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INNOVATION IN THE CENTRAL EUROPEAN AUTOMOTIVE MOBILITY:

THE STRATEGIC NEED OF ADAPTED POLICYMAKING FOR HYDROGEN-ELECTRIC CARS

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ABSTRACT

This dissertation examines the essential policymaking measures for achieving effective hydrogen-powered individual mobility in Central Europe. Three central research questions were formulated, focusing on the essential measures necessary to adopt hydrogen in Central European societies as a private vehicle fuel, followed up by investigating what factors customers value regarding hydrogen and finalized by looking at the development of national key performance indicators based on the aforementioned customer evaluation.

The findings of the literature research indicate that the nations of Central Europe have challenges in achieving effective implementation due to a lack of basic unity. The absence of key elements, such as a unified hydrogen market, standardized regulations for chemical composition, pricing mechanisms, and the presence of resource or governmental subsidies, indicates a lack of fundamental structures in place.

Upon further examination of the demographic of individuals purchasing new automobiles, it has been observed that customers exhibit a preference for the potential benefits offered by hydrogen fuel cell vehicles in comparison to the already established electric vehicles. Specifically, customers are drawn to the anticipated stability of hydrogen prices, which serves as a compensatory factor for the fluctuations in the availability of traditional green energy sources such as wind and solar power. Furthermore, the ecological storage of carbon dioxide-free energy is deemed crucial by these buyers. A subsequent examination of the characteristics of Central European nations, employing a model based on component-based object comparison for the purpose of objectivity, revealed that, contrary to initial expectations, countries like Hungary and Poland, which have faced challenges in transitioning to greener energy sources in recent years, possess the greatest potential for implementing hydrogen-based vehicles in their fleets over the long term. This potential can be realized through comprehensive restructuring efforts, the establishment of specific targets, and the use of quantifiable performance indicators. The steady power price in Hungary has shown that it serves as an optimal foundation for the implementation of emission-free transportation.

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HFC/FCEV – hydrogen fuel cells/fuel cell electric vehicles, vehicle propulsion based on the chemical reaction of hydrogen with oxygen and currently the most "defined" hydrogen powered alternative.

BEV – electric vehicles, that are powered exclusively by a battery-operated electric motor.

COCO - component-based object comparison for objectivity, a quantitative data driven methodological approach of comparing certain entities and variables.

PHEV – Plug-in hybrid electric vehicles, that allow the use of classic combustion engines in combination of batteries. The electric driving is considered to bridge shorter distances and is charged via the engine or via an external power supply unit.

OAM – Object Attribute Matrix of COCO.

OEM – original equipment manufacturer, those businesses in the automotive industry that assemble products using components acquired from suppliers.

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1. INTRODUCTION

The turn of the 21st century witnessed global social and political changes and scientific and technological achievements. Internet services, worldwide infrastructure, and the digital industry 4.0 allow all sectors of the economy to freely exchange data, information, expertise, and seamlessly integrated operations. The first annual worldwide demonstration, implementation, and advertising of regional economic advantages was made feasible by these technologies. Without national borders or trade rules, entrepreneurial processes may thrive and benefit global clientele. The rapid economic growth in major cities created new business prospects.

Increasing urbanisation, as many companies agglomerated in so-called industrial clusters, added the challenge of rising infrastructure needs, which could not keep up. Large cities became so-called megacities, which were confronted with previously unimaginable mobility needs. With increasing prosperity, automobile traffic reached an unprecedented peak (VDA, 2022). Numbers published by the European Union assume a further increase in mobility needs up to a value of 17% until 2030, compared to 2016, with a total increase of 34,4% by 2050 (Siegemund et al., 2017). The resulting ecological effect of emissions always held pace, quickly exceeding the emission tolerances set by the European Union (European Commission, 2022b), as it was seen as the private mobility was seen as one of the crucial sectors for an improvement of environmental conditions (Galarraga et al., 2020; Hammerl et al., 2022). Social impulses such as an improvement in the general standard of living as well as the pressure on producers to assume ecological and ethical responsibility with, at the same time, almost infinite technical possibilities, the new international competition, and the resulting increasing cost pressure force car manufacturers to adapt to the new markets and, if necessary, to make major structural and process changes. In addition, a growth in automobile ownership and use has been linked to major issues such increasing respiratory ailments, hazardous chemical pollutants, traffic noise, and carbon dioxide emissions that contribute to global warming (Nayum et al., 2013), further escalating the need to transform the current concept of mobility.

The hunt for alternative propulsion systems posed an even greater challenge to the industrial sectors of Central Europe. Having invested in automobile technology since its infancy in the previous century, many traditional corporations were caught off guard by the imperative quest for alternatives. Still in its infancy, the development of emission-free driving systems that compensate for societal expenses such as noise and pollutants, therefore giving a sustainable choice for personal transportation. While the current industrial trend is clearly leaning toward electric propulsion, the concept of a diversified energy source that adapts to the needs of the customers, as opposed to the customers adapting to potential shortcomings caused by certain characteristics of energy carriers, should not be undervalued (Siegemund et al., 2017). The demand for effective economic innovation has never been greater than when faced with the maintenance of millions of jobs and an ever-expanding global industrial value chain (A. Buss et al., 2018) with a distinct focus towards environmental standards (Ghadge et al., 2022).

The automobile sector is strongly rooted in the economic, historical, and cultural interconnectedness of Central Europe. As a result of regional differences in the expansion of automobile manufacture and sales, value creation is transferring to emerging markets. Manufacturers' worldwide platform strategies contribute to the urge to localise. Simultaneously, the complexity of automotive goods is increasing, and the inclusion of new technologies, such as software, into automobiles necessitates effective product management and innovation. With the availability of the newest technologies, end-user demands for technical equipment, drive and safety technology increase, but the automotive industry finds it difficult to pass through the higher expenses through higher vehicle pricing (A. Buss et al., 2018).

Automobiles are now subject to multi-step production processes that are only made possible by global supply chains. For instance, the acquisition of rare earths, cobalt, and silicon is only possible through international partnerships. It is essential to acknowledge that these are not produced by the OEMs, original equipment manufacturers, in their home countries, so a growing number of industrial partnerships shoulder the expertise of manufacturing rather than a few companies. Raw materials like lithium, cobalt, nickel, manganese are crucial raw materials necessary for battery manufacturing; rare earth (neodym, terbium, praseidym) are necessary to produce electric motors and other power electronics. Aluminium, zinc, and magnesium are applied in vast amounts for the weight reduction of the chassis to reduce the necessary energy input to move battery operated cars. Further resources are platin, iridium, palladium, rhodium, or yttrium, that all cannot be sourced locally but rather are acquired from countries like Australia, China, Argentina, Chile, Congo or Indonesia. Intermediate products like electronics, chips or semiconductors (Tunisia, Philippines) to independent development of major components such as engines (Hungary) are all integral parts of modern automotive supply chains, indicating the necessity to cooperate globally.

It is more than clear that the skill of designing, manufacturing, supplying, and maintenance is a collective effort involving numerous nations, including but not limited to Germany, Austria, Hungary, and the Slovak Republic. It is evident why they are all heavily committed in the automobile business, given that they are neighbours with diverse skill sets. Consequently, they all follow distinct governing patterns addressing ecological, infrastructural, and mobility considerations compared to nations that have not invested in this area.

However, markets tend to undergo serious change, through internal and external effects. While in the past, products were generalized and could be manufactured globally and sold globally alike, this trend is no longer predominant. Consumer expectations, including but not limited to shared mobility, autonomous driving, electrification, pay-per-use principles, and new market entrants, have never posed greater obstacles to innovation in the automobile sector in Central Europe, owing to its economic strength. (Gao et al., 2016; Türker, 2012). Therefore, instead of solely fiscally motivated outsourcing of all manufacturing stages towards cost-effects, markets need to concentrate more and more on their own distinctive client demands with relation to languages, temperature needs, road and traffic systems, culture, colours and, most importantly, mobility demands such as distance, refuelling and environmental standards.

Several significant numbers in 2019 may be used to demonstrate the significance of the automobile market for the whole EU internal market. In 2012, the European Union's manufacturing sector employed 7.6% of the entire workforce, or about 2.3 million people (ACEA, 2015). This number solely covers those workers who are employed directly by the automakers. The 800,000 workers in the car industry' service division are included to this number.

2. SYSTEMATIC LITERATURE REVIEW

2.1 Definitions and theoretical background

There is no globally standardised definition of the word innovation, despite the fact that the notion of innovation seems apparent in the news. Due to the diverse aspects of innovation based on distinct political, economic, and cultural perspectives, no generalisations can be formed about the development of innovation (Faunce, 2012). Locally prevalent laws and existing infrastructure are merely two of the numerous elements that impact the development and sustained growth of innovation. To define innovation, one must first distinguish between the term’s invention and innovation.

The former describes the technically novel invention of a product or service that is distinguished from the competition by its unique characteristics. Inventions usually comprise experimental products that are not yet available to the public. While the term drastically differs between research fields, the factor of marketability or rather direct financial gain is seldomly evaluated (Dahlin & Behrens, 2005).

However, economic innovation involves commercializing new ideas. This includes product and service launch and ongoing deployment. Goal is to benefit and sustain firm stakeholders. Thus, innovation will promote firm success by improving efficiency, process times, and resource allocation. This should allow sustainable growth, worker workflow optimization, and cheaper, more value consumer products (Dodgson et al., 2014). These variables show that innovation characterizes a corporation's profitable marketing of an invention, not the technical creation. Innovation, regardless of scale, drives economic development, thus many stakeholders want to promote it.

Many innovation actors consider strategic methods to increase their innovativeness based on internal and external factors. Thus, the company's resources and organizational processes determine future innovations' efficacy. Technological advances, new competitors and investors, corporate collaborations, and new regulations are external drivers of innovation. Both politicians as legislative decisionmakers and society as a whole, represented by unions, organizations, voters, and independent research institutes, influence and shape future innovation (Dodgson et al., 2014).

Adoption and diffusion are two technical processes that determine the innovation's pace and effectiveness. According to the concept of adoption, distinct subgroups of customers for a new product or service (termed adopters) require varying periods of time to permanently and regularly use an innovation. Diffusion refers to the formation of barriers that are impacted by cultural, psychological, and personal elements and can reduce or lengthen adoption time intervals (Neumair et al., 2018).

However, customer acceptance is prone to change as regional and global market requirements evolve (Athanasopoulou et al., 2019). Figure 1 depicts the current purchase choices for the most prevalent alternative electric vehicle drivetrains in Central Europe (A. Buss et al., 2018).

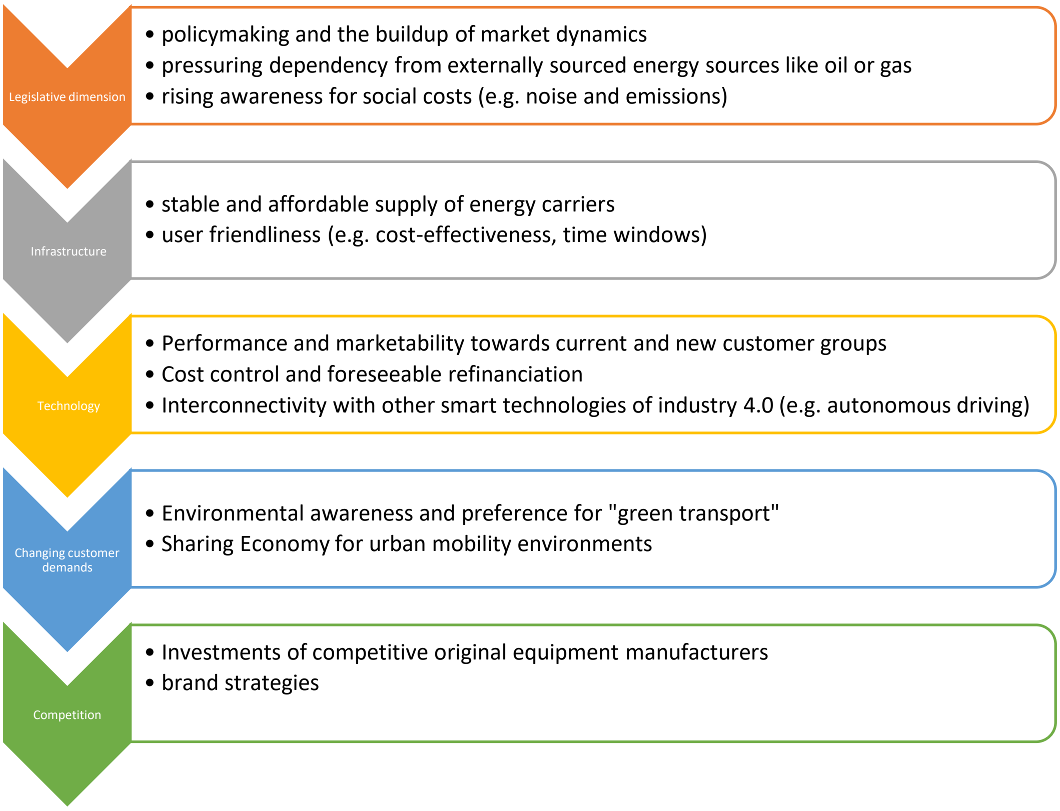

Figure 1: Driving Factors for the market penetration of BEVs (own and extended figure based on A. Buss et al., 2018)

Nation governments rely on time-bound political policies, or "innovation policy," to foster and distribute economic innovation to Europeans. Rapidly growing communities have unique environmental and transportation issues. Among other reasons, the 3% Barcelona target requires all EU governments to invest 3% of their GDP on research and development to prioritize innovation. Regional universities, industries, and other scientific organizations may integrate thanks to financing programs and new supranational entities like the European Institute of Technology. Since these integration efforts have only begun, each European country is pursuing its own innovation agenda, resulting in significant innovation variations (Buhr, 2016; Pichler et al., 2021).

Government backing encourages firms to invest in technology previously uneconomical due to hefty research costs. Life cycle assessment is deteriorating, forcing the auto industry to produce and use new automobiles in the most emission-neutral way possible. Electric or fuel cell propulsion research requires time, money, and legal flexibility to be safe and successful. State help may boost corporate development and reduce risks like cost-cutting, layoffs, and site closures. Exemplary initiatives like tax reductions, state education programs, and infrastructure improvements assist local companies and residents.

2.2 Innovation and its theoretical boundaries

There are several features of economic innovation. However, not all aspects are readily apparent; rather, they operate in the background and indirectly support the growth. The aggressiveness of creativity is a particular feature. There is a contrast between revolutionary, disruptive, and gradual innovation (Ringberg et al., 2019; C. Wang et al., 2022). Changes to the present market systems that are innovative, and revolutionary describe radical innovation. With the assistance of a powerful media campaign, innovation should rapidly increase sales volumes and attain a high level of awareness, therefore drastically transforming existing goods and services (Chirico et al., 2022). Consequently, clients typically face such alterations in the form of a new product or service that likely provides the user with a desirable extra capacity. In modern economic systems, new, distinct items are presented to the market with considerable advantages in a few key categories, such as quality, price, or features. Typically, these items are supported by a new business model or distinct market entrance techniques that emphasise the advantages of purchase for prospective clients (Ulich et al., 2021). Thus, it is feasible to significantly alter whole ecosystems as well as individual products, thus altering market shares and volumes (Athanasopoulou et al., 2019; Oghazi et al., 2022). This generates the attraction of new markets and users alike.

Disruptive innovations are not developed by dominant firms, but rather by previously unknown market participants, such as start-ups or foreign market players. This kind of innovation focuses on gaining market share from existing industry leaders as quickly as possible. The focus of freshly created firm ideas is a direct customer engagement via the adoption of new channels, complemented by high-tech or process-oriented innovation not yet existing on the market (Benzidia et al., 2021). Therefore, they often depend on the financial resources of existing firms or investors to support their endeavours, integrating themselves into their value chain.

Incremental innovations dominate 21st-century innovation, these innovations are created by slowly adding old knowledge to new product generations via little improvements. Minor improvements need not necessarily improve product functionality. Even little modifications to product attributes like color, packaging, content quantity, or marketing might increase economic performance.

While the three components above are considered the core of innovation, enterprises of all sizes may mix and match their strategic decision-making. Instead, corporate product categories may follow different trends. Comparing hybrid and electric vehicle marketing, pricing, and market presence in the automotive business shows this. Hybrid car makers use a low-end invasion strategy with several channels to target price-sensitive customers, whereas electric vehicle producers go for luxury customers (Benzidia et al., 2021). Investing in innovative ideas entails significant risks and substantial financial commitments. In some optimal scenarios, radical innovations have the potential to provide substantial financial gains. Despite their revolutionary nature, several discoveries sometimes face financial constraints that hinder their progression into inventions. This limitation may result in substantial losses or even bankruptcy, representing the most common and statistically significant outcome. By using existing resources, corporate protocols, and relevant expertise, the company may achieve cost savings and generate revenue. German firms have had challenges in swiftly adjusting their corporate structures to accommodate potentially transitory and capital-intensive technologies like as alternative drive systems, primarily due to their extensive knowledge and significant investments in combustion engine technology. However, there have been recent developments in this regard.

Fear of irreversibly destroying competence structures, supplier relationships, and distribution channels, also known as cannibalisation, as well as the potential loss of value of the built-up assets (e.g. patents, production facilities, factory sites), discourages established businesses from pursuing radical innovations (Hervas-Oliver et al., 2022). The effect that a change to other technologies is only associated with high switching costs and is therefore uneconomical is described as a lock-in effect and strengthens the commitment to old technologies. Optimisation at the production level pays off in the long term; with production process control methods such as Kanban, according to which the actual consumption of materials is based on the point of supply and consumption, vehicle manufacturers have ensured a continuous increase in production capacity. Continuous improvement and self-reflection can have enormous economic effects.

Thus, the car sector is compelled to independently create lucrative new technology. Due to the industry's high market entry hurdles, such as the required expertise, manufacturing capacity, and distribution routes, the development of new automotive enterprises is challenging. Due to the fact that radical breakthroughs, as opposed to incremental improvements, are difficult to plan and almost impossible to implement in the short term, German automakers are cautiously pursuing research into new technologies to mitigate the risk of recessions. Nonetheless, it became evident, not least via the diesel crisis of 2015, that avoiding investments in low-risk technology permanently is no guarantee of success (Hervas-Oliver et al., 2022). In endeavours to advance innovation, product and process innovations are distinguished, among other categories. Vehicle manufacturers are concerned not only with the issue of what they must create to be profitable in the future, but also with market positioning strategies to enable mass-market sales of technical advances. To accomplish innovation as rapidly as feasible, customer desires must be prioritised and resolved in a consumer-friendly manner. This is more challenging with process advancements. These alter the real background processes (Dodgson et al., 2014), necessitating a sequence of tiny, fundamental operational improvements to generate company-wide advantages.

2.3 Theories of measuring and verifying innovation

In order to verify and compare inventions, a society's numerous innovation aspects must be analysed and categorised. Due to the fact that regional economic sectors exhibit distinct economic, cultural, and infrastructural characteristics even within a national context, only a handful of globally applicable principles for the development of innovation can be formulated. The fact that distinct geographical systems have distinct properties has been well shown by economic theories (Dodgson et al., 2014).

The model of Porter's five forces evaluates the many influencing elements inside an industry and explains the market structure of the analysed economic area. Observations include the negotiating power of consumers and suppliers, the threat of new rivals and replacement goods, and the competitive intensity within an industry. In this way, far-reaching factors of the market are evaluated, such as the high diversification of a market, strategic risks due to dependence on resources with uncertain future development (such as oil or hydrogen), location advantages, access to distribution channels and concentration of local customer groups (Dulčić et al., 2012). A corporation may do a utility analysis to identify where it stands in relation to its rivals and whether it can produce profits by outperforming the market by conducting internal and external market research. The placement of organisations within Porter's Five Forces also impacts the branding strategies of other market players, so ensuring that market circumstances are continually changing. By optimising their alignment with Porter's "five forces," businesses may create strategic advantages that strengthen their competitive position.

Porter's theory only considers revenue and rivalry, not sustainable innovation. One reason is the undervaluation of organisations and NGOs that create new products and ideas via publicly or privately funded research. Since they don't make money, non-monetary interactions are typically overlooked. Businesses cooperate to save money, improve quality, share technology, and form communication networks.

Another issue with the model is that it restricts the market to rigid grids, when in reality enterprises adjust their business strategies to the ever-changing environment (Granstrand, 2004) .Innovation is the product of several company choices and cannot be linked to a single industry competency or activity (Dodgson et al., 2014)

Innovation's boundaries are not precisely defined. The Organisation for Economic Co-operation and Development (OECD) differentiates between countries with high and low research and development (R&D) innovation and links the density and kind of industry to a country's overall level of development (OECD, 2012). China, which grew from an emerging country to an industrial powerhouse in a few decades, has concentrated on "high R&D intensive" sectors including electronics, medicines, autos, and information and communication technology, contributing to global innovation.

Agriculture and mining developments may help "low R&D demanding" countries improve. Chilean Andes have the most copper and digging capacity. Copper consumption is rising as automakers build hybrid and electric motors and other devices. For the first time, Chile's primary sector is revitalised, and ecological improvements like selective mining for sustainable raw material extraction save money. Lacking current adapted policymaking focusing on incentivising external investments and upgrading the current level of infrastructure, the degree to which these improvements result in long-term cost reductions is dubious, given that the related societal costs have not been accounted for (de Solminihac et al., 2018; Pérez et al., 2021).

Other academics, such as Robson, Townsend, and Pavitt (Robson et al., 1988), classify the economic sectors as core, secondary, and utility from an innovation standpoint. Only technical and haptic advances are covered here. The most innovative industries drive society's progress. These include microelectronics, mechanical engineering, chemical, and pharmaceutical. Due to the nature of their core sector components, "secondary sectors" like the computer and car industries rely greatly on their suppliers' inventiveness and perform little independent research. Services use national resources and absorb innovation from core and secondary sectors, the latter is not considered by Robson et al. as innovative drivers (Dodgson et al., 2014).

When analysing national economies, the national boundary serves as the context for innovation analysis. These bounds are determined by the state's political, legal, and executive authority. Three drivers are responsible for innovation in these systems: the knowledge and technological foundation, actors and networks, and local institutions (Malerba & Mani, 2009).

The knowledge and technology base defines a region's technical advantage or deficiency relative to the top industrialised nations. The combined expertise of the resident enterprises and the number of innovations of proprietary technologies define technical know-how (Ton, Hammerl, et al., 2022). The company's R&D data handling is another factor. Research results are patented and only partly disclosed by companies. Information access greatly affects a region's creativity. Industrial concentration and business-university partnership boost innovation potential. Existing knowledge generates new knowledge faster.

Actors and networks include companies (producers and suppliers), non-commercial organisations (universities, business groups, trade unions, banks), and individuals (consumers, individual scientists, and entrepreneurs). These groups have distinct mentalities, objectives, organisational structures, and (buying) behaviours. They communicate, trade, licence, and compete.

Institutions establish norms, rules, regulations, and standards through passing and modifying legislation. They usually arise from national economic interaction (patents, quality standards, competition protection, customer rights, etc.). Institutions may also participate in agriculture via supranational decisions like European Union subsidies or special regulations that supersede national legislation (Bundesministerium für Ernährung und Landwirtschaft, 2022).

Long-established conventional corporations derived from mid-sized family businesses characterise the automobile sector. In contrast to the pharmaceutical business, these enterprises have historically been subject to little regulatory oversight. The effective introduction of their goods to the market does not need to be validated by years of scientific investigation into potential negative effects. Both automobile manufacturers and their suppliers exhibit incremental innovation (Hammerl et al., 2021). Particularly, suppliers have had a minimal R&D budget since they have manufactured according to the demands of the auto industry, and there was a risk that the technologies and patents they had generated would not be in sufficient demand among automakers (Hebisch et al., 2022). By re-linking current technologies with components, subsystems, raw materials, and services, innovation might be developed (Wengel & Shapira, 2004).

Universities and colleges provide the car industry with well-educated, theoretically savvy workers. Maximizing customer value is the car industry's main goal since customers' purchase choices determine product success. Due to a lack of interest in basic scientific research, theoretical models of thinking, and external research, the car industry has few independent research organisations.

Site selection depends on customer proximity, qualified labour markets, and auxiliary services like banks, institutions, and cooperation partners. Thus, networks form regional industrial clusters. The 2015 German diesel crisis tightened emissions rules, regional driving bans, speed limits, and other traffic restrictions. Scientists and consumers want a traffic reversal, which may hinder multinational automakers' innovation.

Moreover, new product advancements in manufacturing (use of new materials, software, or technologies such as lasers or nanoelectronics) depend not on experience-based or historical knowledge, but rather on closed and specialised expertise that was previously unavailable in the organisation (Ton, Szabó-Szentgróti, et al., 2022). Increased client expectations, particularly about the degree of vehicle customisation, are causing a shift from mass manufacturing to the creation of several series in small amounts.

To do this, manufacturers raise their R&D spending annually and seek collaboration with external partners that specialise in this area. The Entrepreneurial Ecosystem Approach developed by Stam and Spigel in 2016 is a commonly used business model (Stam & Spigel, 2016). This entails studying interconnected circumstances and personnel in an economic sector that allow productive entrepreneurship in a region via cooperation and coordination. According to Stam and Spigel, entrepreneurship is concentrated in clusters—geographic concentrations of linked producers, suppliers, and service providers that leverage internal networks to create value for society. The spillover effect occurs when industry knowledge and benefits are shared with society (or "spill over"). Sociocultural drivers may benefit a region from industry. These include specialised employee training and local government-business synergy.

Entrepreneurs, not corporations, innovate in the Entrepreneurial Ecosystem. Niche-focused firms encourage innovation and rapid growth. Established companies cannot meet these expectations because they rely on organic growth and lack imaginative, out-of-the-box thinking.

State institutions want employees under the entrepreneur's direction to learn via economic activity. Companies make economic decisions based on practise rather than academic study. Mentorship and networking should foster independent, inventive thinking. The Entrepreneurial Ecosystem theory states that when the state allows entrepreneurs maximum economic freedom, startups accelerate. Thus, incentives and subsidies for young talent from local institutions might provide human and investment resources. In addition, the state sponsors events to boost networking.

The company's strong, charismatic management take risks and innovate to outperform their competitors. However, it lacks Hungarian car industry innovation. Start-ups may gain economically more than other market-active firms since socio-cultural and political institutions favour them. However, long-standing rivals use their money and influence to boost their enterprises by illegally or legally influencing society and politics.

In the automotive manufacturing business, national states prefer multinationals over start-ups. Due to Mercedes, Audi, and BMW's far higher investment money. An industrial two-tier in a local economy is expensive and discourages most enterprises due to the high risk of insolvency. Lack of industrial know-how, suppliers, service providers, and, most crucially, consumers threaten the region.

According to Stam and Spiegel, effective business needs other successful entrepreneurs in the subject area. Start-ups need manufacturing and distribution to grow and increase their overall profitability. The Entrepreneurial Ecosystems approach of invention takes years of innovation-mindedness, which most Central European nations lack due to their past. Therefore, the paradigm is unlikely to deliver nations with a brief history of liberal economic growth like Hungary, Slovakia, and the Czech Republic, which have developed little radical innovation, sustainable progress and incremental discoveries. Measuring innovation requires quantitative as well as qualitative indicators, pointed out in the fourth chapter.

2.4 E-fuels and the role of hydrogen as an innovative energy carrier for the automotive industry

All currently developed alternative fuels have one common and shared goal: trying to accomplish an environmentally friendly way of propulsion through a variety of technological solutions. The main attributes, considered vital for the successful establishment of e-fuels are (Siegemund et al., 2017):

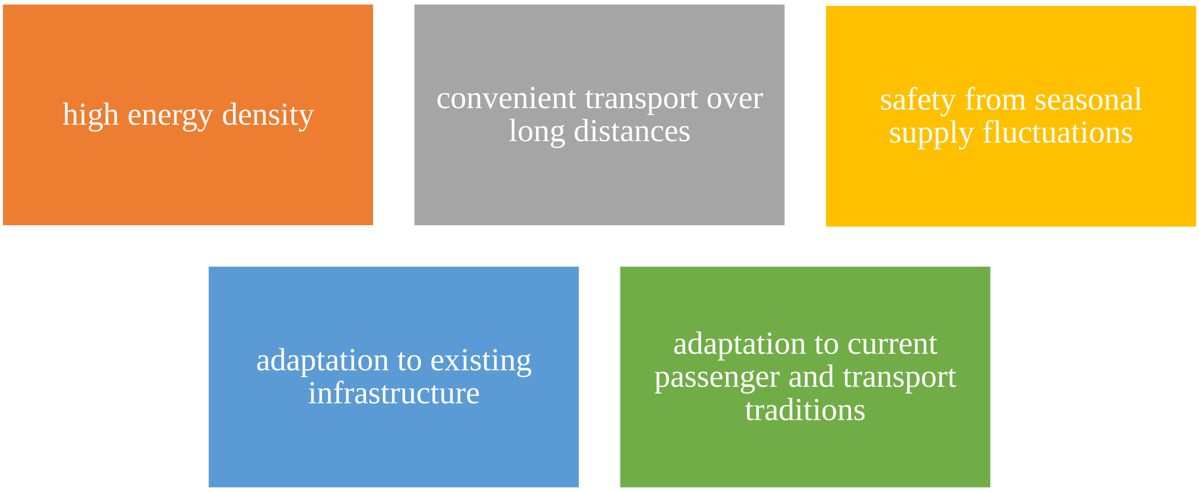

Figure 2. Necessary factors of energy carriers in the sector of mobility, own figure based on Siegemund et al, 2017

Most prominently, the ability to store electrical energy in a stable, transferrable and economically easily adaptable form in contrast to pure electricity generated from alternative energy sources, especially originating from wind and solar power, play a significant role in the feasibility of adopting a hydrogen-based infrastructure.

The most abundant material in the universe is atomic hydrogen, which accounts for around 75% of all normal matter. Hydrogen almost exclusively occurs naturally on the Earth in the form of compounds, the most prevalent of which are combinations of water and hydrocarbons like oil or natural gas. These serve as the basic raw elements for producing hydrogen industrially. Due to this, hydrogen must be created by the dissociation of other molecules, as opposed to fossil fuels (such as coal or natural gas), which already have stored energy that may be released, when employing hydrogen technologies. Initial energy is needed in the form of heat or electricity. Direct burning or the utilisation of fuel cells liberates energy for later usage (Sinay et al., 2021).

While hydrogen-based fuel cell operating vehicles had a competitive advantage over battery operated vehicles in the beginning, multiple reasons led the European automotive industry to adopt a battery-focused mobility concept rather than any alternative.

Firstly, market dynamics regarding adoption of technologies extensively influence the preference, and thereby economic success of any new concept (Mertens, 2021). While technological advantages are necessary for new ideas and concepts to gain importance in the first place, economic innovation is not sufficiently proven just by new technical results. In the early stages of electric propulsion many national and international lawmakers as well as private enterprises decided to greatly increase their funds towards the research of battery cell performance enhancement and manufacturing. Resulting in ever diminishing advantages of HFC over BEV technology, factors like dynamics, refuelling times and energy density of the carrier no longer offered relevant differences. The dedication and expected of cost-reduction made the consideration of hydrogen-based propulsion less and less relevant, as the cost of batteries is expected to be a quarter of the costs in 2015 while almost doubling in range (A. Buss et al., 2018). On the other hand, however, the disadvantages of HFC still persisted, as missing funding resulted in high research and development costs, maintenance-intensive and cost-ineffective manufacturable components, making hydrogen less-marketable on the European market.

While hydrogen offers the capability of using existing fuelling infrastructure, the costs of refitting current fuel stations is connotated with an exorbitant amount of costs, while the steady supply of environmentally friendly sourced hydrogen is not guaranteed (Mertens, 2021). Supplemented by the high transportation costs caused by the volatility, denseness and weight and high cooling necessary to allow the integration of hydrogen in the current refuelling systems of diesel and gasoline cars in Central Europe, the limited interest in hydrogen becomes evident.

Additionally, like electric propulsion, the question of sourcing becomes an environmental as well as logistical issue. Currently, none of the widely adopted methods of generating electric energy for consumers in Central Europe can generate significant amounts directly applicable hydrogen. Rather, the current concept would rely on a very energy-inefficient method of three additional transformation processes: electrolysis, compression or cooling and transportation to the over 20.000 Central European gas stations (FuelsEurope, 2021) further reducing the efficiency of current HFCs. Lastly many components both current combustion engines and bridge technologies like plugin hybrids (PHEV) or other hybrid electric vehicles (HEV) are similar, meaning few adjustments have to be implemented along the supply and manufacturing chain of current OEMs. Except for small components like starter engines or power generators, HEVs and PHEVs tend to only include additional components and technologies like batteries, brake recuperation modules or charging modules (if applicable) rather than reworking the whole drivetrain of the currently market-ready car engine technology (A. Buss et al., 2018).

These aspects, however, are only depictions of the current scope. Lifecycles of innovation do not follow predestined routes, meaning that changes in market dynamics can result in swift economic revaluations regarding hydrogen. Although currently the resource is not regarded as an alternative in the scope of private mobility in the European Union, changes regarding policymaking and consequent price setting mechanics of fuel carriers can deeply influence the technological focus of OEMs and suppliers alike.

As technological progress is made in other sectors, like the adoption of hydrogen technology in heavy goods vehicles due to price, weight and room restrictions in order to achieve lower emissions, innovations and subsequent changes of the current standpoints are guaranteed.

Steps taken by national or supranational institutions are called policymaking. By adjusting certain specifics, like price mechanics, supply, and ecological parameters, they can substantially alter the acceptance or pursuit of certain technologies. With the jointly set targets of the Paris Climate Conference, it was determined that the rise in global temperature should be limited to under 2 degrees Celsius (Siegemund et al., 2017). The necessity of harmonising national laws, regulations, and administrative rules as well as the technological, social, and tax context in which transportation services are crucial to achieve this goal. Additionally, the completion of the European single market, the elimination of internal borders, the reduction in transportation costs as a result of the opening up and liberalisation of transportation markets, as well as modifications to manufacturing and stock management systems, have all contributed to an increase in the volume of goods and passengers. To reach this goal, lately, two diverging major policymaking approaches determine the future regarding the reduction of emissions in the private mobility sector (Chng et al., 2019), namely the promotion of alternative mobility concepts like public transport or similar to reduce the overall number of car usage or the extensive adaption of low emission vehicles to combat.

Policymaking as a tool of lawgivers enacts the multi-facetted task to influence the purchasing behaviour of individual consumers towards a socially expected outcome (Galarraga et al., 2020). The direct incentives or prohibitions like fuel taxes, road tolls and emission limitations aim towards understanding and editing current purchase processes (Peters et al., 2008). Balance is key here, as slightly without causing a detrimental decrease in interest on the one side or ineffective and non-consequential laws. While efforts were taken regarding limiting carbon based fuels before the wider availability of alternative drivetrains, factor like range or unclear charging infrastructure most customers reverted from changing their purchasing behaviour due to missing alternatives (Givord et al., 2018). While the methods and measures vary from country to country, the concept of so-called intensive and extensive goals are shared among all policymakers (Givord et al., 2018), which are further discussed in the upcoming sections.

One of the currently established policy methods of the European Union is the legislative standard to implement so-called energy labels. Based on a predefined grading system, goods of all sorts are evaluated on a chart, valuing goods with a lesser ecological impact with a higher grade than environment-straining goods. Additional information regarding CO_2 emissions, noise levels, the precalculated range of one charge or refill might be included as well, depending on the national legislative policymaking (Bundesministerium für Wirtschaft und Klimaschutz, 2022b).

Due to the nature of missing requirements regarding the legal adaptation of these energy labels, the legal and organizational framework is not harmonized on a common standard (Galarraga et al., 2020). Depending on the local laws and regulations, most countries adapted a so-called absolute label scheme, that compares direct pollutions of cars with each other and labels them accordingly. In direct contrast, few countries, namely Germany or Spain introduced a relative labelling scheme, considering car segments, defined by size or weight. Rather than evaluate in an overarching concept, comparisons are taking place in an intersegment level, allowing for inefficient and larger vehicles with a higher consumption and emission to offer seemingly better results than smaller and more eco-friendly product alternatives (Galarraga et al., 2020).

Absolute and relative labelling follow different goals; while the first mainly focuses on the overall reduction of polluting emissions and convince consumers to question their current purchasing behaviour in the long run (intensive), relative schemes aim to achieve the build-up of a more efficient and thereby less environment-restraining market of individual vehicles and thereby lesser question consumers' current purchasing behaviour (extensive) (Galarraga et al., 2020). As a result, absolute labelling is seen as a much more effective way to promote a wide range of transformation of the mobility sector.

The most adopted mechanic in Central Europe regarding the evaluation and subsequent support of fuel types is the subsequent progressively increasing CO_2 price index. Creating a semi-flexible market structure around the maximum use of carbon dioxide emissions inside national borders shall move consumers to reevaluate their current purchasing behaviour and encourage the seeking for more affordable alternatives (Givord et al., 2018). Fuel tax, as also commonly named, was widely used as a first step in the national policymaking of Central European states to a varying effect. Germany, similar to its neighbours in the west, promoted the purchasing of diesel cars in the hopes of reducing the emissions with the help of technological and incremental innovation. Expectations revolved around the concept of future fuel prices to rise and thereby motivate customers to invest into goods, that decrease the upcoming operating costs adequately (Givord et al., 2018). This however, turned out to a be fatal mistake, as the manufacturing of diesel-powered cars is more CO_2 costly, while being less climate friendly overall due to fraudulent activities by several OEMs (Oldenkamp et al., 2016).

Refining the policies of the 2010-2016 period, the pursuit for zero emission vehicles was further escalated, as tax reforms towards the ever-increasing carbon taxes replaced simpler fuel taxes in order to increase the willingness of consumers to be more conscious regarding their car usage with higher fuel prices and reduce their private automobile mobility (Givord et al., 2018).

One issue with this methodical approach of intensive and extensive policymaking is the so-called energy paradox. The presence of this occurrence is still unclear today, as it relies on subjective evaluation of consumers, whether the willingness to pay higher prices for new vehicles and profit from discounted future fuel costs doesn’t seem to follow a linear progression in most cases (Bento et al., 2012; Givord et al., 2018). As a result, the adoption of supposedly cost-effective, energy-efficient technologies that require comparable trade-offs between initial capital expenditures and ongoing operational expenses are seemingly delayed. Customers neighbouring the Central European countries, which are also heavily invested in the automotive industry like France, offer a very low willingness to even consider investing in efficient automobiles (Givord et al., 2018).

Additionally, further consequences of increasing fuel prices and thereby direct consumer costs, are both the reduced life cycle of current generation automobiles as well the incentive for owners of newly purchased fuel-efficient cars to an excessive consumption, as the costs of upkeep are significantly lower than the previously used generations of cars (Givord et al., 2018), also called the “rebound effect”. Policymaking of national legislatures should therefore aim for a decrease in total emissions rather than a focus in increasing fuel efficiency.

Of the main factors regarding the realistic supply of hydrogen is the taxonomy of declaring and thereby manifesting the origin of hydrogen. Besides the widely adapted colour scale of green, grey or blue hydrogen, indicating the energy source of the manufactured hydrogen, the mixture with other components (methane, natural gas etc.) and thereby consistency of hydrogen is not clearly defined. Similarly, the “colours” of hydrogen also vary from source to source, indicating differences in the definition of the term, presented in Table 1.

Grey (sometimes brown or black) hydrogen	Most of the hydrogen generation and consumption today is dependent on very high emission rates, particularly CO_2. The grey hydrogen represents industrial ready hydrogen produced by steam reforming of natural gas or coal gasification without the collection, use, or storage of carbon. Approximately 50% of grey hydrogen is a waste product of other reactions in chemical supply chains and is therefore utilised for concentrated petrochemical and ammonia manufacture. The biggest disadvantage of grey hydrogen is the high quantity of CO_2 emitted into the environment during the production process. Coal gasification employing various resources and processes (especially lignite, a usually abundant resource in Central Europe) and steam reforming of natural gas, mostly methane, are all examples of how goods may be generated.
Blue hydrogen	Steam methane reforming with CCUS creates blue hydrogen from natural gas or biomass. The simple installation of carbon capture equipment is enough to qualify as blue hydrogen. National and international organisations fund hydrogen as a bridging technology. Whether components of the hydrogen production process are included affects the environmental impact. Even though CCS was powered by renewable energy, natural gas production and transportation caused considerable fugitive methane emissions. Blue hydrogen cuts grey hydrogen emissions by 50% after these conditions. Underground storage and capital costs hinder implementation.
Turquoise hydrogen	Hydrogen created by thermal splitting of methane is termed turquoise hydrogen (methane pyrolysis). This creates solid carbon instead of

	carbon dioxide. The prerequisites for the carbon neutrality of a process are the use of renewable or carbon-neutral energy sources to heat the high-temperature reactor and the permanent binding of carbon
Green hydrogen	Electrolyzing water with clean electricity from excess renewable energy sources, such as solar or wind, produces green hydrogen. Electrolysers use an electrochemical reaction to separate water into hydrogen and oxygen while producing zero carbon dioxide. While the notion of sustainable beginnings is shared by earlier studies, terms such as clean hydrogen and low-carbon hydrogen are used interchangeably, obscuring the environmental supply chain. There are three primary electrolysis technologies: alkaline water electrolysis, polymer electrolyte membrane electrolysis, and solid oxide electrolyser cell. Their widespread adoption is hampered by a variety of technical (and hence economic) obstacles.
Pink /purple or red hydrogen	The synthesis of purple hydrogen is powered by nuclear energy. Through electrolysis and the use of an atomic current, violet hydrogen is produced. Due to the questionable ecologic background of nuclear power plants, many European countries that dislike the use of nuclear energy do not consider this method as sustainable.
Yellow hydrogen	Yellow hydrogen is a relatively new term, indicating two possible origins, hydrogen is either produced via the mixture of grid electricity or sun energy.
Aqua white hydrogen	This approach entails the production of oil from oil sands and oil fields using a revolutionary technique that emits no carbon. The colour represents a state between blue and green, created using fossil fuels (blue) but without carbon emissions (green) (green). The conversion of fossil oil reservoirs or oil sands to hydrogen takes place in underground reservoirs, and only hydrogen should be retrieved as a final step. The most often cited hurdles for this new technology are its scalability and environmental concerns. The colour aquamarine has also been used in the pyrolysis of natural gas using concentrated sun radiation to produce solid carbon and hydrogen. Both recommended hues are still the subject of basic study and are considered experimental.

Table 1. Classification of hydrogen sourcing. Own figure based on (Ajanovic et al., 2022) and (Bundesministerium für Bildung und Forschung, 2020)

Besides the origin of the hydrogen manufacturing, further insights must focus on regarding the ecologic evaluation of each extraction and refinement step. Similarly the properties of hydrogen, compared to current fuels like diesel or gasoline tend to vary (US Department of Energy, 2022), as seen in

Table *2*.

	Chemical Structure	**Fuel Material**	**Gasoline or Diesel Gallon Equivalent**[1]	**Energy Content (lower heating value)**[4]
Gasoline/ E10	C_4 to C_{12} and Ethanol ≤ to 10%	Crude Oil	1 gal[2] = 1.00 GGE 1 gal = 0.88 DGE	112,114–116,090 Btu/gal
Diesel	C_8 to C_{25}	Crude Oil	1 gal = 1.12 GGE 1 gal = 1.00 DGE	128,488 Btu/gal
Electricity	N/A	Natural gas, coal, nuclear, wind, hydro, solar, and small percentages of geothermal and biomass	1 kWh = 0.030 GGE 1 kWh = 0.027 DGE	3,414 Btu/kWh
Biodiesel	Methyl esters of C_{12} to C_{22} fatty acids	Fats and oils from sources such as soybeans, waste cooking oil, animal fats, and rapeseed	*B100* 1 gal = 1.05 GGE 1 gal = 0.93 DGE *B20* 1 gal = 1.11 GGE 1 gal = 0.99 DGE	*B100* 119,550 Btu/gal *B20* 126,700 Btu/gal
Ethanol/ E100	CH_3CH_2OH	Corn, grains, or agricultural waste (cellulose)	1 gal = 0.67 GGE 1 gal = 0.59 DGE	76,330 Btu/gal for E100
Compressed Natural Gas (CNG)	CH_4 (majority), C_2H_6 and inert gases	Underground reserves and renewable biogas	1 lb.[3] = 0.18 GGE 1 lb. = 0.16 DGE	20,160 Btu/lb
Liquefied Natural Gas (LNG)	CH_4 same as CNG with inert gasses <0.5%	Underground reserves and renewable biogas	1 lb. = 0.19 GGE 1 lb. = 0.17 DGE	21,240 Btu/lb
Propane (LPG)	C_3H_8 (majority) and C_4H_{10} (minority)	A by-product of petroleum refining or natural gas processing	1 gal = 0.74 GGE 1 gal = 0.66 DGE	84,250 Btu/gal
Hydrogen	H_2	Natural gas, methanol, and electrolysis of water	1 kg = 1 GGE 1 kg = 0.9 DGE	51,585 Btu/lb 33.3 kWh/kg
Methanol	CH_3OH	Natural gas, coal, or woody biomass	1 gal = 0.50 GGE 1 gal = 0.45 DGE	57,250 Btu/gal

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[1] the quantity of fuel needed to produce one liquid gallon of gasoline or diesel, where one gasoline gallon equivalent (GGE) is equal to 114,300 Btu and one diesel gallon equivalent (DGE) is equal to 128,700 Btu in terms of energy content.

[2] One US gallon equals to ca. 3,785 litres.

[3] One pound (lb) equals to ca. 0,454 kilograms.

[4] Combustion of a fuel or food releases heat, which is its heating value. Treating water as a vapour, the lower heating value is calculated by subtracting the heat of vaporisation from the higher heating value for a material.

	Gasoline/ E10	**Diesel**	**Electricity**	**Biodiesel**	**Ethanol/ E100**	**Compressed Natural Gas (CNG)**	**Liquefied Natural Gas (LNG)**	**Propane (LPG)**	**Hydrogen**	**Methanol**
Energy Content (higher heating value)[5]	120,388–124,340 Btu/gal	138,490 Btu/gal	3,414 Btu/kWh	127,960 Btu/gal for B100	84,530 Btu/gal for E100	22,453 Btu/lb	23,726 Btu/lb	91,420 Btu/gal	61,013 Btu/lb	65,200 Btu/gal
Physical State	Liquid	Liquid	Electricity	Liquid	Liquid	Compressed gas (lighter than air)	Cryogenic liquid (lighter than air as a gas)	Pressurized liquid (heavier than air as a gas)	Compressed gas (lighter than air) or liquid	Liquid
Flash Point	-42°C	74°C	N/A	100°C to 170°C	13°C	-149°C	-14°C	-38°C to -66°C	N/A	12°C
Autoignition Temperature	257°C	~316°C	N/A	~149°C	423°C	540°C	540°C	454°C to 540°C	566°C to 582°C	481°C

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[5] Condensing water vapour from combustion products to the pre-combustion temperature yields the greater heating value. This number implies all water in combustion products is liquid and heat may be utilised.

	Gasoline/ E10	Diesel	Electricity	Biodiesel	Ethanol/ E100	Compressed Natural Gas (CNG)	Liquefied Natural Gas (LNG)	Propane (LPG)	Hydrogen	Methanol
Maintenance Issues				Lubricity is improved over that of conventional low sulphur diesel fuel.	Special lubricants may be required. Practices are very similar, if not identical, to those for conventionally fuelled operations.	High-pressure tanks require periodic inspection and certification.	LNG is stored in cryogenic tanks with a specific hold time before the pressure build is relieved. The vehicle should be operated on a schedule to maintain a lower pressure in the tank.		When hydrogen is used in fuel cell applications, maintenance should be very minimal. High-pressure tanks require periodic inspection and certification.	Special lubricants must be used as directed by the supplier. Can cause serious damage to organs in the body if a person swallows it, breathes it in, or gets it on their skin.
Energy Security Impacts	Manufactured using oil. Transportation accounts for approximately 30% of total U.S. energy needs and 70% of petroleum consumption.	Manufactured using oil. Transportation accounts for approximately 30% of total U.S. energy needs and 70% of petroleum consumption.	Electricity is produced domestically from a wide range of sources, including through coal-fired power plants and renewable sources, making it a versatile fuel.	Biodiesel is domestically produced, renewable, and reduces petroleum use 95% throughout its lifecycle.	Ethanol is produced domestically. E85 reduces lifecycle petroleum use by 70%, and E10 reduces petroleum use by 6.3%.	CNG is domestically produced from natural gas and renewable biogas. The United States has vast natural gas reserves.	LNG is domestically produced from natural gas and renewable biogas. The United States has vast natural gas reserves.	Approximately half of U.S. LPG is derived from oil, but no oil is imported specifically for LPG production.	Hydrogen is produced domestically and can be produced from renewable sources.	Methanol is domestically produced, sometimes from renewable resources.

Table 2. Fuel Properties Comparison between hydrogen and other energy carriers, own figure based on US Department of Energy, 2022

Lastly, the combustion method is important. Hydrogen fuel cell cars get their power from a chemical reaction between hydrogen and oxygen, which causes electrons to flow. Research on the direct combustion of hydrogen is still going on. Because of this, the term "e-fuels" is often used to talk about the future of transportation because it shows how unclear and unclear the process of making alternatives to electric propulsion and then making laws about them is. Even though these fuels are talked about a lot in the news, no one knows where they come from or how they can be used in whole transportation systems. Common methods involve mixing CO_2 gas that has been recovered and hydrogen that has been made by electrolyzing water.

Regulatory and public policies	environmental standards and regulations (emission caps, efficiency standards, quotas, tariffs, labels)
	road tolls
	low-emission zones
	bans
	infrastructure subsidies/restrictions
Financial incentives	reduced purchasing costs (promotions)
	tax reductions (VAT, registration, ownership, fuel)
	Parking fees
	subsidizied fuel supply, access

Table 3. Overview of policy methods promoting or hindering certain technology for private consumers, own figure, based on Siegemund et al., 2017

The energy needed to make these fuels comes from carbon-free electricity (Ababneh & Hameed, 2022).

Besides changing the framework and thereby outcome of consumers, national policymakers apply other policymaking tools presented in Table 3, namely subsidies (Galarraga et al., 2020). To overcome the barriers of failed innovation, national and international legislative organs tend to tailor industry and country-specific policymaking strategies. These follow the classic concept of pushing supply and demand rather than pulling as the cost structure of switching technology is not pursued by many actors due to economic parameters (Siegemund et al., 2017). Therefore, national policymakers must reduce energy network charges, harmonise standards regarding blending limits, formulate guarantees for customers and investors to solidify a stable innovation environment, include the social representants (i.e. universities), and coordinate on a supranational level with neighbouring countries to promote the exchange of overcapacity and equitable distribution in order to push the supply of alternative energy sources (Malerba & Mani, 2009; Siegemund et al., 2017). Currently policymakers only tend to focus on pushing demand in forms of emission targets, CO_2 taxation and similar methods, thereby leading a potential inefficiency of policymaking.

In the following, the hydrogen strategies of the countries of Slovakia, Hungary and Germany are shortly summarized to highlight the similarities and differences of the national policymaking of pushing supply in Central Europe regarding the production, storage, usage and funding of future hydrogen resources. All these countries offer a high sectoral integrity with a special focus on the manufacturing and supply of the Central European Automotive Industry, with varying characteristics, namely population size, energy distribution and hydrogen capabilities.

2.5 Materials and Methods

This systematic review was conducted using the search, conclusion, analysis, and categorization of discovered publications. Each step is mentioned below.

Data sources and search strategies

Multiple databases were considered, with Science Direct providing most of the researched and analysed information. Additional articles were obtained from Google Scholar or other sources (primarily jstor.org and the university libraries of Humboldt University of Berlin and Freie Universität Berlin). In the period between 2010 and 2021, the following keywords were used in both the titles and the body of published articles:

“X automotive AND innovation” OR “Hydrogen OR Electric OR Natural Gas AND Logistics” OR “X Policies AND hydrogen innovation” OR “X society AND hydrogen innovation” OR “X enterprise AND hydrogen innovation”.

X was to be replaced with “European” OR “Central European” OR “German” OR “Hungarian”.

Inclusion/Exclusion criteria

Initially these search criteria resulted in ca. 1.500 journal articles. Consecutively, screening parameters were concluded to limit the scope and increase the focus on hydrogen related automotive developments in legal, economic, social, and ecological areas. Firstly, the majority of included sources (85%) was to be graded with a Q1 journal quality to ensure a high grade of quality among the findings, methodology and evaluation. The remaining sources where either Q2 or Q4 rated (13%) with only 2 selected articles not fulfilling these criteria. This is due to the fact, that these journal publications are highly localized to areas of interest and therefore not coactively in the research field of higher ranked journals.

Another criterium to be reached was that the scholarly published articles are based on qualitative research and were written in English. Book reviews, non-English publications, unpublished articles, working papers and conference papers were not taken into account and subsequently excluded. With regards to content further screening criteria were considered, their implementation was crucial to be included in this systematic review. These criteria are described in Table 4.

Criteria	Inclusion	Exclusion
Focus of article	Hydrogen innovation in the automotive sector from an economic, ecologic, social, AND legislative point of view	„traditional" combustion engine development, purely technical descriptions, one dimensional (scope-limited) economic growth models
Journal quality	Peer reviewed Q1-Q4[6]	unranked or potentially predatory journals
Publication date	2010-2021	Prior to 2010
Publication type	Scholarly published articles of original research journals	Book reviews or chapters, dissertations, conference proceedings, unpublished articles

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[6] With two exceptions, discussed in inclusion/exclusion criteria

Criteria	Inclusion	Exclusion
Research Methods and Results	Qualitative-based identifiable methods and results, detailing on how exactly the study was defined, conducted, and evaluated.	Article reviews, commentaries or missing qualitative methodology-based publications, that do not make clear of data origins or are missing substantial research concepts
Language	Journal articles exclusively written in English	Other languages

Table 4. Process flow selection of articles, own figure

Figure 3 the process of screening the collected research papers involved during the systematic review. Filtering out the duplicates already drastically reduced the number of identified papers to 748 articles. By screening the abstracts and results over half of the searched articles could already be eliminated and reduced the number of usable records to 135. Further detailed analysis nailed down the critical number of full-text articles, that were assessed in their completeness down to 82, this number was reached by removing articles not fulfilling the journal quality or inclusion criteria in full detail. This final sample was then coded and assessed into groups to further outlay the structure of the doctoral thesis.

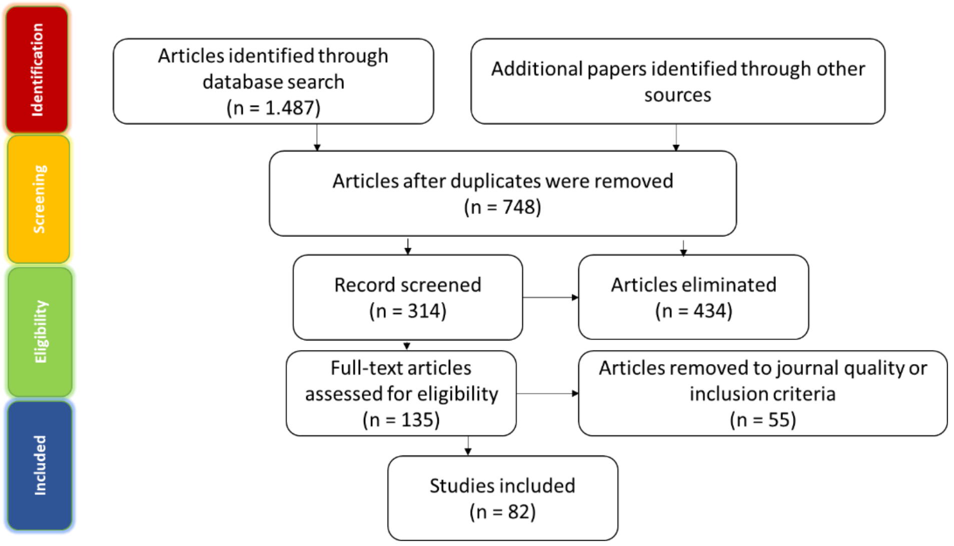

Figure 3. Screening results, own table

2.6 Methodological results

Publication trend on hydrogen automotive innovation in Central Europe

To guarantee the independent research, following data was assessed to show, which journals were sourced and which quantitative importance they represented during the systematic research. Overall, seven Q1 rated journals were concluded as the main source material, representing over 60% of the total screened and evaluated journal papers. Due to the sheer number of publications of over half a million including the keyword "innovation" (ScienceDirect, 2021), only hydrogen or energy/fuel focusing journals were deliberately chosen as the main sources of research.

The publication trend on hydrogen innovation research gained a substantial rise in interest in the last five years. While many research areas suffered under the restrictions of the global pandemic, research in this area still showed a significant growth, due to the social and political pressure of expanding greening and ecological awareness, research incentives in 2021 and 2022 rose constantly. Its increase in research publications is depicted in Figure 4 (ScienceDirect, 2023), complemented by the clustering of research journals in Figure 5.

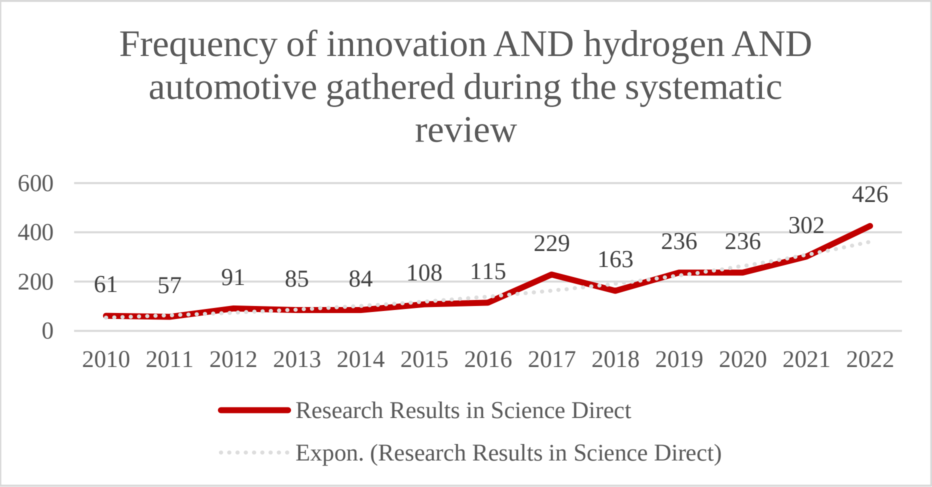

Figure 4. Research tendency, own figure

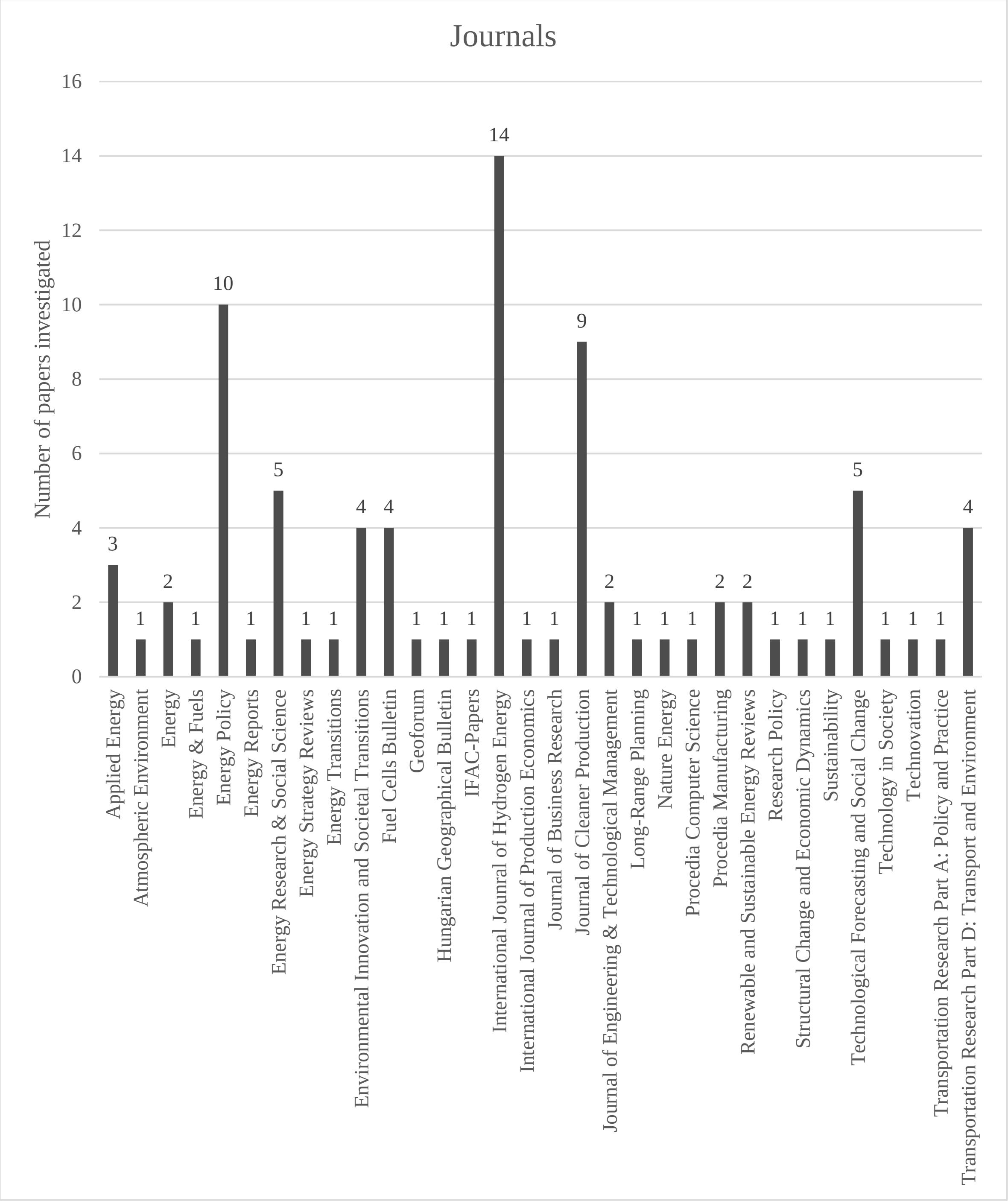

Figure 5. Selected Journal Names that were investigated in the time frame of 2010-2021, own figure

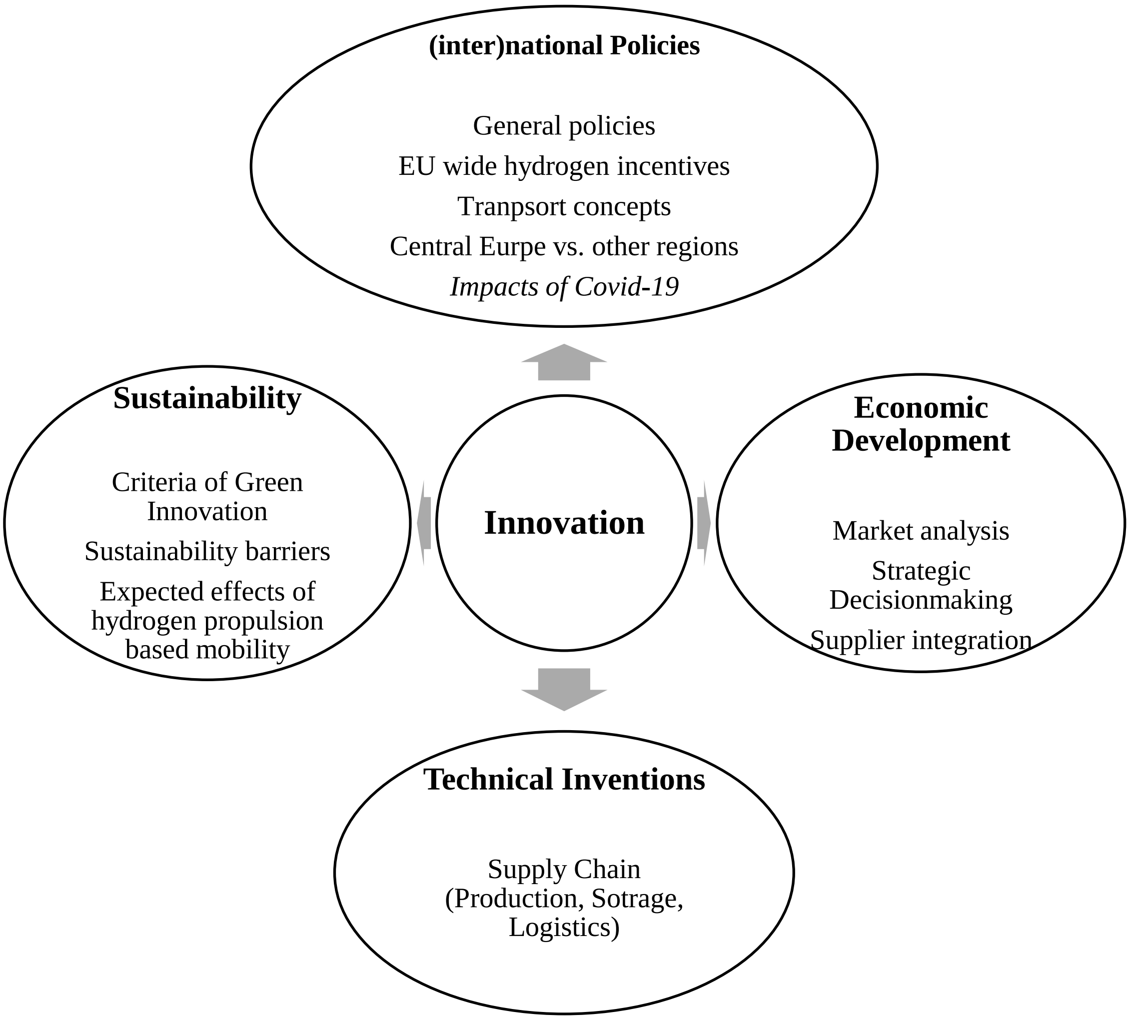

Figure 6. Overview of topics in the investigated papers, own figure

Research topics that appeared in the journals

After screening the selected journals, the corresponding themes were evaluated and categorized. In total five main research categories were concluded, visible in Figure 6. These represent the main research fields that will be further elaborated during the doctoral thesis. Furthermore, keywords for the proposed subclasses were attached.

To give an overview of the results, the used definitions and methods in these papers are described in Table 5 and Table 6 . Besides clustering the topics, all papers were evaluated and sorted into the subcategories of regional differences in mind. The other category includes both non-EU countries, mainly from the Asian region due to the manufacturing and technological origin of necessary components and generalized, more abstract papers, focusing on theoretical approaches.

Category	Total	EU	Germany / Hungary[7]	Other
Policy concepts on hydrogen mobility	34	30	10	4
Economic Factors of hydrogen automotive innovation	18	9	6	9
Market success factors	7	5	4	2
Internal Strategic Research	9	5	2/2	4
Supplier-based economy	4	1	1	3
Technical Inventions	7	0	0	7
Innovation Studies	16	7	3	9
Sustainability	12	4	4	5

Table 5. Definitions used in the selected papers of the systematic review, own figure

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[7] Included in the EU numbers.

Category	Total	EU	Other
Science	82		
Policy and political economics	37	27	10
Strategic & Organizational management	14	8	6
Technomanagement	7	2	5
Innovation management	14	10	4
Corporate Sustainability	12	6	6
Methods			
Interview/expert survey	11		
Narrative/literature review	30		
Case Study	12		
news	2		
model	12		
other	15		
Type of Data			
Qualitative	72		
Quantitative	10		

Table 6. Methods used in papers, own figure

2.7 Analysis of the hydrogen strategies of nation states

2.7.1 Efforts of the Slovak Republic

By defining the so-called National Hydrogen Strategy (NHS (Sinay et al., 2021)), the national legislature of Slovak Republic aims to combine the requirements for the achievement of the newly signed European strategic goals like the European Green Deal (European Commission, 2022a) as well as the Paris Agreement (European Commission, 2022e) with their own adaptation of innovation policies. Following the recommendations of achieving greenhouse gas emission neutrality by 2050, hydrogen was deemed as a critical resource in order to achieve green economic prosperity and successively reduce the dependency from natural gas supply (FCH 2 JU, 2020d).

Aiming for a total conversion of the current status quo, the Slovak administration focuses its efforts on the wide scale manufacturing of hydrogen resources through grey and blue hydrogen until 2030, only later transforming to a fully sustainable green hydrogen-based economy. Focusing on the main hydrogen power users in its current economic setup, the national policymaking focuses especially on the usage in the chemical (mainly ammonia-based industrial companies and refineries) and steel manufacturing sector and their supply through the current gas operated pipelines. With a planned use of up to 200 kilotons of hydrogen a year, the outlined policymaking to successfully transform from a fossil fuel-based infrastructure economy incorporates future, ever-increasing emission price indices and the reduction of costs due to technological advancements. The main driver of hydrogen manufacturing is focused on the output from nuclear power plants, namely in Bohunice and Mochovce with a current total energy output of over 1800 megawatts, which is further increased in a couple of years with the shortly completed newly constructed third and fourth reactor in Mochovce (Ministry of Environment of the Slovak Republic, 2016). A planned utilization for the manufacturing of hydrogen would be transform excess energy into hydrogen, indicating a permanent full load operation and expecting an increase of the commercial viability for the new energy source. As a result expected employment growth amounts for around 1000-3500 newly founded employment numbers (FCH 2 JU, 2020d).

Regarding the policymaking, efforts will be made in the fostering of low-carbon hydrogen technologies. In order to reach this step however, firstly taxonomy and standardization of processes have to take place, as many administrative steps and planning of measures to support new innovations in the hydrogen innovation sector (funding, certification, investor support, stimulating commercial demand, pilot-programmes etc.) are not yet undertaken or finished towards a successful concretization of legislative steps (Sinay et al., 2021). Lastly efforts are planned to promote a second key actor in the innovation research (Malerba & Mani, 2009), the expansion of financial support and further foundation of independent research institutions, competence centres and talent acquisition with an explicit protection strategy towards the protection of intellectual capital. As a result the current strategy is lacking in specific regulations regarding transport subsectors or end-users and lacks in individual national incentives like CO_2 pricing mechanisms and corresponding taxation (FCH 2 JU, 2020d). With the exception of small details about potential 15-40 filling stations for the maximum of 15.000 passenger cars or 2000 heavy duty vehicles, hydrogen in the sector of mobility is held vague.

Further supplemented by the co-called Fuel Cells and Hydrogen Joint Undertaking (European Commission, 2022c), a network of cooperation with the European Commission, based on the nation's capacity for hydrogen production and demand, the gas infrastructure, and the favourable environment, an analysis of national options for hydrogen deployment in Slovakia was conducted. Resulting in two assessments the potential development of a low vs. a high usage of hydrogen was drafted. In the best case scenario, up to 1140 GWh worth of hydrogen are electrolysed by 2030, further underlining the use of blue hydrogen until the end of the current decade (FCH 2 JU, 2020d). This number refers to ca. 1% of the usage of the current

Slovak transport sector, with a planned increase of up to 20% until 2040. The idea of adapting carbon capturing technology to dampen the negative environmental consequences of grey hydrogen in the upcoming years is documented in the Slovak national strategy, however external analysis provided a very limited currently aimed readiness compared to the available wide scale potential of CO_2 storage capabilities (FCH 2 JU, 2020d). Evaluations therefore indicate that the main task of hydrogen in the Slovak energy systems are mostly revolving around the substitution of current gas-intensive industrial segments rather than a revolutionary redesign of the transport sector in the upcoming years.

2.7.2 Efforts of Hungary

Similar to its neighbour in the North, the Hungarian Ministry of Innovation and Technology formulated national hydrogen strategy in 2021. Outlining the goal of achieving the sustainable production of higher capacities of green hydrogen on the base of solar energy, current strategies also incorporate nuclear energy towards a decarbonisation of the current energy system. Formulating goals in the sectors of producing significant amounts of low-carbon hydrogen until 2030, the main usage of hydrogen is applicable to industrial processes and the shift of heavy duty vehicles towards hydrogen rather than gas, while concentrating on user requirements and competitive pricing (Innovációs és Technológiai Minisztérium, 2021). In contrast to the Slovak strategy, concrete numbers of almost five thousand newly added HFC vehicles are also included. Still, aims are currently restricted to a minimum of two percent of yearly gas substitution towards hydrogen.

In the past no policies were adapted regarding the ecological manufacturing of hydrogen, as a result Hungary is aiming for the expansion on blue and turquoise hydrogen production to reach a solid foundation of generating low-carbon hydrogen. Conditions, norms, and monitoring mechanisms for the subsequent build-up of green hydrogen through electrolysis are currently not present and need both the attention of administrative and technical experts.

With this approach the Hungarian government aims to avoid emissions of at least 95.000 tons, mainly through the adoption of hydrogen in the chemical industry, as similarly to the Slovak industrial characteristics, ammonia production is considered the optimal starting point for future use of hydrogen. Infrastructurally speaking, the transport of hydrogen is based on a similar concept as well, through the use of the widely established gas network (see Figure 7). Plans indicate, that until 2030 162.000 tons of hydrogen shall be produced, indicating an energy output of 5,39946 TWh per year[8], with a majority originating from grey hydrogen. Its widest applicability is planned for the aforementioned chemical industry, with rising interest in refineries. Subsequently from 2030 on, domestic so-called hydrogen valleys are planned, that focus on the manufacturing of low-carbon or carbon-free hydrogen, aiming for decarbonisation of industry in the long run.

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[8] Calculated by the official statement of the Hungarian national hydrogen strategy, multiplied with the average energy concentration of 33,33 kwH/kg of hydrogen.

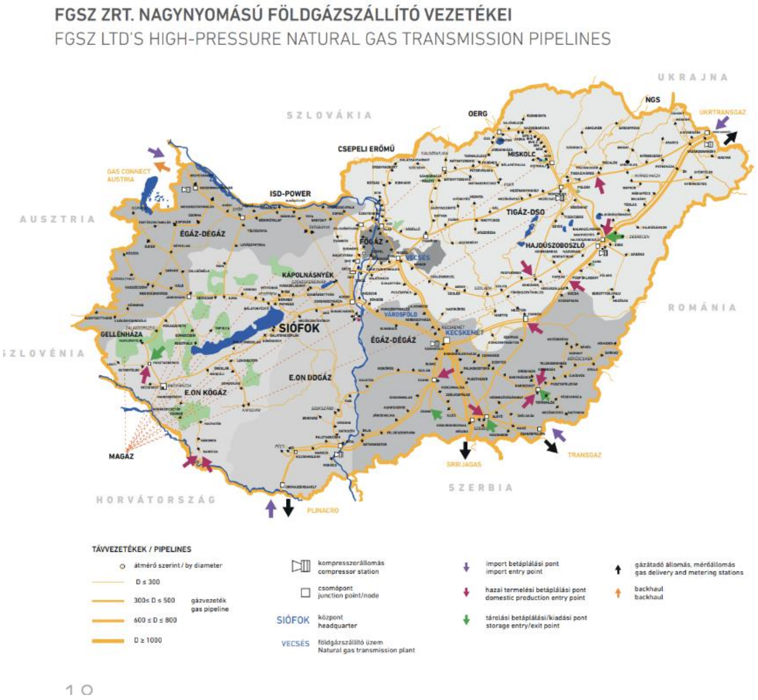

Figure 7. Hungarian Gas network infrastructure (Magyar Energetikai és Közmü-szabályozási hivatal, 2013)

To achieve this effort, planning regarding domestic green hydrogen production facilities are already ongoing, as several spots in Transdanubia (Pétfürdö, Százhalombatta, Dunaújváros, Beremend, Királyegyháza) combined with the energy output from the nuclear plant in Paks and regions in the Northeast (Miskolc, Tiszaújváros, Kazincbarcika) in cooperation with the Mátra power plant are in serious evaluation. These spots were purposefully chosen to the proximity of energy-intensive industrial positions of chemical, iron, steel, cement and similar industrial segments. Furthermore, a mixture of promoting policymaking, the build-up and standardization of market mechanisms, regional and EU-level legislative cooperation and adapted research and development is determined to further integrate of SMEs and large manufacturers and foster the access to external markets.

In contrast to the Slovak national strategy, special focus was also put on the decarbonisation of mobility. While private mobility via fuel cell vehicles is also considered, serious efforts are put into the carbon reduction of heady duty vehicles like commercial trucks and city infrastructure like buses and waste collection. Consequently, further R&D incentives by the Hungarian state revolve around the efficiency gain of electrolysis processes, while carbon capture technologies or other modes of energy generation are seen as medium priority due to the current availability of technological pioneers (see Figure 8). Further interest is put into the sectors of industrial derivative manufacturing as a by-product and greening the transportation and energy sector. Biomass and solar energy production, the concept of underground storage of CO_2 and technological concepts of blending sustainable gas with the current energy mix are only seen as a transitory technology in the medium run by the Hungarian Ministry of Innovation and Technology.

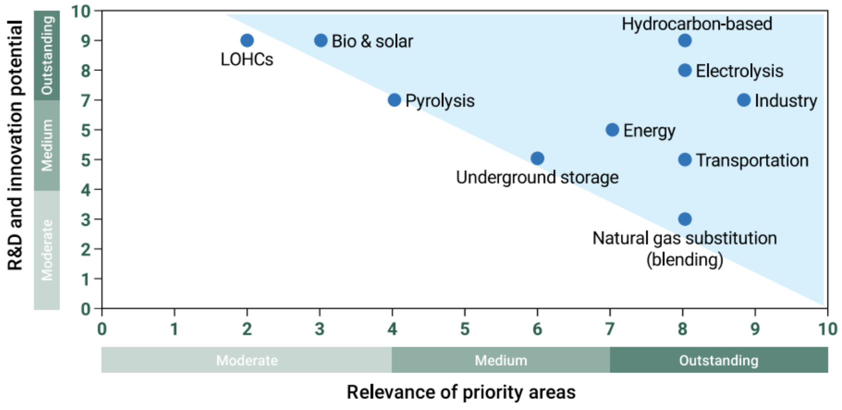

Figure 8. Prioritization of the R&D and innovation potential in Hungary (Innovációs és Technológiai Minisztérium, 2021)

To achieve a certain stable refuelling infrastructure, up to twenty stations à two refuelling points are planned. General supply of hydrogen is to be guaranteed by deeper interconnectivity within the European area.

Concrete policymaking steps cover a budget of minimum 105 billion (ca. 260 million €[9]) include, but are not limited to:

- Establishing a Green Truck Programme for the greening of heavy-duty trucks.
- Modernizing local public transport with the Green Bus Programme
- Setup and successive expansion of domestic hydrogen manufacturing chains via hydrogen valleys.
- Additional funds towards the logistical programmes to transport, store, research and promote the use of hydrogen.

2.7.3 Efforts of the Federal Republic of Germany

Europe is now the biggest market in the world, with over 500 million customers. As the most economically significant member of the European Union, Germany is a desirable place. A reunified Germany is crucial to the expansion of the European single market. Germany is the

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[9] Calculated with the exchange rate of 1€=404 HUF on July 30th, 2022.

gateway to Central and Eastern European markets. In 2021, the sector's enterprises generated a substantial €411 billion in revenue and directly employed almost 786 000 people. Due to its globally established value chain and large export share, the German automobile sector is especially impacted by localisation initiatives and rising trade barriers. This is one of the reasons why the German car sector is developing its connections with Central European nations (Bundesministerium für Wirtschaft und Klimaschutz, 2022a).

In the sake of climate protection and energy security, Germany must achieve fossil fuel independence. As a replacement for natural gas, oil, and coal, hydrogen plays a significant part in this process.

In June 2020 the German Bundesministerium für Wirtschaft und Klimaschutz formulated its own hydrogen strategy called NWS, classifying it, according to its capabilities into five subcategories, namely as an energy carrier, energy storage technology, element as a sector transformation in areas where current green energy solutions are not applicable and as a central resource in the economic field of ammonium production and similar CO_2 heavy industries like cement production (Bundesministerium für Bildung und Forschung, 2020).

Currently the cost of carbon emissions is not included into the pricing of fossil fuels. Therefore, current strategic steps intend to keep lowering the cost of hydrogen technology so that it may be used economically. Establishing a robust and sustainable domestic market for the production and use of hydrogen in the country's energy systems is defined as the first step that must be done to accelerate the adoption of hydrogen technology.

Current plants anticipate a consistent use of 90-110 TWh of hydrogen through 2030. To satisfy a fraction of this demand, there are plans to construct up to 5 GW of production capacity, including the required offshore and onshore energy producing facilities, in order to accomplish this objective. This translates to 14 TWh2 of green hydrogen generation and 20 TWh of energy generated from renewable sources. Most of the required hydrogen will need to be imported because local production of green hydrogen won't be enough to meet all new demand.

Further efforts will be increased to carve out the full potential and increase of generation capacity. To accumulate further sources of green energy, offshore wind energy is deemed to be crucial. Collaboration with the appropriate partner nations is seen as the relevant key factor to supply the currently necessary domestic hydrogen consumption of 55 TWh based on sustainable sources.

The petrochemicals industry and basic chemicals sector, which produce ammonia, methanol and other base components have equal demands for hydrogen due to material manufacturing processes in industry regarding the production of conventional fuels. Most of the hydrogen utilised in these operations is currently grey hydrogen as less than one tenth of used hydrogen are produced through the process of electrolysis.

The accumulation of knowledge in the fields of production, research and innovation, decarbonization of industry, transport and buildings/heat, infrastructure, international collaborations, climate and sustainability requires a governance structure that is adaptable and driven by results. Members include high-level specialists from industry, research, and civil society who are not employed by the public sector and are thus oriented toward sectoral innovation ideas (Malerba & Mani, 2009).

Besides aforementioned goals a comprehensive set of regulatory and financial measures is put into place, that are classified according to their respective origin in Table 7.

Regulatory policies	Transportation sector	Development of national legislative concepts like - a national framework for the effective utilisation of power from renewable sources and arrangement design of the state-induced energy pricing components, mostly wind energy (M1, M4). - implementing current frameworks from supranational institutions like the EU Renewable Energy Directy (RED II) into national law (M5) supporting the output of renewable energy sources, adoption in industrial supply chains and mobility (air traffic) not yet deeply invested in alternative energy carriers. - Formulating a controlling system based on targets to increase the number of zero-emission vehicles (M11) Development of international legislative concepts like - Developing a method for estimating the carbon footprint of energy products and assessing their degree of sustainability in the local, European, and global trade of alternative energy sources (M5) - politically promoting the development of a shared and harmonized European infrastructure regarding fuel cell integration systems (M9, M13), logistics (M10), toll rates (M12), - Exploration of new business and collaboration models for electrolyser operators and grid and gas network operators for transportation systems (M2)
	Industrial sectors	- Apply legal measures (demand quotas etc.) towards the technological adaptation of decarbonisation of energy-intensive industries through carbon capture like chemical industries, steel mills and other sectors like automotive manufacturing and thereby allow a competitive advantage (M16, M17)

	Research & development institutions, education facilities and the promotion of innovation	- Create a joint hydrogen roadmap with the support of science, business and civil society partners for future applications of hydrogen (M23) - Founding a new cross-ministry research campaign aiming to discover, assess, fund, coordinate and evaluate all levels of research projects towards future regulatory projects. Further tasks include the documentation of research advancements, promote networking and cooperation among companies and combine science and businesses (M25, M26, M29), with special industrial focuses of air travel (M27), ships (M28).
	Transformation of infrastructure	- Integrate stakeholders of all sorts towards a common strategy of transformation to formulate recommendations based on market analytics for further steps of hydrogen implementation in the sectors of electricity, heat and gas distribution (M20, M21).
	Cooperation on international levels	- Create EU-wide standards on sustainability, infrastructure and research integration (M30) and streamline investments (M31), joint ventures (M33) and policies for customers in general (M32) - Promote energy partnerships with other countries, create international markets and pursue border-wide cooperation through pilot projects (M34, M35, M36, M37)

Financial incentives	Transportation sector	- facilitating the transition to hydrogen in the industrial sector by providing money for electrolyser investments (M3) Offering investments towards - the research and development of technological development of hydrogen powered vehicles in the sector of light- and heavy-duty vehicles, buses, trains and car fleets regarding reduced emissions, cost reductions and interconnecting regional hydrogen concepts (M6) - the research and development of (green) electricity fuels (M7) - the planning and build-up of refuelling infrastructure (M8)
	Industrial sectors	Offering investments towards - Transforming current industrial processes towards low-emission supply chain processes and the implementation of hydrolyser technology (M14, M15)
	Research & development institutions, education facilities and the promotion of innovation	- Subsidizing demonstration projects to generate attention and promote the usage of supply and technological implementation (M24)
	Transformation of infrastructure	- Modernizing the current distribution of all energy sources for an infrastructure capable of supplying hydrogen in sufficient amounts in road-, rail and waterway systems to promote the use of fuel-cell powered vehicle fleets (M22).

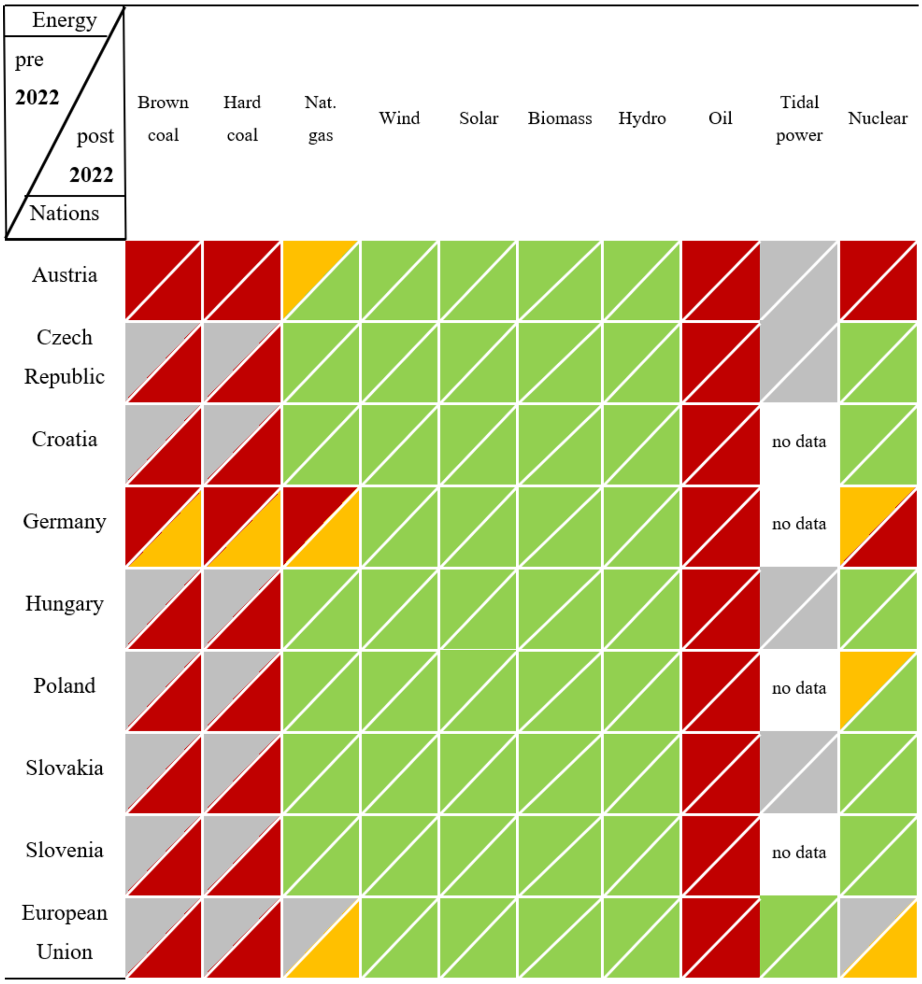
	Heating	- Adopting fuel-cell technology for heating systems to reduce emissions (M18, M19)

Table 7. Classification of measures to promote the use of hydrogen in Germany. Own figure, based on statements from (Bundesministerium für Bildung und Forschung, 2020)

2.7.4 Results in perspective to the EU

By comparing these three selected national hydrogens plans from Central Europe, it is obvious that comparable strategies are being used; yet, the terminology, techniques, and milestones are unclear and difficult to compare, at least among themselves.

It is obvious that the definition of "green hydrogen" shifts depending on the context. For instance, countries who see nuclear power as an essential component of their overall energy portfolio are striving to produce hydrogen over the long-term utilizing nuclear technology. As a transitional technology, the status quo ought to operate as a hybrid via the gas infrastructure. This might be accomplished either by the gradual greening of natural gas with the addition of biomass or through the use of carbon capture technology to fossil fuels. The classification of “green”, indicating environmentally sustainable energy as the factor of green hydrogen manufacturing is country specific and is often not openly communicated. Instead, investments into certain energy technologies reveal the sustainable energy policy definitions, pointed out in Table 8.

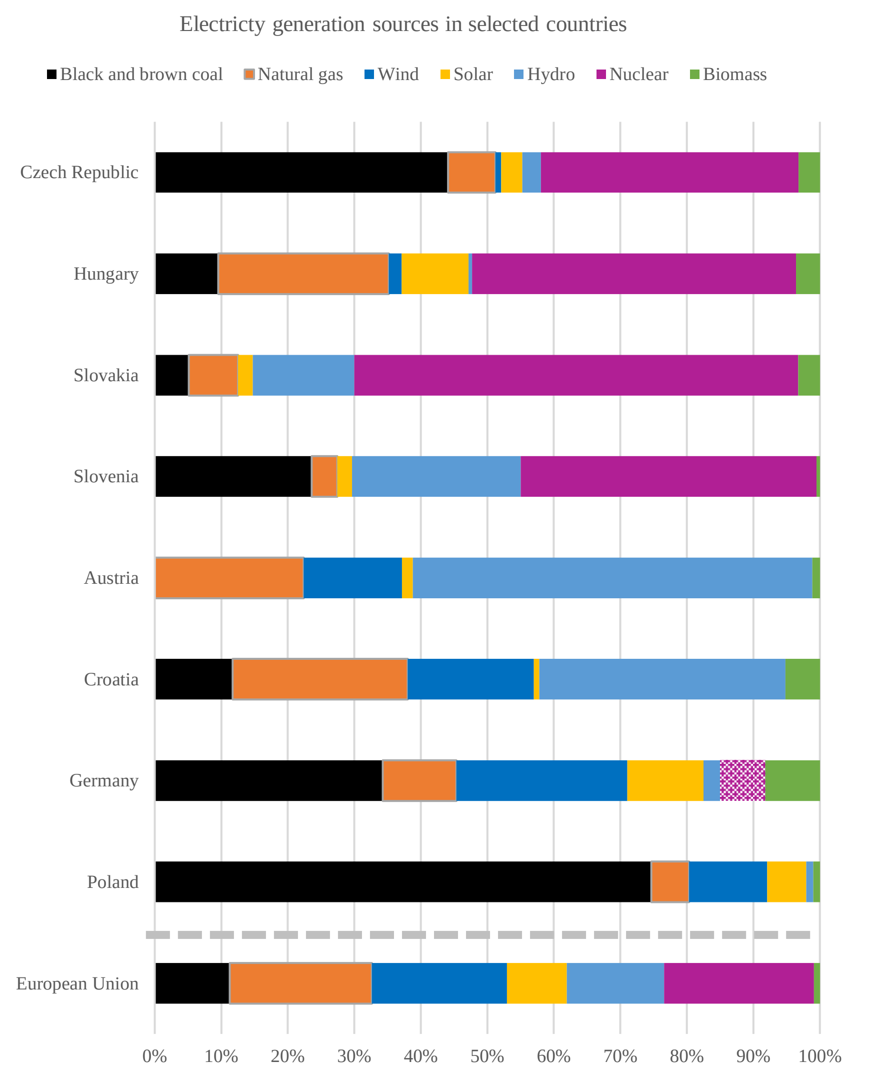


Energy pre **2022** post **2022** Nations	Brown coal	Hard coal	Nat. gas	Wind	Solar	Biomass	Hydro	Oil	Tidal power	Nuclear
Austria	🟥 / 🟥	🟥 / 🟥	🟨 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟥 / 🟥	⬜ / ⬜	🟥 / 🟥
Czech Republic	⬜ / 🟥	⬜ / 🟥	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟥 / 🟥	⬜ / ⬜	🟩 / 🟩
Croatia	⬜ / 🟥	⬜ / 🟥	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟥 / 🟥	no data	🟩 / 🟩
Germany	🟥 / 🟨	🟥 / 🟨	🟥 / 🟨	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟥 / 🟥	no data	🟨 / 🟥
Hungary	⬜ / 🟥	⬜ / 🟥	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟥 / 🟥	⬜ / ⬜	🟩 / 🟩
Poland	⬜ / 🟥	⬜ / 🟥	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟥 / 🟥	no data	🟨 / 🟩
Slovakia	⬜ / 🟥	⬜ / 🟥	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟥 / 🟥	⬜ / ⬜	🟩 / 🟩
Slovenia	⬜ / 🟥	⬜ / 🟥	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟥 / 🟥	no data	🟩 / 🟩
European Union	⬜ / 🟥	⬜ / 🟥	⬜ / 🟨	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟩 / 🟩	🟥 / 🟥	🟩 / 🟩	⬜ / 🟨

Table 8. Overview of green energy categorization, based on (BMWK-Federal Ministry for Economics Affairs and Climate, 2023; European Commission, 2022d; European Parliament, 2023; Waschinski et al., 2023) and the respective energy policies, following the following legend

Green= deemed environmentally friendly
Yellow= not deemed environmentally friendly, but due to technological or logistical restraints deemed acceptable temporarily
Red= not deemed environmentally friendly
Grey= No official position, tolerated

These results are directly linked to the energy mix of all mentioned countries, pointed out in Figure 9.



	European Union	Poland	Germany	Croatia	Austria	Slovenia	Slovakia	Hungary	Czech Republic
■ Black and brown coal	10	73,7	33,5	11,3	0	23,4	4,7	9,3	42,6
🟧 Natural gas	19	5,6	10,8	25,4	21,9	3,8	6,8	25	6,9
🟦 Wind	18	11,6	25,1	18,3	14,5	0	0	1,9	0,8
🟨 Solar	8	5,8	11,2	0,8	1,6	2,2	2	9,8	3,1
🟦 Hydro	13	1	2,5	35,7	58,8	25,2	14	0,5	2,7
🟪 Nuclear	20	0	6,6	0	0	44,1	61,2	47,5	37,4
🟩 Biomass	0,8	1	8	5	1,1	0,5	3	3,5	3,1

Figure 9. Energy mix in the time period of 01.01.2022 to 31.12.2022 (Corbineau et al., 2021). [10]

In addition, all countries have come to an agreement to enhance the technical process of electrolysis. This is especially important for Germany, which is committed to eliminating its reliance on nuclear energy in favour of solar and wind power as the principal sources of hydrogen production. In addition, all the countries that make up Central Europe are working

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[10] The original data is measured on a 1-day basis. An average was calculated due to seasonal fluctuations. Countries with a focus on nuclear energy were placed on top. Germany's nuclear energy was shaded because as of 14.07.2023 Germany does not operate any more nuclear power plants (Clifford, 2023)

toward establishing direct hydrogen linkages with their surrounding countries since they see the development of the technology as a joint undertaking. Regrettably, there is a deficiency in the number of comprehensive concepts, methods, and attempts to harmonize energy networks, industry standards, and codification.

Taking a further look at the European Strategy for a climate-neutral Europe (A Hydrogen Strategy for a Climate-Neutral Europe, 2020), in it, the Commission stresses that the Green Deal and the energy transformation objectives cannot be achieved without the use of hydrogen as an intermediary. The European strategy holds the view that hydrogen will first be used in the manufacturing and transportation sectors of the economy. Brussels depends on subsidy methods to boost production in addition to modified emissions trading, which is used to reduce emissions. It has been argued that CO 2 differential contracts for both low-carbon and green hydrogen might serve as a "potential" sensor. The European Union Commission believes that low-carbon, circular manufacture of steel, fundamental chemical production, shipbuilding, and aviation are all good candidates for pilot projects. In accordance with the strategy, the production of environmentally friendly hydrogen may also make use of more conventional support systems.

In addition to receiving financial aid, nation states have been given the responsibility of working toward the achievement of the goals.

2.8 Descriptive data about Central European green hydrogen capabilities

Figure 10 goes into detail about the planned hydrogen capacities until 2030. Figure 11 offers insights regarding the potential capacities of green energy production in Central Europe, Figure 12 focusing on the potential of solar and wind energy output. Figure 13 are based on Enkhardt, 2022; Eurostat, 2022d; Statista, 2022 and indicate the current level of green energy output compared to the overall energy output as a percentage and absolute value.

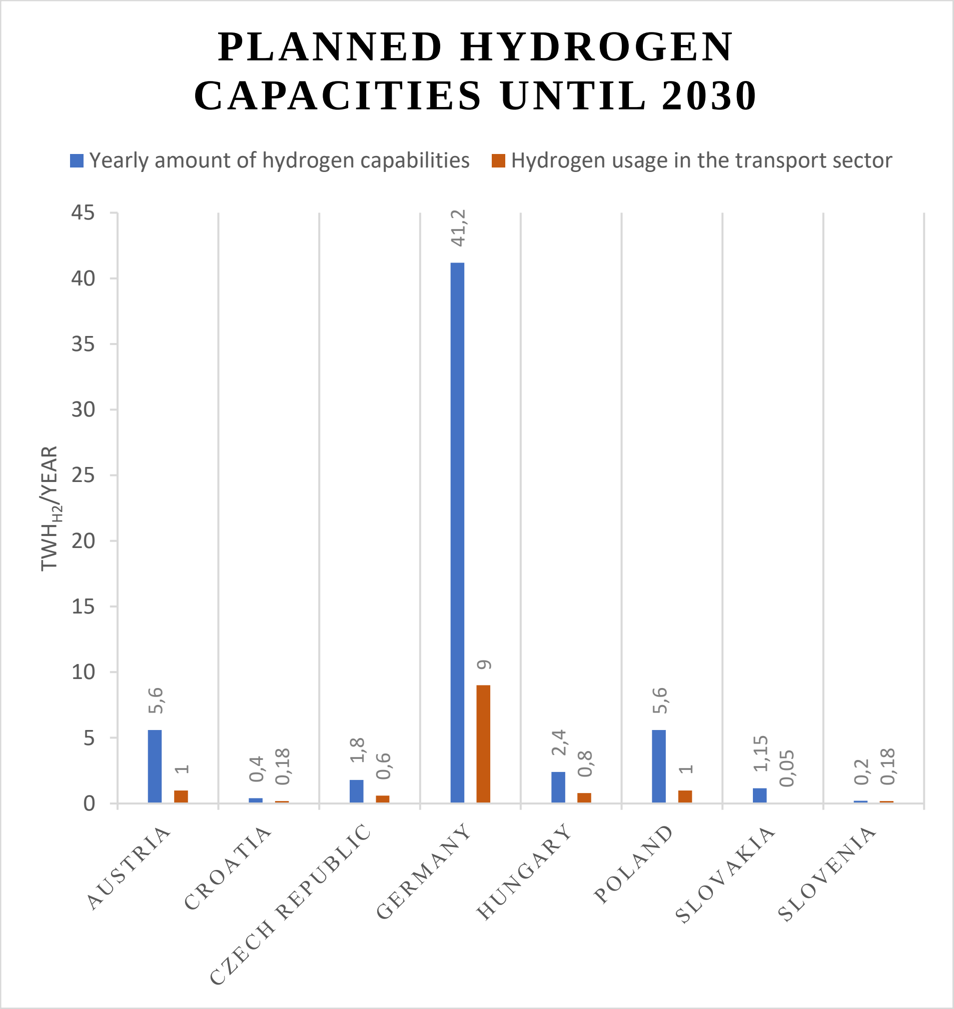

Figure 10. Planned hydrogen usage in the countries of Slovakia, Hungary, Austria, Germany, the Czech Republic, Slovenia and Croatia.[11]

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[11] Due to the data being potential future numbers, all data was sourced from the corresponding national hydrogen strategies formulated by the countries themselves. Own figure, based on data from FCH 2 JU, 2020d, 2020g, 2020e, 2020c, 2020f, 2020h, 2020b, 2020a, respectively. The Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) proposed two scenarios with a low and high outcome. To demonstrate the highest feasibility, the high outcome results were considered.

Solar Energy Potential in TWh

Country	Minimum TWh/year	Maximum TWh/year
Slovenia	3	4
Croatia	5	7
Slovakia	6	9
Czech Republic	10	15
Hungary	10	15
Austria	13	19
Poland	37	57
Germany	118	180

Wind Energy Potential in TWh

Country	Minimum TWh/year	Maximum TWh/year
Slovenia	9,7	16,6
Slovakia	23,5	40
Croatia	36,6	62,5
Czech Republic	37,5	64
Austria	42,8	72,9
Hungary	48,8	83,3
Germany	206,5	394,3
Poland	144,7	449,3

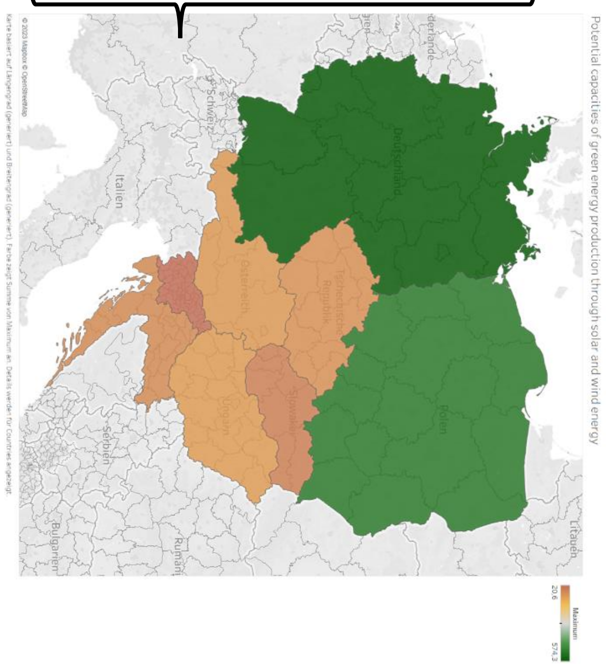

Figure 11. Potential capacities of green energy (solar and wind) measured in TWh in Central Europe. The map was based on the maximum potential output (Slovenia and Germany representing the lowest and highest maximum. Own figure, data sourced from Siegemund et al. 2017, made with Tableau Software.

Green energy potentials of Central Europe in numbers, split up into solar and wind energy potentials from the left.

Own figure, data sourced from Siegemund et al. 2017.

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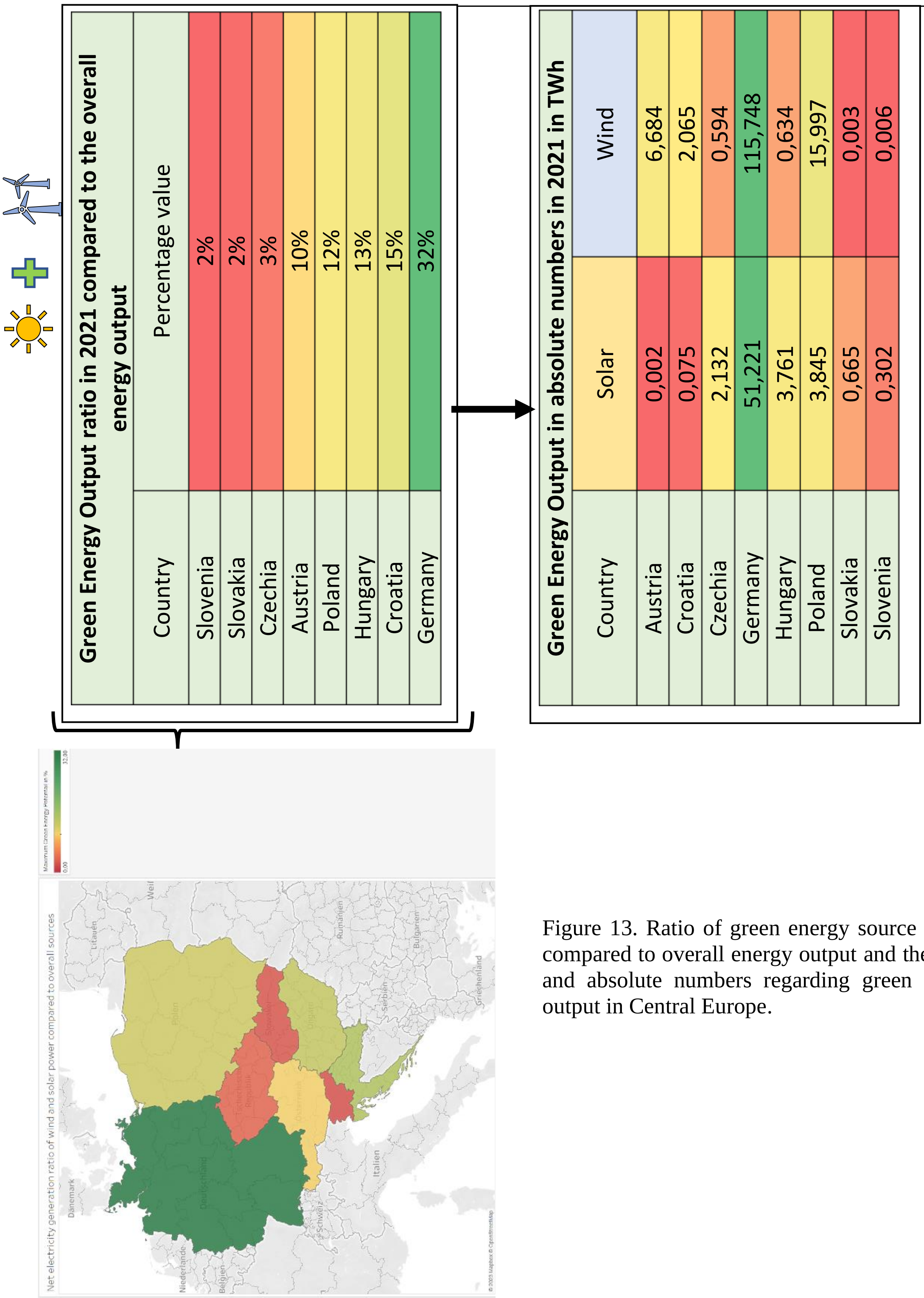


Green Energy Output ratio in 2021 compared to the overall energy output

Country	Percentage value
Slovenia	2%
Slovakia	2%
Czechia	3%
Austria	10%
Poland	12%
Hungary	13%
Croatia	15%
Germany	32%

Green Energy Output in absolute numbers in 2021 in TWh

Country	Solar	Wind
Austria	0,002	6,684
Croatia	0,075	2,065
Czechia	2,132	0,594
Germany	51,221	115,748
Hungary	3,761	0,634
Poland	3,845	15,997
Slovakia	0,665	0,003
Slovenia	0,302	0,006

Figure 13. Ratio of green energy source supply compared to overall energy output and the Ratio and absolute numbers regarding green energy output in Central Europe.

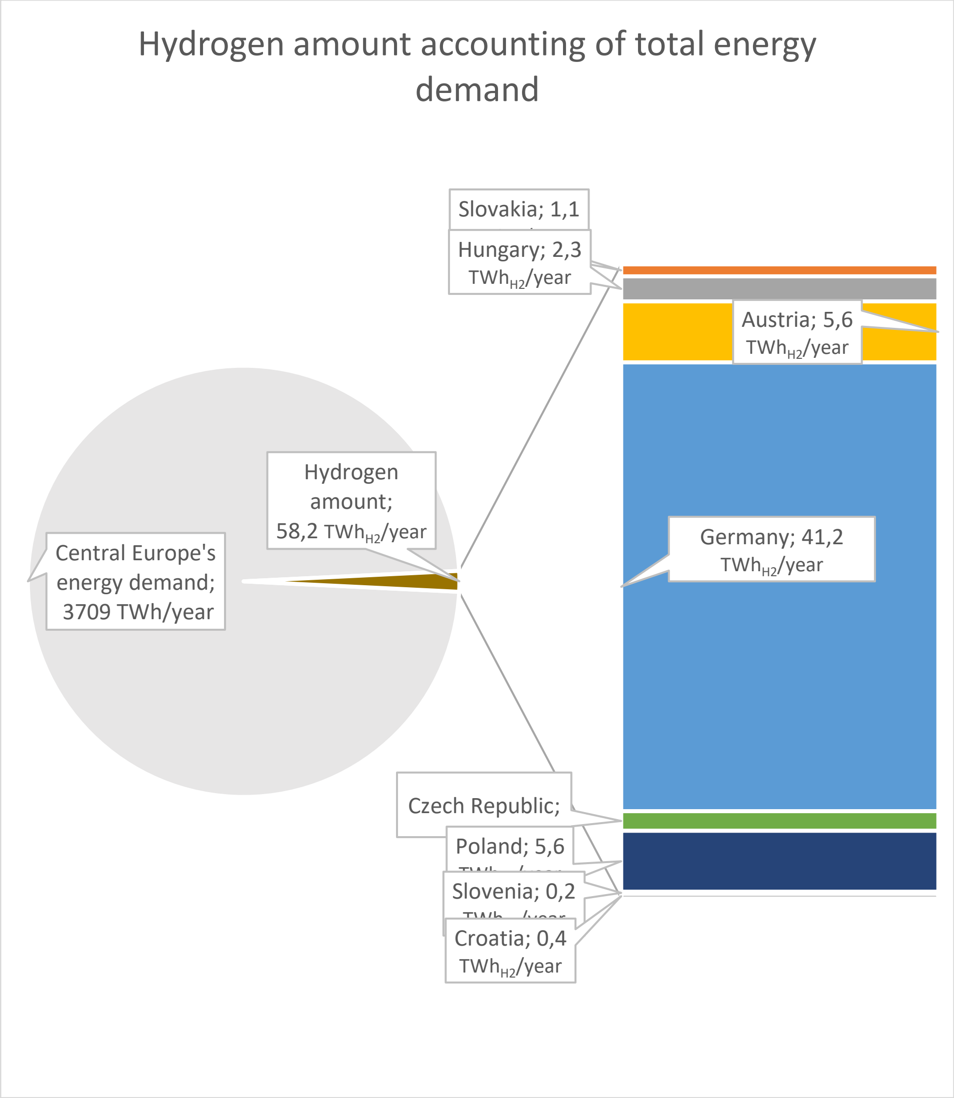


Figure 14: Distribution of Central Europe's Energy demand by 2030 faced with the planned (optimal) hydrogen manufacturing. Own figure based on FCH 2 JU, 2020d, 2020g, 2020e, 2020c, 2020f, 2020h, 2020b, 2020a

As visible in Figure 14, only a small percentage of the total energy mix is aimed to be replaced by hydrogen in the upcoming years. Germany follows one of the most extensive programmes, but even with combined efforts only 1,5% of the total energy consumption of Central Europe is planned to be replaced by hydrogen.

3. OBJECTIVES TO ACHIEVE

Currently humanity is searching for an environmentally friendly alternative to oil-dependent mobility. Lately, the only legislatively supported alternative to carbon-emitting technology seriously anticipated by the European Union is battery electric vehicles, with limited interest in biofuels (European Commission, 2022f). However, to successfully commit to the transformation of mobility the restructuring of the energy infrastructure becomes crucial. Many institutions and experts alike criticize, that the change of propulsion alone circumvents the actual problem: the ecologic supply of the fuel itself, which might still be as carbon intensive as current combustion engines (Bundesumweltministerium, 2022). Hydrogen mobility could take over this crucial role, as green technologies to source hydrogen are abundant and some corporate pioneers have already constructed market ready emission-free hydrogen-operated vehicles. Investigating the current acceptance, infrastructural level and policies leads to the idea, that hydrogen cars are more environmentally friendly, but for the time being - as this is not the focus of current European research and development departments in the automotive industry - there are no commercialised and therefore cheap techniques available.

This dissertation follows the following structure: hydrogen mobility, along with electromobility, is explored in more depth in order to throw light on the precise decision-making process of consumers when it comes to the acquisition of alternative propulsion systems. Initially, fundamental theoretical notions for the examination of innovation are enumerated and distinguished from one another. Then, it is described how and where innovation arises. On the basis of BEVs, so-called battery electric vehicles, market penetration strategies are established, economic innovation is highlighted and made quantifiable, and the role of the legislator in promoting innovation is discussed. The main points and distinctive selling features of different nations will be elicited and analysed with the use of concrete examples. In contrast, the interests of prospective consumers who respond both indirectly and directly to the policies will get significant attention. The following core research question is formulated as follows:

Research Question No. 1: What are the essential measures for the effective adoption of hydrogen as an innovative fuel source in the Central European private vehicle sector?

Objective: Identify three exemplary hydrogen strategies of Central European Countries, with different size, economies, infrastructural needs and thereby evaluate strengths and weaknesses in both an internal national policymaking as well as external EU-wide level.

To address the first study question thoroughly, it is essential to record innovation as a core concept within the automobile sector. Identifying significant players outside of the sector itself makes it clear that a rigorous literature study is required to thoroughly characterise the actors of innovation. While some players, such as legislative institutions, openly reveal their strategic approach and possible flaws, others, such as consumer groups, tend to lack a unified and consistent perspective. Instead, individuals have diverse purchase decision-influencing views and histories, necessitating more investigation. Therefore, the following further research question is posed:

Research Question No. 2: What factors influence customers in favour of purchasing cars with hydrogen fuel-based drivetrains?

Objective: Create a questionnaire centred around customers currently looking for alternative drivetrain vehicles ready to purchase. Identify whether the potential disadvantages of current purely electric drivetrains can be overturned with this way of mobility.

To receive validated responses, a questionnaire is anticipated, with a series of statements to be evaluated by customers in a selected Central European country, based on previously identified benefits and limitations of current and nearly market ready HFC, so-called hydrogen fuel cell vehicles in the systematic literature review. To complement these results and place them in context regarding the current status of potential for hydrogen-based mobility in the Central European states of Austria, Croatia, Czechia, Germany, Hungary, Poland, Slovakia, and Slovenia, a component-based object comparison for objectivity method is applied, revealing both overperformance and underperformance by quantifying the previously adopted questionnaire statements into comparable quantitative data. Consequently, the following third research question is:

Research Question No. 3: How successful are the Central European countries in decarbonising their private transport using hydrogen fuel cell vehicles?

Objective: Based on the questionnaire, factors of sustainability, logistics and finance of all European countries are evaluated to identify those countries, that offer the highest adoption chance for hydrogen mobility in the individual sector.

4. QUESTIONNAIRE

4.1 Introduction

The problem of climate change poses a significant obstacle for humankind, and it is imperative that governments and societies put a stop to the release of greenhouse gases caused by human activities. As a result of the fact that the production of energy, industry, agriculture, and transportation are among the most significant sources of emissions, several governmental organisations throughout the world are now adopting new regulations to reduce the release of carbon dioxide equivalents. Because of this, research into alternative engine designs as well as cleaner and more efficient ways to use fossil fuels has been accelerated. In the last several years, there has been an increase in the production of BEVs for key markets, and substantial efforts have been made to bring down the costs of both automobiles and batteries. However, because to the relatively low capacity of the batteries, BEVs have a drastically reduced driving range, which means that drivers would need to schedule time-consuming journeys to charging stations. To combat these challenges, the concept of supporting the use of HFC vehicles gained momentum lately, supported by the idea of further use of so-called e-fuels, that would sustainably maintain the current level of mobility to a certain degree, while drastically reducing the emission during the operation of the vehicles.

This section combines the extensive insights of previous studies regarding the customer requirements for purchasing new vehicles and adopts key results into a questionnaire aimed at a diversified customer group in order to evaluate, what factors are necessary to successfully promote the use of hydrogen fuel cell vehicles. The survey was conducted in Germany, because it is the largest vehicle market in Europe and has the strictest hydrogen production regulations in Central Europe, which may make it the "greenest" hydrogen transport option. But the results from the questionnaire represent the further steps necessary for the successful policymaking of the nation states of Central Europe, to both reach the legal requirements of further decarbonisation of the mobility sector, but also by dampen the ecologic or furthermore health related damaging consequences for society in the long run. At the same time, it proposes businesses, from OEMs to suppliers alike, to find strategic decision-making concepts, focused on the demands of the customer, to achieve the harmonisation of technological innovation and economic incentives towards a shared society-focused innovation strategy.

The concept of push and pull mechanics are vital to achieve successful innovation adoption, putting the customer groups as the main drivers and thereby gatekeepers of innovation. Changing economic environments, however, deeply influence customer purchasing behaviour, thereby following the principle of the saying” the bait is for the fish to like, not the fisherman”.

4.2 Materials

To understand the main motivation of changing customer demands and wishes, it is crucial to understand the main intention and motivation of individuals or families to purchase a new automobile first. The purchase of a new automobile is evaluated as a very rare financial occurrence, due to the high financial cost the purchasing and upkeep come with. While expecting a cost-benefit analysis would seem likely, previous results indicate, that the expected positive connotations to image, manifested in status symbols, tends to have an extensive impact on the purchasing decision of consumers (Chng et al., 2019). As a result, consumers of higher priced automobiles, tend to more seldomly consider a switch in their current brand choice, while purchasers of smaller and cheaper vehicles, who follow a pattern of lower price elasticity, consider the available choice on the automotive market much more thoroughly (Nayum et al., 2013). Ecological facets, on the other hand, while being evaluated, might not seem to reach the sufficient factor to change the purchasing behaviour of individual consumers (Thornton et al., 2011).

Previous studies (Lane & Banks, 2010; Orlov & Kallbekken, 2019; Peters et al., 2008) analysing the purchasing behaviour of customers identified a deviation between the understanding of policymakers and customers themselves. Most customer interested in purchasing a new vehicle focus on the vehicle segment first (Nayum et al., 2013), before considering other aspects of economic or ecologic background, prioritizing aspects like size, price and reliability. However, all these aspects are overshadowed by the strong brand identity of customers, as luxury attributes may be heavier valued by customers than fuel efficiency (Givord et al., 2018; Noblet et al., 2006) negating most policymaking tools focused on rational and efficiency based decision models for consumers. Furthermore, many customers limit their purchasing research drastically to situational and emotional factors often transported through brand loyalty, thereby overvaluing certain aspects like previous positive purchasing decisions and skipping ration decision-making of alternatives altogether (Nayum et al., 2013). In order to meet the increasingly strict regulations from national and supranational institutions alike (Hammerl et al., 2022), the call to action is more present than ever before.

The purpose of this section revolves around the analysis of factors responsible to convince customers of all groups to change their purchasing behaviour in the long run, away from a combustion engine powered vehicle towards the sustainable concept of hydrogen electric cars and subsequently combine simple arguments into the foundation of future decision-making models.

4.3 Methods

Due to the immensely limited post-prototype selection of possibilities, customers will not be faced with the evaluation of a direct model, but rather confronted with the idea of considering a hydrogen-fuel based vehicle as the purchasing option in case the need of mobility for it arises. Due to car purchases being determined key individual decisions, stakeholders of all directions increase their focus on finding ecological solutions in this sector.

The questionnaire was further built on the premise of uninterrupted growth in the automotive, indicating the national and supranational institutions alike will pursuit two main concepts; promoting the use of private mobility via alternative drivetrains with a deep focus on low-emissions and thereby reduced environmental impact (Chng et al., 2019) and the encouragement of public transport infrastructure. While efforts by corporations invested in the automotive industry, namely the OEMs and their wide network of regional, national and international suppliers is every increasing, the complexity and thereby requirements for technological and strategic knowledge management is also rising (Ton, Hammerl, et al., 2022). As a result, the need for a leadership strategy, focused on customer interest, has never been higher, demanding concepts, that deliver both products and services with increasing international supply chain demands.

Consequently, a twelve statement-based approach was selected, where twelve customer purchasing advantages regarding hydrogen fuel cell cars are presented and to be evaluated by the respondents. Firstly, the ecological effects of hydrogen propulsion were selected, as both from a customer perspective as well as from a wider society-based view, consumers include the ecological impact of their purchasing behaviour into their decision-making (Galarraga et al., 2020). Often accompanied by energy labels, based on national and supranational law, customers may base their decision on factors like the amount of CO_2 emissions (Q1 & Q10) (Q. Wang et al., 2020; Zhang et al., 2020), range (Q4) (Giansoldati et al., 2018), charging or refuelling time (Q5), and many more factors.

Due to the high material costs the purchasing of new cars come with, infrequent and often limited-experienced purchasing behaviour is common. Besides the direct costs and performance factors like image and branding takes an even importance for many customers. As these are unrelated to the general technical innovation of hydrogen mobility, with the exception of higher purchasing costs (due to high investments and risk by the industry -Q3) and limited operative costs (mainly reduced tax incentives and stable fuel prices due to domestic supply-Q2), most of these factors were not further considered for this questionnaire (Chng et al., 2019).

Furthermore, the effects of external issues like temperature are noteworthy. While Central Europe offers a relatively stable climate with mild winters, previous researchers discovered that decreasing climates and factors like winter tires dramatically decreased in reliability and range (Jakobsson et al., 2022), resulting in a need for different consumption behaviours (Q6). Similarly, the topic of potential fire hazards linked to the chemical internal structure of lithium-ion battery packs found in common BEV in accidents (Cui et al., 2022), the potential similar dangers as well as new challenges (Y. Wu, 2008) can also apply to HEVs. Taking into consideration, that hybrid technology, like the innovative adoption cycle of electric propulsion, takes place in hydrogen mobility, many customers refrain from buying alternative drivetrain powered cars (Q7). Lastly, the perception of sound plays a significant role, both for customers who associate a specific engine sound as a quality impression, but also as a safety parameter, meaning that completely silent vehicles at high speeds can cause a variety of possible dangers (Q9). While hydrogen fuel cell vehicles are less noisy than their combustion engine competitors, they do still offer a natural sound, most prominently of operational background like intensive acceleration, often expected by customers (Münder & Carbon, 2022).

Another reason for a potential slow adoption of hydrogen could be the refuelling situations. While the security of supply is seen as a natural occurrence by the majority of customers and is itself dependent on a variety of factors, customer themselves expect a wide number of refuelling stations, scattered around the whole Central European area in order to be convinced. Therefore, besides international collaboration, similar to the hydrogen trade system many countries determined as significant in order to promote the use of hydrogen cars, the issue of infrastructure is seen as critical (Q8) (Crönert & Minner, 2021; Han et al., 2022; Ku et al., 2022; Savari et al., 2022).

Originating from the concept of diversifying transportation in general, many institutions and organizations alike promote the concept of combined transportation. The phrase combined transport is often understood to refer to the sequential employment of at least two separate modes of transport to move an item. Throughout the duration of transit, the items stay in the same transport unit. The transport is carried out by rail, inland waterway, or ocean-going vessel for the majority of the total distance and by motor vehicle for the remainder, which is as short as possible; additionally, when the modes of transport are changed, it is not the goods themselves that are transhipped, but rather the loaded loading units or loaded motor vehicles (Bundesamt für Güterverkehr, 2022; Gronalt et al., 2010; Kaffka, 2013). Similar to this concept, many previous studies point out, that there is no senseful way to incorporate one powertrain, being it electric, hydrogen, hybrid etc., that could effectively incorporate all levels of mobility usage, flexibility and spontaneousness (Wee et al., 2020; Q. Wu et al., 2010). Therefore, it is proposed, that the powertrain should adapt to the customer rather than forcing far reaching changes regarding the current mobility consumption (Q11).

Lastly, the question of purchasing a hydrogen powered vehicle is asked (Q12). All questions are presented in Table 9.

Q1. Hydrogen burns without emitting CO_2 and is classified as CO_2-neutral.
Q2. In contrast to electricity, natural gas or petrol, the price of hydrogen is hardly subject to fluctuations and is currently cheaper than other fuels.
Q3. The price of hydrogen vehicles will be significantly more expensive than diesel/petrol vehicles, compared to electric cars.
Q4. The range of hydrogen vehicles is about the same as that of electric vehicles and is currently still significantly less than that of conventional consumers.
Q5. The refuelling time of hydrogen vehicles is extremely fast. Approx. 15 seconds are enough to fill the tank.
Q6. Hydrogen vehicles are resistant to temperature. In winter, the vehicles can be started without any problems.
Q7. Hydrogen vehicles have an increased risk of explosion in the event of an accident.
Q8. There are currently only a few filling stations that offer hydrogen as a fuel.
Q9. Vehicles with hydrogen engines are noiseless. There is no concern about noise pollution.
Q10. Vehicles with fuel cells are more efficient and environmentally friendly due to the possibility of storing CO_2 free electricity.

Q11.	Different alternative drives fulfil different tasks. There should not be just one solution.
Q12.	If hydrogen vehicles were available in Germany, I would buy a hydrogen vehicle.

Table 9. Questionnaire items, own figure

All answer choices were rated on a bipolar, eleven-point scale ranging from 0 (strongly disagree) to 11 (strongly agree). The objective of this study is to comprehend the opinions/perceptions of participants on a particular "latent" variable (phenomenon of interest as in purchasing a hydrogen vehicle). This 'latent' variable is represented by several 'manifested' items in the questionnaire, denoted by eleven statements, the last of which is a direct response of purchase decision making (Joshi et al., 2015). These built items target a particular dimension of a phenomena in a mutually exclusive way, so that the responder cannot provide a text-based response and must instead state a number between 0 and 11, indicating his or her preference. The higher range of point scale was purposefully chosen to depict a clearer picture of current consumer preferences.

Germany's economic leadership role in Europe, especially Central Europe, in the invention, production, and marketing of vehicles meant that attention could be focused on just one country. Although the Czech Republic, Hungary, and Slovakia, as well as other nearby countries, are playing an increasingly important part in the vehicle manufacturing of Central Europe, most of the planning and design is currently done in Germany. Furthermore, for organisational and managerial reasons, the centre of project management and development, communication channels, and thus cross-functional teams remain in Germany even in the case of cross-border cooperation. Since a consequence, only Germans were able to respond, as the kind of long-term planning that would be necessary for a breakthrough innovation is no longer being done with hydrogen transportation in mind.

The factor of design was also purposefully excluded, while BEVs and HEVs of all sorts do not share common technical parameters (Schönknecht et al., 2016) due to different usage scenarios of batteries, inverters and similar, the common futuristic design and offer less external design differences than classic combustion engine vehicles.

Regarding the social background of the participants, questions around age and educational background were deemed crucial (Givord et al., 2018).

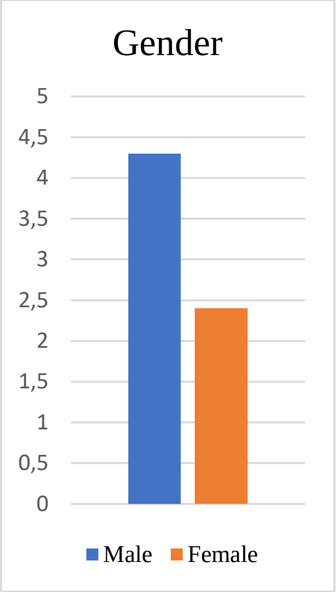
To collect the data, the survey was created on SoSciSurvey.com. Participants took the survey between 11th of July and 4th of August 2022. There was no time restriction for submitting responses.

G-power was used to determine the number of valid replies required to provide verifiable and repeatable findings. Using a model of multiple regression, the connection between a dependent variable and independent variables is determined. Therefore, the Multiple Regression option of the F test (R2 departure from zero) was used. The number of predictors is set to 11 depending on the number of questions pertaining to analysis variables. The impact size of 0.25 was chosen using a combination of the medium and large f2 effect size index, based on Cohen (1988), as a compromise between economic models and personality psychology, i.e. customer-based decision-making models.

No hypothesis test can provide absolute confidence. As the test is based on probabilities, it is always possible to get the incorrect result. In a hypothesis test, two sorts of mistakes are possible: first type error and second type error. These two forms of error are inversely related to one another and are governed by the significance level and the power of the test. A value of 0.05 was used, resulting in a 1- err probability of 0.95, suggesting a 5% chance of rejecting the null hypothesis in error. Based on these assumptions, a total sample size of 111 responses was proposed. Partially Missing data was consequently not further considered.

4.4 Results

The descriptive statistics regarding the main variables of interest of the study are presented in Figure 15, Figure 16 and Figure 17, respectively.



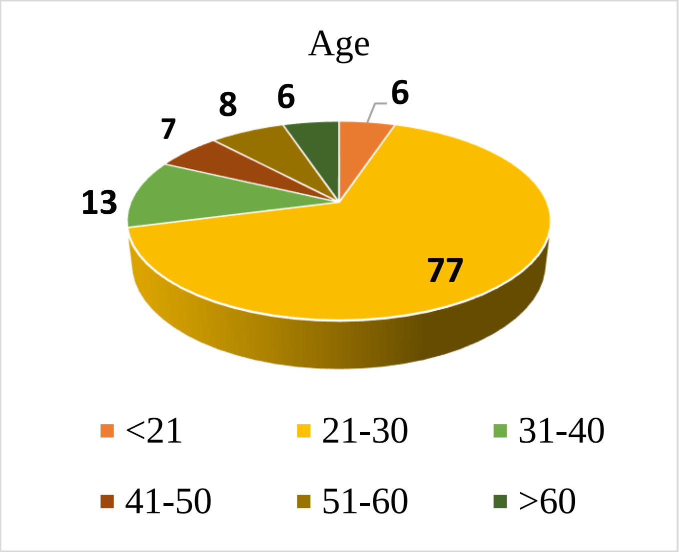


Figure 16. Age distribution of the respondents, own data

Figure 15. Gender distribution of the respondents, own data[12]

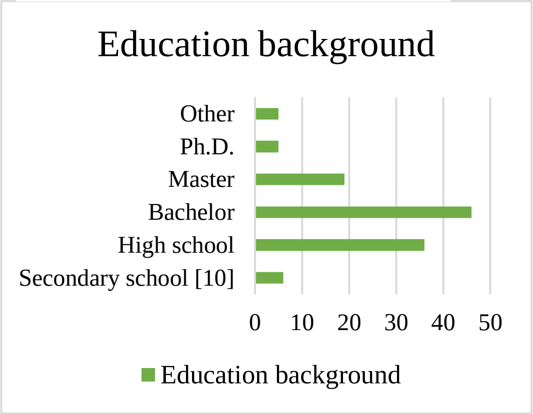


Figure 17. Education background of the respondents, own data

Multicollinearity based on the variance inflation factor is barely measurable. Testing the potential purchasing of hydrogen fuel-based vehicles against the eleven questions resulted in the confirmation of the following significant results. The p-value from the Breusch-Pagan test is present with a very high value, indicating constant variance of the residuals and homoscedasticity present (see Table 10 and Table 11).

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[12] Due to the difference between secondary school levels (namely “Hauptschule” and “Realschule”), the questionnaire included both parameters as possible answers. For simplification and differing school systems worldwide, the answers were combined in this instance.

SOURCE	SS	DF	MS	NUMBER OF OBSERVATIONS	**=**	**117**
MODEL	204,038181	11	18,5489256	F(11,105)	=	4,69
RESIDUAL	415,192588	105	3,95421512	Probability > F	=	0,0000
				R-squared	=	0,3295
TOTAL	619,230769	116	5,33819629	Adjusted R-squared	=	0,2593
				Root MSE	=	1,9885
PURCHASING HFC	**Coef**	**Std. Error**	**T**	**P > t**	**95% Conf. interval**	
ADV. 1[13]	-0,0702685	0,1091358	-0,64	0,521	-0,2866644	0,146128
ADV. 2	0,2411731	0,0890747	2,71	0,008	0,0645544	0,4177918
ADV. 3	-0,0402199	0,0951611	-0,42	0,673	-0,2289068	0,1484669
ADV. 4	-0,078550,	0,103886	-0,76	0,451	0,284537	0,1274364
ADV. 5	0,0876962	0,0758181	1,16	0,250	-0,626371	0,2380296
ADV. 6	0,1133602	0,983473	1,15	0,252	-0,0816443	0,0067916
ADV. 7	-0,1814786	0,094954	-1,91	0,059	-0,3697489	0,0067916
ADV. 8	-0,676462	0,094569	-0,72	0,476	-0,255159	0,1198666
ADV. 9	0,1283822	0,0724516	1,77	0,079	-0,015276	0,0272040
ADV. 10	0,2697161	0,120658	2,24	0,028	0,0304737	0,2948543
ADV. 11	0,1187353	0,0888227	1,34	0,184	-0,0573937	0,2948543
_CONS	2,821134	1,320385	2,14	0,035	0,2030549	5,439213

Table 10. Statistical results regarding the hypotheses, own figure. The ADV. Represent the economic, environmental, or technological advantages, that represent the answer to the Q1-Q11.

Variable	**VIF**	**1/VIF**
Adv. 1	1.62	0.616534
Adv. 6	1.60	0.623726
Adv. 10	1.59	0.628780
Adv. 4	1.52	0.657524
Adv. 5	1.49	0.671412
Adv. 3	1.49	0.672826
Adv. 8	1.46	0.683600
Adv. 11	1.33	0.750513
Adv. 7	1.29	0.777223
Adv. 2	1.27	0.788986
Adv. 9	1.22	0.817688
Mean VIF	1.44	

---

[13] The advantages were directly translated from the questions Q1-Q11.

Breusch-Pagan / Cook-Weisberg test for heteroskedasticity

H0: constant variance Variables: fitted values regarding the results of *Q12 (Would you buy a hydrogen electric car?)*	
Chi^2	0,06
Prob > chi^2	0,8013

Table 11. Evaluation of potential statistical problems, own figure

- Advantage 2, the stability of hydrogen prices due to (to a certain degree) plannable domestic manufacturing and potential competitive pricing are convincing customers (P > t= 0,008).
- Advantage 10, stating that HFC vehicles are considered more efficient ecologically, when fuelled with the corresponding green energy, and at the same time can store CO_2 free electricity (P > t= 0,028).
- Advantage 7 and 9 were barely scraping the significance parameter (P > t= 0,05), however, they are mentioned for their noteworthy presence. Both could be considered convenience factors, as they revolve around the safety aspect (increased risk of explosion in the event of an accident, ADV. 7, P > t= 0,059) and their noise emissions (reduced or non-existent noise emission, ADV. 9, P > t = 0,079).

The overall model is deemed significant (p<0,01) and simultaneously refers to a reasonable chunk of variance regarding the dependent variable (R-squared=0,3295).

5. DISCUSSION OF THE RESULTS

Assessing the research papers during the systematic review revealed several insights. Firstly, the energy transition towards a Central Europe wide hydrogen market requires large amounts of renewable hydrogen (Newborough & Cooley, 2020). The clarification of what renewable hydrogen becomes more difficult however, as policymakers, energy suppliers and industrial actors are uncertain, what original sources of hydrogen production should be considered: a focus on traditional fuels like gas (grey hydrogen), coal (black hydrogen) shifting towards an efficient and widely applied carbon-capturing concept (blue hydrogen) over time or rather skipping this step immediately towards a renewable-based production (green hydrogen) (Dawood et al., 2020; Olabi et al., 2020; Van de Graaf et al., 2020; Weger et al., 2021). As a result, general codes & standards for hydrogen production, infrastructure, taxation, and support are lacking on a wider scale (Sgobbi et al., 2016), resulting in continuous failing both climate targets as well as self-imposed policy targets of substitution in the past (Fernandes et al., 2005). Additional uncertainty is provoked through the discussion over the use of hydrogen. This question implies, whether there should be a direct use of energy rich hydrogen, sourced through mostly nuclear or fossil-fuel based sources or rather enriched hydrogen production using wind and solar energy (Ren et al., 2020; Velazquez Abad & Dodds, 2020). The latter, however, still needs significant efficiency improvements, as high amounts of energy are lost during the enrichment process. Additional blocking factors from the perspective of enterprises were determined (Skoczkowski et al., 2020; Yahiaoui et al., 2019) as well as issues with the production of nuclear-based hydrogen in Central Europe, as efforts to exclude nuclear power production in Central Europe are rising (Schiffer & Trüby, 2018) due to prominent policies like the German "Energiewende" (Ehret & Bonhoff, 2015), while other European neighbours propose differing strategies (Iordache et al., 2019) and even consider other matters of energy like biofuel or "just" natural gas (Panoutsou et al., 2021; Pfoser et al., 2018). Hungary takes a special role in this development, due to the newly established but steadily growing automotive industry, industry trends play a significant role in the economic development and specialisation of the country (Molnár et al., 2020), visible on the diversified focus on both electric propulsion and hydrogen technology alike (Major, n.,d.). These factors in their combination put further pressure on the daily business of the wide range of suppliers, as they follow different strategies, organizational behaviour and planning compared to the OEMs (Mohamad & Songthaveephol, 2020).

Besides the industrial key actors, the policymakers similarly showcase themselves with a self-focused and independent strategy instead of integrating with their neighbours. This reasoning is led back to the critical strategic question of losing control over the national energy system, often raising eyebrows in the national defence strategy. Answering the question of energy systems is by far not the only question, as the development of infrastructure of charging (Funke et al., 2019), refuelling, transport, and storage (McPherson et al., 2018; Modisha et al., 2019) and maintenance is an essential step for any change in the development of mobility (Santos & Davies, 2020). Additionally, the issue of monetary incentives of any kind (Rehfeldt et al., 2020), be it the customer, the society in general or the industry, needs further evaluation, as the smart and the spending of gross national expenditure with a focus on cross -instrumental policies will have an existential impact on the success of innovation (Greco et al., 2020).

By looking into the industrial development and efforts the decision of significant economical actors was investigated (News, 2019a, 2019b) and insights into other automotive invested countries, most prominently positioned in rising markets like China (Chen et al., 2019; Ma et al., 2019; T. Yang et al., 2021) or risk-tolerant industries concerning hydrogen like the Japanese automotive industry (Potter & Graham, 2019) show off the potential but also necessary strategic reconsiderations to successfully integrate hydrogen into the mobility sector.

Lastly the question of consumer behaviour and preferences play a major role in the breakthrough of innovation, eventually their purchase decision is the final variable to declare the economic success of a new technology. Looking into the demand for hydrogen compared to other alternative propulsion systems (Anderhofstadt & Spinler, 2020; Emmerich et al., 2020; Linzenich et al., 2019; Zubaryeva & Thiel, 2013) indicated the immense customer benefits through an easier distribution and facilitation compared to the concept of electric vehicles (Schwabe, 2020).

Followed up by a quantitative approach, the objective of this questionnaire was to investigate, what current customer groups consider regarding purchasing a hydrogen powered vehicle. The main hypotheses revolved around the question, whether there are clear indicators customers expect when confronted with the idea of purchasing a vehicle, that is currently only in concept, but crucial to achieve reduced emissions in the private mobility in the long term. Summarizing the results, it can be safely stated, that the hypothesis can be partially confirmed. In the following all ADV branded variables represent the answers to the Q1-Q11.

While the reduced ecologic impact is visible regarding later advantages, most customer did not prioritize the zero-emission features of current hydrogen concepts. According to the current strategies concerning the mass-manufacturing of hydrogen via emission-heavy coal, gas or methane originating resources, most customers seem to indeed consider the sourcing of the future fuel alternatives respectively (ADV 1). Similarly, the higher prices for innovation are also not statistically relevant, indicating that breaking edge technology is currently valued by customers as a highly research and development heavy venture (ADV 3). ADV 4, 5 and 8 revolved around one of the highly discussed topics of range and refuelling issues, often present with other alternative drivetrain concepts. Surprisingly, these aspects, while arching towards closer significance levels, did not meet the criteria of influencing the purchasing decision. This could be led back to the current state of hydrogen mobility, which, in Central Europe, is very concept-heavy with limited prototypes, not allowing realistic considerations to this date. Like other battery-operated concepts of mobility, external effects like winter weather with its colder temperatures but also corresponding varied environment effects (increased energy regarding heating, tire specifics and all-wheel operation etc.) may drastically limit the range compared to the common Central European mild weather during other seasons. Reaching similar significance levels as ADV 5, it is considered, that many customers do not have realistic experiences with HFC vehicles combined with the ever less mobility-dampening mild winters in the last couple of years in Germany. Lastly, the idea of alternative concepts, mainly BEVs and HFCs fulfil different roles and therefore different customer groups was brought up. While not reaching significance level, it is noteworthy to point out, that previous literature (Hiermann et al., 2019; Y. Yang et al., 2016) indicates, that in contrast to the usage of a fleet consisting of a single vehicle class, the operating expenses of a mixed fleet may be greatly reduced across a wide range of pricing scenarios provided the appropriate policy considerations are used.

Furthermore, ADV 2 and 10 could be fully supported, indicating many customers have a strong financial focus on the upkeep and thereby longevity of their next purchased car, while also valuing the emission-free ecologic propulsion, focusing strictly on the process of hydrogen-burning during the operation of the car itself. ADV 7 and 9 were also considered, although not meeting the strict threshold ($P > t = 0{,}05$), as they focused on factors not present in current diesel or gasoline operated vehicles, which are predominant in the German automotive landscape.

Due to the concentrated opinion in the Central European society, to further promote the use of battery powered electric vehicles, firstly, a more distant view on the use of hydrogen-based mobility must be adapted. Indifferent from the different decision-making based on brand, model, and ecologic footprint of each different car, it is crucial to analyse, whether the factors of hydrogen as power source, can improve or decrease the likelihood of purchases in the future. Therefore, the following quantitative method is connotated to several stipulations.

Firstly, it is assumed, that purchasing behaviour regarding automotive consumers follows a pattern of hierarchical decision-making, meaning consumers prioritize certain aspects of future purchases like safety, range, or price. Based on the previous research results (Chng et al., 2019; Lane & Banks, 2010; Nayum et al., 2013; Noblet et al., 2006; Peters et al., 2008) the car segment plays a specific role in the decision-making process. Car variety based on hydrogen as the main fuel resource, however, is currently scarce, resulting in many customers not having a shared image of hydrogen propulsion in the first place. As a result, model-dependent questions were purposefully not considered, and the focus was rather on the direct specifics of hydrogen regarding as an alternative to BEVs.

Furthermore, the importance of energy efficiency and thereby sustainable mobility is often limited or rather replaced by the idea of reduced running costs rather than primarily to decrease the ecologic footprint of said car (Galarraga et al., 2020). Consequently, customers tend to choose a vehicle segment first, based on factors like usability, reliability and similar and do not prioritise the energy-efficiency as a first parameter. Policymaking focusing on decreasing the emissions of private mobility should thereby focus on financial incentives directed on smaller and overall energy efficiency rather drafting concepts that are intermodal based.

Consumers depend on their own experiences, are affected by situational considerations, and make judgments utilizing heuristic shortcuts as opposed to performing comprehensive research. Prior research demonstrates that choices made regularly and under stable settings typically result in a beneficial outcome, despite not being impacted by attitudes or intentions. Continued study reveals that brand loyalty, operationalized as the number of previous consecutive purchases of the same brand, has a significant influence on future replacement automotive purchases. This argument says that brand loyalty serves the same goal as habits in everyday conduct by expediting the decision-making process (Nayum et al., 2013). Similarly, a clustering of income groups regarding potential hydrogen purchases of said respondents were not considered, due to the missing market presence of automobiles in Central Europe, with the exception of a few niche models compared to previous alternatives to the classic gasoline based engines (Givord et al., 2018).

Lastly, the factor of heteroskedasticity plays a major role, as with higher adoption prices of new technologies questions of income, living conditions, job expectations etc. introduces a bias, that largely alters the results. Studies in countries with a quality life standard (Nayum et al., 2013) and other theoretical research (Givord et al., 2018) explicitly warns that higher income scenarios potentially falsify studies that fully try to explain the purchasing behaviour of customers on socioeconomic factors. Lastly, loyal consumers are more likely to stick with the same automaker, especially those in the diesel, large, and four-wheel drive markets. This result adds to the literature on the significance of brand loyalty in future vehicle purchases.

6. COMPONENT BASED OBJECT COMPARISON FOR OBJECTIVITY

6.1. General methodology

To analyse and compare the performance of Central European countries. the Component-based Object Comparison for Objectivity method (or COCO for short based on (L. Pitlik, 1993)) was used. The COCO approach, also named “similarity analysis in some sources, rests its technique on the notion of comparing different entities on the same features or attributes, while also harmonising the unit of measurement and the associated date. By articulating a primary issue, this approach consistently predicts the performance of objects in relative contrast to one another and then evaluates an overperformance or underperformance.

Initially, a simpler method would include using basic regression functions and calculating averages to validate the current outcomes. All endeavours are founded around an additive model. The COCO technique employs a simpler approach, using a step function type estimate of the dependent variable, as opposed to using constant or functional regression coefficients.

Within the database, the columns correspond to many independent variables $[\underline{x}_i]$, (i=1…n) forming the matrix of $\underline{\underline{X}} \in (R^n \text{ x } R^n)$ and one dependent variable Y ($\underline{y}$). The rows reflect the records of the cases, for example in our case namely 32 European countries. The methodology uses the ranking matrix ($\underline{\underline{RM}}$) of the independent variable component instead of the original matrix $\underline{\underline{X}}$. The $\underline{\underline{RM}}$-array only consists of positive integers, specifically rank-order numbers. A target function is established for the dependent variable, which is estimated by stepwise functions instead of the conventional regression approach. This leads to a Linear Programming Problem for the stages of the stepwise function (Bánkuti, 2012; Bánkuti & Pitlik, 2010).

There are three primary types of similarity analysis, which have since generated several technological solutions. Every solution uses on an external optimization engine, known as a linear programming (LP) engine, to achieve self-termination in a predetermined manner, reaching a near-optimal state via a learning process known as layering (Pitlik M., 2020).

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target function is established for the dependent variable, which is estimated by stepwise functions instead of the conventional regression approach. This leads to a Linear Programming Problem for the stages of the stepwise function.

Anti-discriminative computation, also referred to as ideal seeking, is an artificial method used to generate concepts. In this method, we search for the most different object from the average, based on a given direction towards ideality. This is done through an optimization process, with the objective of ensuring that the objects maintain their identity. This is like determining if all objects can be similar in some ways, but different in others, and if there is a scale to represent this concept (Pitlik M., 2020)

The minimum step size for model COCO Y0 is 1 unit, meaning that the value of each subsequent step must be at least 1 unit less than the value of the preceding step (Bánkuti & Pitlik, 2020; Horváth, 2009; Pitlik M., 2020).

Figure 18, Figure 19 and Figure 20 demonstrate the general methodology when adapting COCO methods.

Figure 18. The applied COCO tool is accessible on the Internet via https://miau.my-x.hu/myx-free/coco/index.html. (COCO, 2022).

Azonosító

Az azonosító megadás NEM kötelező! Abban az esetben, ha az azonosító nem kerül megadásra a DEFAULT értéket fogja kapni. (DEFAULT=Teszt)

Mátrix

A primer mátrix megadása kötelezô!

Irányok

Lépcsôk száma

Figure 19. Website input interface of COCO Ranking

The first interface constructs the ranking matrix of the independent variables, based on the directly or inverse proportionality (irány) of the variables. It may be performed either prior or during this stage.

Verzió: **v2.17** (2012.10.25.)

Azonosító

Az azonosító megadás NEM kötelezô! Abban az esetben, ha az azonosító nem kerül megadásra a DEFAULT értéket fogja kapni. (DEFAULT=Teszt)

Mátrix

A rangsor mátrix megadása kötelezô!

Lépcsök

A lépcsök számának megadása NEM kötelezô! Abban az esetben, ha nem kerül megadásra a DEFAULT értéket fogja kapni. (DEFAULT=objektumok száma)

Modell

Fájlok megtartása

Vizuális beállítások

Az objektum listát NEM kötelező megadni! Ha a lista nem kerül megadásra, akkor a DEFAULT értéket fogja kapni! (DEFAULT=O1..On)

Figure 20. COCO Y0 website input interface

The COCO Y0 method takes a similar trajectory. Similarly, the ranks are shown with the dependent variable in this context as well. Ensure that the Y0 format is maintained at the bottom. The variables or categories, namely European nations, may also be optionally designated on the right.

The COCO STD webpage remains same, with the sole difference being the substitution of Y0 with STD (highlighted in red).

The following questions shall be answered with the COCO methodology:

Q1: How do the Central European countries perform compared to their neighbours regarding their hydrogen passenger-car fleet?

Q2: What does the current development of the variables indicate regarding the future? Is it possible to calculate a variable, that incorporates all data and simultaneously grades the current level of future hydrogen market penetration (i.e. innovation potential index)?

Q3: Based on the results in Q1 and Q2, how did the Central European countries change their policies over the years?

This stepwise type of regression functions have significant advantages over simple calculations of average yearly changes, which will be pointed out in a later chapter. The COCO method is applicable to all datasets and may be used repeatedly to provide predictions and forecasts under a wide variety of input situations. As in regression, the technique explores the relationship between the independent variables forming matrix $X \in (R^n \text{ x } R^n)$ and the dependent variable y ∈ Rn while using a novel approach. For the steps of the staircase functions Linear Programming (LP) Problem must be solved with different goal functions, based on the estimation error minimization type. Sum of the differences makes linear, sum of the absolute value of the differences creates nonlinear, least squares estimation forms quadratic goal function, quadratic linear programming problem. The data mining capabilities of the COCO model use staircase approaches instead of simplified linear regression models, allowing piecewise segmented regression chances. Thereby, instead of coefficients step function type estimations are integrated, delivering more precise results.

The COCO model does not need a true dependent variable but needs positive values, as it cannot process negative or zero values. This is the reason why it uses fabricated Y-values, that are based on the actual, true value with an added appropriately chosen positive value of β_0.. This is arbitrarily put in place, as the low number of current hydrogen cars, especially in some countries going as low as 0, small increments of hydrogen car growth need to be exactly monitored (L. Pitlik, 2022). With the help of the peculiarities of this model, the predicted $\underline{y}$-value is recalculated as the number of hydrogen cars per million people, multiplied by a factor of 1000, and then added to a factor of 1000.

The purpose of the research is to examine a new quantitative performance evaluation of previous policies in order to expose the inefficiency of countries with a high degree of market penetration in the public eye, but which lag behind in relative terms, while revealing the success of hidden champions.

6.2. Use of COCO methods in this dissertation

The applied similarity analysis is based on the concept of production functions, these must always have a genuine dependent variable. In order to evaluate the success of each and every country's aspiration towards hydrogen technology the overall number of hydrogen-powered automobiles per population and year are selected as the defining y-variable, the aforementioned dependent variable. Production functions may be estimated using essentially arbitrary methods (like regressions, neural networks, decision trees, etc.).

The following tasks must be accomplished:

- Undertake a feasibility test regarding the identification of elements that boost or reduce hydrogen mobility's potential without misrepresenting the results and diluting them with extraneous.
- Analyse, whether nations with a significant automobile sector respond differently to breakthrough technologies.
- Determine the existing system's reasonable load capacity.
- Create a SWOT- Analysis to determine long term development.

This thesis follows the format of earlier COCO model papers (Pitlik et al., 2020; Pitlik & Csizmadia, 2021) and the underlying analytical goal is to identify a pattern in the data, namely possible strategic and operational attempts of other European countries that lead to a better hydrogen electric technology adoption. Attempts were made throughout the inquiry to find similar data from the same or surrounding time periods. Essentially, data from 2019 up to 2021 was selected since these provided the greatest insight into trends soon. Observations before 2019 did not prove enough potential due to the highly limited amount of hydrogen vehicles, mostly because of not yet available purchasing objects.

The production function for the number of hydrogen-driven cars was applied to 32 objects, while limited to European countries. The reason for an extended dataset compared to previous analysis of this thesis is multi-facetted. Firstly, the European automotive market is much more diversified and heterogeneous in their supply chains, including but not limited to supplier amount, distribution and product specialisation or brand (marketing, design, brand philosophy, pursuit of technology) differences despite geographical proximity. All these economies either produce motor cars directly or are deeply engaged in the supplier business.

Measuring the success of decarbonising private transport faces the challenge of unclear data, as the amount of cars per thousand capita in the EU steadily rose from the years of 2011-2020, from a value of 486 per thousand capita to 560 per thousand capita in under ten years (Eurostat, 2022c). Still, based on the strategic goals of the European Union (Chng et al., 2019), one significant measure to reduce greenhouse gas emissions is the subsequent increase of alternative zero-emission drivetrains. Studying from the development of previous alternative drivetrains, the main value to measure the success of this policymaking will focus on the variable of the share of zero emission vehicles in newly registered passenger cars (Eurostat, 2022b).

The quantity of hydrogen-powered automobiles was selected as the unit of measurement and, thus the initial dependent variable $y \in R^n$ $y = [y_j]$ $j=1\ldots n$. The additive COCO model estimates these y_j values based (summing up) the values of the stepwise functions calculated by the COCO LP model. It can thereby conclude itself, whether certain variables impact the overall result ($\underline{y}_i$) or whether this do not have any statistical significance. It depicts the calculated amount, according to the model, that should have been achieved when compared with all other formulas. It can thereby evaluate whether country A with its different variables reached the minimum it should have, considering all other countries that potentially achieved more than their efforts would have allowed them. Consequently, a delta appears, that classifies the different performance of the countries in norm like, underperforming or overperforming results.

The following factors were selected as independent variables (xi), with a plus sign indicating direct proportionality and a negative sign denoting inverse proportionality on the number of hydrogen cars (see Table 12), based on previous research.

To summarize the model with mathematical denotation, with vectors of (32,1) – as there are 32 countries taking part in the investigation. Proportionality here is denoted by arrows up, (green, direct) and down (red, inverse).

$$\underline{y} = f\,(\underline{x}_1\,,\ \underline{x}_2\,,\ \ldots\ \underline{x}_{10}\,) \qquad (1.a)$$

$$\begin{bmatrix}\text{No. of H2 cars}\end{bmatrix} = f \begin{bmatrix} \underset{\uparrow}{\text{Gross public expendit.s on R\&D}} & \underset{\uparrow}{\text{No. of passenger cars}} & \underset{\uparrow}{\text{No. cars produced}} & \underset{\uparrow}{\text{No. of H2 Filling Stations}} & \underset{\uparrow}{\text{H2 product. capacity}} & \underset{\downarrow}{\text{Electric. prices}} & \underset{\uparrow}{\text{\% of zero emission Vehicles}} & \underset{\uparrow}{\text{\% of alternat. fuel Trucks}} & \underset{\uparrow}{\text{Petrol prices}} & \underset{\uparrow}{\text{No. of hydrogen cars}} \end{bmatrix} \qquad (1.b)$$

More detailed with measuring units and explanation:

Variable	**Measuring unit**	**Proportionality**	**Explanation**
Gross public expenditure on R&D	per capita	+	This statistic indicates how much a country spends in R&D via grants, research proposals, and bonuses. It encourages innovative technologies, such as hydrogen technology. Based on (Balsalobre-Lorente et al., 2021; Chen et al., 2022; Wei et al., 2023).
Number of passenger cars	per 1000 inhabitants	+	This ratio indicates the number of automobiles per 1,000 people. It represents the strength of the local auto sector as an employer and its contribution to the local economy. This significant reliance compels both vendors and employers to comply with growing European emission regulations, such as via the use of hydrogen technology. Based on (Blume-Kohout & Sood, 2013; Hermosilla & Wu, 2018).
Number of passenger cars produced	per 1000 inhabitants	+	High-vehicle-density nations depend on automobiles for a variety of reasons (convenience, lack of alternatives, long distances, etc.). They are more responsive to new technology and have higher buying power as a result Based on (Solarin et al., 2022).
Number of hydrogen filling stations	per 1 million inhabitants	+	This variable indicates the total quantity of hydrogen refuelling stations. The infrastructure is more advanced the higher the number. A clear incentive impact exists. Based on (Acheampong et al., 2022; Naeem et al., 2023).
Hydrogen production capacity	Tons per 1 million inhabitants	+	In analysing the hydrogen plans of nations, national governments anticipate that a greater proportion of domestic production will have a favourable impact. Based on (Gordon et al., 2022; Lozano et al., 2022).
Electricity prices for household consumers	€/KWh	-	Increasing electricity costs, the major source of green hydrogen generated by electrolysis using wind or solar energy, are the exact opposite of rising gasoline prices. The commercial adoption of alternative propulsion systems fueled by sustainably produced energy will be greatly hampered by high electricity costs. Based on (Durante et al., 2022; Macedo et al., 2022).

Variable	**Measuring unit**	**Proportionality**	**Explanation**
Share of zero-emission vehicles in newly registered passenger cars	%	+	Multiple technologies contribute to innovation. In the past, natural gas was a desired energy source that has since been superseded by battery-powered electric vehicles. They are all competing for the same thing, client acceptability and consequently market penetration, like hydrogen. Diverse technological marketplaces give more opportunities for innovation than concentrated ones.
Percentage of alternative fuels (electric, hybrid, etc.) regarding all (+diesel and petrol) new truck registrations	%	+	Ratio relative to the preceding ratio, selected in particular for nations with a strong logistical capacity (e.g. Poland). Although passenger automobiles there continue to depend more and more on gasoline and diesel, the usage of electrification, biofuels, and hydrogen, which are plainly more economically sensible, is on the rise here as well.
Petrol prices	€/l	+	The price of gasoline has a substantial effect on vehicle use. Increases in gasoline costs have an immediate effect on customers, who choose for more fuel-efficient cars and plan their travels in advance. Conversely, favourable gasoline prices give an incentive to retain the status quo. Based on (Frondel & Schubert, 2021).
Number of hydrogen cars	Car number / Per 1 million inhabitants	+	The outcome variable and factor to be researched, which was identified as the determining factor for the success of hydrogen technology in personal transportation.

Table 12. Variables and proportionality (indicating the expected effects) on the result, own figure.

6.3. Variables and their proportionality – difference between theory and practice

To answer Q1, data was pooled from reputable public sources to ensure reproducibility of results, such as statista.com, a German internet statistics and market research site as well as the database of the European commission and the United Nations, respectively. Missing data was based on assumptions of previous years (ACEA, 2022; Autotraveler.com, 2023; European Commission, o. J.; Eurostat, 2022a, 2022c, 2023a, 2023b; Fuel Cells and Hydrogen observatory, 2023; Fuelo.net, 2022; Kords, 2022; OECD, 2022; Statista Research Department, 2020, 2022a, 2022b), based on averages in other countries. All currencies were converted to Euro-values and all absolute numeric values were calculated to representative relative values (per thousand capita, percentage values etc.). The number of hydrogen refuelling stations was standardized to the value of 2021 due to missing data about previous years. Examples of the dataset in 2021 are presented in Figure 21, Figure 22 and

Figure 23 respectively.

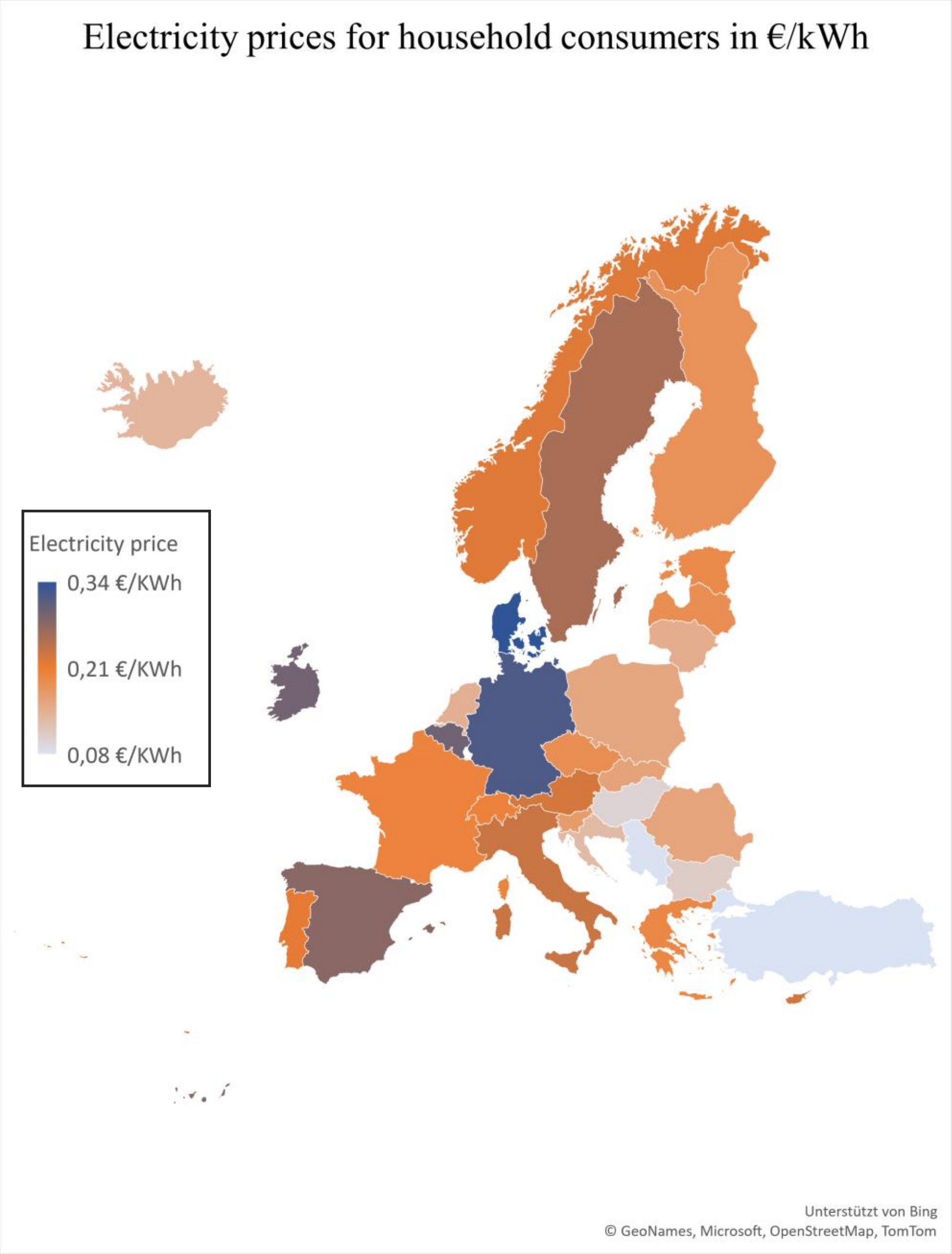

Figure 21. Energy Prices in Europe in 2021, own figure

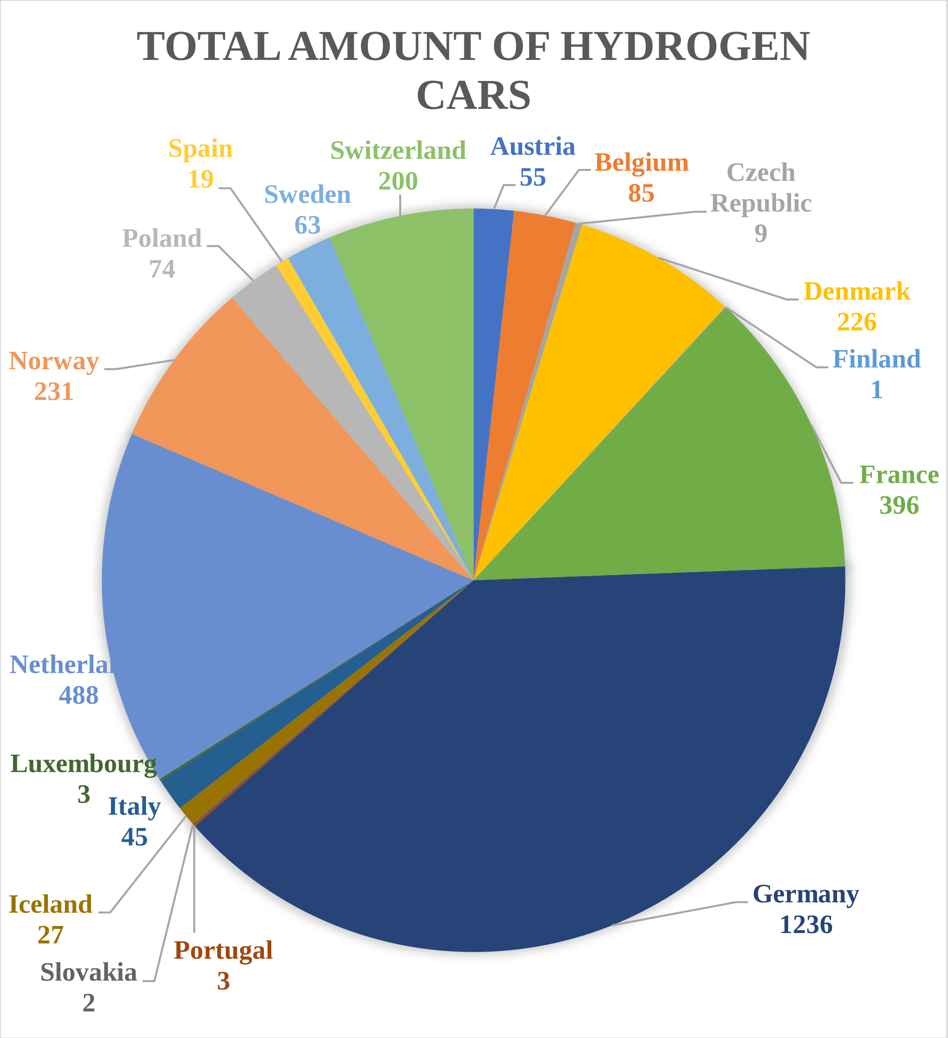

Figure 22. Total amount of hydrogens cars in 2021, own figure

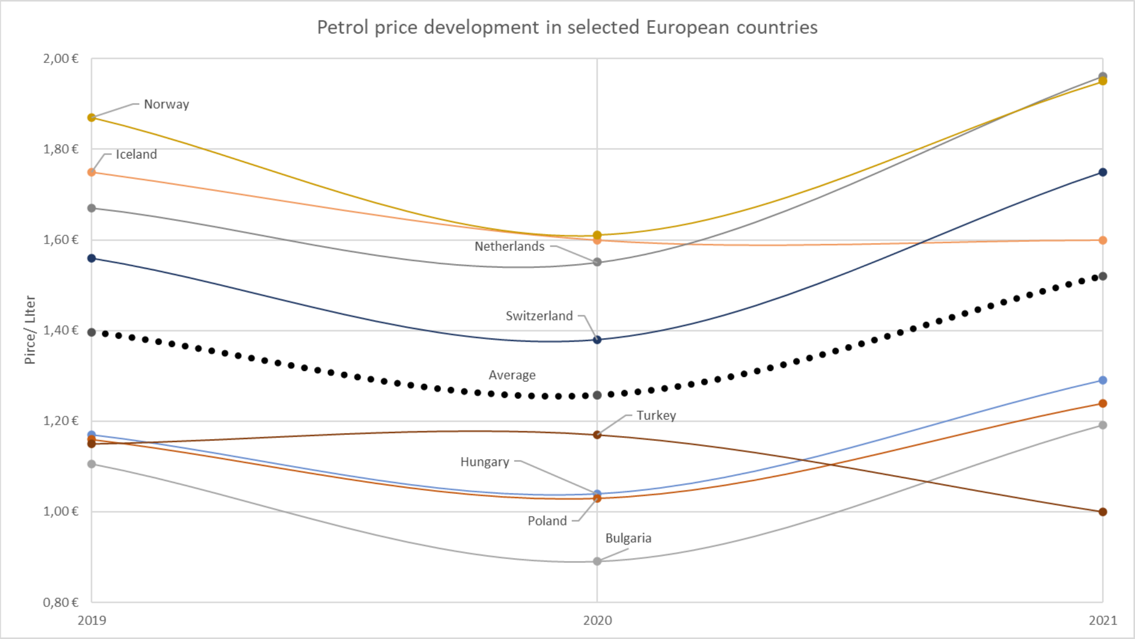

Figure 23. Petrol prices in selected European countries, own figure. [14]

Including the insights from the previously mentioned system (Table 12) and calculating the fundamental correlation between each independent variable and the newly derived y value yields the following results regarding the success rate of hydrogen (see Table 13).

Variables	Public exp. R&D	No. produced cars	No. Passenger cars	No. H-fuel stations	Annual H-Prod.	Electricity price	Newly regist. Alt. Trucks	Petrol prices	0-emission pas. car reg.
Direction based on literature	+	+	+	+	+	-	+	+	+
Direction based on correlation	+	+/-	-	(+)	+/-	+/-	+/-	+	+
Result	Good	Neutral	Contradictory	Good	Neutral	Neutral	Neutral	Good	Good

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[14] Due to the similar development of the petrol price index, only a hand-selected number of countries were presented, with an emphasis on those, that follow an atypical development compared to the average.

Explanation	• Good indicates that the results from previous academic literature and the correlation results from the quantitative dataset match and meet the expectations. • Neutral shows some differences between the predefined and the actual result. These differences limit themselves to showing no connection between each variable. • Contradictory results show the opposite between the academic world and the quantitative results.

Table 13. Determined proportionality direction based on academic literature vs. quantitative correlation, own figure.

It is possible, based on the data from the year 2021, to draw the conclusions that a few variables offer the same direction both in literature and the selected dataset (green), a few variables are only partially congruent (yellow), and that one variable, namely the number of passenger cars, shows contradictory results (red).

These findings illustrate that it is not directly feasible to arrive at a definitive conclusion on the efficacy of so-called policy initiatives. To be more precise, it is hard to see whether public investments in research and development offer any direct or immediate statistical relevance on the intended parameter. This suggests that, as a nation state, investing blindly in any research and development, i.e. without performing due diligence, does not propose any direct influence on the success of hydrogen cars. Furthermore, it is also possible to see a direct contradiction; nations that have made significant investments in the automobile sector have the opposite impact and appear to reject hydrogen technology fairly forcefully, possibly due to lock-in effects or the comfort of having deep ties to local society. Countries that have a high industrial reliance may be more concerned with maintaining the status quo out of fear of losing their market supremacy, which is an indication of a direct conflict of interests.

The number of passenger cars is the only variable that directly contradicts the literature, making it the most interesting variable. Theoretically, a high degree of motorization in private transportation is crucial for the adoption of advanced technologies. Due to the innovation mechanisms of larger markets, it can be presumed that comprehensive market structures, such as Germany's automobile fleet of approximately 50 million passenger vehicles (Statista, 2023), offer more opportunities for alternative pursuits than smaller economies. This is refuted by the correlation, which suggests that countries with a small population may even outperform their larger neighbours.

The data for each nation has been graded to account for the fact that relativized statistics do not yet indicate an appropriate degree of "homogeneity." Table 14 demonstrates a quasi-pattern-free visual impression. Values that share a common stair receive the same value. Corresponding country codes are defined in Table 15.

Stairs	Public exp. R&D	No. produced cars	No. Passenger cars	No. H-fuel stations	Annual H-Prod.	Electricity price	Newly regist. Alt. Trucks	Petrol prices	0-emission pas. Car reg.	No. H-cars
AT	6	12	9	3	14	24	20	25	9	7157
BE	7	10	19	7	4	30	4	8	14	8356
BG	30	19	26	11	9	4	24	30	24	1000
CR	27	19	25	11	6	5	15	28	23	1000
CY	23	19	5	11	24	25	24	24	30	1000
CZ	16	2	11	8	19	15	21	19	22	1857
DK	4	19	22	2	21	32	11	5	6	39698
EST	17	19	6	11	24	17	5	10	21	1000
FIN	9	11	4	11	8	14	6	3	13	1180
FR	13	13	10	6	20	20	10	12	7	6853
DE	8	5	8	1	12	31	12	11	8	15863
GRC	22	19	17	11	7	18	24	4	28	1000
HUN	21	4	27	11	11	3	23	17	17	1000
ISL	3	19	31	11	24	7	22	1	2	74212
IRL	12	19	23	11	23	29	3	13	12	1000
ITA	15	15	2	10	17	26	16	14	16	1759
LVA	29	19	28	11	24	16	17	16	19	1000
LTU	24	19	12	11	1	9	24	23	26	1000
LUX	10	19	1	11	24	19	24	22	10	5726
MLT	26	19	7	11	24	6	24	27	24	1000
NL	11	17	20	4	2	8	2	7	3	28924
NOR	5	19	17	11	3	23	18	2	1	43846
POL	25	16	3	11	10	10	13	26	28	2955
PRT	19	8	14	11	16	22	14	15	11	1291
ROM	31	9	29	11	18	11	1	29	17	1000
SRB	32	18	30	11	24	2	24	21	32	1000
SVK	28	1	24	11	5	12	19	20	26	1366
SVN	14	3	13	11	24	13	24	31	15	1000

Stairs	Public exp. R&D	No. produced cars	No. Passenger cars	No. H-fuel stations	Annual H-Prod.	Electricity price	Newly regist. Alt. Trucks	Petrol prices	0-emission pas. Car reg.	No. H-cars
ESP	18	6	16	9	15	28	7	18	19	1400
SWE	2	7	21	5	13	27	8	9	4	7069
CH	1	19	15	11	22	21	9	6	5	24067
TUR	20	14	32	11	24	1	24	32	31	1000

Table 14. Conditionally formatted ranking OAM matrix with the COCO result (last column) regarding 2021, own figure

Levels that are close to the top are shown in green, while those that are close to level 32 are displayed in yellow or red. Countries with equal results are allocated the same number; this is the case if no hydrogen fuelling stations exists. The last column indicates the extrapolation result for hydrogen vehicles per million persons, which was described in the previous section.

Countries Coding table	
Code	**Country**
AT	Austria
BE	Belgium
BG	Bulgaria
CH	Switzerland
CR	Croatia
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
ESP	Spain
EST	Estonia
FIN	Finland
FR	France
GRC	Greece
HUN	Hungary
IRL	Ireland
ISL	Iceland
ITA	Italy
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MLT	Malta
NL	Netherlands
NOR	Norway
POL	Poland

PRT	Portugal
ROM	Romania
SRB	Serbia
SVK	Slovakia
SVN	Slovenia
SWE	Sweden
TUR	Turkey

Table 15. Country Coding for the COCO Models, own figure

Already at this level, first insights are possible. The analysis, referred to as a "naive" approach in the following, reveals that certain nations are pioneers in certain categories; the result reveals that Germany has the most hydrogen filling stations, while many nations, such as Switzerland, Turkey, Serbia, Malta, or Iceland, have no hydrogen infrastructure for private customers. However, one may also observe that certain countries may be better in all respects on average. Cyprus and Latvia, for example, have several red or yellow ratings, but Denmark and Belgium, with a few exceptions, score pretty well.

Variables	
Public exp. R&D	Gross public expenditure on R&D per capita
No. Passenger cars	Number of passenger cars per 1000 inhabitants
No. produced cars	Number of passenger cars produced per 1000 inhabitants
No. H-fuel stations	The number of hydrogen filling stations per 1 million inhabitants
Annual H-Prod.	Hydrogen production capacity in tons per 1 million inhabitants
Electricity price	Electricity prices for household consumers in €/KWh

0-emission pas. car. reg.	Share of zero-emission vehicles in newly registered passenger cars in %
Newly regist. Alt. Trucks	Percentage of alternative fuels (electric, hybrid, etc.) regarding all (+diesel and petrol) new truck registrations in %
Petrol prices	Petrol prices in €/l
No. H-cars	Number of hydrogen cars per 1 million inhabitants

Table 16. Variable coding for the COCO Models, own figure.

6.4. Results of the COCO:STD analysis

The COCO STD: model has now attributed weights to the various rankings and identified the No. H vehicles as the total of these weights. COCO produces a new, fictional variable named No. O. H-cars using this weighting. This indicates the projected outcome based on the model's weighting of all nations. Fact-0 reflects the true quantity. This leads in a delta, the difference between the predicted and actual outcomes, which is also shown as Delta/Fact relative. Already available are insights on the degree to which the countries' performance exceeds or falls short of expectations. To justify the judgement, so-called inverse observation is used. The same idea applies, with the directions reversed. After comparing the inverse and direct delta values, the validity of the result may be determined by the sign. Non-valid results cannot be considered for further examination since they cannot be reproduced in reverse and are graded N.C. (no comment). This relates to Denmark, Estonia, France, Hungary, Italy, Luxembourg, Poland, and Sweden in 2021.

When we examine the delta/fact more closely, we see that several of them are quite near to 0. This is mostly due to rounding mistakes and does not represent a significant variation. These are known as "norm like," or standard-compliant. In 2021, the Czech Republic, Slovakia, and Slovenia are among them. They represent the standard and are thus the most numerous.

The final categorization is based on the easily verifiable obvious variances. On a scale ranging from green to red, they may be positive or negative. They are higher or lower than the mean and signify inefficiencies or accomplishments. In 2021, for instance, more hydrogen cars were registered in Belgium, Cyprus, Latvia, and Spain than the model predicted, indicating overperforming sales. On the other side, Austria, Finland, and Germany registered fewer automobiles than anticipated given the specified specifications, getting the label of underperforming sales. Due to the vast number of countries with geographical, economic, and social aspects, only nations with comparable characteristics are examined.

Additional findings may be found under the COCO assessment. "S1 Amount" indicates the maximum number of extra automobiles that might exist on the market if a nation excels in all categories. In addition, the difference between the actual total number of hydrogen cars per million people (Fact amount) and the sum estimated by the model (Estimate amount) may be distinguished. The lower this number, the more precisely this model represents reality.

2021																	
COCO:STD	Public exp. R&D	No. produced cars	No. Passenger cars	No. H-fuel stations	Annual H-Prod.	Electricity price	Newly regist. Alt. Trucks	Petrol prices	0-emission pas. Car reg.	No. H-cars	Fact+0	Delta	Delta/Fact	Validity	inverz delta	Country	Comment	Result
AT	5829	0	156	725	0	450	0	101	147	7407	7157	-250	-3,49	1	504	AT	ins. sales	-3,49
BE	5829	0	156	725	146	0	504	302	45	7707	8356	648,6	7,76	1	-4256,1	BE	over. sales	7,76
BG	101	0	156	0	0	752	0	0	0	1009	1000	0	-0,85	1	-10086	BG	Normlike	
CR	101	0	156	0	0	651	101	0	0	1009	1000	0	-0,85	1	-9994,6	CR	Normlike	
CY	101	0	312	0	0	450	0	101	0	963	1000	36,8	3,68	1	-12804,7	CY	over. sales	3,68
CZ	101	285	156	725	0	505	0	101	0	1872	1857	-15,4	-0,83	1	763,9	CZ	Normlike	
DK	5829	0	156	21237	0	0	348	302	2916	30787	39698	8910,8	22,45	0	7834,5	DK	N.C.	
EST	101	0	156	0	0	450	348	101	0	1155	1000	-155,2	-15,52	0	-7097,3	EST	N.C.	
FIN	101	0	312	0	0	505	348	302	45	1612	1180	-432,3	-36,64	1	457,1	FIN	ins. sales	-36,64
FR	101	0	156	725	0	450	348	101	2916	4796	6853	2057,3	30,02	0	3737,6	FR	N.C.	
DE	101	0	156	21237	0	0	348	101	147	22089	15863	-6225,9	-39,25	1	3727,8	DE	ins. sales	-39,25
GRC	101	0	156	0	0	450	0	302	0	1009	1000	0	-0,85	1	-10537,3	GRC	Normlike	
HUN	101	0	156	0	0	752	0	101	0	1109	1000	-109,3	-10,93	0	-2823	HUN	N.C.	
ISL	5829	0	0	0	0	605	0	36081	32293	74808	74212	-596,3	-0,8	1	45308,2	ISL	Normlike	
IRL	101	0	156	0	0	0	504	101	147	1009	1000	0	-0,85	1	-16061,6	IRL	Normlike	
ITA	101	0	1670	0	0	0	101	101	0	1973	1759	-213,7	-12,15	0	-5394,3	ITA	N.C.	
LVA	101	0	156	0	0	505	101	101	0	963	1000	36,8	3,68	1	-10445,9	LVA	over. sales	3,68
LTU	101	0	156	0	146	505	0	101	0	1009	1000	0	-0,85	1	-7356,2	LTU	Normlike	
LUX	101	0	4975	0	0	450	0	101	147	5773	5726	-46,5	-0,81	0	-2462,7	LUX	N.C.	
MLT	101	0	156	0	0	651	0	101	0	1009	1000	0	-0,85	1	-6737,3	MLT	Normlike	
NL	101	0	156	725	146	605	504	302	26618	29157	28924	-233,2	-0,81	1	17613,9	NL	Normlike	
NOR	5829	0	156	0	146	450	0	302	37316	44199	43846	-352,5	-0,8	1	26581,3	NOR	Normlike	
POL	101	0	1670	0	0	505	348	101	0	2724	2955	230,8	7,81	0	1553,2	POL	N.C.	
PRT	101	0	156	0	0	450	348	101	147	1302	1291	0	-0,84	1	-1145,4	PRT	Normlike	
ROM	0	0	0	0	0	505	504	0	0	1009	1000	0	-0,85	1	-3182,9	ROM	Normlike	
SRB	0	0	0	0	0	907	0	101	0	1008	1000	0	-0,8	1	-10086	SRB	Normlike	
SVK	101	515	156	0	0	505	0	101	0	1378	1366	0	-0,84	1	-2908,3	SVK	Normlike	
SVN	101	202	156	0	0	505	0	0	45	1009	1000	0	-0,85	1	-93,1	SVN	Normlike	
ESP	101	0	156	679	0	0	348	101	0	1385	1400	45061	1,11	1	-5353,2	ESP	over. sales	1,11
SWE	5829	0	156	725	0	0	348	101	2916	10074	7069	-3005,2	-42,51	0	-2865,3	SWE	N.C.	
CH	20090	0	156	0	0	450	348	302	2916	24261	24067	-194,2	-0,81	1	14367,5	CH	Normlike	
TUR	101	0	0	0	0	907	0	0	0	1008	1000	0	-0,8	1	-20732,5	TUR	Normlike	

S1 amount:	121.771
Estimate amount:	287.578,5
Fact amount:	287.579,0
Fact-estimate difference:	-0,5

Table 17. COCO STD: Results 2021, own figure

A green validity, marked with "1" indicates, that the COCO model could successfully reproduce the expected amounts of currently active hydrogen cars in said country. Valid values result in a positive to negative discrepancy, shown on a scale from red (high negative), yellow (medium to almost norm-like) and green (high positive). Red tones indicate underperforming sales while green numbers indicate overperforming sales. In contrast, a grey zero does not allow any further data processing.

2020

COCO:STD	Public exp. R&D	No. produced cars	No. Passenger cars	No. H-fuel stations	Annual H-Prod.	Electricity price	Newly regist. Alt. Trucks	Petrol prices	0-emission pas. TR reg.	No. H-cars	Fact+0	Delta	Delta/Fact	Validity	inverz delta	Country	Comment	Result
AT	147	16	157	4995	0	676	0	0	77	6068	5943	-124,8	-2,1	1	3454,8	AT	ins. sales	-2,1
BE	147	122	3	4843	199	676	97	45	0	6132	6554	421,7	6,43	1	-1443,1	BE	over. sales	6,43
BG	0	0	3	0	13	985	0	0	0	1001	1000	0	-0,1	1	-19810,3	BG	Normlike	
CH	16393	0	80	0	0	1001	0	45	222	17741	17732	-8,6	-0,05	1	10033,6	CH	Normlike	
CR	0	0	3	0	199	798	0	0	0	1001	1000	0	-0,05	1	-19810,3	CR	Normlike	
CY	0	0	202	0	0	721	0	0	0	923	1000	76,6	7,66	1	-6409,2	CY	over. sales	7,66
CZ	0	122	80	215	0	676	0	0	0	1094	1093	-0,5	-0,05	1	386,6	CZ	Normlike	
DE	122	122	157	9399	0	0	0	0	77	9877	9873	-4	-0,04	1	3208,4	DE	Normlike	
DK	147	0	3	9399	0	676	0	15982	222	26430	26417	-12,6	-0,05	1	10035,6	DK	Normlike	
ESP	0	122	80	215	0	676	97	0	0	1191	1190	0	-0,04	1	402,6	ESP	Normlike	
EST	0	0	157	0	0	843	0	0	0	1001	1000	0	-0,05	1	-6409,2	EST	Normlike	
FIN	122	122	202	0	13	676	0	45	0	1181	1180	-0,5	-0,04	1	444,2	FIN	Normlike	
FR	122	122	157	4843	0	676	97	45	222	6284	6704	419,6	6,26	0	4007,2	FR	N.C.	
GRC	0	0	3	0	154	721	0	122	0	1001	1000	0	-0,05	1	-11937,1	GRC	Normlike	
HUN	0	122	0	0	0	923	0	0	0	1046	1000	-45,5	-4,55	0	-12995,8	HUN	N.C.	
IRL	122	0	202	0	0	676	0	0	0	1001	1000	0	-0,05	1	-6408,9	IRL	Normlike	
ISL	147	0	3	0	0	923	0	38249	10077	49399	61417	12017,9	19,57	0	40253,3	ISL	N.C.	
ITA	0	16	0	0	0	676	850	45	0	1587	1586	0	-0,04	1	-14222,7	ITA	Normlike	
LTU	0	0	80	0	199	721	0	0	0	1001	1000	0	-0,05	1	-6489,9	LTU	Normlike	
LUX	122	0	1828	0	0	676	0	0	77	2704	4194	1490,3	35,53	1	-3311,4	LUX	over. sales	35,53
LVA	0	0	1828	0	0	721	97	0	0	2647	1000	-1646,7	-164,67	0	-6409,2	LVA	N.C.	
MLT	0	0	157	0	0	798	0	45	0	1001	1000	0	-0,05	1	-6409,2	MLT	Normlike	
NL	122	0	3	4843	199	721	0	15982	222	22093	22082	-10,6	-0,05	1	14291,1	NL	Normlike	
NOR	147	0	3	0	199	721	0	38249	10077	49396	37329	-12067,1	-32,33	1	24391,9	NOR	ins. sales	-32,33
POL	0	16	202	0	13	721	97	0	0	1049	1000	-49	-4,9	0	-957,9	POL	N.C.	
PRT	0	122	80	0	0	676	0	45	77	1001	1000	0	-0,05	1	325	PRT	Normlike	
ROM	0	122	0	0	0	721	0	0	0	843	1000	156,6	15,66	1	-12995,8	ROM	over. sales	15,66
SRB	0	0	0	0	0	1001	0	0	0	1001	1000	0	-0,05	1	-14921	SRB	Normlike	
SVK	0	122	3	0	199	676	0	0	0	1001	1000	0	-0,05	1	-12995,5	SVK	Normlike	
SVN	77	122	80	0	0	721	0	0	0	1001	1000	-0,5	-0,05	1	116	SVN	Normlike	
SWE	147	122	3	4843	0	676	97	45	222	6155	5550	-605,3	-10,91	0	-620,5	SWE	N.C.	
TUR	0	16	0	0	0	985	0	0	0	1001	1000	0	-0,05	1	-14921	TUR	Normlike	

S1 amount:	78.117
Estimate amount:	225.844,2
Fact amount:	225.844
Fact-estimate difference:	0,2

Table 18. COCO STD: Results 2020, own figure

2019

COCO:STD	Public exp. R&D	No. produced cars	No. Passenger cars	No. H-fuel stations	Annual H-Prod.	Electricity price	Newly regist. Alt. Trucks	Petrol prices	0-emission pas. Car reg.	No. H-cars	Fact+0	Delta	Delta/Fact	Validity	inverz delta	Country	Comment	Result
AT	1113	0	0	4445	0	0	0	0	74	5631	5628	-2,7	-0,05	1	3334	**AT**	Normlike	
BE	1113	89	0	2235	44	0	866	236	0	4582	4579	0	-0,06	1	-813,9	**BE**	Normlike	
BG	0	0	0	0	0	1001	0	0	0	1001	1000	0	-0,05	1	-19258,1	**BG**	Normlike	
CH	13058	0	0	0	0	0	44	236	74	13411	13405	-6,4	-0,05	1	4474	**CH**	Normlike	
CR	89	0	0	0	44	868	0	0	0	1001	1000	0	-0,05	1	-19258,1	**CR**	Normlike	
CY	89	0	603	0	0	0	44	236	0	972	1000	28,5	2,85	1	-7773,3	**CY**	over. sales	2,85
CZ	89	912	0	0	0	0	0	0	0	1001	1000	0	-0,1	1	-477,7	**CZ**	Normlike	
DE	1113	89	0	6251	0	0	44	0	0	7496	7492	-4,1	-0,05	1	2661,9	**DE**	Normlike	
DK	1609	0	0	6251	0	0	44	10672	0	18576	18567	-9,4	-0,05	1	109,7	**DK**	Normlike	
ESP	89	89	0	0	0	0	866	0	0	1043	1042	0	-0,1	1	-435,7	**ESP**	Normlike	
EST	89	0	0	0	0	868	44	0	0	1001	1000	0	-0,05	1	-6617,6	**EST**	Normlike	
FIN	299	0	603	0	0	0	44	236	0	1182	1181	0	-0,09	1	-296,7	**FIN**	Normlike	
FR	89	89	0	2235	0	0	866	236	74	3587	3585	-2,2	-0,06	1	1949,6	**FR**	Normlike	
GRC	89	0	0	0	0	0	0	912	0	1001	1000	0	-0,1	1	-10871	**GRC**	Normlike	
HUN	89	89	0	0	0	868	0	0	0	1045	1000	-45	-4,5	0	-11468,7	**HUN**	N.C.	
IRL	89	0	603	0	0	0	0	236	74	1001	1000	0	-0,1	1	-8109,6	**IRL**	Normlike	
ISL	1113	0	0	0	0	868	0	48575	74	50629	65427	14798,3	22,62	0	44013,2	**ISL**	N.C.	
ITA	89	0	0	0	0	0	932	449	0	1469	1468	0	-0,08	1	-12787,2	**ITA**	Normlike	
LTU	89	0	0	0	44	868	0	0	0	1001	1000	0	-0,05	1	-6953,9	**LTU**	Normlike	
LUX	299	0	2451	0	0	0	0	0	0	2750	4257	1506,7	35,39	1	-4852,6	**LUX**	over. sales	35,39
LVA	0	0	2451	0	0	0	0	0	0	2451	1000	-1451,2	-145,12	0	-8109,6	**LVA**	N.C.	
MLT	89	0	0	0	0	868	0	236	0	1192	1000	-192,1	-19,21	0	-6953,9	**MLT**	N.C.	
NL	89	0	0	2235	44	0	44	10672	74	13157	13151	-6,3	-0,05	1	8431,8	**NL**	Normlike	
NOR	1113	0	0	0	44	0	44	48575	74	49849	34782	-15066,8	-43,32	1	23089,6	**NOR**	ins. sales	-43,32
POL	89	0	0	0	0	868	44	0	0	1001	1000	-0,5	-0,05	1	355,6	**POL**	Normlike	
PRT	89	89	0	0	0	0	44	236	74	530	1000	469,7	46,97	1	-477,7	**PRT**	over. sales	46,97
ROM	0	89	0	0	0	868	44	0	0	1001	1000	0	-0,05	1	-11626,3	**ROM**	Normlike	
SRB	0	0	0	0	0	1001	0	0	0	1001	1000	0	-0,05	1	-12284,9	**SRB**	Normlike	
SVK	0	912	0	0	44	0	44	0	0	1001	1000	0	-0,05	1	-12782	**SVK**	Normlike	
SVN	89	912	0	0	0	0	0	0	0	1001	1000	0	-0,1	1	-814	**SVN**	Normlike	
SWE	1609	89	0	2235	0	0	866	236	74	5108	5105	-2,9	-0,06	1	708,2	**SWE**	Normlike	
TUR	0	0	0	0	0	1001	0	0	0	1001	1000	0	-0,05	1	-12284,9	**TUR**	Normlike	

S1 amount:	73.297
Estimate amount:	197.669,4
Fact amount:	197.669
Fact-estimate difference:	0,4

Table 19. COCO:STD Results 2019, own figure

In Figure 24 all results of the COCO:STD are shown graphically. In summary, the following results can be derived:

- In 2019, the volume of hydrogen cars was at a manageable minimum. With just under 1500 vehicles, the market was new, and most countries have hardly reacted so far. This makes for many "norm like" assessments. Cyprus has, by its standards, more vehicles in its statistics, but is still very close to the average. Luxembourg and Portugal show up very positively in the overview, they are well above the norm and have this year geared their policy instruments towards a positive climate for hydrogen vehicles. Norway, on the other hand, is the only country with a negative rating. The reason for this could be the strong focus on electric cars, which makes an additional focus on hydrogen seem superfluous for legislators, although the danger of a lock-in effect is great. („Norwegian EV policy“, 2022).
- In 2020, the market has changed fundamentally. The number of average countries has decreased, and countries have positioned themselves more clearly. Austria emerges as the only Central European country and shows a small deficit. Belgium and Cyprus are close to the average but show an above-average result. Luxembourg is again the top performer, Norway again scores well below average.
- In 2021, the results have changed again. Cyprus and Belgium again show a positive result above expectations, complemented by Latvia and Spain. Austria was unable to catch up with its deficit and continues to show slight weakness. Finland and Germany show a significant deficit and deviate enormously negatively from the norm.
- In all years, the market has generally grown, visible in the increasing size of S1. All countries are trying to open up to hydrogen technology, albeit in unequal proportions.

In summary, it can be seen that the COCO:STD model shows results that are unexpected. For example, many Southern and Eastern European countries are on average or even slightly above average in some cases. Norway, as a Nordic country, has long been considered a pioneer of zero-emission mobility, but had at times put the focus on a different technology. Smaller countries, such as Cyprus, Luxembourg or Belgium, are often better positioned in terms of their attributes, despite the limited technological and fiscal possibilities of larger industrialised nations. Finally, it is also noticeable that countries with a strong automotive focus represent at best the norm regarding hydrogen vehicles, but mostly show a slight underperformance (Austria).

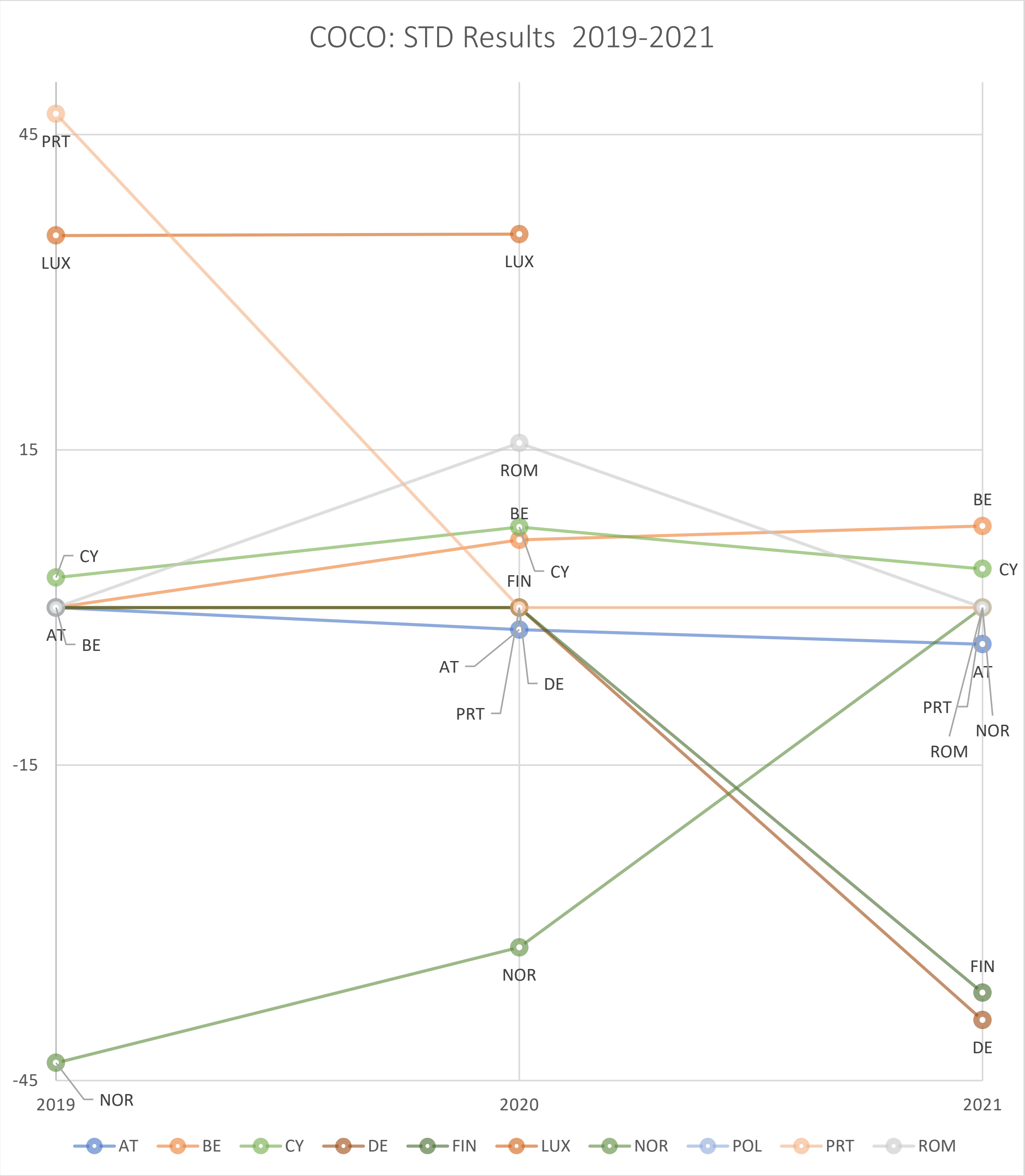

Figure 24. COCO:STD results from 2019 to 2021*. Relevant changes have been mapped accordingly. The axis demonstrates on the basis of the COCO model, how far the countries digress from the norm. Only norm-like performing countries were not mapped for visual readability. Some countries, like Luxembourg in 2021, did not provide valid results in certain years and were subsequently no mapped. Own figure.

LH

*due to many countries labelled as norm like, not all country tags are visualized.

6.5. Innovation Potential Index based on the COCO-Y analysis

The COCO model gives the potential of an anti-discriminatory model in addition to the STD: model, mentioned in the previous chapter. Based on the ranking of the COCO:STD model, a rating is determined by the COCO Y0 model (*COCO*, 2022). The objective of this study is to determine the amount to which the ranking of the factors influences a newly established index, the so-called innovation potential index, rather than the actual number of hydrogen cars. To produce a result that is as precise as possible and to account for the low hydrogen vehicle density in Europe, the index is multiplied by a factor of one million, allowing for a second assessment that may be reviewed independently of earlier evaluations. Several one million or slightly above or below indicates conformity with the standard. Clear values above this indicate a better interdisciplinary structure and innovative strength than countries that meet the norm; similarly, countries that fall below the norm must catch up in a few disciplines to be able to promote hydrogen innovation in their countries over the next few years. The findings are re-verified using an inverse calculation, see Table 20, Table 21 and Table 22.

The results show that in 2021 the countries Finland and the Netherlands have the highest index, while Cyprus and Ireland, and especially Latvia, have the lowest index. In contrast to the COCO:STD model, future developments are outlined here rather than assessments of the respective year in retrospect.

2021

direction	0	0	0	0	0	1	0	0	0	0	0	0	0	
Stairs	Public exp, R&D	No, produced cars	No, Passenger cars	No, H-fuel stations	Annual H-Prod,	Electricity price	Newly regist, Alt, Trucks	Petrol prices	0-emission pas, Car reg,	No, H-cars	Number of hydrogen cars	Index	Validity	Country
AT	6	12	9	3	14	24	20	25	9	8	1000000	999996,6	1	AT
BE	7	10	19	7	4	30	4	8	14	7	1000000	999997,1	1	BE
BG	30	19	26	11	9	4	24	30	24	19	1000000	999987,6	1	BG
CR	27	19	25	11	6	5	15	28	23	19	1000000	1000001,1	1	CR
CY	23	19	5	11	24	25	24	24	30	19	1000000	999943,1	1	CY
CZ	16	2	11	8	19	15	21	19	22	13	1000000	1000022,6	1	CZ
DK	4	19	22	2	21	32	11	5	6	3	1000000	999979,6	1	DK
EST	17	19	6	11	24	17	5	10	21	19	1000000	999983,6	1	EST
FIN	9	11	4	11	8	14	6	3	13	18	1000000	1000077,6	1	FIN
FR	13	13	10	6	20	20	10	12	7	10	1000000	999997,6	1	FR
DE	8	5	8	1	12	31	12	11	8	6	1000000	1000008,1	1	DE
GRC	22	19	17	11	7	18	24	4	28	19	1000000	999960,6	1	GRC
HUN	21	4	27	11	11	3	23	17	17	19	1000000	1000033,6	1	HUN
ISL	3	19	31	11	24	7	22	1	2	1	1000000	999996,6	1	ISL
IRL	12	19	23	11	23	29	3	13	12	19	1000000	999954,1	1	IRL
ITA	15	15	2	10	17	26	16	14	16	14	1000000	1000026,1	1	ITA
LVA	29	19	28	11	24	16	17	16	19	19	1000000	999917,6	1	LVA
LTU	24	19	12	11	1	9	24	23	26	19	1000000	1000011,6	1	LTU
LUX	10	19	1	11	24	19	24	22	10	11	1000000	1000023,1	1	LUX
MLT	26	19	7	11	24	6	24	27	24	19	1000000	999996,6	1	MLT
NL	11	17	20	4	2	8	2	7	3	4	1000000	1000065,6	1	NL
NOR	5	19	17	11	3	23	18	2	1	2	1000000	1000019,6	1	NOR
POL	25	16	3	11	10	10	13	26	28	12	1000000	1000027,1	1	POL
PRT	19	8	14	11	16	22	14	15	11	17	1000000	999977,6	1	PRT
ROM	31	9	29	11	18	11	1	29	17	19	1000000	999996,6	1	ROM
SRB	32	18	30	11	24	2	24	21	32	19	1000000	999996,1	1	SRB
SVK	28	1	24	11	5	12	19	20	26	16	1000000	1000015,1	1	SVK
SVN	14	3	13	11	24	13	24	31	15	19	1000000	999986,1	1	SVN
ESP	18	6	16	9	15	28	7	18	19	15	1000000	999975,6	1	ESP
SWE	2	7	21	5	13	27	8	9	4	9	1000000	1000018,1	1	SWE
CH	1	19	15	11	22	21	9	6	5	5	1000000	1000013,1	1	CH
TUR	20	14	32	11	24	1	24	32	31	19	1000000	999996,1	1	TUR

Table 20. COCO Y0 2021, own figure

2020

direction	0	0	0	0	0	1	0	0	0	0,00	0,00	0,00	0,00	
Stairs	**Public exp, R&D**	**No, produced cars**	**No, Passenger cars**	**No, H-fuel stations**	**Annual H-Prod,**	**Electricity price**	**Newly regist, Alt, Trucks**	**Petrol prices**	**0-emission pas, Car reg,**	**No, H-cars**	**Number of hydrogen cars**	**Index**	**Validity**	**Country**
AT	4	13	10	3	14	27	25	26	9	9	1000000	1000001,2	1	**AT**
BE	6	10	20	7	4	30	4	13	14	8	1000000	1000001,2	1	**BE**
BG	30	19	27	11	9	4	25	32	24	16	1000000	999954,2	1	**BG**
CH	1	19	16	11	22	1	11	9	5	5	1000000	1000053,2	1	**CH**
CR	26	19	26	11	6	9	24	18	23	16	1000000	999988,2	1	**CR**
CY	22	19	6	11	24	18	25	27	30	16	1000000	999945,2	1	**CY**
CZ	16	2	12	8	19	22	18	20	22	15	1000000	1000001,2	1	**CZ**
DE	8	4	9	1	12	32	8	16	8	6	1000000	1000001,2	1	**DE**
DK	3	19	23	2	21	31	12	4	6	3	1000000	1000001,2	1	**DK**
ESP	18	6	17	9	15	28	7	20	19	13	1000000	999976,2	1	**ESP**
EST	17	19	7	11	24	7	13	17	21	16	1000000	1000003,7	1	**EST**
FIN	9	11	5	11	8	21	13	7	13	14	1000000	1000030,7	1	**FIN**
FR	13	12	11	6	20	23	5	11	7	7	1000000	999999,7	1	**FR**
GRC	20	19	18	11	7	16	23	5	28	16	1000000	999962,7	1	**GRC**
HUN	21	5	28	11	11	5	25	29	17	16	1000000	1000023,2	1	**HUN**
IRL	12	19	3	11	23	29	20	15	12	16	1000000	1000000,2	1	**IRL**
ISL	7	19	24	11	24	6	20	2	2	1	1000000	1000017,2	1	**ISL**
ITA	15	15	29	10	17	26	1	6	16	12	1000000	1000001,2	1	**ITA**
LTU	23	19	13	11	1	10	25	25	26	16	1000000	1000001,2	1	**LTU**
LUX	10	19	2	11	24	24	25	27	10	11	1000000	999998,7	1	**LUX**
LVA	28	19	1	11	24	13	3	24	19	16	1000000	1000026,2	1	**LVA**
MLT	25	19	8	11	24	8	10	12	24	16	1000000	999998,7	1	**MLT**
NL	11	17	21	4	2	12	9	3	3	4	1000000	1000039,7	1	**NL**
NOR	5	19	18	11	3	11	15	1	1	2	1000000	1000039,7	1	**NOR**
POL	24	16	4	11	10	15	5	30	28	16	1000000	1000027,7	1	**POL**
PRT	19	9	15	11	16	25	16	7	11	16	1000000	1000001,2	1	**PRT**
ROM	32	8	30	11	18	14	20	31	17	16	1000000	999949,2	1	**ROM**
SRB	31	18	31	11	24	2	25	14	32	16	1000000	999949,2	1	**SRB**
SVK	27	1	25	11	5	20	17	20	26	16	1000000	1000001,2	1	**SVK**
SVN	14	3	14	11	24	17	19	18	15	16	1000000	1000017,2	1	**SVN**
SWE	2	7	22	5	13	19	2	9	4	10	1000000	1000030,7	1	**SWE**
TUR	29	14	32	11	24	3	25	23	31	16	1000000	999958,7	1	**TUR**

Table 21. COCO Y0 2020, own figure

2019													
direction	0	0	0	0	0	1	0	0	0	0	0	0	0	
Stairs	Public exp, R&D	No, produced cars	No, Passenger cars	No, H-fuel stations	Annual H-Prod,	Electricity price	Newly regist, Alt, Trucks	Petrol prices	0-emission pas, Car reg,	No, H-cars	Number of hydrogen cars	Index	Validity	Country
AT	6	13	10	3	14	24	20	25	8	7	1000000	999998,2	1	AT
BE	8	11	19	7	4	30	5	15	15	9	1000000	999998,2	1	BE
BG	30	19	27	11	9	2	20	32	23	15	1000000	999998,7	1	BG
CH	1	19	14	11	22	21	13	7	5	4	1000000	999998,2	1	CH
CR	26	19	26	11	6	7	20	19	24	15	1000000	999957,7	1	CR
CY	22	19	4	11	24	26	15	13	20	15	1000000	999964,7	1	CY
CZ	16	2	13	8	19	17	18	20	26	15	1000000	999998,2	1	CZ
DE	7	4	10	1	12	31	8	17	13	6	1000000	999998,2	1	DE
DK	3	19	23	2	21	32	15	4	26	3	1000000	999993,2	1	DK
ESP	18	6	17	9	15	28	2	22	18	14	1000000	999998,2	1	ESP
EST	17	19	7	11	24	9	7	16	13	15	1000000	999998,2	1	EST
FIN	9	12	4	11	8	18	8	8	11	13	1000000	1000054,7	1	FIN
FR	13	10	9	6	20	20	4	9	9	11	1000000	999997,7	1	FR
GRC	21	19	20	11	7	12	20	5	29	15	1000000	999998,7	1	GRC
HUN	20	5	28	11	11	4	19	28	16	15	1000000	999998,2	1	HUN
IRL	12	19	3	11	23	29	20	12	6	15	1000000	999998,2	1	IRL
ISL	5	19	24	11	24	11	20	2	3	1	1000000	999998,7	1	ISL
ITA	15	17	29	10	17	27	1	6	20	12	1000000	999998,2	1	ITA
LTU	24	19	15	11	1	5	20	26	24	15	1000000	999998,2	1	LTU
LUX	10	19	2	11	24	19	20	26	12	10	1000000	999998,2	1	LUX
LVA	28	19	1	11	24	14	20	24	20	15	1000000	999998,2	1	LVA
MLT	25	19	8	11	24	6	20	13	10	15	1000000	999998,2	1	MLT
NL	11	16	21	4	2	23	6	3	2	5	1000000	999998,2	1	NL
NOR	4	19	18	11	3	16	8	1	1	2	1000000	999998,2	1	NOR
POL	23	15	6	11	10	8	15	29	26	15	1000000	999998,2	1	POL
PRT	19	7	16	11	16	25	12	11	6	15	1000000	999979,2	1	PRT
ROM	32	9	30	11	18	10	11	30	17	15	1000000	999998,2	1	ROM
SRB	31	18	31	11	24	1	20	18	31	15	1000000	999998,7	1	SRB
SVK	27	1	25	11	5	13	13	20	29	15	1000000	999998,2	1	SVK
SVN	14	3	12	11	24	15	20	22	18	15	1000000	999998,2	1	SVN
SWE	2	8	22	5	13	22	3	10	4	8	1000000	1000094,7	1	SWE
TUR	29	14	32	11	24	3	20	30	31	15	1000000	999998,2	1	TUR

Table 22. COCO Y0 2019, own figure

The results get ranked again (see Figure 25 and Figure 26), whereby the development from 2019 to 2021 can be re-evaluated here. Due to the few differences in 2019, these values are only shown if they deviate significantly from the 2020 assessment.

Now the rank generated by the COCO Y0 model can be compared with the naïve solution already briefly mentioned in the previous chapter. In the naïve solution, the relative values are ranked and then the average is calculated. With the naïve solution, countries with different values can obtain the same result on average, as the dispersion is not included - in contrast to the COCO-Y0 model.

Due to the limited data available, it has only been possible so far to derive findings from three years. Similar to the findings with the COCO STD: method the year of 2019 show a very homogenous index depiction, with hard to read results for the future. Focusing on 2021, however, shows a different picture. The following findings refer to 2021, as this is the year with the latest data.

There are discernible differences between a weighted anti-discriminatory analysis and a naive method, as indicated. In instance, Denmark is placed tenth in the naive assessment, while COCO ranks it twenty-sixth. This is mostly due to one ranking, the price of power. This is the highest value recorded for Denmark in the whole data set. The price of electricity, which is essential for the affordable production of hydrogen through sustainable energy, underpins the concept of electrolysis (Durante et al., 2022; Macedo et al., 2022), making hydrogen innovation adoption the least viable solution with significant obstacles among all studied countries. Due to the absence of attention to dispersion, a naive perspective of 10 would not investigate this element further. The naive approach would also obscure the below-average commercial significance of private automotive transportation and the immature hydrogen production.

Additionally, the inverted technique reveals distinct distinctions. In the naive method, Hungary was given a slightly below-average score of 18 points. The majority of Hungary's characteristics were rated as ordinary, however with one of the most advantageous power costs and the third-largest automobile production in Europe, it would be inaccurate to consider Hungary simply as average and should therefore evaluate as one of the candidates with the highest potential in Europe to pursue a hydrogen-based automotive innovation adoption. Because of these quantitative facts, a convincing SWOT analysis may be conducted to interpret the findings.

Evidently, personal preferences or interests play a large part in this context, since not everyone values the same attributes/directions in a subjective world – but not in a causal interpretation, where the optimal model should exist as such: The optimal modelling strategy is one that can provide the most resilient (objectively near) approximations relative to the data, as shown by the COCO Y0 Model. The results of the anti-discriminative modelling, which are referred to as the Innovation Diffusion Index, illustrate how many hydrogen-powered automobiles each country could support in comparison to the average number of cars in the world. The naïve viewpoint gives the dispersion, which is the root of this discrepancy, very little consideration.

Therefore, according to the naïve perspective, certain countries are superior, even though their dispersion conceals enormous inefficiencies and, as a result, may cause decision makers to reach the incorrect conclusions. The use of large numbers may cloud the problems at hand and make it more difficult to make acceptable adjustments to levers such as the government's budget.

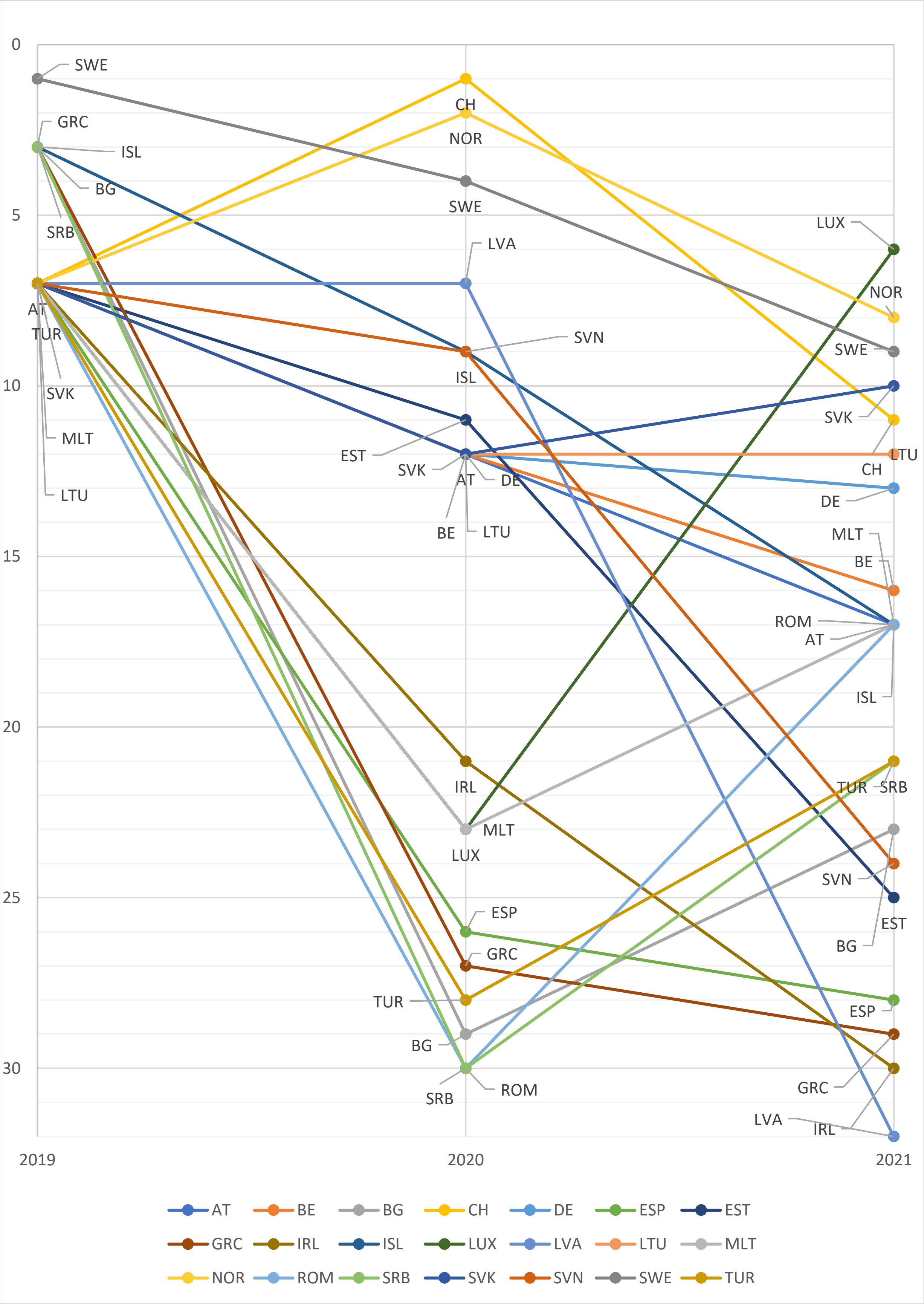

Figure 25. Countries with shrinking hydrogen innovation index performance since the status quo 2019, ranked from 1 to 32
(Results from the COCO Y0 Model in a time perspective)

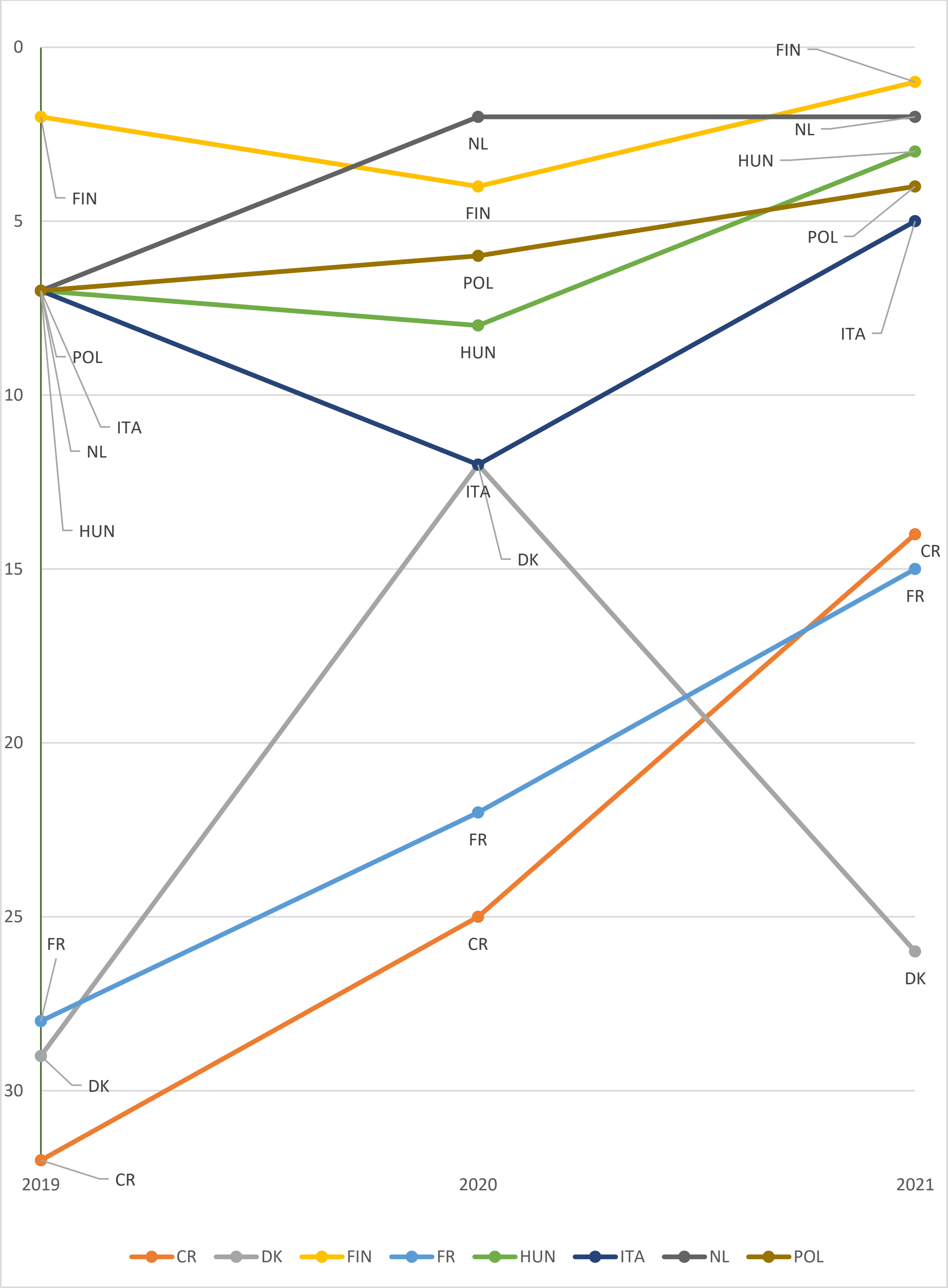

Figure 26. Countries with improving hydrogen innovation index performance since the status quo 2019, ranked from 1 to 32
(Results from the COCO Y0 Model in a time perspective).

6.6. SWOT and final implications regarding the COCO models

SWOT is an acronym that describes a company's strengths, weaknesses, opportunities, and threats. By doing a SWOT analysis, you may better understand the possibilities and dangers facing your company (O -T). A more complete understanding of the issue helps in both strategic planning and decision-making (The University of Kansas, 2022), therefore the COCO model was extended by the SWOT function, developed by previous researchers (L. Pitlik, 2013).

In the SWOT analysis, the estimated goal number of hydrogen-powered vehicles was compared to their actual values (No. H-cars vs. Fact+0) for COCO:STD and for COCO Y0 results. Deviation of 1% was considered to be "norm-like"; large negative deviations were marked as Weakness, while strong positive deviations were marked as Strength. As not all years were verifiable in the COCO:STD observation, no evaluation of the future was conducted for these years. Observing the outcomes of the COCO Y0 investigation over three years permits a conclusive future assessment, these values were evaluated as norm-like with a fraction of the significance (0,000001%) due to the low differences. The phrases “Threat” or “Opportunity” were selected based on the corresponding growth and decline (see Table 23).

COCO:STD	2019	2020	2021	COCO Y0	2019 Y0	2020 Y0	2021 Y0	2019 2021 Y0
AT	N	W	W	AT	N	S	W	T
	N	S	S	BE	N	S	W	T
BG	N	N	N	BG	N	W	W	O
CH	N	N	N	CH	N	S	S	T
CR	N	N	N	CR	W	W	S	O
CY	S	S	S	CY	W	W	W	T
CZ	N	N	N	CZ	N	S	S	O
DE	N	N	W	DE	N	S	S	O
DK	N	N	-	DK	N	S	W	T
ESP	N	N	S	ESP	N	W	W	T
EST	N	N	-	EST	N	S	W	T
FIN	N	N	W	FIN	S	S	S	T
FR	N	-	-	FR	N	N	W	O
GRC	N	N	N	GRC	N	W	W	T
HUN	-	-	-	HUN	N	S	S	O
IRL	N	N	N	IRL	N	N	W	T
ISL	-	-	N	ISL	N	S	W	T
ITA	N	N	-	ITA	N	S	S	O
LTU	N	N	N	LTU	N	S	S	O
LUX	S	S	-	LUX	N	N	S	O
LVA	-	-	S	LVA	N	S	W	T
MLT	-	N	N	MLT	N	N	W	T
NL	N	N	N	NL	N	S	S	O
NOR	W	W	N	NOR	N	S	S	O
POL	N	-	-	POL	N	S	S	O
PRT	S	N	N	PRT	W	S	W	T
ROM	N	S	N	ROM	N	W	W	O
SRB	N	N	N	SRB	N	W	W	O
SVK	N	N	N	SVK	N	S	S	O
SVN	N	N	N	SVN	N	S	W	T
SWE	N	-	-	SWE	S	S	S	T
TUR	N	N	N	TUR	N	W	W	T

Table 23. SWOT analyses results, own figure[15]

Threats and opportunities consider the overall development. This cannot be applied to absolute quantities like those in the COCO:STD analysis. With calculated relative values, however, such as the innovation index of the COCO:Y0 analysis, a change over time is conceivable based on a variety of factors. Countries that were able to gradually increase their lead as well as those that were able to close the distance with the leaders are rated as opportunities. Threats, on the other hand, impact nations that have successively underperformed or that have halted their positive progress, and thus risk slipping behind in the long run.

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[15] W = Weakness, S = Strength, N = Norm-like, O = Opportunity, T = Threat

The SWOT analysis is a summary of the COCO analyses performed for this thesis. It demonstrates that Central European nations have seen a diverse evolution in retrospect. The method permitted the integration of the SWOT analysis. Its purpose is to determine, under the assumption of fixed directions, to what extent the entire system of phenomena moves in accordance with the directional logic of the Y0 (ideal search) model. In other words, the variable of time is introduced and countries whose performance has increased or decreased over the past few years are evaluated.

In 2020 and 2021, Austria did not reach the anticipated quantity of hydrogen cars. While the innovation potential index marginally outperformed in 2020, it moderately declined in 2021. The average outperformance was less than the negative index development, therefore the development may be characterized as negative.

In terms of their hydrogen vehicle fleet, Croatia was able to keep the benchmark, but in terms of innovation potential index, it was mostly in the bottom half of the group, with a short positive exception in 2021. The development is seen as an opportunity since the gap has shrunk.

In terms of hydrogen cars accomplished, the Czech Republic also represented the average. If we examine the index, we can see that it has been above normal since 2020 and has hit an all-time high in 2021. This is seen as a long-term potential for innovation in the field of hydrogen.

In the first two years, Germany was likewise able to maintain the norm, but in 2021, a deficit appeared. The index was positive in 2020 and 2021, developed progressively, and is thus seen as an opportunity, albeit it is lower than, for instance, in the Czech Republic.

In the COCO:STD model, Hungary was unable to yield any relevant results, yet its innovation index steadily increased from year to year as a consequence of the variables. This is seen as an opportunity since it is the greatest value among Central European nations.

Poland was able to keep the norm in 2019, after which no conclusions could be drawn on the quantity of automobiles. The index has grown in tandem with Hungary, with 2021 essentially continuing the current rate of expansion.

In the COCO:STD study, Slovakia and Slovenia were deemed to be norm-like. Yet, Slovakia was able to consistently widen the gap relative to the norm, Slovenia has surpassed Slovakia's growth in 2020, but had to almost return to the norm in 2021; however, the standard or norm has grown steadily in all nations over time.

6.7. Discussion of the COCO model and its implications

The COCO model has some shortcomings regarding its methodological approach. Firstly, by calculating weighted averages, some specific data development cannot be taken into consideration. For example, if a country achieves a 1st in the positioning and so, within the context of the model, occupies a dominating position, the model cannot logically include areas where it lags. Thus, nations might be within the norm even if they have significant deficiencies in all other areas.

Secondly, the COCO model is an additive model, i.e., an effort is made to mimic the outcome from the addition of the different weights. There is no facility for multiplication, subtraction, or division, therefore only a linear method is possible.

In contrast in economics, non-linear developments like the so-called "S-curve" are often used to show market penetration. It shows linear progress, but the rate at which new ideas spread has a big effect on the shape of the curve. In contrast to the first phase of the diffusion process, when the slope is still relatively modest, the curve 'picks up pace' and rises abruptly once the so-called critical mass is reached. Once this threshold is crossed, the innovation propagates itself across the system (Karnowski & Kümpel, 2016). Late in the process, the curve begins to flatten out as even the last holdouts begin to accept the innovation. These early adopters, who make up just 2.5% of the population, are known as innovators because they are very risk-taking and tolerant. They are also well-placed to "infiltrate" new ideas into their own social structure since they often have many (geographically scattered) connections. Conversely, the early adopters are crucial to the spread of a phenomenon because they are well rooted in the local social structure. For the rest of the social system to embrace the innovation, it must be modelled by people who are respected and sought out for guidance. When a new idea has enough traction, more people start using it. This is when the early majority forms. Members of the early majority are less likely to be opinion leaders than the early adopters, but they still have extensive networks that help disseminate the innovation.

The late majority tends to be sceptical of new ideas and only gives in to them when economic or social pressure becomes overwhelming. People in the late majority have fewer financial resources than those in the early majority, therefore they can and will tolerate only minimal levels of uncertainty. These people are deeply resistant to change, socially isolated, and nostalgic. The late majority, who must decide based on less resources, understandably choose not to take chances.

Thirdly, lock-in and lock-out factors cause theoretical performance curve deviations. Lock-in factors are changes to the top half of the S-curve that occur because of implementation risks, inefficiencies, or a lack of resources. However, lock-out factors represent an upward shift of the top section of the curve as a result of attempts to block or postpone the technology's replacement.

Fourthly, statistical data must constantly be examined considering reality. Results reveal that in the case of Iceland in 2021, the number of cars produced or the number of vehicles per 1000 people is "worse" than in other nations. However, it cannot be argued that Iceland should immediately implement tax cuts, for instance to increase sales or local production. This would be in direct opposition with the European climate goals. The facts must instead be seen from a bird's-eye perspective. The tiny Icelandic automotive market may make it more difficult to achieve successful market penetration of hydrogen if, for example, car models must be imported from overseas or if the country's small, yet dense population renders a major automotive emphasis redundant.

Consequently, the COCO model should provide one thing above all else: a quantitatively based, quantitatively automated control instrument that permits equitable and generalized managerial competence. Due to the vast quantity of accessible data, none of which are harmonised, it is impossible to conduct an impartial comparison. Likewise, the model's limitation becomes apparent: it can only interpret the data it gets. As the years go, it is important to incorporate more data sets to acquire further interpretations. Since hydrogen technology is still in its infancy and it has already become apparent in 2019 that the countries hardly differ due to the small number of hydrogen vehicles, it is necessary to continue observing the technology's development over the next few years in order to create a knowledge database that can be operationalized in the long term.

Ineffective policymaking that impedes market penetration and economic innovation jeopardizes economic progress and consumer response. Using a component-based object comparison approach for objectivity, the present position of Central European nations in adopting and successfully altering hydrogen-based autos was assessed based on eight criteria. The factors of ecology, price elasticity, and infrastructure are considered.

It is essential to recognize the limitations of research notwithstanding its enormous successes. The weaknesses of the method are explored first. Only Europeans were included in the data and subsequent research, and policymakers and innovation initiatives focused only on the increase of personal automobile mobility in this particular region. Consequently, these findings only reflect the situation in its current context; research in other locales may yield drastically different results due to substantial differences in autonomy, political decision-making, external consequences of radical change, industry standards, and managerial practices. In addition, this study did not focus on certain brands or firms; rather, it included a vast array of automotive manufacturers. In addition, not every aspect of innovation was investigated. It is not believed that varied political situations have a considerable impact on each member state's innovation policy. A systematic examination of policies was tried as opposed to a thoroughly individual-focused approach; however, this may reveal further micro-level outcomes not included by this research. Moreover, owing to the fact that the energy sector remains a national asset and is only advised and coordinated to a limited extent at the European level, many governments in Central Europe opt for individualized and hence less integrated plans. As energy production is restricted to a small number of key partners that are heavily invested in specific energy carriers and, as a result, have international dependencies from outside of Central Europe, certain negative effects of oligarchic market structures and entanglements of policymakers and businesses alike tend to reveal irrational strategic leadership or market irregularities on a certain scale. Due to their very varied legal and historical foundations, it would have been difficult to compare the policymaking processes of these components. On the Central European landscape, the question of emission-free and thus green energies remains unanswered, as many ecologically focused political parties tend to reject the use of nuclear energy as a viable alternative to green energy, whereas the European Union and nuclear-dependent member states accept and promote it.

Lastly, the factor of reduced emissions must be evaluated along the whole supply chain, since just the emissions from point A to point B are now considered. Additional resources and potentially shorter product lives, as well as circular economy components that do not yet exist, are not considered.

Thus, further empirical focus should be put on prior-year data and other technological trends that may contribute to the success of the hydrogen energy business, but not exclusively.

Similarly, any OAM characteristic may likewise be viewed as a dependent variable (Y). This multi-layered interpretation (including additional years) will result in an automated SWOT analysis and/or a kind of data quality assurance from which probable statistical inaccuracies may be deduced.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Concepts for future scientific studies

Despite its many accomplishments, it is essential to acknowledge the limitations of research. The limitations of the technique are presented first. Only Central European persons were included in the data and subsequent study, and policymakers and innovation strategies focused entirely on the growth of individual vehicle mobility in this predetermined region. Consequently, these findings only represent the scenario in the current context; investigations in other locations may yield significantly different results due to significant changes in autonomy, political decision-making, external effects of radical change, industry norms, and management practises. In addition, this study did not focus on specific brands or firms, but rather represented a broad spectrum of Central European businesses. Additionally, not all aspects of innovation were considered. It is not taken into consideration that differing political circumstances have a significant impact on the innovation policies of the individual member states. With different political perspectives and consequently considerations regarding how certain policymaking should be accomplished, a standardised analysis of policies was attempted as opposed to a deeply individual-focused approach, although this may indicate additional micro-level results not included in this research. Moreover, owing to the fact that the energy sector is still a national asset and is only advised and coordinated to a limited extent on a European level, many nations in Central Europe prefer to concentrate on individual and hence less integrated approaches. As the production of energy is restricted to a small number of key partners that are heavily vested in specific energy carriers and, consequently, have international dependencies from outside of Central Europe, certain negative effects of oligarchic market structures and entanglements of policymakers and businesses alike tend to reveal irrational strategic leadership or market irregularities on a certain scale. Due to very diverse legal and historical histories, it would have been impossible to compare the policymaking processes of these factors. The question of emission-free and thus green energies is not satisfactorily answered on the Central European landscape, as many ecologically focused political parties tend to reject the use of nuclear energy as a viable alternative to green energy, whereas the European Union and member states dependent on atomic energy accept and promote it.

Lastly, the factor of reduced emissions must be evaluated regarding the whole supply chain, as currently only the emissions of moving from point A to point B are considered. Additional resources and potentially lower life of products or currently non-existent circular economy aspects are not considered in many studies.

Further empirical focus should therefore be directed towards, but not limited to:

Alternative Research Question 1: How do other regional clusters of Europe, i.e., the Nordic countries or the Mediterranean countries, approach the challenge of hydrogen mobility in contrast to Central Europe?

Alternative Research Question 2: What is the potential of hydrogen fuel cell technologies for other modes of transport, namely heavy-duty vehicles, ships or airplanes?

Alternative Research Question 3: How do emerging technologies, such as autonomous vehicles and drone delivery, impact the future of mobility?

Alternative Research Question 4: How can urban planning and design be optimized to support sustainable and equitable mobility?

Additional inquiries may emerge about the prospective economic decision-making process of nation states. Energy carriers, which play crucial roles in the everyday operations of both consumers and industry, are often subject to strict tax and tariff rules. The current favourable aspects of hydrogen may not remain beneficial in the future if the underlying data, upon which this dissertation is based, suffers significant alteration. Moreover, the adoption of consumer markets is of utmost importance. If the supply fails to match the demand, a new pricing equilibrium may be established, potentially hindering the use of hydrogen. Likewise, the future trajectory of the economic aspects of current carbon-based fuels is a subject of discussion and uncertainty.

In February 2024, several nation states and the European Union are prioritizing the implementation of long-term taxation measures to address significant expenses associated with factors like as noise, CO2 emissions, nitrogen oxides, and other comparable factors in the road freight transport sector. Starting in 2027, private mobility will be included into the calculation of external costs as part of the European Green Deal and the related Emission Trading System II. The implementation of certificate trading or other mechanisms, such as the establishment of municipal tolls or charges on rural routes, might be a significant advancement in promoting the use of hydrogen-powered vehicles. It is crucial to analyze the circumstances consistently and carefully in all instances to effectively influence the development of alternative driving systems.

7.2. Discussion of all applied COCO methods

The objective of this combined qualitative and quantitative methodological approach was to develop a model that presents the current strategic investments of the nation-states of Central Europe in hydrogen electric private mobility, highlighting the customer responsiveness and technological acceptance towards a different propulsion in privately owned cars and drafting a current picture of the status quo potential in the countries themselves. By analysing many parameters derived from prior research and the questionnaire produced by the authors, as well as evaluating the component-based object comparison for objectivity, the following conclusions may be drawn.

Designing ineffective policymaking that does not enable the market penetrations and successive economic innovation is a critical danger to economic development and customer responsiveness. Firstly, the dimensions and the general term of innovation and its accompanying processes are documented. Based on the lesson from previous drivetrains going through similar processes that hydrogen mobility still has to face, the concept of innovation policies was discussed. While innovation as a term often suffers from the lack of measurement, different methods were discussed to highlight its presence with both qualitative and quantitative methods. Additionally, the concept of e-fuels was brought up, gaining importance in the last couple of years. It could be identified that all energy sources, that want to be widely used in mobility need to fulfil certain criteria, namely, the adaptation to current passenger and transport traditions, a factor often overlooked in the analysis. Complemented by the origin and subsequent colouring of hydrogen it became clear, that the legislative policymaking fulfils the central role of coordinating, supporting, dampening and overall, strategically planning the energy output and thereby possibilities of mobility for private consumers in the upcoming decades.

Consequently, three nation states of the Central European area, distinct by their size, automotive dependence, and energy mix, namely the Slovak Republic, Hungary and the Federal Republic of Germany, were evaluated regarding their hydrogen strategies, key strategic documents outlying policymaking standards, plans and funding towards reaching sustainability goals of the European Union, for the years of 2030 and 2050 respectively. While certain criteria could be harmoniously evaluated, two countries put more effort in the concrete quantitative planning and funding (Slovakia and Hungary), while the other formulated detailed policymaking on operative levels, however lacking concrete numbers or incentives.

Followed up by a systematic literature review, the academic interest and thereby significance of hydrogen innovation in the automotive industry was strengthened. The intensive analysis pointed out, that innovation can be assessed by four different dimensions, including sustainability, economic development, technical inventions, and international policies. The latter was increasingly evaluated by many previous studies as lacking, indicating the need to gather data and subsequently evaluate the necessary policymaking in order to promote the alternative drivetrain.

Additionally, an overview of the status-quo insights into the current purchasing decision-making of consumers regarding the purchase of automobiles with hydrogen drivetrains was formulated. As an introduction, the increasing importance of companies in the automotive sector as well as policymakers promoting sustainable mobility was briefly show-cased. Followed-up by some insights into the general concept of purchasing decision-making, the majority of the paper revolved around the question of which relevant items to include into a questionnaire directed at individuals seeking to purchase a car in the near future.

Based on extensive literature, subsequently eleven items including questionnaire was formed, based on an eleven-point scale ranging from strongly disagreeing to strongly agreeing positions. The questionnaire was exclusively presented and promoted in Germany, due to the strong automotive focus as well as the only country in Central Europe which focuses their hydrogen manufacturing on green energy-based sources.

For further research, it is suggested to focus on the policymaking concept of hydrogen use, manufacturing, and promotion in neighbouring countries of Central Europe due to varying diversification of the energy mix as well different mobility demand and customer demands.

Overall, it can be safely stated, that customers focus on two main concepts when considering hydrogen fuel-based cars. Firstly, the expected price stability by domestic hydrogen manufacturing is deeply valued, due to the current high dependence of fossil fuels, that are subject to a variety of external effects, not in direct influence of consumers. Secondly, the ability to use individual mobility, that can be fuelled with a sustainable energy carrier is deemed as crucial, resulting in a necessity of bivariate consideration in future research.

The previous analysis of national hydrogen strategies reveals clear weaknesses in the concrete schedule and shows how hydrogen is generated but does not identify any changed preconditions for the successful

#l adoption of FCEVs and thus permanently runs the risk of guaranteeing demand stimulation.

Lastly, a component-based object comparison for objectivity method was applied, to highlight the current status quo of Central European countries regarding the adoption and thereby successful transformation of hydrogen-based vehicles, based on ten selected variables. These follow the logic structure of the results from the questionnaire, evaluating ecological, price elasticity-focused and infrastructure related variables.

First, the COCO:STD approach, which is based on production functions, was implemented. The primary objective was to determine how the chosen relative factors resulting from the questionnaire may be quantified and impact the relative number of hydrogen automobiles in European nations. Europe was represented by 32 nations in order to expand the model's size and provide repeatable and verifiable findings. At first glance, the quantitative data did not correspond with either the previous academic literature or the survey results, suggesting that variables such as the price of electricity or the increased share of sister technologies (such as the number of newly registered trucks with alternative drivetrains) do not correlate or even negatively correlate with the relative number of hydrogen cars.

The COCO:STD model is an additive model, which attempts to estimate the predicted number of hydrogen-powered vehicles depending on the ranking of all factors. If the numbers match, the nation performs normally; nevertheless, underperformance and overperformance are also represented. In a few instances, the model was unable to identify any results. In 2019, the vast majority of nations exhibited normal behaviour. Some nations, mostly of smaller size and economy, such as Luxembourg, Cyprus, and Belgium, were consistently outperforming their peers as time passed. Surprisingly, nations such as Norway, Finland, and Germany, which are often identified with strong links to alternative drivetrains, did badly relative to their norms.

Next, an anti-discriminatory analysis was conducted using the COCO-Y0 model. This approach utilizes already defined rankings but fails to place hydrogen-powered vehicles in context. Instead, it computes a grade, allowing for the establishment of an index. This measure focuses on the dispersion component and is barely influenced or deceived by nations with comparable rankings. Like the previous study, 2019 began similarly for all nations, since the hydrogen technology had not yet been extensively embraced in Europe. With the passage of time, the 2021 index yielded data suggesting that, although Finland, for instance, lacks hydrogen-powered automobiles at now, it has one of the greatest potentials in Europe to embrace hydrogen-based mobility on a big scale, based on the chosen criteria. Similarly, Hungary occupies the third position, which is remarkable given that the ordinary person would put it far lower on the scale. It can be determined that the model accurately balanced some elements, since Hungary performs largely averagely but excels in two crucial areas, namely energy pricing and automobile manufacturing. Hungary has a greater potential than its neighbours, particularly Germany, which is suffering from one of the highest power prices in Europe.

In conclusion, a SWOT analysis was undertaken, which consolidated all prior data and, by analysing the innovation index's evolution, may not only identify direct strengths, weaknesses, and norm-like behaviour, but also forecast possible threats and opportunities. Central Europe had heterogeneous outcomes, despite their integration through automotive supply chains, transportation, and culture. Apart from Austria, the Central European nations of Germany, Poland, the Czech Republic, Hungary, Slovakia, and Slovenia all share the quality of opportunity. They may not have the same historical history, but they all have a favourable tendency in the dissemination of hydrogen innovation.

It is essential to note that this dataset can only provide insights for the near future; as time passes, the model gets more aware of outliers and specific trends and may thus recommend more precise solutions.

8. FINAL CONCLUSIONS

This dissertation examined and assessed the various policymaking approaches of Central European nations towards the adoption of hydrogen-powered, long-range private transportation in the future years. The practicality and promise of hydrogen as a resource, as well as the subject of consumer preferences in relation to effective legislation, have not been addressed in any prior research. In addition, the novelty of this dissertation includes a component-based object comparison for objectivity method applied to all Central European states in order to evaluate current status quo standards and discrepancies in comparison to neighbouring countries in terms of economic, ecological, and infrastructural development.

This thesis consists of the first study focused on the analysis of the national policymaking strategies regarding hydrogen mobility in the context of evaluating Central European countries, a first quantitative questionnaire focusing on the Central European area regarding the customer evaluation of advantages and disadvantages when confronted with purchasing a hydrogen-based car as the next vehicle and lastly the first adaptation of a component-based object comparison for objectivity in the context of current prerequisites of the nation’s states of Central Europe regarding the adoption of alternative drivetrains, based on their economic and infrastructural development in 2019, 2020 and 2021.

The following research findings could be summarized:

I. According to the literature, any future energy source for private mobility must meet five essential criteria: high energy density, convenient long-distance capability, safety from seasonal supply fluctuations, easier adaptation to existing infrastructure and to corresponding customers. These variables have not yet been present in a system and thus appear as variables in the methods in Chapters II and III.

    - One of the prerequisites for the future success of hydrogen mobility is the adoption of a European taxonomy, as certain nations and political institutions do not designate certain energy carriers as green energy (and, consequently, hydrogen products as green). General codes and standards have not yet been harmonised or conceptualised; instead, each nation pursues its own national strategy.

- As a result, all potential sources of hydrogen were color-coded according to their previous energy sources (e.g., solar energy, gas, nuclear, etc.). The evaluation of each energy source was then color-coded to provide an overview of which energy carriers each Central European nation considers to be sustainable. These results are presented below. Notably, Germany, the European Union, and to a lesser extent Austria place a greater emphasis on a stricter framework than their neighbours.
- A successful Central European hydrogen market requires all governments to cooperate to target significant volumes of green hydrogen as an emission-free fuel. According to the data, Europe may be split into "energy regions," or nations with comparable energy strategic goals. For example, northern countries choose hydropower owing to their great availability and low industrial demand. Hungary, Poland, the Czech Republic, Slovakia, Slovenia, and Croatia pursue a medium-term nuclear plan, compensating for deficits with gas-powered technology. Central European states want a hydrogen-powered economy by 2050.
- The concept of consumer behaviour is not sufficiently considered in the formulation of policy measures in Central European nations, with the potential danger of a latency in economic demand and, consequently, a lag in innovation.

II. A survey, with the question listed below, was conducted in Germany resulted the new scientific findings below. Germany was chosen due to two reasons. First, it's Europe's biggest vehicle market, allowing for the most market adoption. Second, it has the strictest hydrogen production standards in Central Europe, revealing the "greenest" hydrogen transportation option.

- A regression function revealed the independent factors that favourably and adversely affect hydrogen car buying potential (bold variables).

- emission-free combustion and hence CO_2-neutral mobility,
- **price stability due to hydrogen as an efficient and storable energy carrier**,
- increased purchase price of new vehicles due to upfront innovation costs,
- the increased range compared to battery electric vehicles,

- significantly reduced recharging time compared to electric vehicles,
- higher strength and resistance to cold,
- **the potential increased risk of explosion in the event of accidents,**
- the limited hydrogen refuelling infrastructure,
- **the almost silent noise compared to internal combustion vehicles,**
- **the increased efficiency and reduced environmental impact due to the possibility of storing CO_2 free electricity,**
- and the question of whether customers consider one or more propulsion systems to be useful.

III. The questionnaire results indicate that national legislations should reevaluate their current strategic policies. Consequently, a focus on the performance status quo becomes essential. Using the data mining technique component-based object comparison for objectivity (COCO), it is possible to compare various country variables. To enable for a more refined analysis, the 8+1 countries have been expanded to 32 countries, encompassing all significant nations with links to the European market with data from 2019 to 2021. The strength of the method is that it enables grading the performance of each country based on the same characteristics or attributes, by harmonizing the unit of measurement and the corresponding date.

- The component-based object comparison for objectivity standard (COCO STD) approach ranks each country’s attributes and, via a production function, assign weights to the independent variables and assesses over- or under-performance, thus providing a so-called interdisciplinary ranking. Based on the questionnaire the following variables were evaluated:

X variables	Y variable
Public expenditure on R&D Number of passenger cars Number of cars produced Number of H-fuel stations Annual Hydrogen production Electricity price 0-emission passenger car reg. Newly registered alternative propulsion trucks Petrol prices	Number of hydrogen cars

Results: Austria, Finland, and Germany were ineffectual in the 2021 study. Cyprus, Belgium, Luxembourg, and Romania outperform Austria and Norway in 2020. Hydrogen car sales increased from 73 000 to 121 000.
Surprisingly, Germany and Austria, who have high multidisciplinary rankings, cannot compete with less resourceful countries because to energy prices.

- The analysis was continued with another notation for anti-discrimination calculations (COCO Y0 model), also known as an ideal search model, in which, for each independent variable, after specifying the direction, based on the expected positive or negative effect it has on the dependent variable, an optimization is performed to identify the most deviant object. Thus, it ranks each country with a focus on data dispersion and provides results that are significantly more adaptable than simple average rankings. A naive strategy of arithmetically aggregating all ranks would disregard the variance at the root of this divergence.

X variables	Y variable
Public expenditure on R&D Number of passenger cars Number of cars produced Number of H-fuel stations Annual Hydrogen production Electricity price 0-emission passenger car reg. Newly registered alternative propulsion trucks Petrol prices	Innovation index for hydrogen cars

Results: Finland and the Netherlands show the highest index in 2021, while Cyprus, Ireland, and Latvia indicate the lowest.

The adopted weighted anti-discrimination analysis differs from the old technique. Denmark is tenth in the naïve evaluation but twenty-sixth in the analysis. Electricity prices are the key reason. Denmark's data set's highest value. Electrolysis, which is necessary for economical hydrogen generation using renewable energy, is based on electricity prices, making hydrogen innovation the least feasible approach with considerable constraints in all nations analyzed. A naïve approach would likewise hide the modest economic value of passenger vehicle travel and hydrogen generation.

The inverted method also shows differences. Hungary scored 18 points naïvely. Hungary was rated average for most of its characteristics, but with one of the lowest energy costs and the third largest car production in Europe, it should be considered one of the candidates with the highest potential for hydrogen-based automotive innovation in Europe.

❖ Finally, the method permitted the integration of the SWOT analysis (COCO_SWOT (Strengths, Weaknesses, Opportunities, Threats)). Its purpose is to determine, under the assumption of fixed directions, to what extent the entire system of phenomena moves in accordance with the directional logic of the Y0 (ideal search) model. In other words, the variable of time is introduced and countries whose performance has increased or decreased over the past few years are evaluated.

<table>
<tr><th>X variables</th><th>Y variable</th></tr>
<tr><td>Public expenditure on R&D
Number of passenger cars
Number of cars produced
Number of H-fuel stations
Annual Hydrogen production
Electricity price
0-emission passenger car reg.
Newly registered alternative propulsion trucks
Petrol prices</td><td>Performance evaluation of each country in a three year period</td></tr>
<tr><td colspan="2">Results: Austria missed its 2020 and 2021 hydrogen vehicle targets. In 2020, the innovation potential index marginally outperformed. In 2021, it considerably dropped. The index's negative evolution exceeded the average overperformance, hence the evolution was negative.
Croatia maintained the benchmark hydrogen vehicle fleet but was mainly in the bottom half of the group in innovation potential index, with one brief positive exception in 2021. The narrowing margin presents an opportunity.
Hydrogen vehicle production in the Czech Republic was average. The index has been above normal since 2020 and hit an all-time high in 2021. Hydrogen innovation has long-term promise.

Germany kept up for two years, but by 2021 it was falling behind. The indicator was favourable and increasing in 2020 and 2021, making it an opportunity, but lower than in the Czech Republic.</td></tr>
</table>

Hungary's innovation index rose gradually owing to the factors, even if the model showed no outcomes. As the highest in Central Europe, we view this as an opportunity.

Poland maintained the standard in 2019, hence vehicle volume could not be determined. In 2021, the index will grow with Hungary.
Slovakia and Slovenia were normal. Slovenia exceeded Slovakia's growth in 2020 but virtually recovered to the average in 2021, yet the norm or standard has continuously grown for all countries.

All Central European nations, with the exception of Austria, have a rising innovation index and, as a consequence, one of the highest potentials for hydrogen innovation diffusion in the future years. Hungary ranks first among Central European countries and third in all of Europe.

9. NEW SCIENTIFIC RESULTS

In this dissertation four new scientific results can be documented:

1. The five essential criteria for future energy sources for decarbonised private mobility, based on an extensive literature review, include: High energy density; Convenient long-distance capability; safety from seasonal supply fluctuations; Easier adaptation to existent infrastructure and customers.

2. Based on an own questionnaire from 2022 directed at German individuals (n=117) tempted to buy a hydrogen car, the stability of hydrogen prices due to (to a certain degree) plannable domestic manufacturing and potential competitive pricing are important ($P > t = 0{,}008$). Additionally, HFC vehicles are considered more efficient ecologically, when fuelled with the corresponding green energy, and at the same time can store CO_2 free electricity ($P > t = 0{,}028$).

3. The Component-based Object Comparison for Objectivity (COCO) based interdisciplinary ranking suggested that Austria, Finland, and Germany were ineffective regarding their hydrogen performance in the 2021 research. Austria and Norway are surpassed by Cyprus, Belgium, Luxembourg, and Romania in the year 2020. Despite their high interdisciplinary rankings, Germany and Austria are unable to compete with less resourceful nations due to energy costs.

4. Looking at the performance of 32 European states, the SWOT analysis indicates that all national legislations need to reevaluate their current strategic policies. They need to focus on low electricity prices, annual domestic hydrogen production and steadily rising petrol prices to offer incentives to customers to embrace innovative drivetrains. However, solely focusing on the increase of price mechanisms of current-generation carbon-based infrastructure without providing an alternative will not allow a mobility change as expected by the EU.

10. SUMMARY

Hydrogen adoption in Central Europe is a topic of growing interest. The major driver behind the development of these corridors is the adoption of hydrogen associated with the decarbonisation of industry, transport, and power across Central Europe. The major driver behind the development of these corridors is the adoption of hydrogen associated with the decarbonisation of industry, transport, and power, particularly new green steel projects, commercial and private mobility.

There are several challenges to the widespread adoption of green hydrogen in Europe, including the high cost of production, which is currently significantly higher than fossil fuels. To improve the current situation nation states all over Central Europe need to develop all-encompassing strategic frameworks, mainly focusing on hydrogen production, availability and market adoption.

Subsequently, the question arises, what measures are effective in Central European states regarding hydrogen adoption. What are the countries planning regarding both regulatory and financial regulations? Which key performance indicators are chosen? How do three selected countries differ regarding their infrastructure, energy diversification and short to mid-term strategic approach? An analysis of published hydrogen strategies from the countries of Germany, Slovakia and Hungary gives answers and offer different levels of commitment, policies and expectations regarding hydrogen. Current alternatives to environmentally harmful mobility are centred around the promotion of battery electric vehicles, which is struggling to jump from the stage of early adopters to suffice an early majority of customers. What do customers really pursue when purchasing new cars, which role can hydrogen fill in this situation? A questionnaire was formulated, focusing on insights from a customer point of view, rather than a legislative top-down orientated view. Factors currently out of scope of many legislators, as stable hydrogen prices or the guarantee of CO_2-free hydrogen availability are not answered and pose a significant danger for market adoption.

At this stage, the status-quo and the inefficiencies of hydrogen-based policymaking are documented. However, how do the selected countries perform regarding the attribute’s customer value the most? How fluctuant is the price of electricity, what about factors like car dependency or sister technologies like trucks with alternative drivetrains? A series of component-based object comparison for objectivity revealed, that countries typically seen as less developed underdogs, mainly Hungary, Poland and other eastern Central European countries are offering much more desirable market situations regarding hydrogen adoption, due to lower electricity prices, better infrastructure and reliable domestic, mainly nuclear based, energy prospections.

11. APPENDICES

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A. Uhlich ; **L. Hammerl** ; P. Maier (2021). Business innovations: The Significance of Transition for Small & Medium-Sized Enterprises. *b.i.t.online - Bibliothek - Information - Technologie* (1435-7607 2193-4193): 02 24 (2021), pp 163-172, https://www.b-i-t-online.de/heft/2021-02-fachbeitrag-ulich.pdf

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A4: Short professional CV

Time	Company	Position
Since 08/2023	Toll Collect GmbH	Consultant for Corporate Strategy & Business Development
05/2021 – 05/2023	VDA e.V. (German Association of the Automotive Industry)	Junior Consultant for Member Services and Start-ups
10/2020 – 04/2021	Alexander von Humboldt Institut für Internet und Gesellschaft e.V.	Junior Research Fellow
02/2018 – 02/2019	UBEEQO GmbH	Project Intern in Sales & Business Development

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13. DECLARATION

I hereby affirm that I am the author of this dissertation and that I have not utilised any supplementary materials other than those listed.

I hereby declare that this dissertation is my original work, prepared after registering for the Ph.D. degree at the Hungarian University of Agriculture and Life Sciences Kaposvár Campus, and that it has not been previously included or submitted in any work for a degree, diploma, or other qualification at this or any other institution. I have reviewed the most recent University Ethics Policy and take responsibility for its implementation. I have sought to identify any hazards connected with doing this study, got the necessary ethical and/or safety permission (where applicable), and am aware of my responsibilities and participants' rights.

Laszlo Hammerl

Kaposvár, Tuesday, 05 March 2024 Laszlo Hammerl