UNIVERSITY OF CAMBRIDGE | Energy Policy Research Group

Modelling Flexibility Requirements in European 2050 Deep Decarbonisation Scenarios: The role of conventional flexibility and sector coupling options

EPRG Working Paper 2302

Cambridge Working Paper in Economics CWPE2309

Chi Kong Chyong, Michael Pollitt, David M Reiner, Carmen Li

In June 2021, the European Union adopted a climate law that requires its member countries to reduce their greenhouse gas emissions by 55% by 2030 and reach net-zero (NZ) emissions by 2050. This policy has been supported by several major initiatives, such as the EU Energy System Integration Strategy and the EU Hydrogen Strategy, aimed at promoting a sustainable and secure energy transition. However, Russia’s recent full-scale military invasion of Ukraine has raised concerns about Europe's energy security and dependence on foreign energy suppliers. In response, the European Commission published its RePowerEU plan, which aims to phase out fossil fuel imports from Russia by 2027. While the RePowerEU plan and in particular phasing out import dependence is compatible with net zero targets, concerns over short-term security of supply now have greater resonance, which leads to a key question that is now of utmost importance, namely, *what are the sources of flexibility to support a fully decarbonised European energy system by 2050*?

We address this question by developing and employing a Pan-European energy system model to analyse the role of conventional flexibility options and sector coupling technologies. The academic literature has long stressed that flexibility plays a crucial role in the design, operation, and management of renewable-dominated energy systems, and that the integration of flexible technologies and operating strategies is essential for achieving a low-carbon, reliable, and least-cost energy system. We contribute to this growing literature by examining the role and interactions between traditional sources of flexibility (e.g., networks and storage) and emerging, flexible sector-coupling technologies (e.g., electrolysis and hybrid heat pumps) in deep decarbonisation scenarios. Few studies have looked at the combination of both large-scale sector-coupling technologies – electrolysis, power-to-gas and power-to-liquids – and small-scale technologies such as hybrid heat pumps – with traditional flexibility technologies.

Our research indicates that electricity and electricity-based end-use technologies play a central role in reaching net-zero GHG emissions by 2050 in Europe. The results show that renewable energy, in particular wind and solar electricity, will need to be scaled up significantly to replace fossil fuels. The net-zero energy system in Europe will be based on zero-carbon electricity generation, with 78% from variable renewable energy (VRE), 12%

from nuclear, 3% from hydro, and the rest from dispatchable sources like combined cycle gas turbines (CCGT) with carbon capture and storage (CCS) and biomass energy with CCS (BECCS). To reach this ambitious target, policy makers should focus on streamlining local planning procedures for large-scale renewable energy infrastructure and support R&D of other low-carbon technologies like CCS and hydrogen. The EU recently agreed on accelerated permitting rules for renewables to eliminate its dependence on Russian gas, a step in the right direction.

We found that sector coupling occurs not just at the supply level (e.g., via electrolysis) but also potentially at end use level (e.g., via hybrid heat pumps in buildings). Despite adopting a rather optimistic assumption around bioenergy availability, the role of methane will still need to be substantially reduced as we decarbonise the economy. In terms of energy throughput requirements, the flow of methane (CH_4) will be reduced by 35% relative to the 2018 level. At the same time, we see a larger decrease of at least 50% in CH_4 flow at primary supply level. In particular, the role of fossil gas will be reduced dramatically in the structure of final consumption (just 7% of the 2018 supply level), while imports are expected to reduce to 907 TWh, or ca. 23% of the EU27's gas imports in 2021.

In terms of flexibility technologies, we define energy system flexibility requirements as incorporating (i) energy networks to provide spatial flexibility, (ii) intraday flexibility, and (iii) seasonal flexibility provided by various storage technologies. Our modelling results clearly show the importance and need for both temporal and spatial flexibility.

Electricity cross-border interconnections are necessary to support widespread deployment of renewable energy sources (VRE). Electricity cross-border trade is increasing as economies electrify, with the share of total trade in final consumption at least doubling in decarbonisation scenarios relative to 2018. Imports of fossil gas from non-EU countries is reduced, leading to a decrease in cross-border natural gas trade by a factor of at least four. However, higher demand for hydrogen in the NZ scenario compared to the 90% scenario may result in increased CH_4 imports and cross-border trade. That said, given potentially higher gas import prices as well as sensitivities around dependence on import of fossil gas, this higher hydrogen demand may be filled by hydrogen from water electrolysis. Thus, to reach deep decarbonisation goals, electricity cross-border trade will become more important than CH_4 trade, with total cross-border trade in electricity expected to be double that of CH_4. This is a dramatic structural change, given that in 2018 cross-border trade in CH_4 exceeded that of electricity by almost eight times. In our deep decarbonisation scenarios, we find that cross-border trade in hydrogen is limited because it is locally produced in every EU member state.

More generally, in the deep decarbonisation scenarios, our work indicates the rising importance of electricity networks relative to CH_4 networks. For example, our results suggest that the electricity transmission capacity will expand by a factor of 2.8-3 and is just 13-19% smaller than the CH_4 system in 2018. Both cross-border trade in electricity and national network capacity will provide flexibility for integrating VRE. The H_2 network is small due to the limited H_2 in the scenarios and because storage and flexible operation of electrolysers reduce the need for H_2 network to provide spatial flexibility. To reach NZ, both electricity and H_2 network capacity will increase, with the H_2 network expected to increase by almost 5 times compared to the 90% scenario. Thus, the role of hydrogen will become more important in the NZ scenario.

On the role of energy storage in deep decarbonisation, we found that traditional inter-seasonal flexibility is delivered by a combination of (i) a much-reduced capacity of seasonal CH_4 storage (reduced by a factor of four compared to current capacity) and hydrogen storage, and (ii) new forms of seasonal storage – green H_2 production. Green hydrogen production and H_2-based storage serve mainly to support the differences between winter and summer VRE production (notably solar) to minimise potential curtailments, while CH_4 (and to lesser extent hydrogen) storage supports seasonal variations in heat load and hence requirements to shift biomethane and e-gas supply to buildings. Similar to the role of the H_2 network, we found that as we move from the 90% scenario to the NZ scenario, H_2 storage (especially medium-duration) gains in importance at the expense of CH_4 and electricity-based storage. We found that intraday flexibility in our scenarios is mostly provided by traditional electrical energy storage (e.g., hydro-based electrical storage and generation, and electrical energy battery storage) as well as new forms of intraday electricity-based flexibility (e.g., V2G from EVs). To a lesser extent, the intraday flexibility is also provided by the H_2-based intraday storage solutions, like pressurised H_2 tanks and liquid H_2 storage technologies. While not a storage solution, it is important to note the role of hybrid heat pumps in meeting intraday demand for flexibility in deep decarbonisation scenarios. This sector-coupling flexibility technology allows for greater optimisation between electricity and gas-based networks to provide within day ramping requirements for heat loads.

As noted by Pollitt and Chyong (2021), the NZ target remains an extremely challenging policy goal, involving the roll out of multiple new technologies at scale within a time frame of less than 30 years. Thus, delivering three times carbon reduction as compared to the last 30 years while facing increasing marginal costs of emissions reduction will be challenging. Lack of scaling up of key technologies such as renewable energy, biomethane, hydrogen, or carbon capture and storage will make it difficult to reach net zero emissions by 2050, unless there is an unforeseen technological breakthrough. Even RES-E, which has seen the most successful scale up to date is still far from being on a trajectory to full decarbonisation, which will become increasingly difficult since it will need either significant negative emissions and/or effective incentives for delivering far more short-term and longer-term energy storage, which returns to our central focus on flexibility.

To conclude, the electricity supply sector and electricity-based end-use technologies are crucial for deep decarbonisation. Other low-carbon sources such as biomethane, hydrogen, synthetic e-fuels, and BECCS will also play a role. We find that temporal and spatial flexibility are required to fully decarbonise the European energy system by 2050. This involves investments in electricity networks and cross-border interconnections for the aggressive rollout of renewables, which will lead to increased cross-border trade in electricity with larger transmission capacity than natural gas in 2050. Hydrogen storage and green hydrogen production can provide inter-seasonal flexibility. Lastly, the role of hydrogen networks and storage will increase, while the need for natural gas networks and storage will decrease in high decarbonisation scenarios.

Contact kc3634@columbia.edu
Publication February 2023
Financial Support CERRE