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Multiple Roles of Hydrogen in Future Mobility

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Sustainability and GHG reduction are the pivotal points of any future mobility. The European policymakers prioritised the BEV technology from 2035 onward. This decision was based on the universal consensus that the BEV technology offers the highest efficiency and that sufficient green energy will be available on time. In this study, the authors will analyse the feasibility of this concept. Due to the stochastic availability of renewable power, a reliable power supply requires adequate storage capacity at the necessary scale and time. The other universal statement is that the production of e-fuels is too inefficient to compete with BEV technology. Based on different publications, the authors are convinced that only chemical storage can fulfil the requirements nationally or globally. The inevitable first step of this energy conversion is water electrolysis, energised by renewables. The losses occurring during the production of green hydrogen are an unavoidable burden on green electricity production. Due to the availability of the produced hydrogen, these losses do not count toward producing e-fuels like methanol, methane, and ammonia. In that case, the baseline of any efficiency comparison alters, and alternative and e-fuels will severely challenge the BEV technology in multiple applications and locations. These fuels will allow further improvements in the ICE technology. The most important finding of this study is that the investigation of separated sub-systems will not deliver the optimum solution for mobility. Only a holistic approach considering the interactions between power generation, power storage, and propulsion technology leads to reliable answers, and hydrogen is the key element of the solution.

1. Introduction

Reducing greenhouse gases (GHG) is one of the projects humankind has prioritised the most. Considering the continuously growing GHG emissions (Tiseo, 2024), it is among the least successful. What are the reasons for the disappointment? In Europe, the status quo is that BEV technology energised by renewables offers the most efficient and lowest carbon solution. This paper will analyse the weak points of decision-making. In many cases, the numbers used for decision-making have limited meaningfulness, such as the tank-to-wheel approach of the European Union. The "Energiewende" (energy turnaround) delivers an excellent opportunity to analyse the challenges of integration of renewables into the existing power grid. The authors investigate the validity of the most complex standardised Life-Cycle-Assessment (LCA) methodology in compounded systems. (Hanula, 2021) The strategy's dead end can be overcome only with adequate storage capacity. The various storage options must be investigated for capacity, price, and storage time. The roundtrip efficiency of this electricity storage must be considered to determine the carbon footprint of renewables.

And here, hydrogen will play a significant role in future energy systems and will find its way into mobility. There was already a run on hydrogen as a road-transportation fuel in the 90’s. BMW presented its first hydrogen internal combustion engine (ICE) in 1989 (White, 2006), and Daimler and Ford acquired a significant chunk of Ballard Power Systems, the pioneer of hydrogen fuel cells (Smith, 2022). The focus was the immediate abatement of 3 important harmful pollutants (unburned hydrocarbons HC, carbon-monoxide CO, and particulate matter PM) and, in the case of the fuel cell, even nitrous oxides. The other driver was the substitution of oil-derived fuels because of the feared lack of oil resources. Today, the main driver is entirely different! In the meantime, it is known that the exhaustion of oil resources will not prevent GHG-induced climatic change, so alternative propulsion technologies and energy carriers must solve the problem. Since, on a national level, only molecules seem to have enough storage capacity (Bothe, 2018). "This paper contributes to the ongoing

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discourse by critically examining decision-making processes and methodologies, such as the tank-to-wheel approach and the Life-Cycle-Assessment (LCA) in compounded systems, often oversimplified in current policy frameworks. The analysis highlights gaps in integrating renewable energy and storage solutions, particularly in the context of hydrogen's role in future energy systems. By revisiting historical and current hydrogen technologies, the research offers new insights into their potential to improve efficiency and reduce GHG emissions, addressing key issues that have hindered prior solutions." This reopens the discussion of alternative fuels and propulsion technologies.

2. Analysis of the renewable energy supply based on the German energy turnaround

Germany consumed 498 TWh of electricity in 2023 (Electricity Maps, 2024). It equals an average power of 57 GW. The peak energy demand is about 80 GW. The German power generation and storage capacity is 272.4 GW, including the 8,5 GW nuclear power station capacity, which was stopped in 2023 in technically perfect condition. This means that the average load of all energy investments is 21 %. Among all European countries, Germany has the largest renewable capacities; only the solar and wind capacity exceeds 150 GW, see Figure 1.

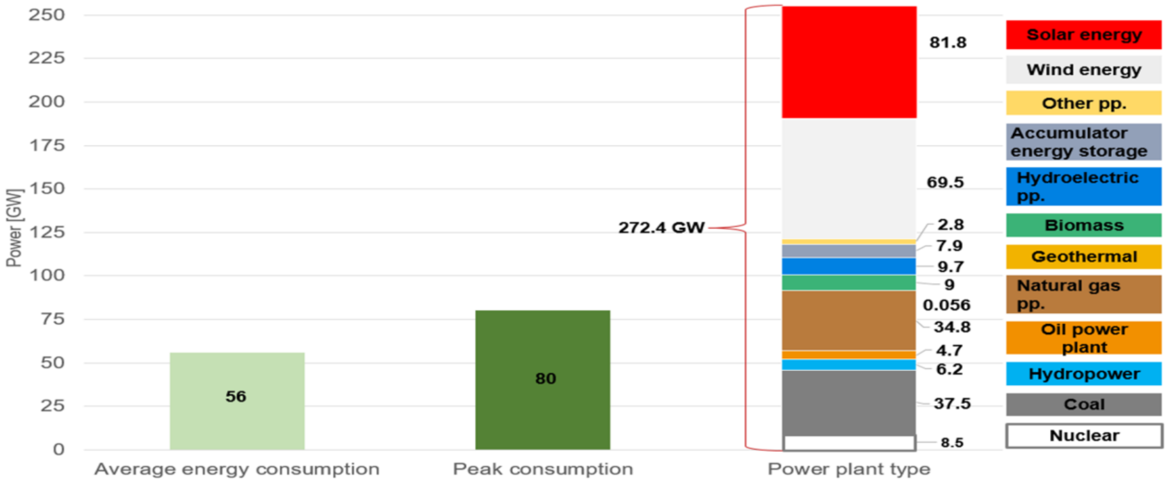

Figure 1: Capacity of German electricity production and storage 2023 (Data source: Electricity Maps, 2024, diagram created by the authors)

Can this capacity be turned into superior low-carbon electricity? Not. Figure 2 shows the average LCA-based CO_2 content of the electricity of all European countries (Electricity Maps, 2024). Only former Eastern European socialist countries have even higher specific CO_2 content in their electricity. Because of the frequency stability, 10-20 GW conventional power stations typically must always run. To cover the peak power demand, roughly 90 GW of dispatchable power capacity is required. It is given together with the existing coal power stations. The issue is that under sunny and windy conditions, more than 100 GW of wind, solar, and biogas capacity is obsolete. During dark doldrums, the necessary coal power pushes the specific CO_2 to value up to 800 g/kWh.

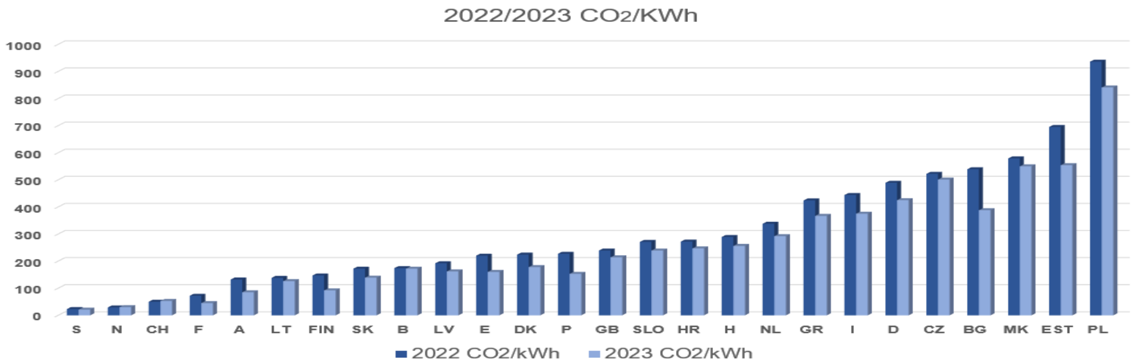

Figure 2: Average CO_2 content of the electricity in Europe (Electricity Maps, 2024)

Figure 3 shows the daily average CO_2 content of German electricity on the 2nd of December 2023. Beyond these accessible and well-known figures, we can understand that even the LCA methodology cannot consider the effect of the wasted money. This lost money has to be replaced by money earned from other businesses, which will only run with GHG emissions. A former study showed that the world average of 1 € GDP contains roughly 500 g CO_2 (Hanula, 2021). Since then, German electricity's true specific CO_2 content has been significantly higher than the widely communicated figures. The whole picture clearly shows that the existing renewable capacity cannot be integrated into the grid without the necessary storage capacity.

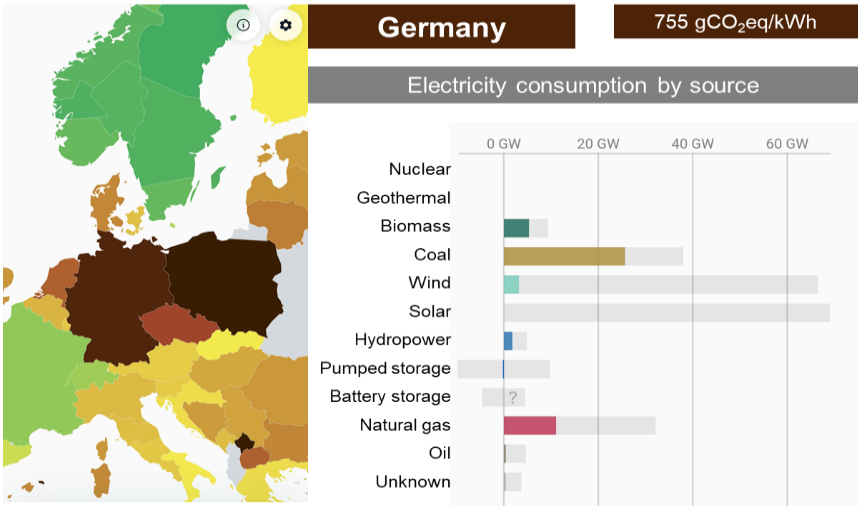

Figure 3: CO_2 content of German electricity on December 2nd, 2023 (Data source: Electricity Maps, 2024, design modified by the authors)

How much storage is required to realise the net zero German plan until 2050? The literature estimates vary from 20 to 40 TWh (Beck et al., 2017; Wind Journal, 2024). Based on these data, the authors apply a mid-case scenario and assume the most probably required storage capacity value to be 30 TWh. Figure 4 shows the required and available capacity (Fraidl et al., 2024).

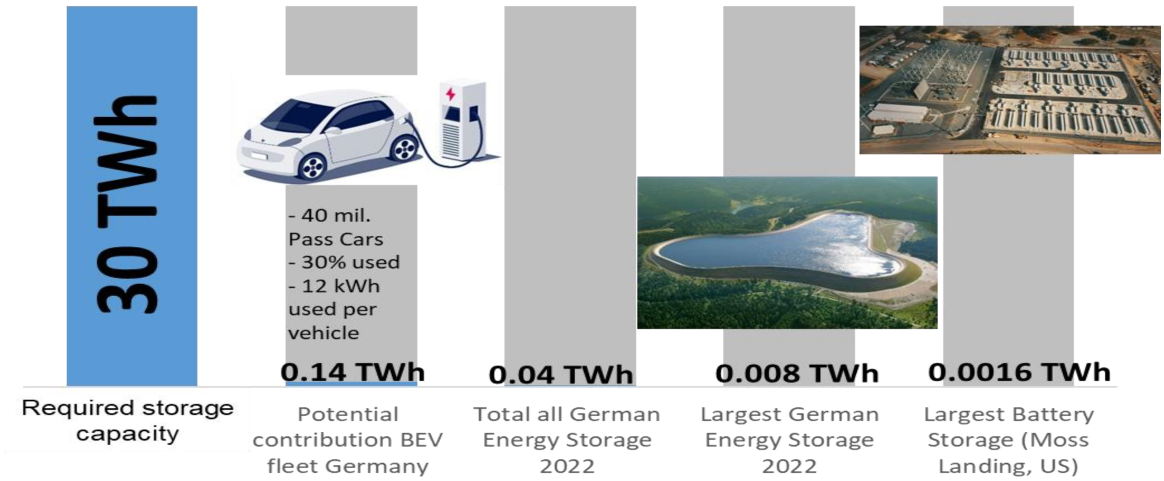

Figure 4: Necessary and available electricity storage capacity in Germany summarised from (Fraidl, 2024, authors)

The message is unmistakable: The existing capacity should be increased by a factor of 750 within a few years. The frequently mentioned "smart grid," i.e., the integration of the batteries of the electric car fleet, would add less than 0.5 % of the required capacity. Even the largest German pumped hydro, the Goldistahl station, offers only 0.008 TWh. Figure 5 (Bothe, 2018) summarises the available technologies. There is no other option for the long-term balancing of the grid than molecules. It is inevitable that water will be split by electrolysis and stored as hydrogen or in a further processed form like methane or methanol, etc.

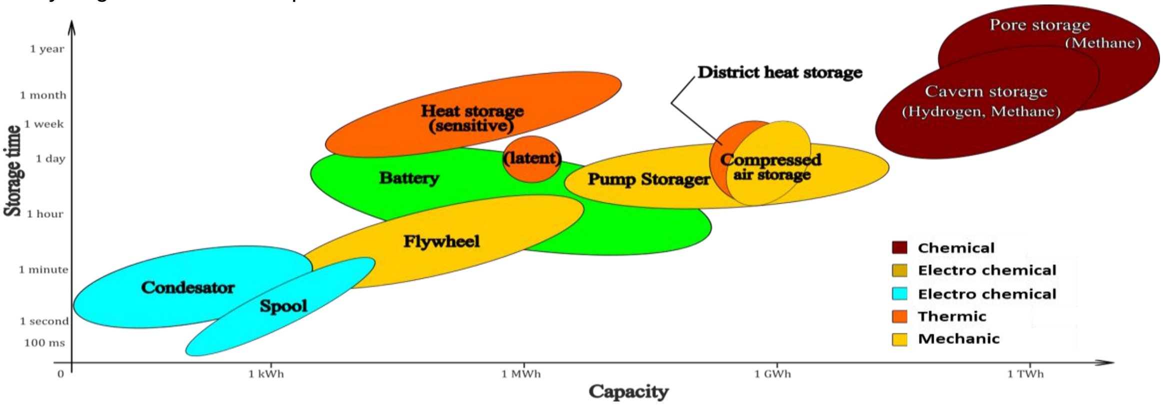

Figure 5: Practicable range of different energy storage technologies (Bothe, 2018)

3. The potential of green hydrogen

Figure 6 shows (Bothe, 2018) a frequently used argumentation that BEV technology is superior to e-fuel technologies. It assumes that renewable electricity can be directly used in the batteries of BEVs, and 69 % of it will be efficiently used for the propulsion of vehicles. The average load will decrease because the net zero vision requires even more renewable capacity to be installed. Under consideration of the finding mentioned above, the authors assumed that 85 % of the harvested renewable electricity must be stored. The storage in molecules includes multiple processes: electrolysis, compression, storage, and reconversion in electricity. The roundtrip efficiency of hydrogen storage based on electrolysis and fuel cell systems is generally around 40 % (Headley and Schoenung, 2022), meaning that approximately 40 % of the energy used to produce hydrogen with electricity can be turned back into electricity. This is somewhat low compared to 70-90 % for Li-ion battery storage, though laboratory hydrogen systems have demonstrated efficiencies as high as 50 % (Headley and Schoenung, 2022). The left side of Figure 9 shows the same efficiency comparison, assuming that 85 % of the renewables must be stored. The applied 40 % roundtrip efficiency is a "best case" scenario; in reality, the losses of the necessary conversion of hydrogen into synthetic methane would further reduce it, and it is hardly imaginable that all the reconversion into electricity will be realised by SOFC fuel cells. It is far more probable that hydrogen or methane will be burned in conventional thermal power stations with a far lower efficiency, as shown in Figure 7 (Ajanovic et al., 2024).

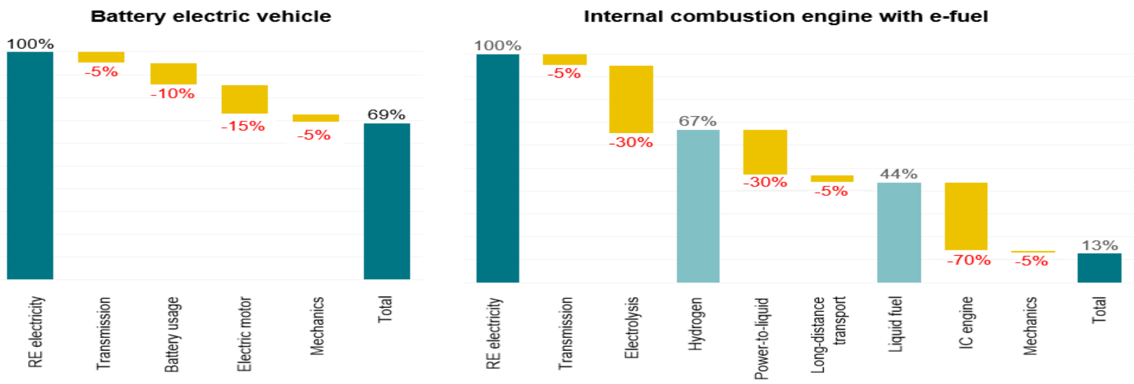

Figure 6: Comparison of the overall efficiency of battery electric vehicles and ICE vehicles running with e-fuel (Bothe, 2018)

The fact that hydrogen will be produced in large quantities unburdens the use of hydrogen or its derivatives in mobility. The logic of the right side of Figure 6 is questionable as well. It is evident that every step of the way from hydrogen to e-fuel reduces the efficiency and improves or eases the usability—for example, green electricity – hydrogen – syngas – Fischer-Tropsch-liquid-fuel. But in reality, it is not necessary to go the whole way! In many applications, the usability of intermittent products (e.g., hydrogen, e-methanol, or e-methane) is comfortable enough that further conversion would not be reasonable. However, according to the location, usage, purpose, and equipment for mobility, green hydrogen is the key to numerous non-battery mobility options. Figure 8 (Kranenburg et al., 2020) shows the diverse e-fuels with or without added carbon.

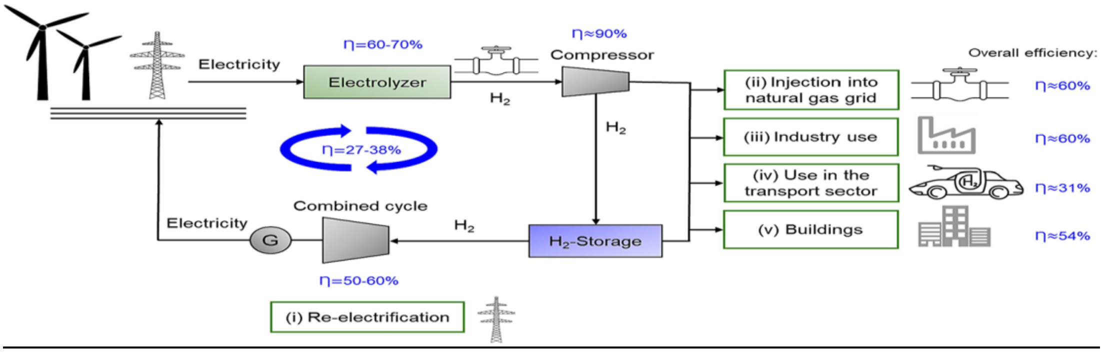

Figure 7: Renewable energy supply system with storage loop (Ajanovic et al., 2024)

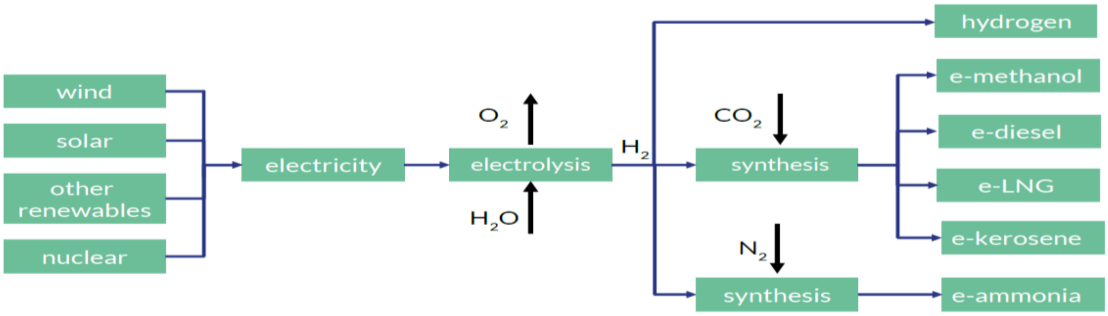

Figure 8: Different pathways of green hydrogen usage in future mobility (Kranenburg et al., 2020)

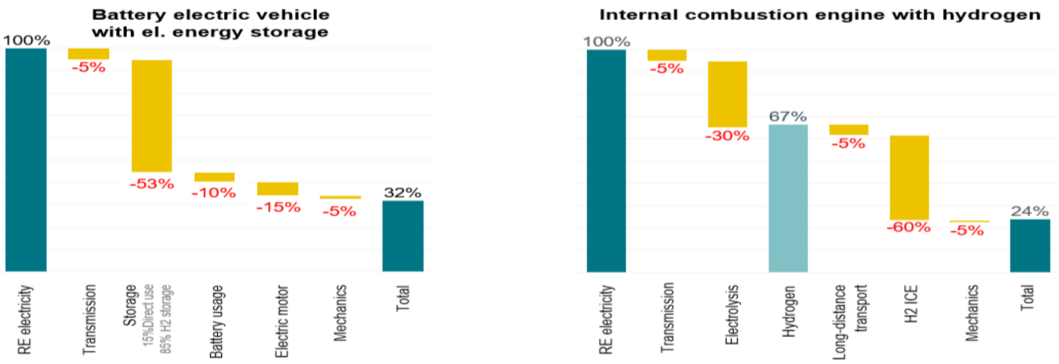

Figure 9: Comparison of the overall efficiency of battery electric vehicles and ICE vehicles running with e-fuel. Assumptions: 85 % of the renewables must be stored; experimental HD-ICE engine e-hydrogen direct injection (Basic figure: Bothe, 2018, further developed by the authors

It must be considered that the efficiency of the combustion propulsion systems is still improving, especially in connection with the possible beneficial properties of e-fuels. During the 45th International Vienna Motor Symposium, Westport and Scania presented an experimental hydrogen engine (Shariff et al., 2024). This engine offers over 50 % peak efficiency in early development stadiums and over 40 % during regular highway operation. The right side of Figure 9 shows the efficiency of such an engine running on e-hydrogen. Green ammonia can improve onboard hydrogen storage and supply efficiency. (Barros et al., 2024) It is unmissable that e-fuels and e-hydrogen will seriously challenge BEV technology.

4. Conclusions

The European political decision-makers and the majority of media are convinced that Battery Electric Vehicle technology combined with renewable electricity is the clear future of nearly all mobility applications. This paper clearly shows that renewable electricity based on solar and wind energy will only be disposable if adequate storage capacity is already built. Under consideration of the magnitude of the amount of energy to be stored and the necessary storage time on a national level, only molecules can offer the required capacity. That means that producing green hydrogen by electrolysis of water is an inevitable first step in energy storage. This strongly relativizes the consideration that renewable electricity directly used in BEVs is superior to all e-fuel applications. These statements ignore the necessity of storage and the relatively low roundtrip efficiency of this in real life. Conversely, the availability of green hydrogen and its derivatives opens attractive opportunities for fuel cell and combustion engine applications.

Nomenclature

BEV – Battery Electric Vehicles
CO – carbon monoxide
CO_2 – carbon dioxide
FCEV – Fuel Cell Electric Vehicles
GDP – Gross Domestic Product
GHG – greenhouse gases
HC – hydrocarbons
HEV – Hybrid Electric Vehicles
ICE – Internal Combustion Engines
LCA – Life-Cycle-Assessment
PHEV – Plug-in Hybrid Electric Vehicles
PM – particulate matter
SOFC – Solid oxide fuel cell

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