ASSESSING ALTERNATIVE END-USE TECHNOLOGIES FOR ECONOMY-WIDE DECARBONISATION

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Overview

The path towards economy-wide net-zero greenhouse gas emissions involves a complex competition among various technologies to decarbonise end uses in economically sustainable ways. While battery electric vehicles (BEVs) and electric heat pumps (HPs) appear the favoured options for future road mobility and building heating applications, respectively, other sectors feature more uncertainties in the competition, without a single dominant technology. For example, medium- and high-temperature industrial heat generation, where heat pumps face limitations, may involve boilers fed by gaseous fuels (such as biogenic or synthetic methane and hydrogen) as well as electric boilers. Similarly, in primary steelmaking, hydrogen-based direct reduction of iron (DRI) competes with methane-based DRI coupled with carbon capture and storage (CCS). Each alternative is characterised by different advantages and drawbacks, with no clear technological winner. In addition, the choice of one technology over another can have substantially different impacts on the broader energy system, highlighting the need for a comprehensive approach to support informed decision-making. Within this framework, this work uses an integrated energy system model that endogenously optimises the choice of end-use technologies to investigate the technological alternatives that should be prioritised to achieve economy-wide decarbonisation. Looking at the case of Italy, the analysis explores both cost-optimal and near-optimal solutions, offering a deeper understanding of the interactions between different technology alternatives. The approach enables the identification of the implications that different choices in demand technology adoption have on the broader energy system, providing a wider perspective for informed decision-making.

Methods

This study uses the bottom-up integrated energy system model OMNI-ES [1], which features the endogenous optimisation of the selection of demand technologies. Given the final demand of a certain sector (e.g., km travelled for road mobility) and a set of alternative options (e.g., BEVs, fuel cell electric vehicles - FCEVs, and internal combustion engine vehicles - ICEVs) together with the related techno-economic data (including specific fuel consumption and capital expenditures), the model solution determines the technology portfolio that meets such demand at lowest total system cost. This feature is implemented for all the sectors that feature relevant technology competition, as graphically summarised in Figure 1. The analysis is extended to explore the near-optimal decision space, developing a Modelling to Generate Alternatives (MGA) [2] approach that allows to generate diverse solutions with different choices in end-use technology adoption, constraining the total annual cost to remain within a 5% threshold of the optimal solution.

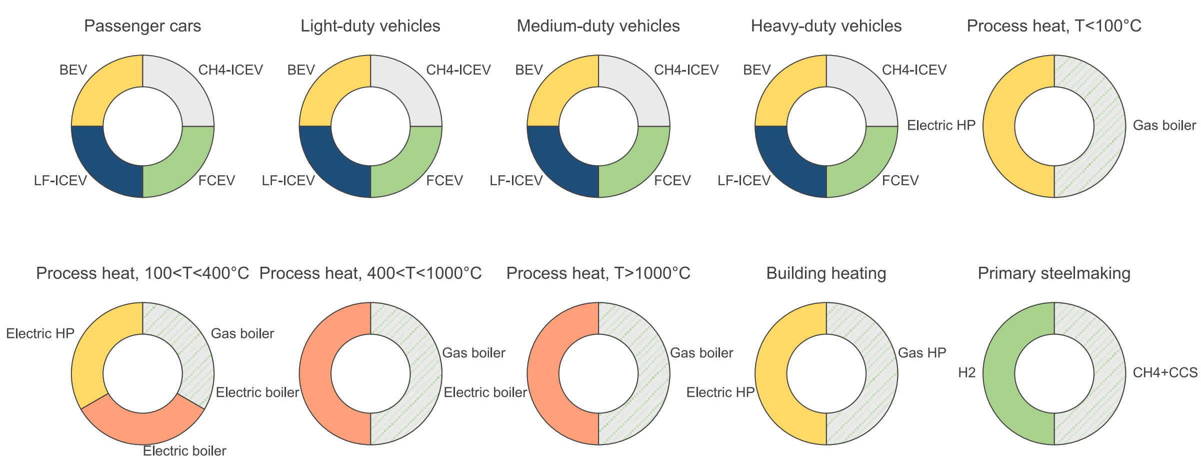

Figure 1. Set of technological alternatives in each end use. 'LF' stands for 'liquid fuel', indicating a generic C-based fuel of fossil, biogenic, or synthetic origin.

Results

The analysis looks at a long-term scenario for Italy, considering the achievement of net-zero CO_2 emissions (taking into account direct emissions and supply-chain related ones for imported vectors). Results show that a variety of configurations are available to achieve net-zero emissions cost-effectively, graphically reported in Figure 2. In road mobility, BEVs tend to dominate as the preferred technology, as their adoption is maximised across a wide range of near-optimal solutions. However, a variety of balanced solutions exist with BEV adoption ranging from 40% to 60% in passenger cars (with an exogenous limit of 75%), and from 18% to 60% in light-duty vehicles (with an exogenous limit of 60%). Fuel cell electric vehicles emerge as the next-best alternative, frequently replacing BEVs entirely when their adoption is reduced to zero. Configurations with 100% adoption of liquid fuel (LF)-ICEVs are present for medium- and heavy-duty vehicles. In process heat generation, gas boilers fed with a blend of methane and hydrogen are competitive, but there are many solutions where electric boilers are adopted, occasionally covering up to 100% of the demand. A similar dynamic is observed in primary steelmaking, where the competition between H_2-based and CH_4-based DRI technologies is evident. In the building heating sector, gas-based systems show moderate adoption, peaking below 65%.

Figure 2. Near-optimal decision space for demand technology adoption. Red lines indicate exogenous upper boundaries.

Conclusions

This work highlights the potential for flexible strategies in achieving economy-wide decarbonisation, allowing adaptation to resource availability, infrastructure constraints, and policy priorities. While certain end uses exhibit clear technological preferences, others are characterised by strong competition, leading to a diversity of technically feasible and cost-efficient solutions. Road transport falls into the first category, with BEVs emerging as the dominant option. FCEVs are often prioritised if electrification is constrained, while LF-ICEVs maintain some competitiveness in heavy transport. Similarly, electric heat pumps consistently outperform gas-based systems in building heating. In contrast, medium- and high-temperature industrial heat and primary steelmaking lack a clear technological dominance. Accordingly, decisions in these sectors should consider the impacts on the broader system. Specifically, electrification increases the need for battery storage and firm generation capacity, while hydrogen deployment in end uses increases the total electricity consumption of the country and requires adequate storage to manage fluctuations in renewable hydrogen production. Overall, results of this analysis offer decision makers manoeuvring space to identify the most suitable solutions balancing trade-offs between costs, technology adoption, and other strategic priorities, in order to account for the needs of the multiplicity of stakeholders involved in the energy transition towards decarbonisation.

References

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