition—from business-as-usual to net-zero CO_2 emissions. We focus on the direct use of electricity and hydrogen in the FEC of three main end-use sectors—industry, transportation (excluding international aviation), and buildings—hence leaving for follow-up research the indirect role that electricity and hydrogen could play, that is, in intermediate energy consumption, for instance as input for the production of synthetic fuels (also referred to as e-fuels or solar/renewable fuels; see e.g., [28,29]). The latter could significantly broaden the breadth of a potential "hydrogen economy". In the "Methods" section below we concisely elaborate on the eight models that we use for our study and specify in detail the common assumptions that they adopt, so that the models jointly deliver a uniform set of scenarios. With these scenario specifications, any researcher in possession of these models can replicate the results that we report in this paper. Our three scenarios—named NPI (National Policy Implementation), C0-80 (CO_2 price growing to 80 $/t$CO_2$ in 2040), and C400-lin (CO_2 price growing to 400 $/t$CO_2$ in 2040)—represent three distinct possible pathways for the European energy transition until 2050, with different levels of CO_2 emissions reduction.

Results

Direct hydrogen use

Our results are created using output variables available in the public ECEMF database (see https://data.ece.iiasa.ac.at/ecemf). All the models listed above are represented in the collection of figures reported in this section, but not every figure necessarily includes the complete set of eight models: occasionally one or two models may be missing in some of the figures, because they do not generate or report these variables (see also refs. 7,8, for a similar observation). In this article, we focus only on the direct use of electricity and hydrogen in end-use sectors. While all models allow for direct consumption of electricity in end-use sectors, for hydrogen this is not always the case. Table 1 shows

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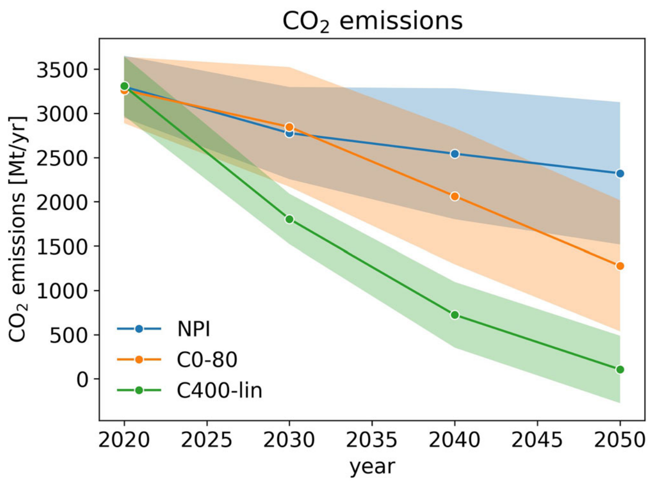

Fig. 1 | CO_2 emissions reduction pathways across three scenarios. Dots and solid lines correspond to average CO_2 emission levels (in Mt/yr); the shading refers to uncertainty ranges across models. The three scenarios depicted are NPI (National Policy Implementation), C0-80 (CO_2 price growing to 80 \$/tCO_2 in 2040), and C400-lin (CO_2 price growing to 400 \$/tCO_2 in 2040).

an overview of models that allow for direct hydrogen use in our three selected end-use sectors. Euro-Calliope and World Induced Technical Change Hybrid (WITCH) only consider direct hydrogen use in one sector, industry and transportation, respectively, while all other models simulate its direct usage in at least two sectors. Because of this topological discrepancy, results from Euro-Calliope and WITCH in some cases lie well outside the range outlined by the other models. In such cases, we omit the results from these two models (analogous figures including all models are available from the authors).

Emissions and energy carriers

Figure 1 depicts the reduction pathways for total CO_2 emissions across the three ECEMF scenarios analyzed for the purpose of this study. The solid lines represent the average CO_2 emission trajectories, calculated by taking the mean over all models that reported this variable, while the shading corresponds to their respective standard deviations (a convention we use for all shaded line plots in this article). The four dots per scenario refer to the years 2020, 2030, 2040, and 2050, respectively, from left to right (a convention we use in all plots of this kind throughout the paper). As can be seen, the NPI scenario yields modest cuts in CO_2 emissions, which confirms that the current EU climate policy is by far not consistent with the goal of net-zero GHG emissions by 2050. For the C400-lin scenario, on the other hand, net-zero CO_2 emissions are approximately achieved by the middle of the century, which implies that CO_2 taxation increasing linearly to 580 \$/tCO_2 roughly achieves the target of carbon neutrality in 2050 and brings the EU a large step towards climate neutrality by then. While in this figure we only report CO_2 emissions, further inspection of model outcomes reveals that, in the C400-lin scenario, GHG emissions in 2050 are on average reduced by over 90% versus 1990 levels, but not down to 100%, as significant non-CO_2 emissions remain (roughly 400 MtCO_2e). Hence additional mitigation efforts are needed, on top of those shown here, to reach the full GHG neutrality target stipulated by the EU Green Deal. We may occasionally refer to this scenario as the "net-zero emission" pathway in the remainder of the paper, while strictly speaking it implies net-zero emissions of CO_2 only. C0-80 lies somewhere in between the other two scenarios, as expected given our assumptions regarding the development of the CO_2 price in this scenario.

Figure 2 shows the electricity and H_2 supply mix across the three scenarios for one historical year (2020) and three future years (2030, 2040, and 2050). The bars in Fig. 2 represent the cross-model averages, while the thin lines indicate their 95% confidence levels (a convention we use for all bar plots in this article). The "Electricity" panels depict the levels of electricity generated from the main production means, i.e., biomass, hydropower, nuclear energy, solar and wind energy, fossil fuels, and hydrogen. As can be seen, solar and wind energy become the leading power production methods, especially (but not only) in the net-zero emission scenario, while nuclear and fossil-based electricity generation is generally on the decline during the coming three decades. The use of fossil fuels is almost completely phased out in the C400-lin scenario. The use of biomass is projected to remain well below the stable contribution of hydropower due to limited domestic resources. The "H_2" panels depict the levels of H_2 produced through three main channels, i.e., from electricity, biomass, and fossil fuels (with and without CCS). Clearly, in the net-zero emission (C400-lin) scenario, electrolysis becomes the predominant means (in some models the only means) to produce (mostly green) H_2, outshadowing the roles played by biomass and fossil-fuel-based H_2 production. On the other hand, in the NPI scenario, electrolysis-based (as well as biomass-based) H_2 production is negligible, and models only project a modest amount of fossil-fuel-based H_2 in the European energy system in the absence of strong climate policy. The C0-80 scenario takes a middle position, with electrolysis and fossil fuels roughly equally contributing to a modest overall supply of H_2.

In Fig. 3, we summarize our results in terms of the mix of carriers in FEC of the three main demand sectors: industry, transportation (excluding bunker fuels), and buildings (which encompasses both private dwellings and commercial buildings). We observe that, in industry, direct electricity use plays a leading and increasing role over time in all three scenarios, while in the C400-lin scenario, the penetration of gases, liquids, and solid fuels is reduced, that of heat remains relatively constant, and the direct use of (mostly green) hydrogen rapidly expands to exceed the contribution from heat in 2050. In transportation, the contribution of electricity grows exponentially (driven by the large-scale uptake of electric vehicles), that of gases stays roughly stable, that from liquids decreases—for the C0-80 and the C400-lin scenarios even more radically than in NPI—and the role of hydrogen remains relatively small despite its growth in this sector. Residential and commercial buildings are subjected to substantial electrification in all three scenarios, mostly driven by the rapid uptake of heat pumps. We see that the adoption of energy efficiency measures in this sector drives a gradual decrease over time of nearly all other energy carriers—notably of the use of gases in C400-lin—while the penetration of H_2 remains negligible throughout the modeling horizon.

Electricity and hydrogen shares

The shares of (renewable) electricity and H_2 directly used in FEC are expected to increase drastically over the coming decades in order to decarbonize the economy. This is confirmed in Fig. 4 for all three scenarios, especially in C400-lin so as to meet the net-zero emission target. While the mean share of electricity (across models) increases to around 50% in 2050 in NPI, from a little over 25% in 2020, for the C400-lin scenario it reaches nearly 60%, with C0-80 following closely. For H_2 much lower shares materialize: the cross-model mean attains no more than 1% in NPI, while a share of 2–6% materializes in 2050 for C0-80 and C400-lin. Hence, our models suggest that electricity plays overall a much larger role than H_2 as the main sector-coupling driver for achieving deep CO_2 emission cuts towards GHG neutrality, but H_2 still plays a key contribution to decarbonize specific market segments in which electrification is challenging or not yet commercially available (cf. primary steel-making, heavy-duty transport or aviation). The models display large ranges for both carriers, even somewhat for electricity in 2020, which highlights the intrinsic uncertainty and practical difficulty in accurately estimating sometimes even historic

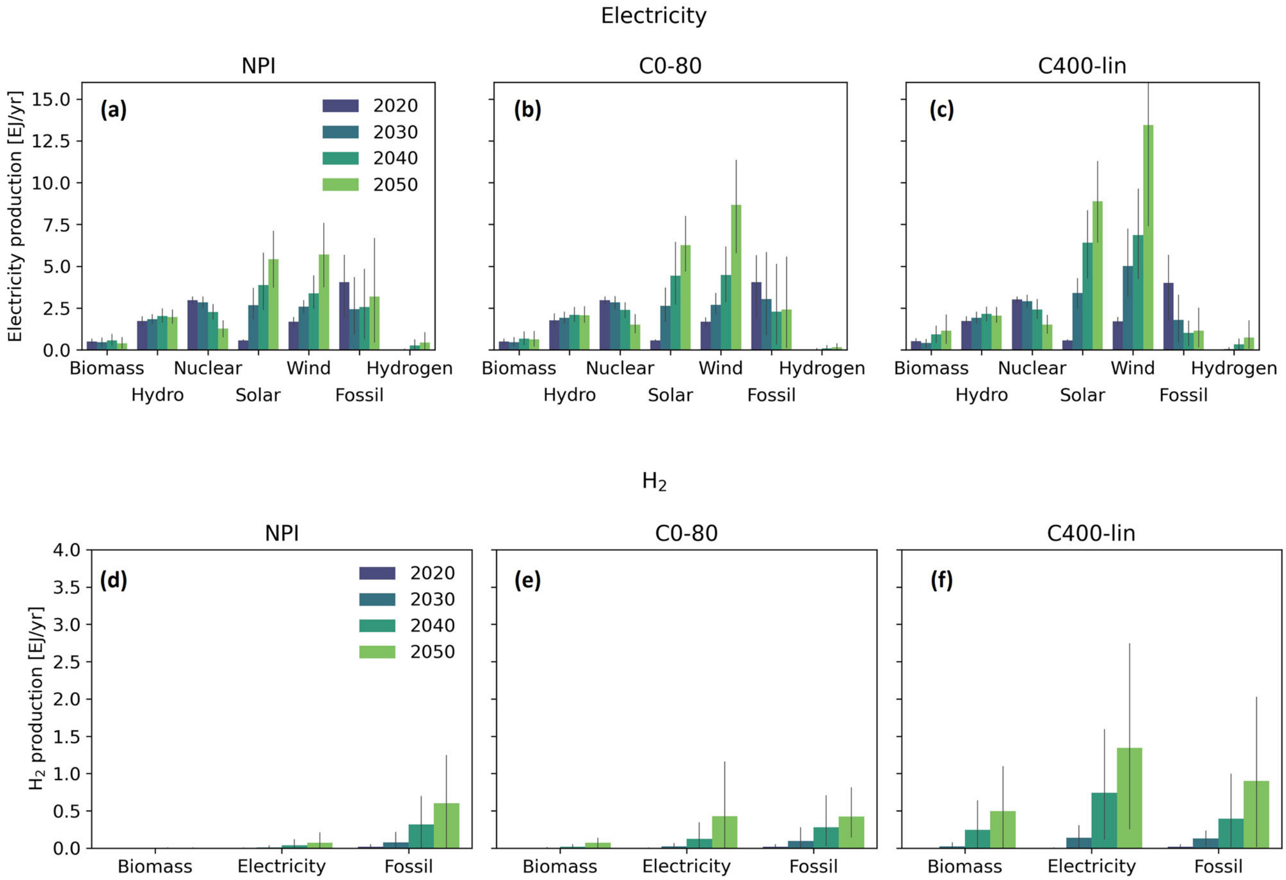

Fig. 2 | Electricity and H_2 production means across three scenarios. For electricity (**a**–**c**) we specify production (in EJ/yr) for seven production options: through biomass, hydropower, nuclear energy, solar energy, wind energy, fossil fuels, and H_2. For H_2 (**d**–**f**) we specify production (in EJ/yr) through three options: via biomass, electricity, and fossil fuels. The three scenarios depicted are NPI (National Policy Implementation), C0-80 (CO_2 price growing to 80 \$/tCO_2 in 2040), and C400-lin (CO_2 price growing to 400 \$/tCO_2 in 2040).

values of these shares (for instance, as a result of slightly differing accounting methods).

Figure 5 takes a closer look at the shares of electricity and direct use of H_2 in FEC by inspecting their respective roles in industry, transportation, and buildings. The horizontal line segments in Fig. 5 refer to the cross-model medians, the boxes correspond to the first and third quartiles (Q1 resp. Q3), hence visualizing the interquartile range. The whiskers indicate the Q3 ± 1.5(Q3−Q1) levels (a convention we use for all box-and-whisker plots in this article), and the diamonds represent outliers (i.e., single data points falling well beyond the whiskers). We see that all sectors are subject to increasing electrification; this occurs most radically in transportation, followed by buildings and industry, respectively. The H_2 share experiences much less expansion, particularly in buildings (where its contribution remains negligible even by 2050), but the net-zero emission scenario ranges still display values up to about 20% by 2050 for industry and transportation. The wide ranges observed across models—especially for transportation—highlight the uncertainties underlying our projections.

In Fig. 6, overall CO_2 emissions in Europe are shown for the 2020–2050 period, plotted against the direct shares of electricity and H_2 for our three scenarios. A clear monotonically decreasing relation between these variables can be observed, both in the case of electricity and H_2. While the NPI scenario achieves modest CO_2 emission reductions and thereby relatively small shares for electricity and H_2 in FEC, the CO_2 emission reductions and increasing shares for electricity and H_2 are much more pronounced in the C0-80 and C400-lin scenarios. In Supplementary Fig. 1 (see Supplementary information) we present similar plots, but with explicit inclusion of the results for individual models, so that the differences between models can be inspected (see for that purpose, and in much more detail, also ref. 7). Note in Fig. 6 the difference in x-axis range and curvature of the trajectories between the two panels. The former is simply a reflection of the different penetration levels of electricity and H_2 in the system. The latter indicates that—in these scenarios, with this set of models—the correlation between emissions and electrification is more linear than that between emissions and H_2 penetration. This suggests that, while electrification remains an efficient means for decarbonizing demand sectors throughout the entire path to net zero, sector coupling through H_2 is needed only in later stages of the process (which also partly explains the relatively low eventual overall penetration level). This confirms that H_2 is expected to undergo a larger uptake when the energy transition has progressed to the stage of having to decarbonize some of the sectors with hard-to-abate emissions, such as heavy-duty transportation and steel production. For the C400-lin scenario, the H_2 share increases only from 0% to 0.5% when CO_2 emissions drop from 3.5 GtCO_2/yr down to 1.7 GtCO_2/yr; in other words, H_2 plays only a small role in these initial large emission reductions. Yet the H_2 share increases substantially more in later stages of the energy transition: as can be observed, it grows from 0.5% to nearly 6% (i.e., more than an order of magnitude) when CO_2 emissions decline from 1.7 down to about 0 GtCO_2/yr.

Figure 7 breaks down the CO_2 emissions versus direct shares of electricity and H_2 in FEC plots of Fig. 6 into their respective components for the three main demand sectors, i.e., industry, transportation, and buildings. While the NPI scenario shows at most limited dynamics in some sectors, the C0-80 and C400-lin scenarios yield substantial

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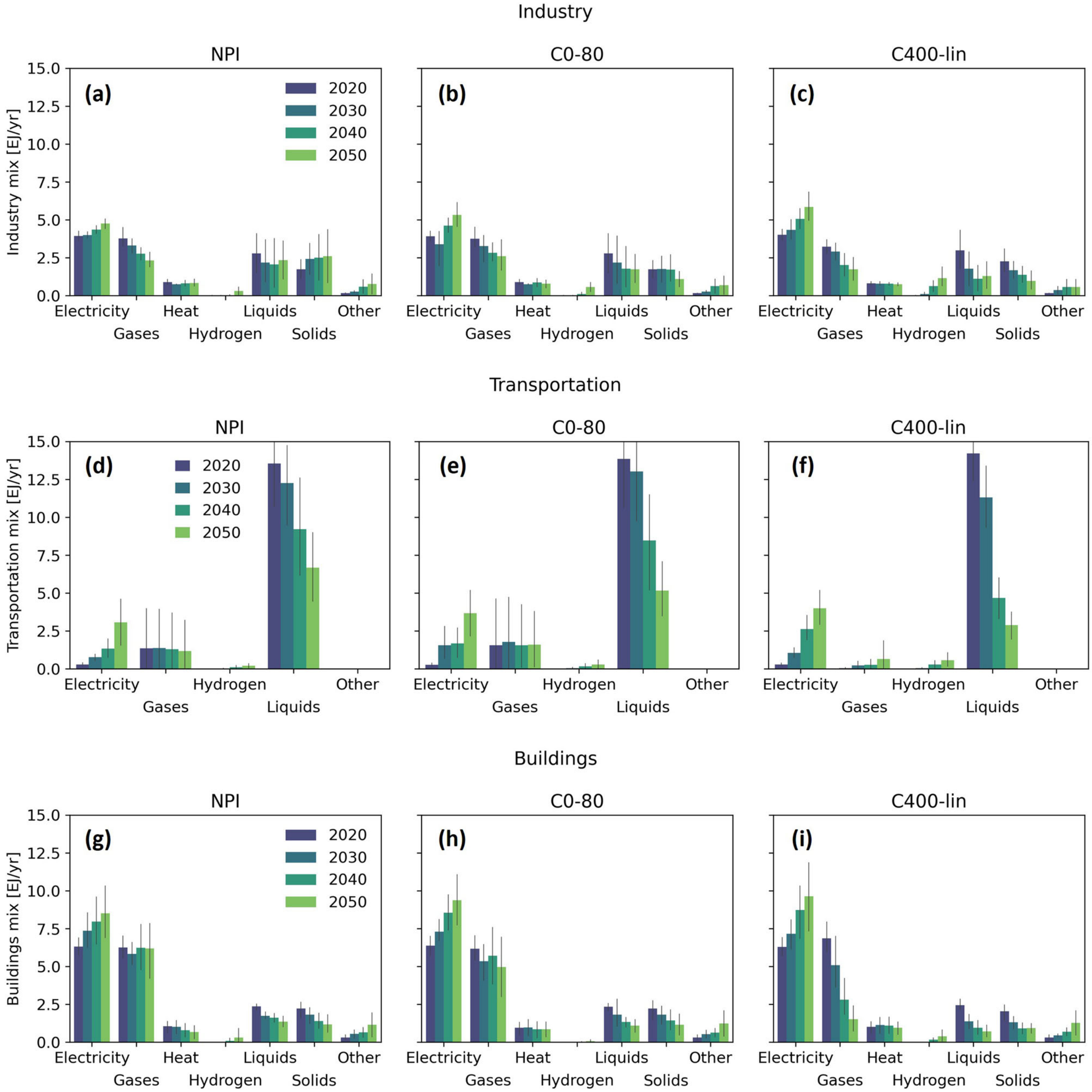

Fig. 3 | Energy carriers in main demand sectors across three scenarios. In industry (**a**–**c**) and for buildings (**g**–**i**) we distinguish between seven options (in EJ/yr): electricity, gases, heat, H_2, liquids, solids, and others. For transportation (**d**–**f**) we distinguish between five options (in EJ/yr): electricity, gases, H_2, liquids, and others. The three scenarios depicted are NPI (National Policy Implementation), C0-80 (CO_2 price growing to 80 \$/tCO_2 in 2040), and C400-lin (CO_2 price growing to 400 \$/tCO_2 in 2040).

change. For our net-zero emission scenario, we see an increase in the electricity share from around 30% in 2020 to about 50% in 2050 in industry, from around 1% to some 50% in transportation, and from a little over 30% to well over 60% in buildings. For the same scenario, we see an increase in H_2 share from consistently close to 0% in 2020 to around 12% in 2050 in industry, to nearly 10% in transportation and to at about 3% in buildings. Figure 7 shows that the difference in curvature between the electricity and H_2 panels observed in Fig. 6 also holds for each of the demand sectors.

Discussion

While our results reveal several robust findings, as spelled out in the preceding section, it is also clear that some outcomes of our scenario analysis yield substantial differences across our models. The relatively large variance that we observe across some specific results, like in other ECEMF cross-model comparison exercises[7–9], reflects the uncertainties that exist in the shape of potential cost-optimal low-carbon emission pathways for Europe. Here, we explore the nature of these differences between models, as well as between the scenario results calculated with them, in some greater detail.

Figure 8 depicts a scatterplot version of Fig. 6, showing the decline of total European CO_2 emissions, plotted against the direct electricity share ("Electricity" panel) and direct H_2 share ("H_2" panel) across models (different colors), scenarios (different symbols), and sectors and time periods (no differentiation), along with their corresponding linear (OLS) regression (black line) and variance (gray shaded area) as guide to the eye, meant to visualize the trend and spread in the data. For electricity, the correlation is clear, and

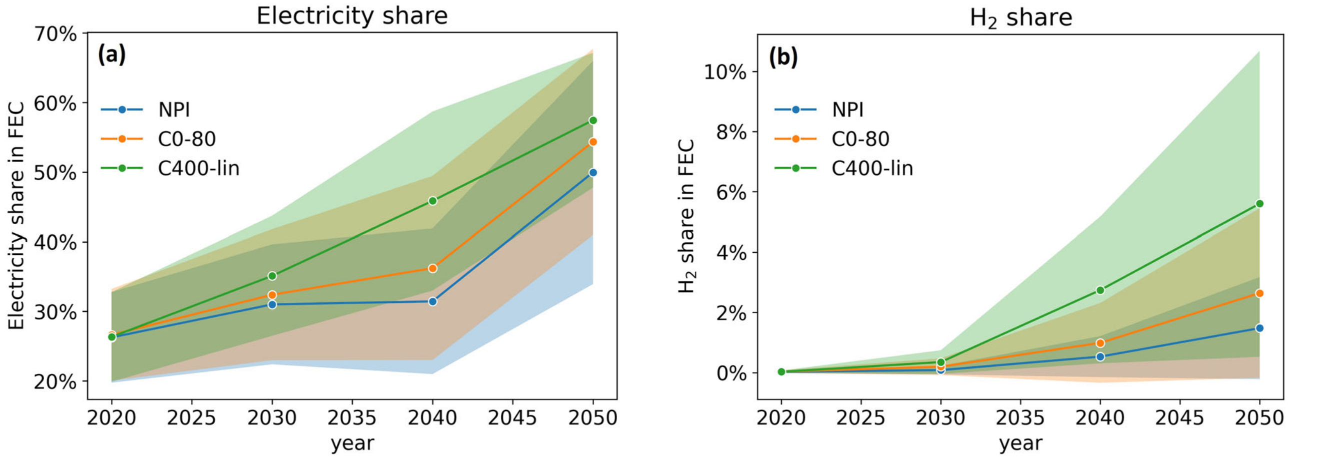

Fig. 4 | Electricity and H_2 shares. Shares of electricity (**a**) and H_2 (**b**) directly used in final energy consumption (FEC) across three scenarios. Dots and solid lines correspond to average electricity and H_2 shares in FEC (in %); the shading refers to uncertainty ranges across models. The three scenarios depicted are NPI (National Policy Implementation), C0-80 (CO_2 price growing to 80 \$/tCO_2 in 2040), and C400-lin (CO_2 price growing to 400 \$/tCO_2 in 2040).

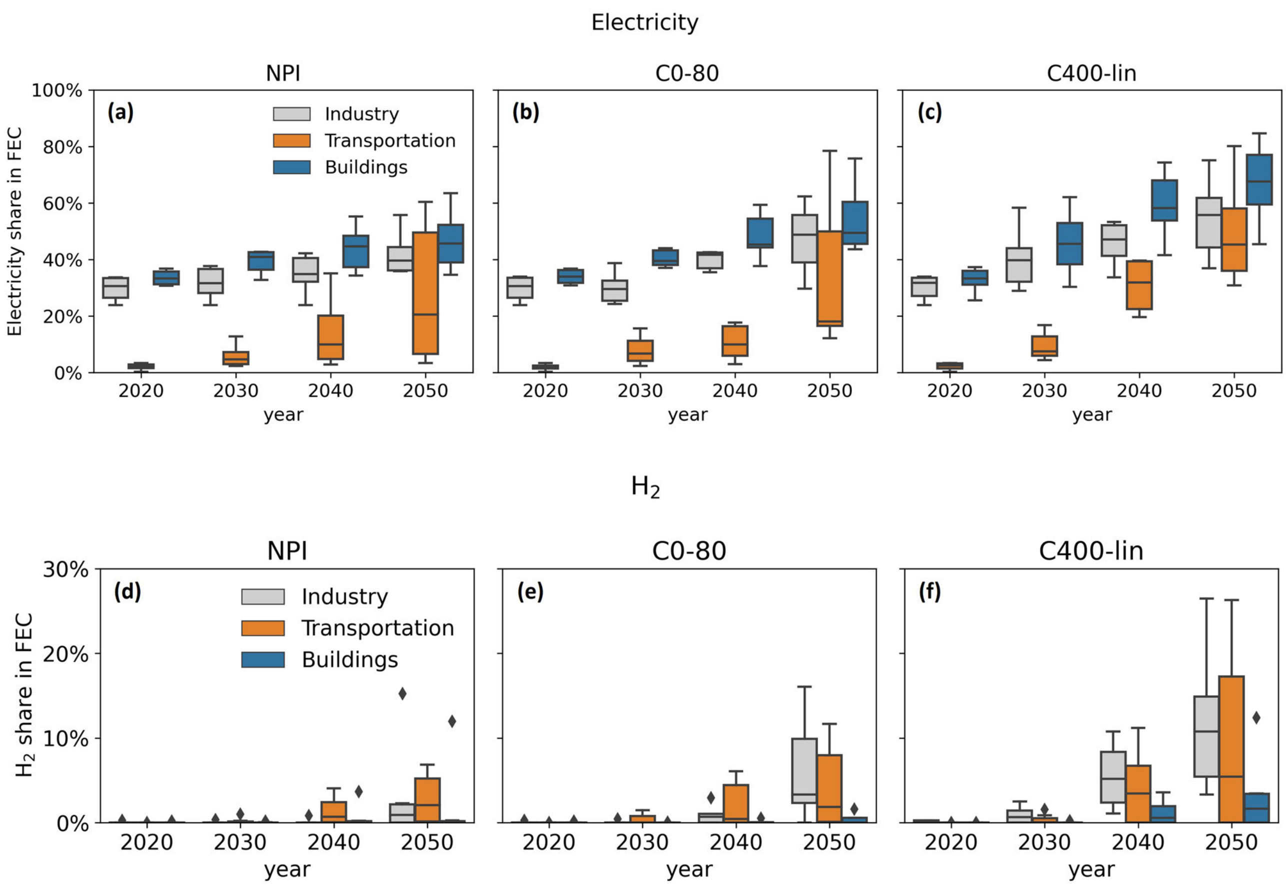

Fig. 5 | Electricity and H_2 shares across sectors. Shares of electricity (**a**–**c**) and direct use of H_2 (**d**–**f**) in final energy consumption (FEC) in three main demand sectors across three scenarios. Horizontal line segments refer to cross-model medians, boxes correspond to first and third quartiles (Q1 resp. Q3), whiskers indicate Q3 ± 1.5(Q3−Q1) levels, and diamonds represent outliers. The three scenarios depicted are NPI (National Policy Implementation), C0-80 (CO_2 price growing to 80 \$/tCO_2 in 2040), and C400-lin (CO_2 price growing to 400 \$/tCO_2 in 2040).

thereby the important role played by electrification in reaching deep CO_2 emission cuts. For H_2, the correlation is less obvious (larger shaded area), which reflects the observation that the curvature in Figs. 6 and 7 is more pronounced for hydrogen than for electricity. The lower degree of linear correlation observed for H_2 may be related to its relatively low overall penetration level (and its uncertain competition with low-carbon options like biofuels in e.g., transportation), and may reflect the time it takes for H_2 to start playing its role in reaching GHG neutrality (that is, if H_2 were to reach higher penetration shares, the trend might become more linear). In any case, the plots highlight that H_2 can fulfill—along with electricity—a significant function in obtaining CO_2 emission reductions, especially when carbon neutrality is targeted. See Supplementary Fig. 2 (Supplementary information) for similar plots, but with overall CO_2

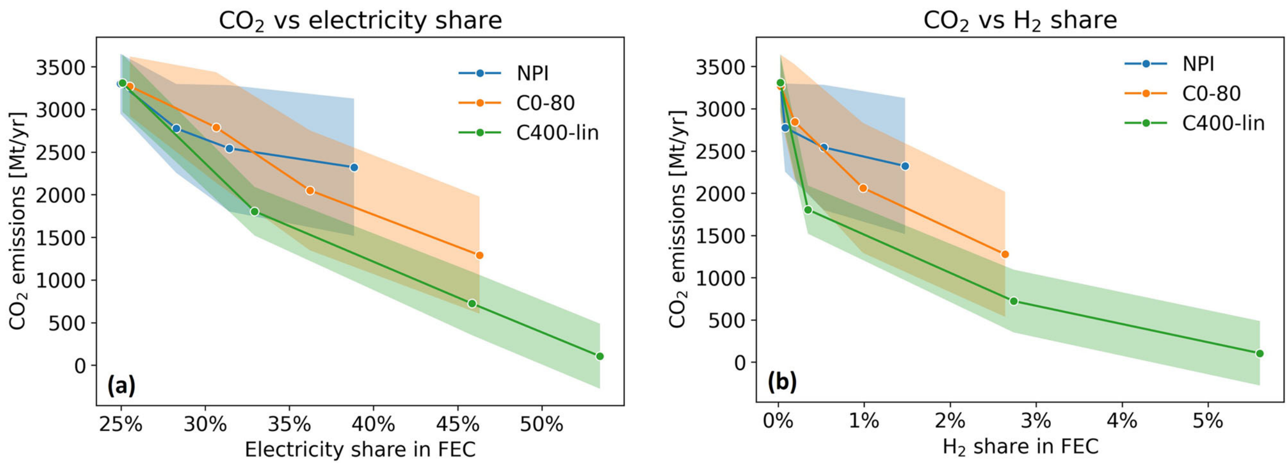

Fig. 6 | CO_2 emissions. CO_2 emissions against direct electricity share (in %, **a**) and direct H_2 share (in %, **b**) in final energy consumption (FEC) across three scenarios. Dots and solid lines correspond to average CO_2 emissions (in Mt/yr); the shading refers to uncertainty ranges across models. The three scenarios depicted are NPI (National Policy Implementation), C0-80 (CO_2 price growing to 80 \$/tCO_2 in 2040), and C400-lin (CO_2 price growing to 400 \$/tCO_2 in 2040).

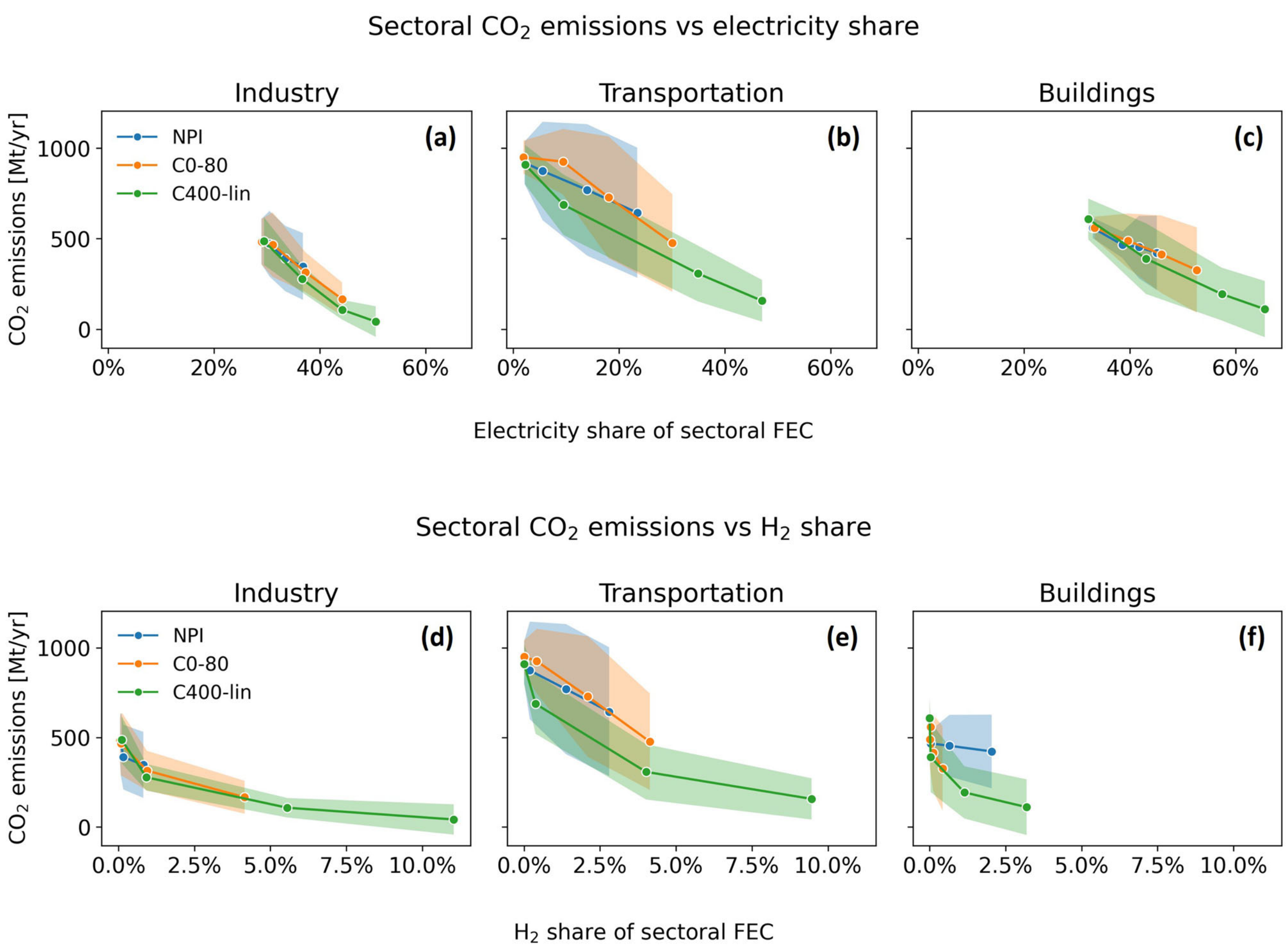

Fig. 7 | CO_2 emissions across sectors. Sectoral CO_2 emissions against direct electricity share (in %, **a**–**c**) and direct H_2 share (in %, **d**–**f**) in sectoral final energy consumption (FEC) across three scenarios. Dots and solid lines correspond to average CO_2 emissions (in Mt/yr); the shading refers to uncertainty ranges across models. The three scenarios depicted are NPI (National Policy Implementation), C0-80 (CO_2 price growing to 80 \$/tCO_2 in 2040), and C400-lin (CO_2 price growing to 400 \$/tCO_2 in 2040).

emissions split into the main demand sectors (i.e., the scatterplot version of Fig. 7).

To further explore the diversity in pathways by which the different models realize the various scenarios, Fig. 9 brings together the three main dependent variables investigated in our study: direct shares of electricity and H_2 in FEC, and CO_2 emissions. The data are presented as a scatterplot of electricity versus hydrogen shares for the year 2050 (using the same colors and symbols as in Fig. 8) super-imposed on a contour plot showing CO_2 emission levels with a color scale. NPI dots are typically located around the summit of this color scale (brown to white),

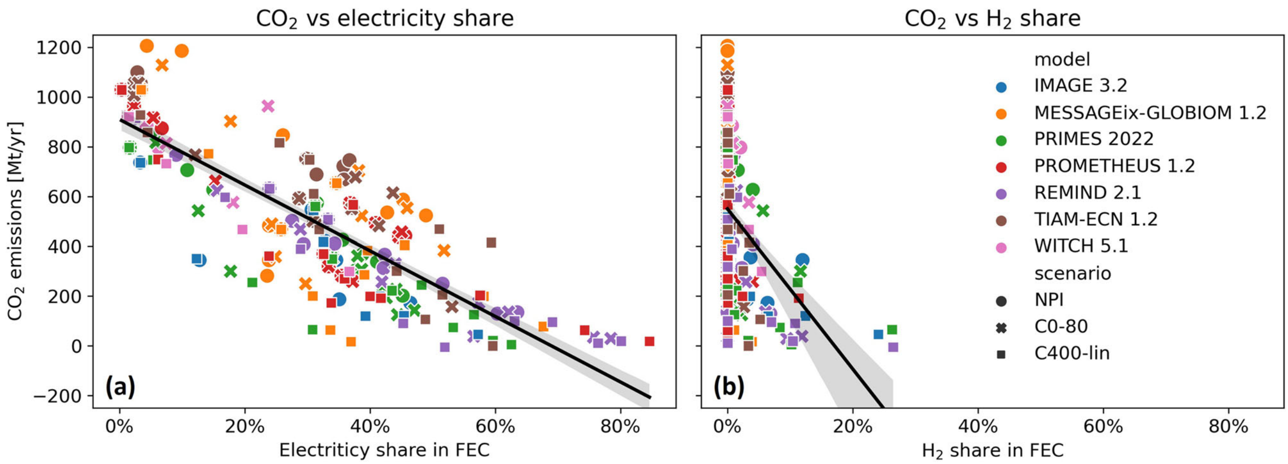

Fig. 8 | CO_2 emissions across models. CO_2 emissions (in Mt/yr) against direct electricity share (in %, **a**) and direct H_2 share (in %, **b**) in final energy consumption (FEC) across models, scenarios, sectors, in four time periods (2020, 2030, 2040, 2050). The color coding of the dots corresponds to individual models; the shape of the dots refers to scenarios. The solid black line indicates a linear regression, and the gray shading the variance. The three scenarios depicted are NPI (National Policy Implementation), C0-80 (CO_2 price growing to 80 \$/tCO_2 in 2040), and C400-lin (CO_2 price growing to 400 \$/tCO_2 in 2040).

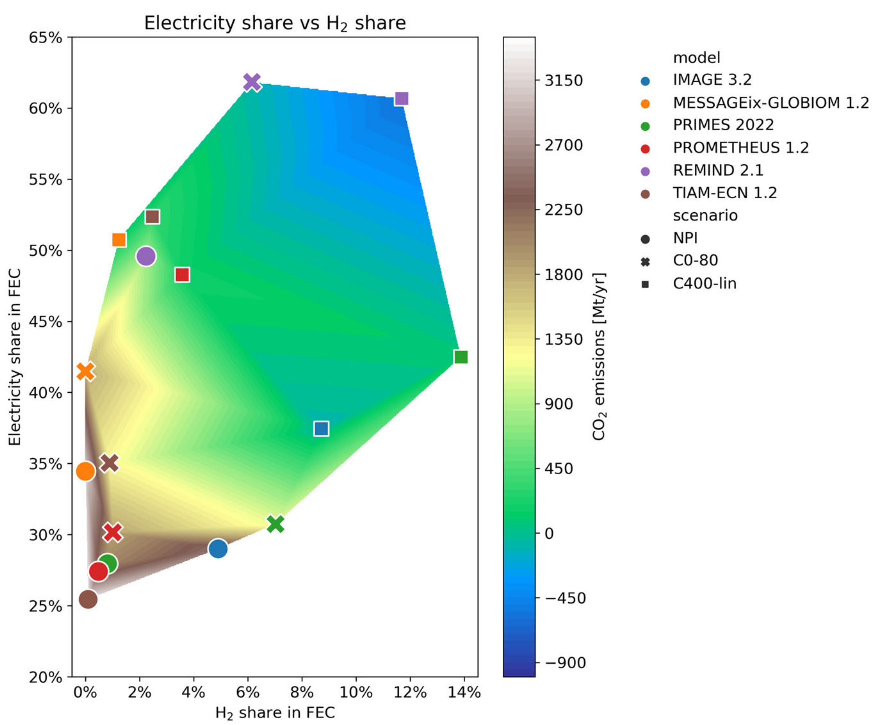

Fig. 9 | Electricity versus H_2 shares (%) in final energy consumption (FEC) (scatterplot), and CO_2 emissions (contour plot) in 2050 across models and scenarios. The color coding of the dots corresponds to individual models; the shape of the dots refers to scenarios. The color coding of the contours refers to CO_2 emissions (in Mt/yr). The three scenarios depicted are NPI (National Policy Implementation), C0-80 (CO_2 price growing to 80 \$/tCO_2 in 2040), and C400-lin (CO_2 price growing to 400 \$/tCO_2 in 2040).

while the points associated with net-zero CO_2 emissions are positioned in its valleys (green to blue). In the C400-lin scenario (squares in Fig. 9), the shares are spread across models between, respectively, 38%–60% for electricity, and 2%–14% for H_2, while CO_2 emissions vary from roughly −450 Mt/yr (Regional Model of Investment and Development (REMIND)) to about 200 Mt/yr (PROMETHEUS)—see also Supplementary Fig. 1 (Supplementary information). The generally positive emissions from demand sectors (Figs. 7 and 8) are in some cases counterbalanced by negative emissions from supply sectors (e.g., electricity generation through biomass and CCS).

Figure 9 visually captures the diverse range of outcomes that our models project in 2050 for the direct penetration of electricity and H_2 in the European energy system. This diversity highlights, on the one hand, the uncertainties in the energy transition pathways towards 2050, and, on the other hand, the complex correlation between CO_2 emissions and direct electricity and H_2 shares of FEC. Regarding the latter, we observe in Fig. 9 an overall trend towards lower emissions as the percentages of electricity and H_2 increase, i.e., the colors of the contour plot change from white to blue as one moves from the bottom-left to the top-right within the figure. However, this trend is broken by the point corresponding to the Integrated Model to Assess the Global Environment (IMAGE) model in the C400-lin scenario, which depicts a possible realization of a net-zero emissions pathway with relatively low electricity and H_2 penetration (38% and 9%, respectively).

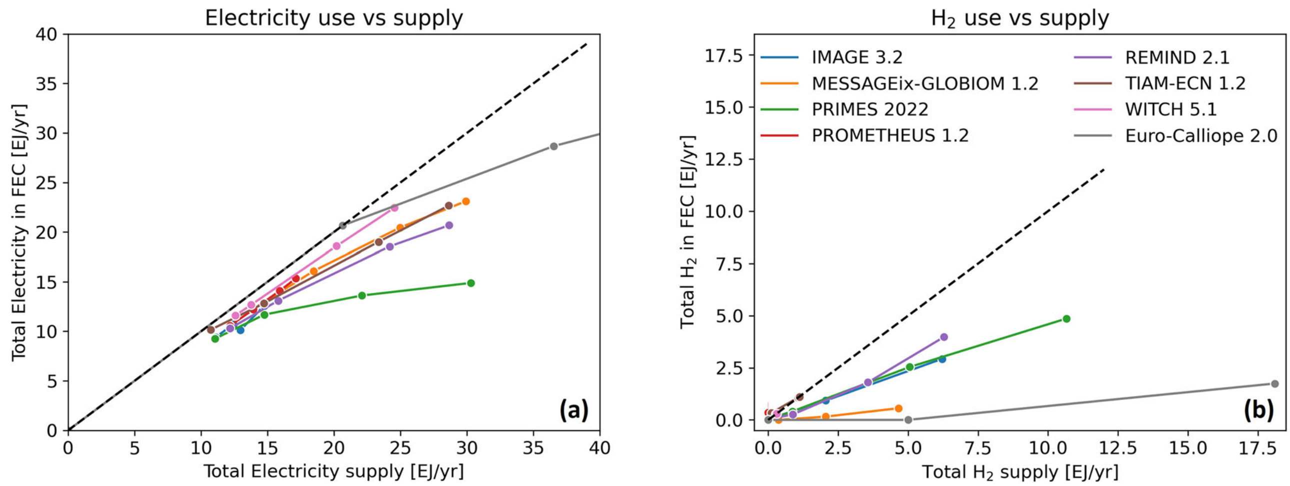

Fig. 10 | Total electricity and H_2 use versus total supply. Total direct use (in EJ/yr) in final energy consumption (FEC) versus total supply (in EJ/yr) for electricity (**a**) and H_2 (**b**). The color coding refers to individual models, and the dots to individual years (2020, 2030, 2040, 2050). The dashed diagonal represents the symmetry line.

One of the key assumptions that greatly influences the diversity of outcomes highlighted in Fig. 9 is the model-specific "topology" adopted for each energy carrier, i.e., which conversion routes are simulated in the model to bring electricity and H_2 to end-use sectors. Some models favor the direct use of hydrogen in FEC, others can only deploy H_2 in end-use sectors after a series of transformations to convert it into other types of fuels (typically synthetic H_2-based liquid hydrocarbons), others yet allow both direct and indirect use depending on the sector. These differences largely account for the wide spread of H_2 shares in the various modes. Similar considerations apply, albeit to a lesser extent, for electricity. Our present analysis only considers the direct use of electricity and H_2 in FEC, hence missing the indirect uses of both energy carriers. In order to visualize how large the contribution of the indirect use of electricity and H_2 may be in the various models, in Fig. 10 we show the total amount of these two energy carriers that is directly used in FEC versus the total amount that is supplied to the system (i.e., locally produced plus imported electricity and H_2). If the full amount of supplied electricity (respectively, H_2) were directly used in FEC, all data points would lie on the diagonal (dashed black line). Because of indirect uses (compounded, in the case of electricity, with line losses), the lines tend to appear below the diagonal for most models. Euro-Calliope and MESSAGE are clearly skewed towards indirect H_2 use, with, respectively, only 10% and 12% of the supplied H_2 directly penetrating FEC. In these models, H_2 is thus likely to provide a contribution to the liquid fuels used in FEC. With reference to Fig. 3, liquid fuels deployment displays a decreasing trend in time, for all scenarios and sectors. In the C400-lin scenario, by 2050, liquid fuels remain a relevant option mainly in the transport sector and in industry.

When considering the full amount of H_2 that is, directly and indirectly, supplied to the system, our estimate of total H_2 penetration increases by a factor of 3 (on average over all models) to about 20% of FEC in 2050 for C400-lin. This estimate, solely based on the data underlying Fig. 10, assumes that all the supplied H_2 is used for energy production. In reality some—possibly a large part—of this H_2 could be directed to non-energy uses, e.g., the production of feedstocks such as ammonia used in the agricultural sector for fertilizers. Therefore, a penetration of H_2 of 20% of FEC should be interpreted as an upper limit, which needs to be corroborated by a rigorous accounting of indirect H_2 usage in the various models, which we intend to carry out in follow-up work in ECEMF.

In short, in this article, we show to what extent electricity- and hydrogen-based sector coupling might underpin the energy transition towards a deeply decarbonized economy in Europe until 2050. We do so by a cross-model comparison exercise, in which we contrast the findings of eight well-established energy system or integrated assessment models under a set of deep decarbonization or net-zero CO_2 emission pathways. Our models display differences in design and (non-parametric) assumptions. Consequently, as in other cross-model comparison research efforts (e.g. ref. 30), under the present project[6] we observe a large variance across model results. This variance reflects the inherent uncertainties in the shape of possible net-zero CO_2 emission pathways. It increases over time towards 2040 and 2050, which indicates that our model results are more consistent for relatively short-term projections, while the uncertainty increases when moving to the long term.

To follow deep decarbonization scenarios during the forthcoming three decades and satisfy growing energy demand through low- and zero-carbon resources, large amounts of renewable electricity need to be produced—mostly for direct electrification of different demand sectors, but some also for the production of hydrogen. In this study, we conclude that renewable electricity and hydrogen can be cost-effectively provided by scaling up wind and solar energy capacity, in addition to several other renewable energy options like hydropower and geothermal energy that play a smaller role. We find that, naturally, the diffusion of renewable electricity and hydrogen in the energy system results mostly from the CO_2 emission reduction ambitions stipulated in the EU Climate Law and EU Green Deal.

Among our central findings is that direct electricity and hydrogen shares in FEC increase substantially to achieve net-zero CO_2 emissions, albeit from different starting points and to different final levels. We observe that by 2050 these shares in FEC may rise to around 60% and 6%, respectively. We thus confirm the common finding that renewable-based electrification is likely to constitute the most cost-efficient decarbonization route in the majority of economic sectors until the middle of the century. Hydrogen, on the other hand, may provide a relatively small—though essential—contribution to decarbonization pathways, especially for industry and transportation (e.g., for steel-making and heavy-duty vehicles, respectively).

In the public and scientific debate, a "hydrogen economy" is often proffered as the ultimate solution to the climate change conundrum. While being quite abstract, the notion appears over-sold by certain energy specialists and representatives from industry, but it seems under-appreciated by those who do not believe in a sizable role for hydrogen in mitigating GHG emissions. In this work, we substantiate and quantify the concept of "hydrogen economy", insofar as hydrogen may be used as an alternative clean fuel to fulfill energy services demand in a net-zero emissions environment. We show the extent to which, under different scenarios, a hydrogen economy might play a role as part of the energy transition: under cost-optimal trajectories, we find it to be limited to specific energy-using sectors rather than encompassing all of the economy. We find that assuming a cost-optimal transition with our set of models and assumptions, the role of direct hydrogen use would not readily exceed 10% of FEC by 2050, with only a negligible share in buildings.

In its broadest sense, the concept of "hydrogen economy" also encompasses other uses for hydrogen which not all models yet include and that therefore we do not explicitly focus on or address in our present paper, e.g., as green feedstock in the iron and steel industry or for the production of fertilizers and e-fuels. Follow-up studies (single-model ones, as well as cross-model comparison exercises like ours) on the potential for the combined use of hydrogen as fuel and feedstock in a deep decarbonization context might reveal more complex dynamics and larger penetration levels than those highlighted in the present article. This question, which we leave for future research, emphasizes the need for tools and platforms that could simultaneously model the energy transition and its materials counterpart in a holistic and integrated manner. In short, our analysis highlights on the one hand the large diversity in approaches to model direct hydrogen penetration in FEC in modern IAMs, and on the other hand the need to further develop the ECEMF reporting framework—and the scenario reporting infrastructure employed in modeling exercises such as used by the IPCC—so as to fully account for the possible deployment of hydrogen in our transitioning economies, including both its direct and indirect use. After all, while at present we collectively draw the conclusion that there may possibly remain only a limited role for the direct use of hydrogen to satisfy FEC, we acknowledge that this conclusion is based on the fact that some models leave it out in certain sectors, as a result of which hydrogen may be under-represented. If indirect or intermediate uses of hydrogen are also accounted for in all models—with still unknown effects on its direct usage—its aggregate role is likely perceived as larger. Projecting the mid-century extent of aggregate hydrogen usage is a subject that deserves concerted attention by researchers and modelers like ourselves, as well as the broader policy-making and private sector communities. Other remaining questions that these communities should address include (1) what are possible future cost trajectories for hydrogen production and how do they impact its deployment, (2) how do the multiple production types and corresponding diffusion pathways of (e.g., green versus blue) hydrogen relate to each other, (3) what do hydrogen usage projections look like if one extends the European scenarios proffered in the present study to an analysis that covers a global scale, (4) will or should hydrogen become a strongly decentralized energy carrier (with many diffuse small production devices located close to consumption) or a highly centralized one (with large-scale production facilities at a limited number of sites across the world complemented with global export and import infrastructure), and—last but not least—(5) how may social acceptance affect the scalability of hydrogen use domestically and hydrogen trade internationally?

Methods

Models

We use eight different energy system and integrated assessment models (collectively referred to as IAMs for brevity) for this study. Models of this type are widely used to create long-range scenario projections of the energy-economy-environment system (globally and/or for a specific region of the world), among others by the IPCC[2,3]. IAMs rely on a detailed bottom-up techno-economic description of the energy system in terms of hundreds of processes to convert energy from its raw forms (e.g., wind potential, solar radiation, and fossil fuels) to end-uses in-demand sectors (such as lighting, refrigeration, heat, and transport). This collection of conversion routes forms the model-specific *topology*. Demand and supply of energy are matched through a constrained minimization procedure to find the cost-optimal energy system. Cost minimization does not faithfully represent how decisions are made in reality, but provides a systematic and consistent paradigm to compare the outcome of specific policy scenarios (e.g., CO_2 abatement targets, or subsidization of renewable energy technologies). Constraints are used, among others, to ensure that models are calibrated to the latest statistics, to provide limits for maximum resource availability at any given time, and to simulate behavioral responses and the effects of policy measures. While being based on a common approach, IAMs differ from each other in terms of their geographical and temporal scope and disaggregation, topology, techno-economic assumptions, objective function formulation, set of constraints, and sectoral representation. This diversity implies that, even under identical scenario assumption, two models will most often calculate different cost-optimal energy systems. In our present paper, we take advantage of this feature to identify robust trends as well as areas of uncertainty within our decarbonization scenarios.

We here list the eight models employed in this study, and briefly explain under what mechanism they operate and what their salient peculiarities are. In the indicated references, and the websites of several of the models, detailed information can be found on their topology, model formulation, regional disaggregation, and sectoral representation. While a thorough description of each model is outside the scope of this paper, we do want to highlight that (i) all selected models can provide results for Europe, albeit with different levels, of detail (see ref. 8), (ii) population and GDP growth projections until 2050 have been harmonized to the second Shared Socioeconomic Pathway (see ref. 31) to provide identical drivers for energy demand in all models, (iii) the ways in which the outcomes of these models differ (the so-called "energy model fingerprints") have been analyzed and mapped in detail (see ref. 7), and (iv) the scenario assumptions for this study have been consistently implemented in all models.

IMAGE. The IMAGE model is a process-based integrated assessment model, with a recursive-dynamic energy module (TIMER) representing the global energy system, disaggregated into 26 regions[32].

MESSAGEix(-GLOBIOM). The Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGEix) framework is an energy systems optimization modeling framework, with a macro-economic module that provides demand response to energy prices using a stylized computable general equilibrium model[33].

PRIMES. The Price-Induced Market Equilibrium System (PRIMES) model is an energy system model that covers all main energy sectors in the EU and provides projections for energy demand, supply, prices, and investments[34].

PROMETHEUS. PROMETHEUS is a global energy system simulation model with recursive dynamics focusing on technology uptake, energy demand, supply and price projections, and assessment of energy and climate policies in the EU and other major emitting regions[35].

REMIND. The REMIND is a Ramsey-type general equilibrium growth model of the macro-economy in which inter-temporal global welfare is maximized and that is linked to a linear technology-based energy system module[36].

Euro-Calliope. Sector-coupled Euro-Calliope is an energy system model that optimizes capacity expansion and system operation at sub-national spatial and hourly temporal resolution over a full year of weather data—a much higher resolution than in previously discussed models[37].

Table 2 | Scenarios used for our ECEMF sector-coupling study

Scenario name	Main feature
NPI	National Policy Implementation: no additional policies are included except those agreed upon to date.
C0-80	The CO_2 price grows from 0 to 80 \$/tCO_2 before 2040, and increases with a 5%/yr rate after 2040.
C400-lin	The CO_2 price grows linearly from 130 to 580 \$/tCO_2 between 2025 and 2050.

The main features of each of our three scenarios are specified, where applicable, with the corresponding exogenous CO_2 price trajectory over time (in \$/tCO_2).

TIAM-ECN. TIAM-ECN, based on the TIMES Integrated Assessment Model (TIAM) framework, is a global cost-optimization model, developed at ECN and now operated at TNO, that minimizes discounted energy system costs with a partial equilibrium that fulfills end-use demand under various constraints[38].

WITCH. The WITCH model is an inter-temporal optimal growth model with a compact representation of the energy sector in which energy investments and resources are chosen optimally[39].

Scenarios

With these eight (European or global) models, sets of scenarios were generated in the context of the ECEMF project. For the purpose of this paper, we focus on the set specifically designed to diagnose how the various models react to different assumptions on decarbonization levels and mitigation pathways[7,8]. Within this set, we selected three representative scenarios that correspond to shallow, medium, and deep decarbonization, and allow us to draw robust conclusions on sector coupling across the EU energy system. The main features of these three scenarios are listed in Table 2. In ECEMF[40], detailed instructions are given for how these features should be implemented in the various models. With the information provided here, complemented by the instructions in ECEMF[40], any researcher with access to these models should be able to reproduce the results presented in this study.

In the NPI scenario, the major energy and climate policies are included that have been agreed upon, legislated, and enacted by individual countries or the EU as a whole until 2021 (and the rest of the world for the global models). The Fit-for-55 program and its multiple policy packages or other additional policies, that may still be adopted to reach the targets of the Paris Agreement and the EU Green Deal, are not included. The C0-80 scenario assumes that the CO_2 price grows from 0 to 80 \$/tCO_2 before 2040, and increases with a 5%/yr rate thereafter until the end of the modeling horizon. In the C400-lin scenario, a CO_2 price is introduced that grows linearly from 130 \$/tCO_2 in 2025 to 580 \$/tCO_2 in 2050, which in most models implies reaching carbon neutrality by the middle of the century (and close to climate neutrality, since GHG emissions reduce on average by more than 90% versus 1990). NPI represents a business-as-usual baseline, which is useful as a benchmark against which one can gauge the depth of decarbonization achieved in the other two scenarios. C0-80 and C400-lin are both based on an exogenously imposed increasing CO_2 price trajectory. Carbon prices are implemented globally (or to the whole geographical scope for the regional models) across all sectors. All models will respond to a growing carbon price by reducing the amount of fossil-fuel-based processes deployed in the energy system. This will entail additional costs above the levels identified in NPI, and, for the reasons outlined above, will result in each model projecting a different energy system for Europe. By inspecting how the various models react to the three carbon price trajectories in our scenarios, we can thus identify robust sector-coupling trends and uncertainties under a wide range of decarbonization pathways.

Data availability

Our results are created using output variables available in the public ECEMF database (see https://data.ece.iiasa.ac.at/ecemf). The specific set of data (both raw and processed) used in this study is available at https://zenodo.org/records/13951775, for transparency and reproducibility reasons.

Code availability

The code of the models used for our analysis, or parts thereof, can be made available upon request to the individual modeling teams, since the models tend to be exceedingly large, and different sharing policies apply for different models. The Python code used to generate the figures presented in this paper is available together with the data at https://zenodo.org/records/13951775.

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Author contributions

B.v.d.Z., A.F., F.D.L., M.M.D., D.v.V., R.P., R.R., F.S., D.H., J.E., S.P., F.L., P.F., M.K., T.F., G.T., and W.U. conceived the study and diagnostic experiments, and contributed to the scenario runs and to the writing of the manuscript. B.v.d.Z., A.F., and F.D.L. analyzed the model output. B.v.d.Z. and F.D.L. devised the framework of the study and performed the analysis. F.D.L. generated the figures. B.v.d.Z. wrote the first draft of the paper and produced several revisions.

Competing interests

The authors declare no competing interests.

Additional information

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