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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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1. BACKGROUND OF THE WORK AND ITS AIMS

Technological advancement, product invention, and market penetration shortening require an ever-changing approach. Mobility worsens. Low-emission or emission-free powertrains are being driven by environmental and social concerns and regulatory framework demands. Technology demands resources and expertise, but it does not ensure economic success. New technical items are less likely to be picked by clients who are not forced to accept more value or severe drawbacks.

A greener alternative to oil-based mobility is sought. Battery technology is the sole EU-considered solution to carbon-emitting technology. Biofuels are less important (European Commission, 2022b). Transportation transformation requires energy infrastructure restructuring. Changing propulsion ignores the environmental impact of fuel, which may still be as carbon-intensive as combustion engines, according to several organizations and scientists. (Bundesumweltministerium, 2022). Many green hydrogen-sourcing technologies and company pioneers have produced market-ready emission-free hydrogen-operated vehicles, so hydrogen mobility could take over this critical function. Given current acceptability, infrastructure, and legislation, hydrogen automobiles are more environmentally benign, but European automotive research and development departments do not focus on commercializing and cheaping them.

Organization of this dissertation: Hydrogen and electromobility are researched to understand alternative propulsion technology customer decision-making. Starter theories for studying innovation are outlined and distinguished. Explaining innovation's beginnings follows. 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?

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?

Using the systematic literature review's findings on the advantages and cons of existing and nearly market-ready HFC, or hydrogen fuel cell vehicles, Central European customers will answer a questionnaire. To contextualize these results and the current status of hydrogen-based mobility potential in Austria, Croatia, Czechia, Germany, Hungary, Poland, Slovakia, and Slovenia, a component-based object comparison for objectivity method quantifies questionnaire statements to reveal overperformance and underperformance. Thus, the third research question:

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

2. MATERIALS AND METHODS

2.1 Definitions

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).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 the following:

Grey (sometimes brown or black) hydrogen	Most hydrogen production and use today relies on substantial CO2 emissions. Industrial hydrogen generated by steam reforming natural gas or coal gasification without carbon collection, utilization, or storage is grey hydrogen. About 50% of grey hydrogen is a waste product of chemical supply chain processes and is used to make concentrated petrochemicals and ammonia. Grey hydrogen's greatest drawback is its substantial CO2 emissions during generation. Goods may be made through coal gasification, notably using lignite, a plentiful resource in Central Europe, and steam reforming of natural gas, predominantly methane.

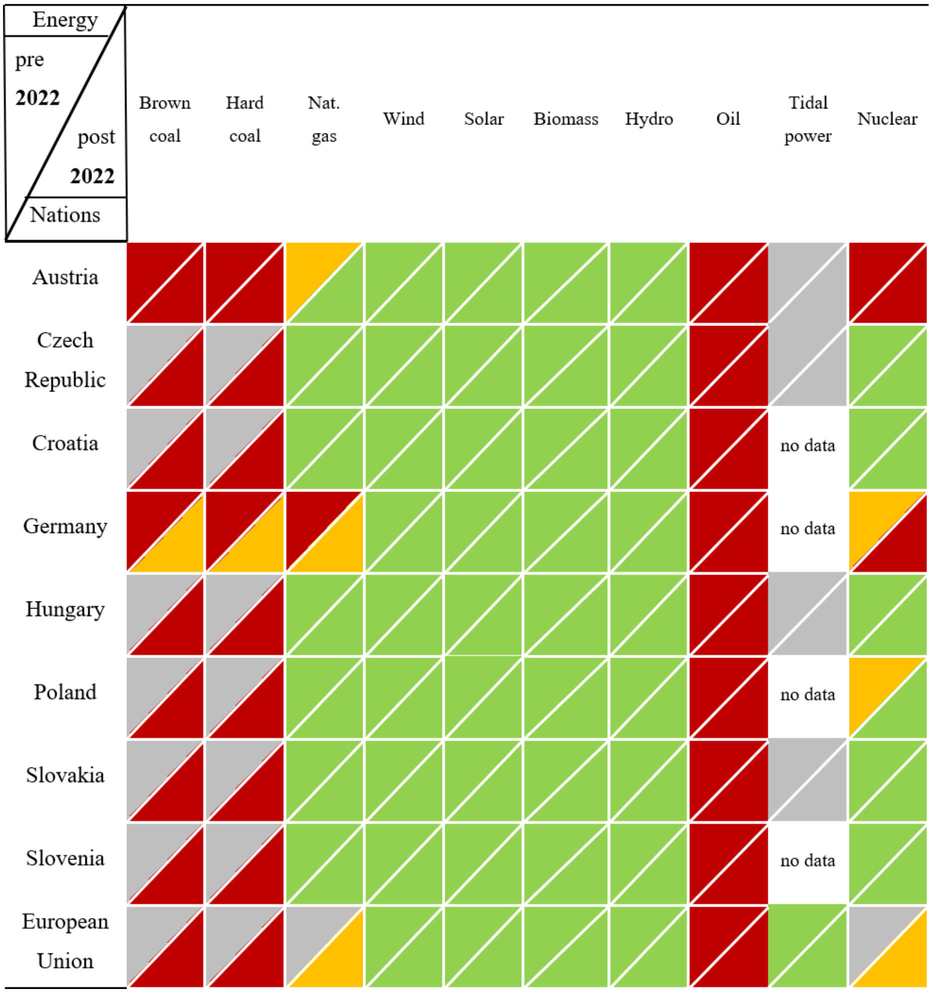
Blue hydrogen	CCUS steam methane reforming produces blue hydrogen from biomass or natural gas. Just installing carbon capture equipment produces blue hydrogen. National and international organizations sponsor hydrogen bridges. Inclusion of hydrogen generation components impacts environmental effect. CCS was powered by renewable energy, but natural gas production and transportation released methane. Following these circumstances, blue hydrogen reduces grey hydrogen emissions by 50%. Underground storage and capital expenses impede adoption.
Turquoise hydrogen	The thermal splitting of methane produces blue hydrogen. Instead of CO2, solid carbon is created. A procedure must employ renewable or carbon-neutral energy to heat the high-temperature reactor and permanently bind carbon.
Green hydrogen	Green hydrogen is produced by electrolyzing water using extra renewable energy like solar or wind. Electrolysers split water into hydrogen and oxygen without carbon dioxide. Early studies shared the idea of sustainable beginnings, but they utilized clean and low-carbon hydrogen interchangeably, confusing the environmental supply chain. Alkaline water, polymer electrolyte membrane, and solid oxide electrolyser cell electrolysis are the main electrolysis methods. Many technological (and economic) challenges prevent their broad use.
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 method produces oil from oil sands and fields using a new carbon-free method. The color is blue because fossil fuels were used to make it, but green because carbon emissions were avoided. Only hydrogen should be collected when subterranean fossil oil deposits or oil sands are converted to hydrogen. Scalability and environmental considerations are the biggest challenges for this new technology. Aquamarine has been used to pyrolyze natural gas to make solid carbon and hydrogen using focused solar light. Basic research and experiments are ongoing for both proposed colours.

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

First intentions of the analysis include the documentation and visualization of data, as many quantitative factors used in later steps require an aggregation of information. The analysis of the hydrogen strategies of nation states inquires hat comparable strategies are being used; yet the terminology, techniques, and milestones are unclear and difficult to compare, at least among themselves.

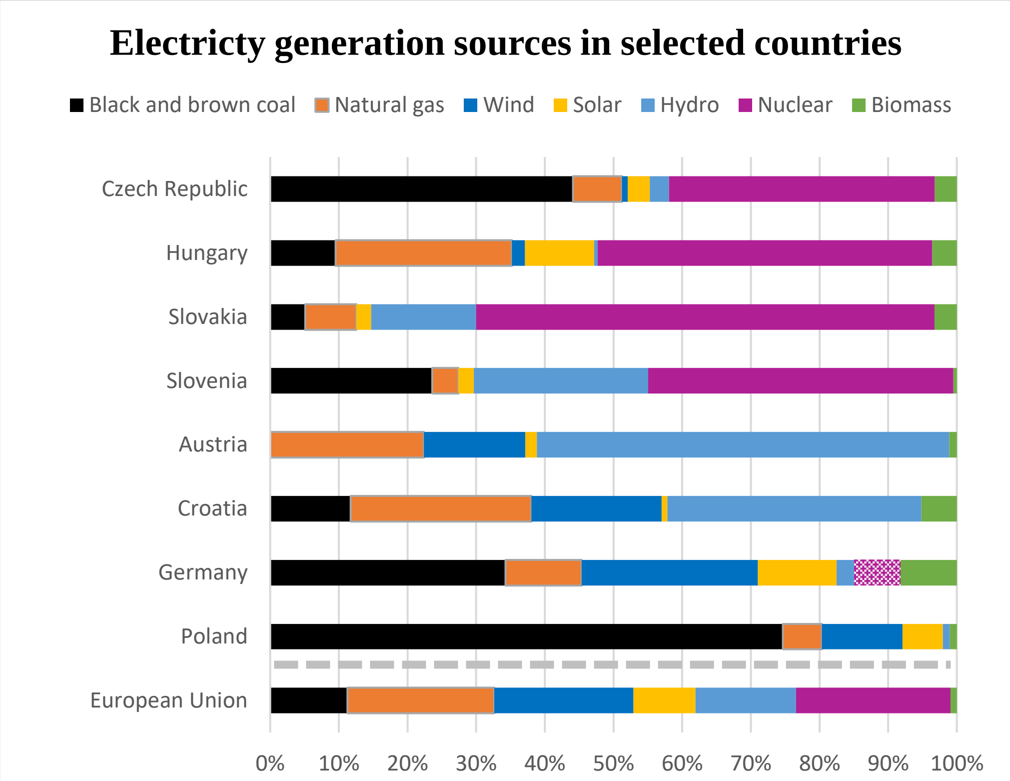
It is obvious that the definition of "green hydrogen" shifts depending on the context. For instance, countries who see nuclear power as an essential component of their overall energy portfolio are striving to produce hydrogen over the long-term utilizing nuclear technology. As a transitional technology, 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



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

through the use of carbon capture technology to fossil fuels. Investments into certain energy technologies reveal the sustainable energy policy definitions. These results are directly linked to the energy mix of all mentioned countries, pointed out below. 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). The following figures offer insights regarding the potential capacities of green energy production in Central Europe, furthermore focusing on the potential of solar and wind energy output.



	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

Energy mix in the time period of 01.01.2022 to 31.12.2022 (Corbineau et al., 2021).

2.2 Systematic review

Hydrogen was deducted both by many industry experts (Böhringer et al., 2020) as well as society (Chapman et al., 2020), research (Emmerich et al., 2020), and institutions (Pichler et al., 2021) as a viable alternative for emission-heavy industries, however not without a wide variety of requirements and changes fulfilled before a successful hydrogen-based mobility sector can be achieved (Sgobbi et al., 2016).

This systematic review focused on various publications to investigate:

- the current policies in the regarding the use of hydrogen, partially from a sustainable renewable source, their incentives, and disturbing factors, as well as distinctive characteristics of the Central European region and effects on the development of these due to the Covid-19 pandemic.
- the economic development of hydrogen, taking into account a current market analysis, potentials, and risk factors of the implementation.
- the detailed examination of green innovation requirements, sustainability hurdles, and anticipated ecological repercussions of a hydrogen-powered transportation system.

2.3 Questionnaire

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).

This section analyses the factors that will persuade customers of all groups to switch from combustion engine cars to hydrogen electric cars in the long run and combine simple arguments into future decision-making models.

Consequently, a twelve statement-based approach was selected, where eleven customer purchasing advantages regarding hydrogen fuel cell cars are presented and to be evaluated by the respondents.

All questions are presented in the following:

Q1. Hydrogen burns without emitting CO2 and is classified as CO2-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 CO2 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.

Questionnaire items, own figure

2.4 Component based object comparison for objectivity

2.4.1 Introduction to the methodology

While a plethora of measures were taken to get a clear and conclusive statistical conclusion, a certain amount of unexplainable residual variance imbalance persists, suggesting that further methods should be applied. Due to a preselected sample size of consumers, the COCO (component-based object comparison for objectivity) method (Pitlik, 1993) was used to further analyse the present performance level of Central European nations.

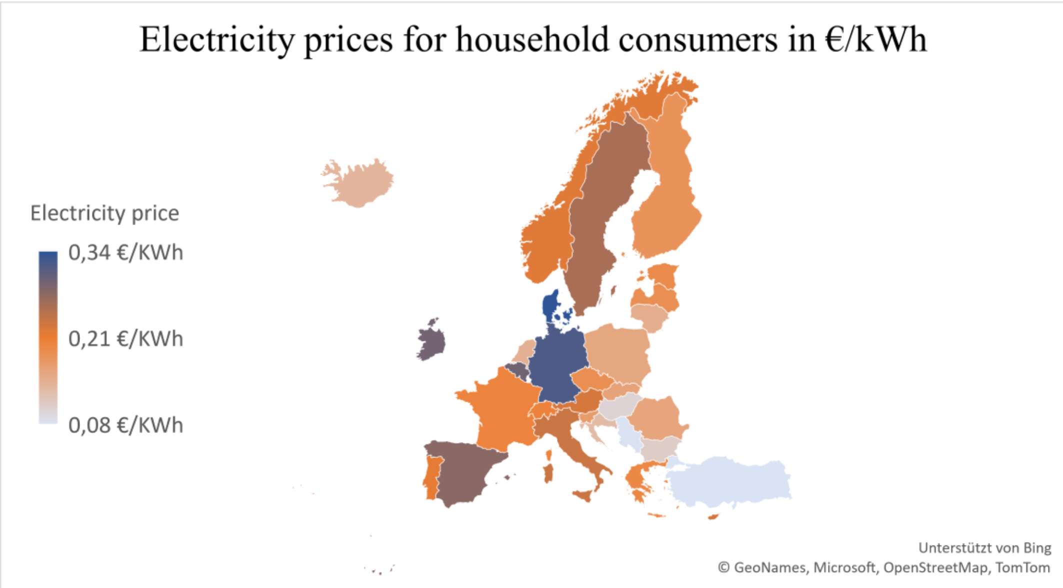
The COCO approach rests its technique on the notion of comparing different entities on the same features or attributes, while also harmonising the unit of measurement and the associated date. By articulating a primary issue, this approach consistently predicts the performance of objects in relative contrast to one another and then evaluates an overperformance or underperformance. A key finding on the fear of range, which is holding many customers back from investing in alternative propulsion systems, was expressed in the COCO analysis in terms of the number of hydrogen refuelling stations. Similarly, as an example, the price of green hydrogen, which depends on local electricity prices, was carried over into the COCO analysis and defined as a variable..

This method is applicable to all datasets and may be used repeatedly to provide predictions and forecasts under a wide variety of input situations. This may also cause us to erroneously interpret the correlations between our data, or even to believe that there is a causal connection between them. All of the aforementioned statistical analyses will furthermore provide quantifiable outcomes (approximations). It is our responsibility to assess if anything is reasonable or feasible (c.f. consistent). Since these computations always provide a result (a number), we are susceptible to being misled about the future of our date (e.g., sales projections, exchange rate projections, etc.).

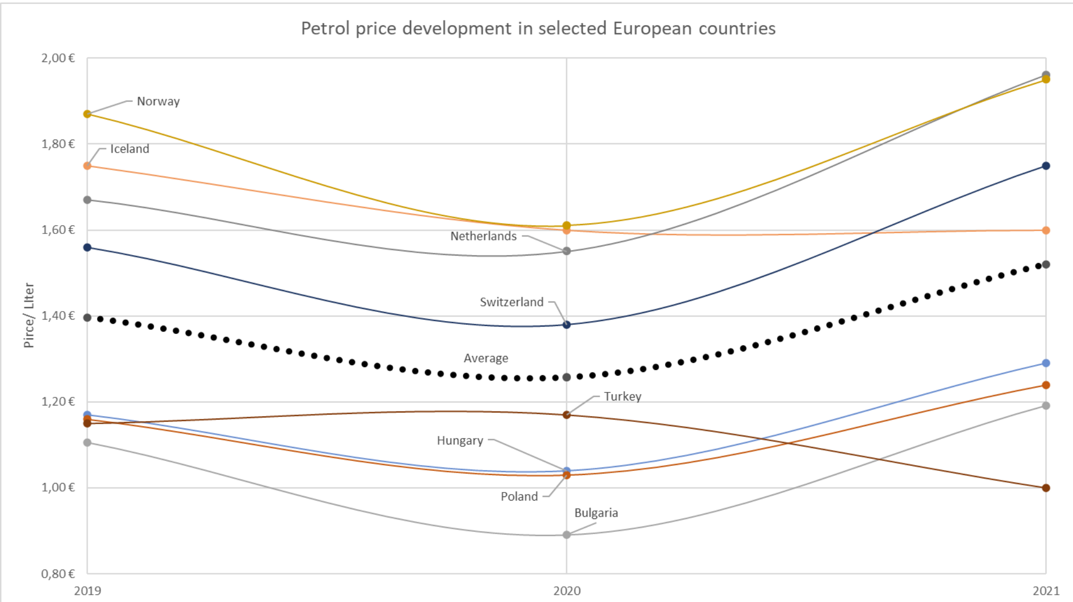
2.4.2 Materials

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 quantity of hydrogen-powered automobiles was selected as the unit of measurement. Due to the current low sales volume, it is projected that only so-called early adopters would acquire these cars. This refers to consumers who purchase vehicles based on their confidence in the technology, notwithstanding the immaturity of the industry (refuelling infrastructure, purchase price, tax incentives, etc.).



Energy Prices in Europe in 2021, own figure



Petrol prices in selected European countries, own figure.
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.

The data are first evaluated in a chronological order, and then additional comparisons are done that go beyond what can be accomplished with descriptive statistics. In a concise study, the utilization of a pivot table makes it possible to quickly and readily access all of the national variables.

It is possible, based on the data from the year 2021 to draw the conclusions that a few variables are quantitatively and qualitatively correlated (green), that one variable only partially represents y (yellow), and that a number of variables either have no connection or the opposite of the predicted impact (red). These findings illustrate that it is not directly feasible to arrive at a definitive conclusion on the efficacy of so-called policy initiatives. It is possible to see that public investments in research and development do not in any way pose any statistical relevance.

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.

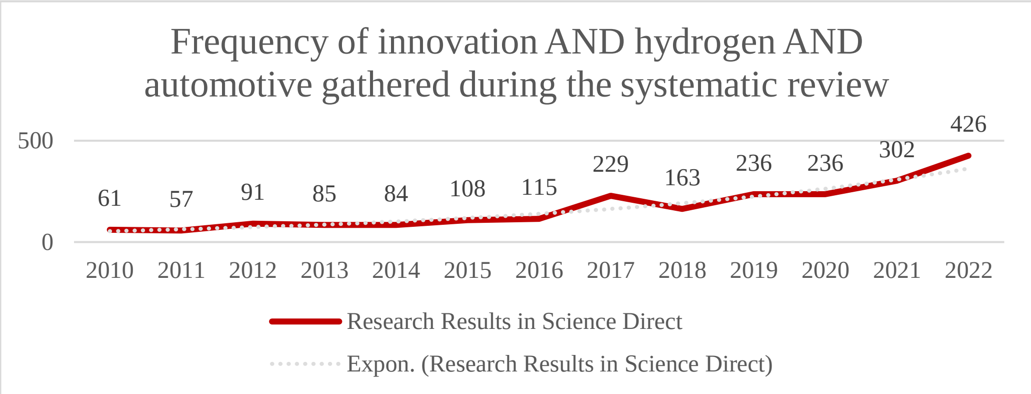
The analysis, referred to as a "naive" approach in the following, reveals that certain nations are pioneers in certain categories; the result reveals that Germany has the most hydrogen filling stations, while a large number of nations, such as Switzerland, Turkey, Serbia, Malta, or Iceland, have no hydrogen 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 a number of red or yellow ratings, but Denmark and Belgium, with a few exceptions, score pretty well.

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
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

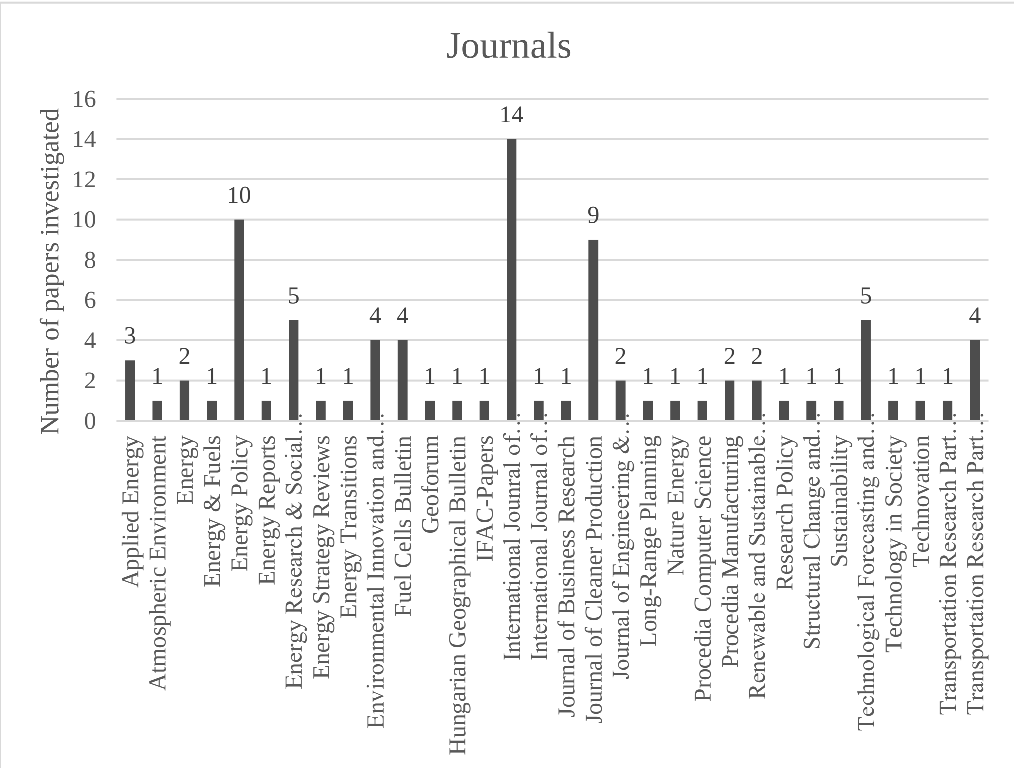
Conditionally formatted ranking OAM matrix with the COCO result (last column) regarding 2021, own figure

3. RESULTS

In the systematic review the following data was evaluated to determine which journals were retrieved and their quantitative value during systematic investigation to assure independence.



Research tendency, own figure



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

Category	Total	EU	Germany Hungary	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

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

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		

Methods used in papers, own figure

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 (see figure below). The p-value from the Breusch-Pagan test is present with a very high value, indicating constant variance of the residuals and homoscedasticity present.

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	-0,0702685	0,1091358	-0,64	0,521	-0,286664	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	-0,228906	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	-0,081644	0,0067916
ADV. 7	-0,1814786	0,094954	-1,91	0,059	-0,369748	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	-0,057393	0,2948543
_CONS	2,821134	1,320385	2,14	0,035	0,2030549	5,439213

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	

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

Evaluation of potential statistical problems, own figure

In summary, the following particular results can be derived from the Component based object comparison for objectivity analysis.

The number of hydrogen cars in 2019 was manageable. The market was young with 1500 cars, and most countries had hardly reacted. Several "norm-like" assessments result. Cyprus has more cars than average, however the gap is narrow. Luxembourg and Portugal stand out in the analysis for targeting hydrogen vehicle legislation this year. Norway is the only bad rated country.

Markets changed drastically in 2020. There are fewer ordinary countries and better country location. Austria has Central Europe's only small deficit. Close but above average: Belgium and Cyprus. Luxembourg leads again with Norway struggling. Results changed again in 2021. Latvia and Spain join Cyprus and Belgium in outperforming. Austria remains weak after its deficit. Finland and Germany have big deficits and are unusual. S1 grows with market expansion every year. All countries are adopting hydrogen technology, although in varying proportions.

Many Southern and Eastern European countries are average or above. Nordic country Norway pioneered zero-emission transportation but occasionally emphasized other technologies. Despite their technological and fiscal restrictions, smaller industrialized nations like Cyprus, Luxembourg, and Belgium are usually better off. Countries with a high automotive concentration are optimal for hydrogen automobiles, however Austria has a small share.

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. The results get ranked again 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.

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 results as well. The phrases “Threat” or “Opportunity” were selected based on the corresponding growth and decline (see figure below).

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
BE	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

SWOT analyses results, own figure
W = Weakness, S = Strength
N = Norm-like, O = Opportunity
T = Threat

The COCO analyses are summarized in the SWOT analysis. The approach allowed SWOT analysis integration. Its objective is to establish how much the whole system of phenomena follows the Y0 (ideal search) model's directional logic under defined directions. Thus, time is used to assess nations whose performance has improved or declined in recent years.

Austria failed to produce enough hydrogen vehicles in 2020 and 2021. While the innovation potential index somewhat excelled in 2020, it considerably dropped in 2021. Since average outperformance was smaller than negative index development, the development was negative. Croatia maintained the standard for its hydrogen vehicle fleet, but its innovation potential index was primarily in the bottom half, with a 2021 bump. The margin has narrowed, creating an opportunity.H2 automobile production in the Czech Republic was ordinary. Since 2020, the index has been above normal and reached an all-time high in 2021. This might lead to hydrogen innovation. Germany maintained the standard for two years, but in 2021 it ran a deficit. The index was positive in 2020 and 2021 and grew gradually, making it an opportunity, but lower than in the Czech Republic. Hungary did not do well in the COCO:STD model, although its innovation index grew annually due to the factors. It's Central Europe's best value, therefore this is a chance. Poland maintained the standard in 2019, therefore car numbers could not be determined. Hungary and the index have increased together, with 2021 continuing the trend.

The COCO:STD research found Slovakia and Slovenia norm-like. However, Slovakia constantly increase the gap compared to the usual, Slovenia eclipsed Slovakia's growth in 2020 but virtually returned to the norm in 2021, and other countries' standards have risen gradually

5. CONCLUSIONS AND RECOMMENDATIONS

This combined qualitative and quantitative methodological approach aimed to develop a model that presents the current strategic investments of Central European nation-states in hydrogen electric private mobility, highlighting customer responsiveness and technological acceptance of a different propulsion in privately owned cars and showing the status quo potential in the countries.

Ineffective policymaking that hinders market penetration and economic innovation threatens economic growth and consumer response. First, the scope and methods of innovation are described. Innovation strategies were proposed based on earlier drivetrains' comparable processes that hydrogen mobility now faces. Innovation is typically unmeasured, although qualitative and quantitative techniques were presented to emphasize its existence. In recent years, e-fuels have gained popularity. All energy sources that seek to be extensively employed in mobility must adapt to present passenger and transport traditions, a point frequently disregarded in study. Combined with the origin and subsequent coloring of hydrogen, it became clear that legislative policymaking coordinates, supports, dampens, and strategically plans energy output and mobility for private consumers in the coming decades.

Thus, the Slovak Republic, Hungary, and Germany, three Central European nations differing in size, automotive dependence, and energy mix, were evaluated on their hydrogen strategies, key strategic documents outlining policymaking standards, plans, and funding to meet EU sustainability goals for 2030 and 2050. While some criteria may be holistically assessed, Slovakia and Hungary focused on quantitative planning and finance, while the other developed thorough policymaking on operative levels without numbers or incentives.

The extensive investigation showed that innovation may be measured by sustainability, economic progress, technological innovations, and international policy. Many earlier research found the latter inadequate, highlighting the necessity to collect data and analyze policymakers to promote the alternative drivetrain. A status-quo analysis of customer buying decisions for hydrogen-powered cars was also created. Introduction: Automotive firms and governments supporting sustainable mobility are growing in prominence. After some background on buying decision-making, the article focused on which elements to include in a questionnaire for automobile buyers.

Based on considerable reviews, eleven questions, including a questionnaire, were created on an eleven-point scale from strongly disagreeing to strongly agreeing. Due to its automotive concentration and being the only Central European nation that manufactures hydrogen from renewable energy, Germany mainly marketed the questionnaire. Due to energy mix diversification, mobility need, and consumer expectations, hydrogen usage, manufacture, and promotion policy should be studied in Central European adjacent countries.

Customers examine two primary aspects while selecting hydrogen-fueled automobiles. First, domestic hydrogen manufacturing's predicted price stability is highly prized owing to fossil fuels' heavy dependency on external factors outside customers' control. Second, bivariate study is needed because individual mobility powered by a sustainable energy carrier is essential.

Finally, a component-based object comparison for objectivity technique was used to assess Central European nations' acceptance and effective transition of hydrogen-powered cars based on 10 characteristics. These evaluate ecological, price elasticity, and infrastructural factors based on the questionnaire findings.

COCO:STD was developed first. The main goal was to quantify the questionnaire's relative components and their influence on European hydrogen car sales. The model was expanded to include 32 countries from Europe to ensure repeatability and verifiability. The quantitative data did not match the academic literature or survey results, suggesting that variables like electricity prices or the share of sister technologies (like the number of newly registered trucks with alternative drivetrains) do not correlate or even negatively correlate with hydrogen car numbers.

Luxembourg, Cyprus, and Belgium, typically smaller and poorer countries, outperformed their neighbors throughout time. Strangely, Norway, Finland, and Germany, which are known for their alternative drivetrains, fared poorly.

Next, COCO-Y0 was used for anti-discrimination analysis. Since hydrogen technology had not yet taken hold in Europe, 2019 started identically for all countries, as in the prior research. According to the 2021 index, Finland has one of the largest potentials in Europe to adopt hydrogen-based transportation on a large scale, even if it does not yet have hydrogen-powered cars. Hungary, which most people would rank lower, ranks third. The model properly balanced several aspects since Hungary performs averagely but excels in energy cost and car production. Hungary can outperform its neighbors, especially Germany, which has Europe's highest electricity costs.

In conclusion, a SWOT analysis combined all previous data and analyzed the innovation index's development to find direct strengths, weaknesses, norm-like behavior, and potential threats and opportunities. Automotive supply networks, transportation, and culture unified Central Europe, but results were mixed. Besides Austria, Germany, Poland, the Czech Republic, Hungary, Slovakia, and Slovenia provide potential. They may have different histories, but they all promote hydrogen innovation.

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 measures, easier adaptation to existing infrastructure and to corresponding customers.

- ❖ 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 Co2-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 CO2 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 and every country's attributes and 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.

<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>Innovation index for hydrogen cars</td></tr>
<tr><td colspan="2">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 analysed. 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</td></tr>
</table>

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.

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	Performance evaluation of each country in a three year period

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.

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.

6. NEW SCIENTIFIC RESULTS

In this thesis 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.

7. APPENDICES

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A2: Listed publications

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A3: 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 – 4/2021	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

Laszlo Hammerl

7. 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.

Kaposvár, Tuesday, 05 March 2024 Laszlo Hammerl