Decarbonizing Western Europe: Extension of the Model 'EnergyScope MultiCell' for the Analysis of Renewable Fuel Potential

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ABSTRACT

Recent developments in the European Union's energy strategy have highlighted the significance of renewable fuels for the sustainability of the continent's energy system. However, their diverse production methods and end-use possibilities, along with untapped cross-sectoral synergies, call for energy modeling to identify optimal pathways for renewable fuel production and utilization. With hydrogen emerging as a foundational energy vector for these fuels, and recognizing the critical role of energy interconnections in Europe, a hydrogen network has the potential to be a powerful tool in a decarbonized energy system. To comprehend the complex mechanisms driving the energy transition, we analyze the potential roles of each renewable fuel and hydrogen interconnections as we increase CO_2 emission restrictions. This study encompasses the electricity, buildings, transport, agriculture, and industry sectors across Western Europe, employing an hourly time resolution to fully capture the potential of those fuels within a system with high shares of renewables. The analysis employs the EnergyScope MultiCell model, which enables integrated optimization of the energy system, spanning from resource utilization to the selection of end-use technologies. The findings reveal that while renewable fuels entail a substantial increase in system costs, they prove effective in reducing the final 20% of emissions, using 1990 emission levels as a reference. Furthermore, they empower Western Europe to achieve self-sufficiency, even without CO_2 storage. As hydrogen production reaches 3300 TWh, a hydrogen network facilitates the energy transition by reducing its costs by 7.5% (35 b€/year).

KEYWORDS

renewable fuels, sector coupling, energy modeling, climate-neutral, hydrogen network

INTRODUCTION

Aligned with the Paris Agreement's commitment to limit global temperature rise to well below 2°C, the European Union (EU) has set its climate strategy in motion with the European Green Deal, aiming for a net-zero CO_2 emissions EU by 2050. To solidify its dedication to these goals, the EU enshrined them into law through the European Climate Law, along with a newly established target: a 55% reduction in CO_2 emissions by 2030. In response to this milestone, the EU's strategy has evolved with the introduction of the Fit for 55 package.

The Fit for 55 package comprises a series of proposals aimed at revising and updating the EU legislation. Notably, three documents—Alternative Fuels Infrastructure (AFIR), ReFuelEU Aviation, and FuelEU Maritime—highlight the crucial role of alternative fuels in the transport sector, which accounts for over a quarter of the EU's emissions.

After Russia's military aggression in Ukraine, the EU unveiled the RePowerEU plan, seeking to reduce its reliance on fossil fuels from Russia. This plan underscores the urgent need to transition from fossil fuels to renewable alternatives and highlights the necessity for developing hydrogen infrastructure, particularly a pan-European hydrogen network.

Given the anticipated prominence of renewable fuels in the future European energy system, energy modeling becomes essential to ascertain optimal utilization strategies for each fuel. The diversity of renewable fuel production pathways, coupled with distinct suitability for specific end-uses and the complex interactions between energy sectors, necessitates energy system modeling to guide decision-making and determine the most promising pathways.

METHODS

The model used to perform the energy system optimization is EnergyScope MultiCell. It is an energy system optimization model that minimizes the annualized cost of the system while verifying constraints on CO_2 emissions. It ensures the energy balance and the satisfaction of the demands on an hourly basis, which allows for the characterization of systems with high penetration of intermittent energy sources. Although other models such as *Pypsa Eur* [1] [1], *GENeSYS-MOD*[2] [2] can also extensively model cross-sectoral interactions, they adopt a representation based on Final Energy Consumption (FEC) for the energy demand. With that approach, the quantity of each fuel required to fulfill the demand in a given sector is predetermined prior to optimization. This presupposition stems from the assumption that certain end-use technologies will dominate specific domains, while others will not. However, predicting the leading technologies in a future energy system hinges not only on technological attributes but also on regional resource availability, fuel supply chain costs, demand scale, and potential alternative uses of the fuel across sectors. Consequently, making assumptions about fuel types and quantities for end use leads to considerable uncertainties when seeking to determine the optimal system configuration.

A solution to this challenge lies in representing demand using an end-use demand (EUD) framework, as adopted by the *JRC-EU-TIMES* [3] model [3]. EUD signifies the energy or service that directly reaches the consumer. For instance, while the energy consumed by a heat pump to warm a house constitutes the FEC, the actual heat delivered into the building constitutes the EUD. Adopting the EUD perspective enables the consideration of diverse technologies to fulfill this heat demand, including options such as a gas burner, heat pump, or electric heater. Figure 1

[1] https://github.com/PyPSA/pypsa-eur
[2] https://git.tu-berlin.de/genesysmod/genesys-mod-public/-/releases/genesysmod3.0
[3] https://data.jrc.ec.europa.eu/collection/id-00287

illustrates the distinction between the FEC and EUD energy system approaches.

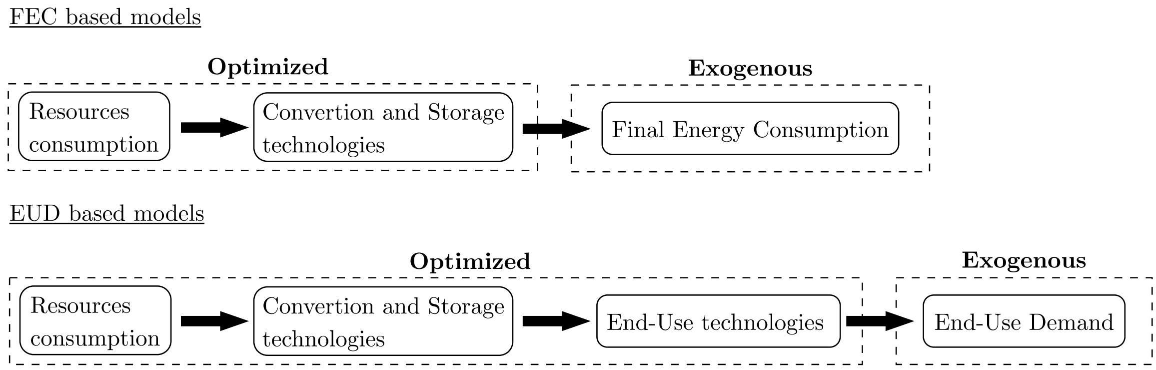
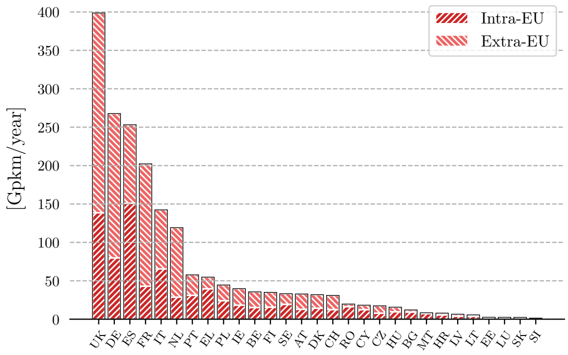
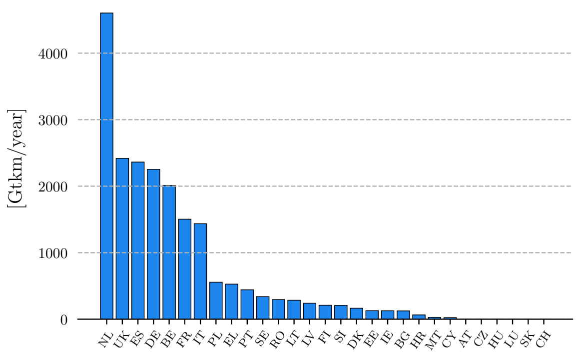


Figure 1: FEC versus EUD based energy models.

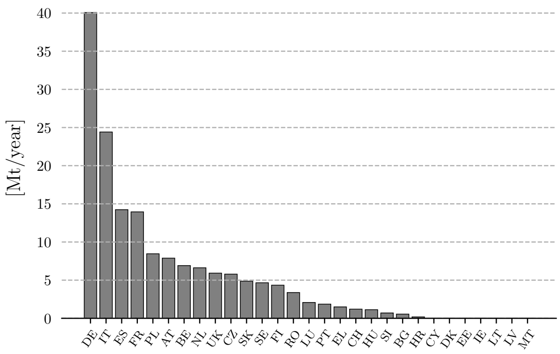
To analyze the role of renewable fuels in decarbonized scenarios, it is imperative to consider the sectors of maritime and aviation transport, but also the steel industry, which sees hydrogen as a pivotal technology for the decarbonization of its hard-to-abate underlying processes. To that end, EnergyScope has been extended to consider these demands, represented in Fig 2. They have been obtained using the open-source databases of Eurostat, the EU reference scenario 2020, Eurocontrol, and the European Steel Association. Data for all the European countries have been gathered for future use in the model, but only a part of them have been used and aggregated for this analysis, which considers the regions presented in Figure 3



(a) Aviation



(b) Freight shipping



(c) Steel production

Figure 2: Demands included in EnergyScope MultiCell.

Figure 3: Aggregated regions considered in the model.

Besides the addition of these demands, additional conversion technologies used to supply the different renewable fuels have been included in the model. A diagram representing the renewable fuels production pathways in EnergyScope is shown in Figure 4.

A summary of the demands and technologies added to the model is presented in Figure 5. End-Use technologies are technologies used to satisfy the newly added demands.

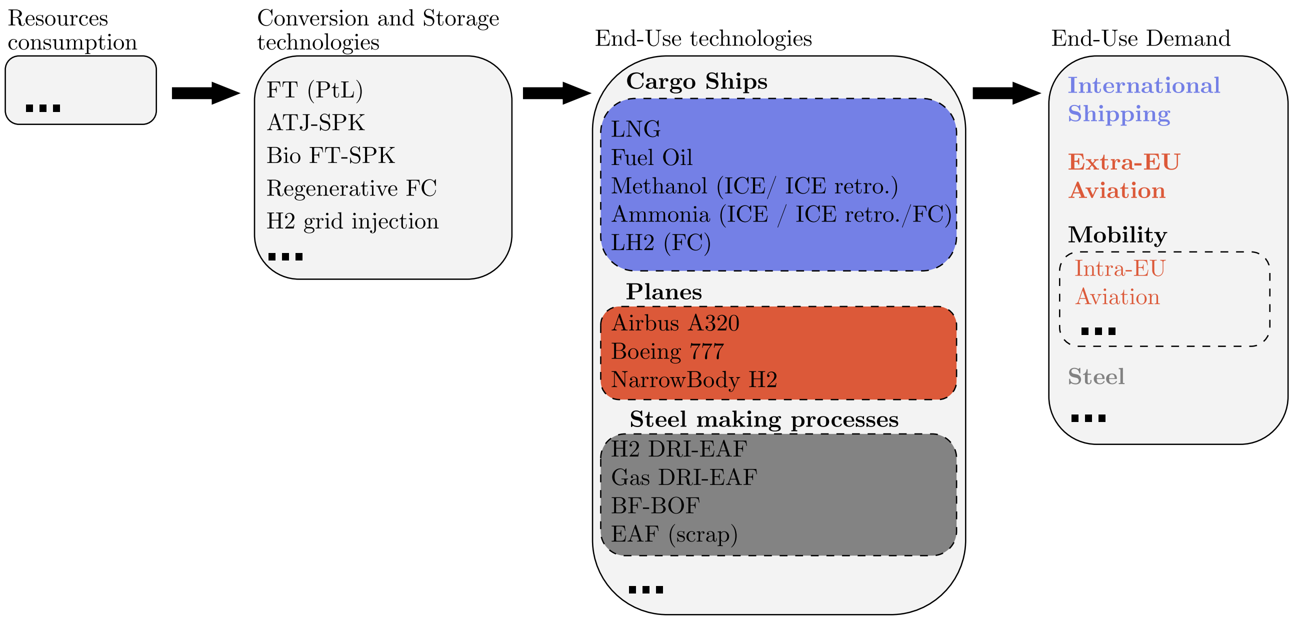


Figure 5: Summary of the technologies and demands integrated into EnergyScope MultiCell.

CASE STUDY

The simulations are performed with the objective of understanding the impact of renewable fuel utilization in a decarbonized energy system. In these scenarios, imports of fossil resources are permitted, while imports of renewable resources like hydrogen or ammonia are not. This approach is motivated by the goal of analyzing Europe's potential to meet its demand with renewable sources in a self-sufficient manner, compared to previous and current fossil-based energy supply approaches.

The reference scenario corresponds to a net-zero emissions case. Negative CO_2 technologies are not included in the model, as coherent CO_2 storage capacities are not yet assessed and integrated into the model. The aim is to identify more complex but useful mechanisms for reducing EU emissions, considering the uncertain characteristics of future CO_2 capture technologies. Besides, this is in continuity with EnergyScope MC's philosophy of not considering CO_2 negative emissions technologies.

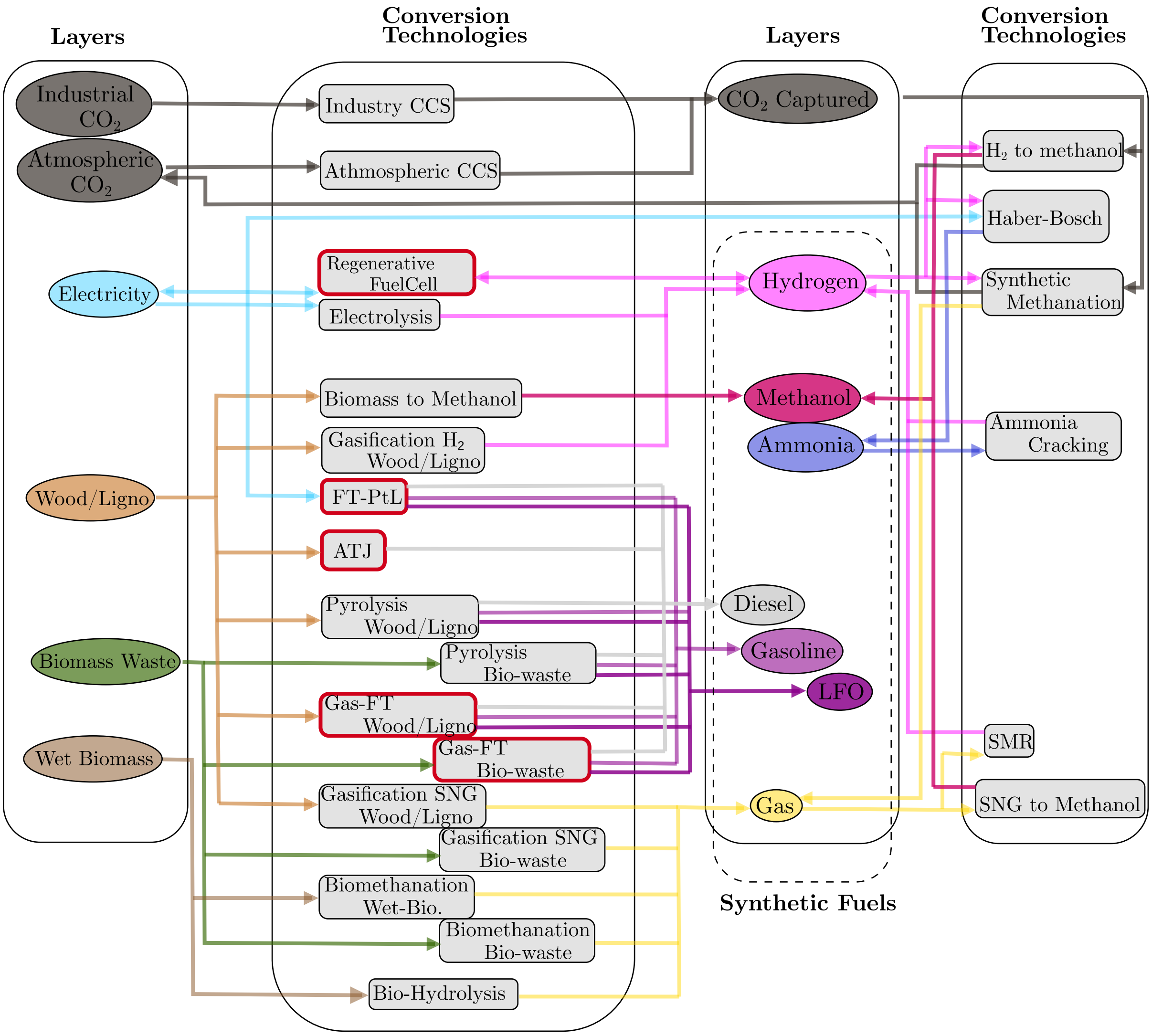


Figure 4: Summary of the implementation of synthetic fuels layers and related conversion technologies. Newly added technologies are highlighted in red. The figure also includes CO_2 management. Abbreviations: Steam Methane Reforming (SMR), Light Fuel Oil (LFO), Fischer-Tropsch (FT), Power to Liquid (PtL), Alcohol to Jet Fuel (AtJ), gasification + Fischer-Tropsch (gas-FT), Synthetic Natural Gas (SNG), Carbon Capture and Storage (CCS).

RESULTS AND DISCUSSION

System Design

Figure 6 illustrates the Sankey diagram for the reference scenario, showcasing the layers, technologies used, end-use demands, and the connecting fluxes.

To get rid of CO_2 emissions, massive electrification of the system is required. Electricity, produced in the majority by solar and wind technologies, is not only needed for direct use in the mobility and heating sectors but also as the primary energy source for methanol, ammonia, and synthetic fuel production. Hydrogen is also heavily required as an intermediate energy vector for the production of these fuels but is also directly used in road freight transportation. It is also used in steel production and aviation to a lesser extent. Electricity is massively produced from solar and wind technologies, and from nuclear, hydro and geothermal power plants to a lesser extent. Biomass is largely used for the production of methanol and methane.

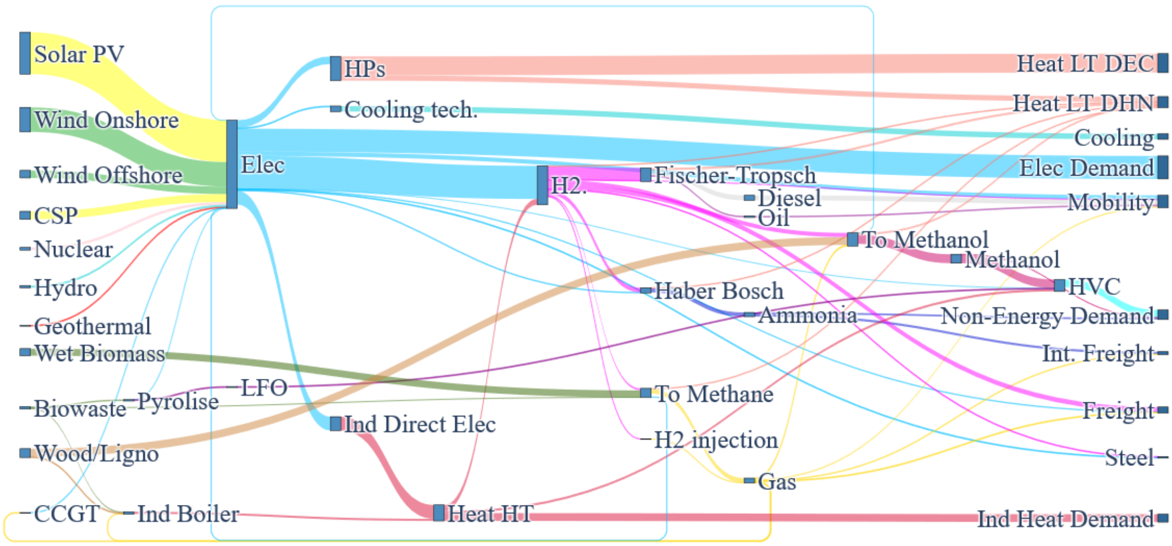


Figure 6: Sankey diagram for the yearly operation of the global optimized system, with net 0 CO_2 emissions. Technologies with similar outputs are grouped together. Abbreviations: International maritime Freight (Int. Freight), Low-Temperature Decentralized Heat (Heat LT DEC), District Heating Network (DHN), High-Value Chemical (HVC), Combined Cycle Gas Turbine (CCGT), Industrial Boiler (Ind. Boiler), High Temperature (HT), Concentrated Solar Power (CSP), Light Fuel Oil (LFO), Heat Pumps (HPs).

Cost of the energy transition

The previous section emphasizes the necessity of ambitious electrification targets, which entails investments in renewable electricity production technologies, conversion technologies, and suitable end-use technologies. Additionally, it requires enhanced storage capacities and robust grid infrastructures to accommodate intermittent energy sources. This section aims to highlight the sectors requiring the most significant investments to achieve electrification targets. It also seeks to develop an understanding of CO_2 mitigation options, their effectiveness in reducing emissions, and their cost-effectiveness.

Figure 7 illustrates the evolution of system costs in b€/year, encompassing discounted investment costs and annual operation and maintenance costs, as CO_2 emissions decrease. This figure serves as a foundation for comprehending various system design possibilities and their implications on emissions and costs.

The cost trajectory can be divided into two segments: from 0 to 50%, 50% to 85%, and 85% to 100% reduction. The cost increase in the first segment is relatively small, while it is much more substantial in the second and the third. In the initial segment, the reduction in CO_2 emissions is achieved by substituting coal-based electricity production with renewable and gas-based electricity. This design change allows for abating 50% of the CO_2 emissions with almost no cost implications. It does not constitute true electrification, as total electricity production remains relatively unchanged. However, it should be noted that heat pumps are used from the start of decarbonization and the evolution of home heating electrification is therefore not captured. The system electrification and the take-off of the direct use of hydrogen take place in the second segment, during which electricity production increases by 1880 TWh. The third phase marks the extensive use of hydrogen-derived fuels. These fuels could contribute to abate 20% of the EU emissions but their use would contribute largely to the price of the energy transition. Finally, a hydrogen network used along with renewable fuel use could decrease the cost of the energy transition by 7.5% (35b€/year).

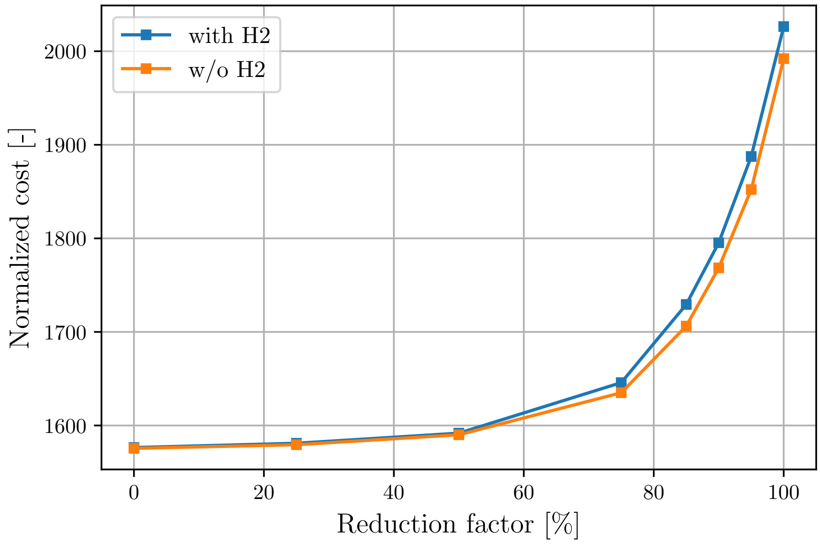


Figure 7: Evolution of system total price with increasing percentage of CO_2 emissions reduction, compared to 1990.

Figure 8 provides insights into the sectors most impacted by the decarbonization process. Transitioning from 0 to 100% emission reduction results in a system cost increase of 417 b€/year in the reference scenario. The distribution of costs across sectors and infrastructures is illustrated in the figure.

The shift of electricity production towards renewable technologies necessitates 341 b€/year. These technologies rely on intermittent energy sources, thus requiring grid reinforcement and storage facilities, contributing to an indirect cost of 191 b€/year. Conversion technologies play a role in transforming electricity into energy vectors suitable for challenging-to-electrify sectors, such as aviation, maritime, and non-energy sectors. Electrolyzers, Haber-Bosch, Sabatier plants, and other conversion technologies contribute to a 154 b€/year increase in the system cost. Subsequent to electrification, the mobility and heating/cooling sectors transitioned to more expensive but efficient technologies, including hydrogen fuel cells and electric vehicles. Additionally, reducing fossil fuel imports enables regions to save 322 b€ per year when comparing the two scenarios.

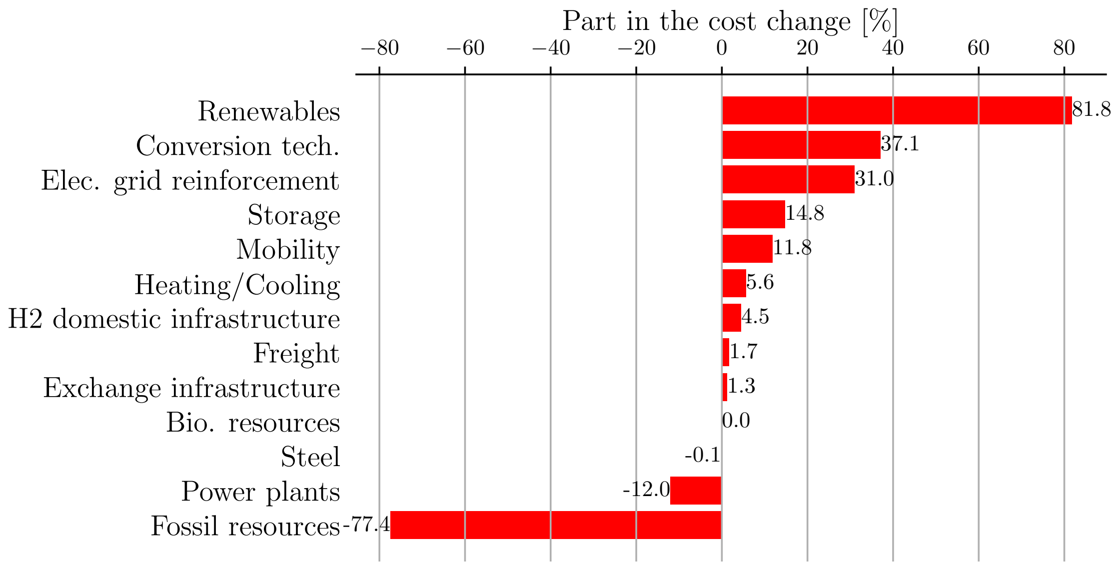


Figure 8: Allocation of system cost difference between 0% and 100% CO_2 emissions, categorized by groups.

An alternative approach to understanding the impact of CO_2 emissions reduction is to examine the cost of eliminating the final ton of carbon dioxide from the system to attain the emission target. In the optimization problem, this cost is viewed as the dual value of the CO_2 constraints:

$$\forall\, c \in \text{REGIONS} \tag{1}$$
$$CO^c_{2,\text{ emissions}} \leq CO^c_{2,\text{ emissions, max}}$$

The dual value of these constraints, one for each region c, represents the change in the objective function (i.e., global system cost) when $CO_{2,\text{ emissions, max}}$ is incremented by one ton in the considered region. Conversely, the cost of decreasing $CO_{2,\text{ emissions, max}}$ by one ton—the price of the last ton of CO_2 before reaching the reduction target—is the opposite of this value.

The cost of the final ton of CO_2 to achieve a specified emission target can be linked to the price of CO_2 quotas in the ETS trading system. This cost reflects the expense of decarbonizing the most expensive sectors necessary to meet the target, directly tied to the price of quotas that should be applied to motivate these sectors to invest in decarbonization.

Figure 9 depicts the cost of eliminating the last ton of CO2 in each individual country. Costs across regions are relatively comparable, showing that under this design, every country undergoes the same level of difficulties to abate CO_2 emissions relative to the renewable potential that they possess. If energy transfers between countries were to be limited, central Europe would see its CO_2 abatement cost significantly increase.

The pronounced cost increase aligns with findings that the last 10% of decarbonization will be the most challenging due to the adoption of emerging, costlier technologies to address the remaining small fraction of demand not yet decarbonized [4]. These technologies, such as ammonia fuel cells for international maritime shipping, hydrogen-to-methanol plants, and processes for synthetic fuel production, emerge between 85 and 100% emissions reduction, as seen in Figure 10. In addition to conversion technologies, the demand for storage significantly rises toward the conclusion of decarbonization, further contributing to escalating costs, as presented in Figure 11. The price of CO_2 for net zero emission scenarios reported by Victoria et al. [5] ranges between 300 and 400 €/ton, lower than the presented values. This discrepancy can be attributed to the absence of Negative Emission Technologies (NETs) in this analysis.

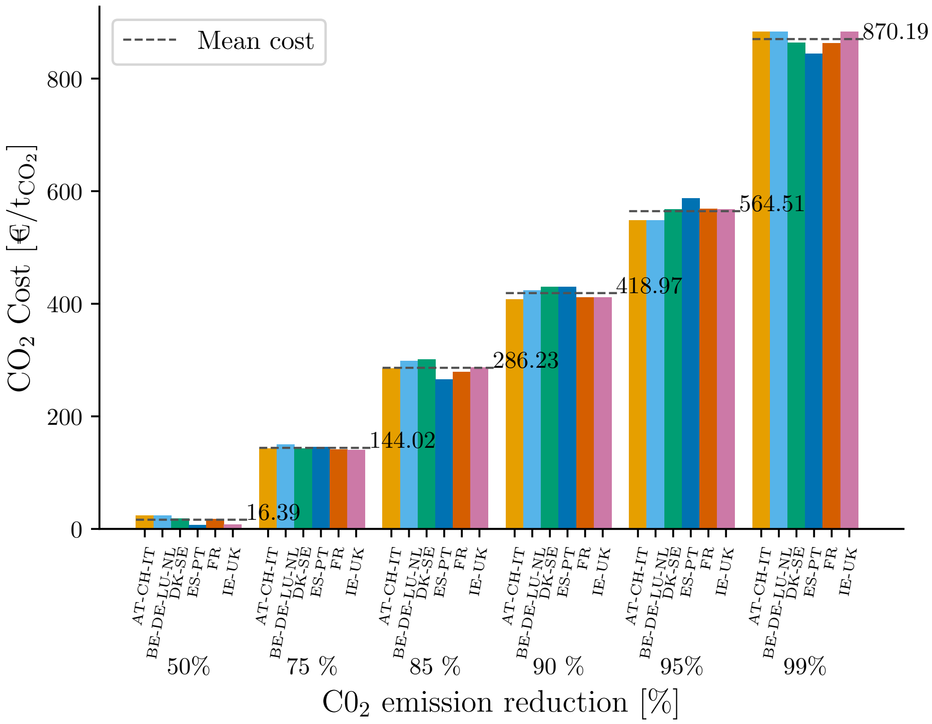


Figure 9: Cost of a ton of CO_2 as a function of emissions reduction compared to 1990 levels.

Hydrogen use

In terms of consumption, hydrogen predominantly serves as an intermediate chemical, facilitating the production of other energy vectors, as shown in Figure 10. It is a key input for methanol production within the chemical industry, ammonia production for international maritime shipping and agriculture, and for the production of synthetic fuels used in aviation. Hydrogen is also directly used in road freight transportation, the steel-making process, and, to a lesser extent, aviation. Towards the latter stages of decarbonization, hydrogen contributes to methane production.

Direct hydrogen utilization amounts to 670 TWh/year, while hydrogen exchanges between countries account for 968 TWh/year. Overall, hydrogen production reaches 3300 TWh annually. This projection surpasses predictions from most existing models analyzing the net zero scenarios for the EU-28. For instance, projections from the McKinsey Institute, the FitFor55 package, and the JRC TIMES model estimate demand at 1700, 1400, and 1250 TWh/year, respectively [6].

The Hydrogen Backbone consortium and the Pypsa-Eur model estimate higher demands of 2750 TWh/year [7] and around 2500 TWh/year [1], respectively. EnergyScope's projected demand, even for a sub-part of the EU, significantly exceeds these predictions. This difference is attributed to the extensive use of hydrogen-derived fuels in international shipping, agriculture, and the chemical industry, as well as the direct utilization of hydrogen for freight transportation. The optimization algorithm identifies end-use technologies and pathways utilizing hydrogen-derived fuels, offering a clean and efficient approach to fulfilling energy demand while addressing storage and flexibility requirements.

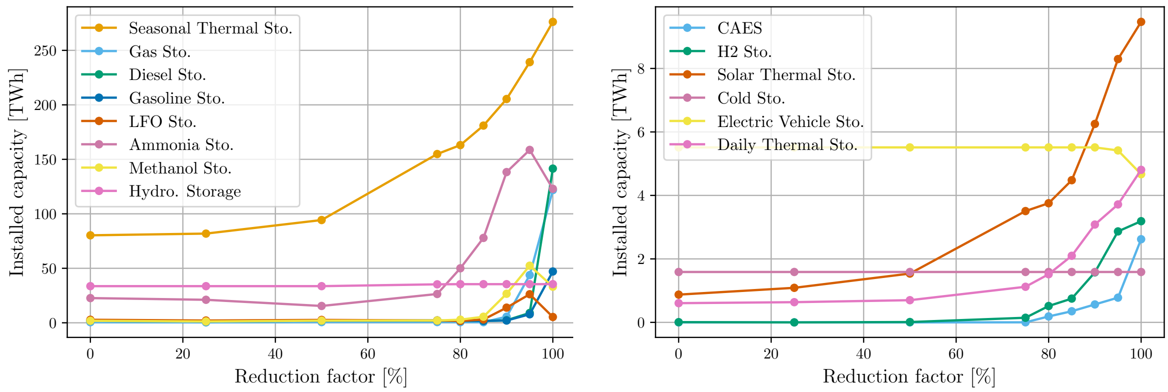
Figure 10: Hydrogen production methods and consumption sectors.

Storage Technologies

Energy storage plays a pivotal role in energy systems by enabling the storage of surplus power during peak production periods and releasing it during periods of high energy demand. This capability enhances the integration of intermittent energy sources into the grid.

Figure 11 illustrates the increase in installed capacity of various energy storage technologies throughout the decarbonization process. While certain storage types are better suited for long-term storage purposes, others excel at mitigating intra-day energy production fluctuations. Thermal storage plays a critical role in both seasonal and daily timescales. Notably, the depicted hydrogen storage capacity is lower than the values found in [1]. This discrepancy is attributed to the consideration of only steel tank storage in the present analysis, which is approximately three times costlier than underground storage. Interestingly, the demand for storage, particularly of the chemical type, intensifies after reaching the 80% emissions reduction threshold. This shift is influenced by declining firm electricity production, increased integration of intermittent energy sources, and the expanded production of renewable fuels. A similar trend is observed in [8]. Finally, stationary lithium batteries are not installed in the system, consistent with the scenario presented in [9], which considered optimal transmission capacities between countries.

It is important to highlight that the conversion of electricity into other energy vectors is unidirectional. Very limited energy is converted back into electricity, as the system does not deploy hydrogen fuel cells. Moreover, Combined Cycle Gas Turbines (CCGTs) are only constructed in central Europe, totaling 78 GW to generate 51 TWh of electricity from renewable gas.



(a) Long-term storage *(b) Short-term storage*

Figure 11: System daily and seasonal storage capacities as a function of the decarbonization ratio.

CONCLUSION

This study has illustrated that Western Europe has the potential to achieve self-sufficiency in meeting its energy demands with net-zero CO_2 emissions, driven by strong synergies across various energy sectors. This achievement remains attainable even under conservative assumptions regarding energy exchange capacities between countries and without relying on negative emissions technologies. However, reaching such ambitious decarbonization goals comes at a substantial cost, with an increase of 417 billion euros per year compared to the optimal system design with 1990 emission levels. Furthermore, the associated cost of CO_2 abatement for achieving 100% decarbonization reaches 870 euros/ton_{CO_2}, significantly surpassing the current price of approximately 90 euros and the projected price of 300 euros for net-zero emissions in [5].

Renewable fuels play a pivotal role, particularly in the latter stages of decarbonization (above

80%), effectively addressing emissions in challenging sectors. Their utilization results in a substantial increase in system costs due to the adoption of expensive conversion technologies, aligning with the concept of the ”last 10%” described in [4]. Biomass and hydrogen contribute significantly to renewable fuel production processes, accounting for 33% and 67% of the processes' inputs, respectively.

The transformation of electricity into other energy vectors exhibits a one-way process, with minimal reconversion back to electricity, barring a few exceptions such as Compressed Air Energy Storage (CAES). Static batteries are not employed for electricity storage. Instead, long-term storage predominantly encompasses thermal and chemical storage solutions. Short-term storage primarily comprises thermal storage and hydrogen storage technologies.

Furthermore, hydrogen utilization is predominantly focused on its conversion into other energy vectors, accounting for 80% of its applications. Additionally, hydrogen serves direct applications in road freight transportation and steel-making, with a direct consumption of 670 TWh per year. Facilitated by its interregional exchange, hydrogen plays a pivotal role in reducing the overall system cost, with 968 TWh of annual energy exchange. This contribution notably stems from enabling the adoption of energy-efficient technologies in challenging-to-decarbonize regions. Overall, the total annual hydrogen production for Western Europe alone reaches 3300 TWh, surpassing many scenarios in the literature.

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NOMENCLATURE

Acronyms	
EUD	End-Use Demand
FEC	Final Energy Consumption
EnergyScope MC	EnergyScope Multi-Cell
HVC	High-Value Chemical
NED	Non-Energy Demand
LFO	Light Fuel Oil
LNG	Liquified Natural Gas
LH2	Liquified Hydrogen
HEFA-SPK	Hydro-processed Esters and Fatty Acids Synthetic Paraffinic Kerosene
AtJ	Alcool to Jet
FT	Fischer-Tropsch
FC	Fuel Cell
EAF	Electric Arc Furnace
DRI	Direct Reduced Iron
BF-BOF	Blast Furnace-Basic Oxygen Furnace
PtL	Power to Liquid
CSP	Concentrated Solar Power
CCGT	Combined Cycle Gas Turbine

REFERENCES

[1] F. Neumann, E. Zeyen, M. Victoria, and T. Brown, "The potential role of a hydrogen network in europe," *Joule*, vol. 7, no. 8, pp. 1793–1817, 2023.

[2] K. Hainsch, T. Burandt, C. Kemfert, K. Löffler, P.-Y. Oei, and C. von Hirschhausen, "Emission pathways towards a low-carbon energy system for europe: a model-based analysis of decarbonization scenarios," 2018.

[3] S. Simoes, W. Nijs, P. Ruiz, A. Sgobbi, D. Radu, P. Bolat, C. Thiel, and S. Peteves, "The jrc-eu-times model: Assessing the long-term role of the set plan energy technologies," 2019.

[4] T. Mai, P. Denholm, P. Brown, W. Cole, E. Hale, P. Lamers, C. Murphy, M. Ruth, B. Sergi, D. Steinberg, *et al.*, "Getting to 100%: Six strategies for the challenging last 10%," *Joule*, vol. 6, no. 9, pp. 1981–1994, 2022.

[5] M. Victoria, E. Zeyen, and T. Brown, “Speed of technological transformations required in europe to achieve different climate goals,” *Joule*, vol. 6, no. 5, pp. 1066–1086, 2022.

[6] D. Tarvydas *et al.*, “The role of hydrogen in energy decarbonisation scenarios,” 2022.

[7] A. Wang, J. Jens, D. Mavins, M. Moultak, M. Schimmel, K. V. D. Leun, D. Peters, and M. Buseman, “Analysing future demand, supply, and transport of hydrogen - executive summary,” 2021.

[8] M. Victoria, K. Zhu, T. Brown, G. B. Andresen, and M. Greiner, “The role of storage technologies throughout the decarbonisation of the sector-coupled european energy system,” *Energy Conversion and Management*, vol. 201, p. 111977, 2019.

[9] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner, “Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable european energy system,” *Energy*, vol. 160, pp. 720–739, 2018.