1 Introduction

For the European Union to become the first climate-neutral continent by 2050, the decarbonisation of the energy sector will be crucial. Production and use of energy accounts currently for more than three quarters of the EU's greenhouse gas emissions[1], and most of the EU energy system still relies on the combustion of oil, natural gas and coal. Meanwhile, the potential to reduce demand for energy services is most likely limited and therefore most energy services currently based on fossil-fuels need to be replaced by climate-neutral alternatives. One of the open issues is the relative role of different non-fossil fuels[2] – primarily electricity, hydrogen and synthetic methane – in final energy use.

We present three extreme scenarios to highlight the consequences of different energy-policy choices: first, the full electrification of the economy; second, the widespread use of hydrogen; and third, widespread use of synthetic methane. In practice, a combination of the three scenarios is most likely to be implemented, and the three scenarios are not equally probable.

Irrespective of the choices made, we emphasise three main 'no-regret' policies that should in any case be implemented[3]: (a) rapid deployment of more renewable electricity generation, (b) electrification of significant shares of final energy uses (such as heating and transportation), and (c) the swift phase-out of coal. Our analysis also highlights that the current national e main advantage of synthetic methane is that it can be fed into the existing natural gas

tricity generation levels must at least double by 2050 compared to today (with potential deployment abroad in the case of energy imports). We assume that all of the growth will come from renewables, mostly wind and solar. Electricity generation in the EU from coal and natural gas will have to be phased out in line with international commitments such as the Glasgow Climate Pact[7].

Figure 2: Electricity generation in 2019, 2030, and 2050 in TWh

Source: Bruegel (see Zachmann *et al*, 2021). Note: RES = renewable energy sources.

e greater role of electricity will be visible in the future through more direct use of electricity in nal energy use ('electri cation', eg of transportation) and through the introduction of hydrogen and synthetic methane produced from electricity ('indirect electri cation').

Figure 3 shows that direct electri cation will play a major role in all scenarios because it is a low-cost way of decarbonising many energy demand areas. Due to their energy-ine cient production processes, hydrogen or synthetic methane will only become viable bulk-energy carriers if low-carbon electricity generation in Europe (or in the interconnected neighbourhood) turns out to be severely limited. Even assuming learning and cost decreases, only small amounts of hydrogen and synthetic methane are no-regret decarbonisation solutions[8] for sectors where electri cation is impossible or hard to achieve.

Figure 3: Change in final energy consumption by fuel between 2020 and 2050 (TWh)

Source: Bruegel (see Zachmann *et al*, 2021).

The scenario approach helps us to investigate the relative costs of each decarbonisation option. Clearly, there is too much uncertainty around key parameters (learning rates, future appliance costs, supply constraints, etc) to be able at this point to determine the optimal future energy system. However, some insights are gained from comparing the three scenarios.

First, different scenarios have different investment needs (Figure 4). For example, the 'all-electric world' scenario with widespread electrification requires massive expansion of electricity grids, even more than in the other scenarios because of the interconnection of all possible demand areas. In contrast, a hydrogen-focused energy system will incur costs for the retrofitting of pipelines to enable hydrogen to be transported.

Second, all scenarios require significant investment in low-carbon power supply. Expansion costs for low-carbon electricity generation are more than half the domestic EU investment costs in all scenarios.

Third, the need for domestic generation investment would be even greater in the 'hydrogen imports' and 'green gases' scenarios, unless much of the electricity production is offshored and imported in the form of hydrogen and synthetic methane. This leads to high import costs (Figure 4).

Figure 4: Annualised investment costs (left-hand bars) and fuel import costs

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example: greenhouse gas pricing, which increases the costs of carbon-intensive production, but is neutral about its alternatives[11]; bans on/strict standards for internal combustion engine vehicles and gas boilers, which phase out the use of fossil fuels but do not prescribe specific alternatives; and mandates to stop fossil-fuel investment that would only be economically viable if there is still unabated combustion after 2045, which do not prescribe a specific replacement technology. However, such technology-neutral policies are not necessarily sufficient to end the use of fossil fuels, as shown by coal.

There exists no foreseeable future in which coal will play any (significant) role in the European energy system. Especially in electricity and heat production, which presently uses almost half of hard coal[12] and almost all lignite in the EU, a coal phase-out must be achieved swiftly to not over-exploit Europe's carbon budget and to maintain international credibility. Using coal to generate electricity and heat is highly emissions-intensive: coal provides only 17 percent of total electricity and heat production in the EU, but generates half of the greenhouse-gas emissions in this sector (Figure 6).

Figure 6: Share of coal in emissions and electricity and heat production (2019)

Source: Bruegel based on Eurostat (ngr_bal_peh) and EU CRF Tables reported to UNFCCC (see https://www.eea.europa.eu/publications/annual-european-union-greenhouse-gas-inventory-2021/eu_crf_tables_eua_2021_unfccc_2021.zip/view). Note: Renewables are without biomass and renewables waste; biomass includes renewables waste; 'other fossil fuels' includes non-renewable waste.

The importance of coal in electricity and heat production varies across the EU, with many countries – predominantly in North and West Europe – having no or almost no coal in their systems, and a few countries – in Central and East Europe – with very high shares (Figure 7). Seven EU countries (Poland, Czechia, Bulgaria, Slovenia, Germany, Greece and Romania) have coal shares above 20 percent. On the other hand, twelve EU countries have shares around 10 percent. Germany has the fifth largest share of coal, but due to its size has the second-largest coal-sector in the EU.

Figure 7: Share of coal in electricity and heat production in the EU (2019)

3.2 Ensuring availability of low-carbon alternatives

Policy must focus not only on ending the use of fossil fuels, but also on providing credible low-carbon alternatives. To do so, certain actions are essential under all scenarios. The first is to build out low-carbon electricity generation capacity. At least an additional 2,000 terawatt-hours of domestic electricity generation in 2050 compared to 2019 is required in all scenarios, which is approximately a 70 percent increase. Second, in certain areas, direct electrification appears likely to be the optimal solution, including for passenger vehicles[15], large shares of household heating[16] and low-temperature industrial heat[17]. Here, policymakers should be willing to do what is needed to provide the policy framework (infrastructure, regulation, support for research, development, demonstration and deployment) to enable the fast roll-out of decarbonised systems. This does not imply that policy will blindly favour one system, but that the burden of proof will be on alternative technologies to provide not-yet-seen evidence of their superiority. Direct electrification will work for a substantial percentage of EU's decarbonisation needs and this should be swiftly exploited.

The coal phase-out is a prime example highlighting the need for significant deployment of new low-carbon electricity capacity. The deployment record in the past two decades indicates that renewable electricity is the cost-efficient option[18]. However, as wind and solar PV power plants have structurally lower full-load hours (hours in which the entire power capacity of a power plant is used), the overall capacity of the power plant fleet has to be substantially increased to provide the same amount of energy. Among EU countries, the need to deploy renewable power plants in order to phase-out coal varies. Countries with a low share of coal in electricity and heat production will be able to replace coal with modest investments in additional renewable energy capacities. Countries with high shares of coal (especially Poland, Czechia, Bulgaria and Slovenia) must invest aggressively in renewable energy capacities so they can phase-out coal in the next decade. Renewable capacities need to be multiplied by a factor of at least six by 2050 in the seven most coal-intensive EU countries (Figure 8). However, all EU countries need to increase renewable energy deployment rates substantially to achieve climate neutrality by 2050.

1 [illegible] https://www.eea.europa.eu/ims/new-registrations-of-electric-vehicles.
[illegible] https://www.bloomberg.com/news/articles/2021-12-09/peak-oil-demand-is-coming-but-not-so-soon.
1 [illegible]

Figure 8: Wind and PV power plant capacities needed for decarbonisation in the seven most coal-intensive EU countries (in GW)

Source: Zachmann *et al* (2021). Note: The data covers EU countries with significant shares of coal in electricity and heat production: Bulgaria, Czechia, Germany, Greece, Hungary, Poland, Romania and Slovenia.

As the coal phase out progresses, gas-fired power plants could play an important transitional role. They have relatively low capital costs (about half that of coal plants) and can be dispatched more quickly than coal plants when needed to back-up fluctuating wind and solar PV power plants. They can thus support the system for the few days/weeks of the year when demand exceeds renewable energy production.

However, new gas power plants risk becoming stranded assets if they cannot be operated commercially under strict carbon-neutrality constraints. Depending on the needs of the future power sector, three different types of gas fired power plant are conceivable: 1) plants with relatively low capital costs and low planned load factors, and which can be switched to carbon-neutral fuels such as synthetic methane or hydrogen; 2) plants designed to recover their fixed costs over a short period; 3) very efficient plants with higher load factors that can be commercially operated with carbon capture and storage. Given the legacy power plant fleet and the decreasing cost of renewables, the first niche currently appears to be the largest. A predictable regulatory environment and a well-functioning electricity market is the best approach to identify efficient solutions.

Beyond these two uncontroversial solutions (direct electrification where appropriate and the massive deployment of renewable electricity generation), the most promising solutions for other energy uses (including significant industry applications, aviation or seasonal energy storage) are less clear.

Hence the approach should be two-pronged: to provide a European and national policy framework encouraging the rapid deployment of the uncontroversial solutions, and encouraging companies to explore in depth different solutions in the less-clear areas.

In the next decade, this two-pronged approach will be particularly important for industry and households (including transport). In these sectors, emissions reductions have so far been too slow; in order to meet 2030 targets, a step change is necessary. The major focus on these areas in the European Commission's Fit-for-55 policy push, and the spending plans of countries under Next Generation EU (Darvas *et al*, 2021), reflect this. The policy challenge is to strike the right balance between allowing fair competition between low-carbon technologies while providing enough of a technologically-specific push for the required solutions to be deployed at scale in time.

For comparison, the 2005 launch of the EU ETS placed neutral pressures on the power sector to decarbonise, but was accompanied by the roll-out of massive support schemes for renewable power generation. These policies favoured the development of those renewa-

4 Enhancing the transition toolbox

As Europe decarbonises, lessons must be learned to provide guidance to the later stages of European decarbonisation and also to third-countries that want to follow Europe's path. As a bloc of 27 countries with different geographies, economies and politics, there is likely to be significant divergence in the pathways EU countries follow to reach net-zero. While coherence and collaboration in certain areas are important for efficient investments, in certain areas a diversity of approach should be celebrated. The pursuing of different policies, and ultimately fuel mixes, by EU countries will provide important data on the pros and cons of respective pathways.

However, country-level plans must conform to minimum levels of ambition. So far, EU countries' national energy and climate plans (NECPs) are insufficient as net-zero pathways. For example, Figure 9 shows that NECPs consistently miss required energy efficiency gains. Member states that will fall short in terms of energy efficiency gains must demonstrate that they are able to make up for this shortcoming with alternative policy, eg more rapid deployment of renewable capacity.

Figure 9: Final energy consumption projections in 2030 (TWh), selected countries

Source: Zachmann *et al* (2021).

Finally, efforts should be made at EU and member-state level to improve the collection and transparent communication of relevant data. Currently, NECPs are difficult to compare and not structured coherently. The European Union should consider creating a European Energy Agency (similar to the United States Energy Information Administration), which would be responsible for detailed analyses of NECPs and all other aspects of the EU's low-carbon energy transition. The policies implemented over the coming years will fundamentally reshape the lives of every European citizen. A transparent reference point for the often very technical issues will be essential to ensure high quality political discussions.

References

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