Empirical Investigation of Sustainable Growth of Energy Hydrogen Production in Malaysia

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Abstract
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The present study examined the sustainability of hydrogen energy development in Malaysia by exploring R&D, infrastructure and policy/regulation. Hydrogen is gaining recognition as a clean energy technology for its capability to decarbonize energy supply and cut GHG emissions. Despite its potential, deployment faces hurdles, including technological, economic and regulatory obstacles along with critical need for infrastructure development. The results showed from the usage of ANOVA and regression analysis that R&D, infrastructure and policy had significantly affect the hydrogen growth. The constraint limitations are data limitations, the width of the study, time and methodology limitation, policy changes from external environments and limited stakeholder participation. This implied for research including wide ranging dataset, cross national and time-bound study, a combination of method, and wide stakeholder participation. The results of the study implied that increasing in R&D investment, wide coverage of infrastructure plan and effective policy regime can guarantee the sustainability of hydrogen growth. The study enriched existing knowledge on Malaysian hydrogen situation and will provides some insights for further research and policy-making to achieve the low-carbon transition in Malaysia.

Keywords: Hydrogen energy, greenhouse gas, issues, low carbon economy

1 Introduction

Proposed strategy for hydrogen development in Malaysia to align with Hydrogen is seen as a key enabling factor for a sustainable future worldwide. By 2030, the Hydrogen Council states there are already over 680 proposed projects with a value of US $240 billion and this number could increase to US $700 billion in investment by 2030 in order to meet net-zero goals (SparkedAdmin, 2022; Staff, 2022) and by 2050, it could make up to 10% of all energy use (Sampson, 2023). Today however, hydrogen generation overwhelmingly relies on steam reforming of natural gas, with a figure of 95% of global production coming from this source (IEA, 2019). Fossil-fuel based production is expected to decrease as green hydrogen generation is predicted to increase to 660 metric tons by 2050, with significant growth being driven by applications such as aviation, shipping, transportation, and power generation (McKinsey, 2021). The efficient storage and delivery of hydrogen will be crucial in facilitating the wider uptake and integration of it within society. Hydrogen can be stored physically or by material-based solutions (Nejc Klopi et al., 2023). Delivery methods for hydrogen can include either pipelines for smaller volumes, or cryogenic tankers for greater distances (Yousef, 2021). Beyond domestic utilization there are international plans such as the U.S. DOE Hydrogen Plan promoting the scaled up production of hydrogen (Energy.gov, 2022). In Malaysia the Hydrogen Economy Technology Roadmap (HETR) launched in 2023 predicted an increase of RM49-RM61 billion to GDP and RM12.1 billion in revenue by 2030 (MIDA, 2023). In addition the roadmap outlined a plan to reduce green-house gas emissions by up to 1.3% by 2030 (Kasturi, 2023). To ensure environmental sustainability, Malaysia plans to have 70% renewable energy use by 2050. Hydrogen plays a critical role in the semiconductor industry where it is used for epitaxy, annealing, deposition and ion implantation. With projected RM 500 billion investment in the sector, the demand and use of hydrogen can be expected to play a significant role (Danial, 2024). It can be concluded that the research in producing and delivering hydrogen provides a critical practical contribution to Malaysia's economic growth by highlighting relevant issues and opportunities and aiding diversification efforts in the energy sector, boosting energy security through expansion of green hydrogen production and could inform future hydrogen and CCUS policies while also establishing international partnerships necessary to support Malaysia becoming a leading hydrogen economy by 2050. Theoretically the study has examined Malaysia's production potential and current delivery of hydrogen and particularly the sustainability benefits of green hydrogen generation. New knowledge is established regarding the drivers behind its development, relevant variables, market characteristics and importance of hydrogen within the Malaysian energy sector, as well as the environmental benefits that may arise, such as reduced emissions, in turn facilitating a international energy and Paris agreements.

2 Literature Review

2.1 Global Perspective on Hydrogen Growth

The hydrogen market is growing, with demand for both clean energy and emission reduction. 67% of global hydrogen production by 2050 is anticipated to be green, and thus not lead to CO2 emissions (Kim et al., 2021; Dash et al., 2023). The growth of the market relies on implementation of strategies from countries and significant capital investment in particular in developing countries (Martnez-Burgos et al., 2021). One of the largest areas of growth is in transportation which produced 7Gt of CO2 in 2020. By 2050 the Net-Zero Emissions scenario aims for the transport industry to produce 90% less emissions despite increase in travel (Hydrogen Decarbonization Strategies, 2022). Technological advancements including electric vehicles, fuel cells and hydrogen based fuels have been driving these trends. Use of hydrogen in heavy trucking, shipping and aviation is expected to rise significantly by 2040.

2.1.1 Sustainable Growth of Hydrogen Energy

There is increasing interest around the world on sustainable hydrogen due to its' benefits, of having less emission while maintaining a sound economic growth. This demand is expected to be between 125–585 Mtpa in 2050 (McKinsey & Company, 2024). The biohydrogen and the renewable electrolysis methods are promising as they are considered to have the smallest impact on the environment (Ababay et al., 2024). As well as it creates new sectors and trade routes worldwide (J.P. Morgan, 2024). It requires policies and incentives to make widespread deployment (Wood, 2022; Hassan et al., 2024). There are also predictions suggesting that 2/3rd of hydrogen produced will be green by 2050. Generally sustainable hydrogen is a factor of economic development and the climate change mitigation. (Capurso et al., 2022).

2.2 Malaysia's Perspective on Hydrogen Growth

Malaysia is well endowed with renewable resources and the country is promoting hydrogen as a part of its transition to new forms of energy, and its governments as well as various NGOs actively promote its use. Diversification of energies in Malaysia also includes the promotion of fuel cells based on hydrogen and biofuels (Seong & Lalchand, 2019; Ahmad et al., 2021). Sarawak Hydrogen Roadmap (2005-2030) also suggests interest from Malaysia but hurdles such as integrating hydrogen with present energy infrastructure, higher price and lack of experience are still obstacles (Wintle, 2024; Hutchinson, 2023). This initiative culminated in the launch of Hydrogen Economy & Technology Road Map (HETR) in 2023, forecasting a contribution of 49-61 billion ringgit (GDP) to Malaysia by 2030 (Skrine, 2023).

2.2.1 Sustainable Growth of Hydrogen Fuel in Malaysia

Its wealth of natural resources provides Malaysia with significant renewable hydrogen potential. Several national and state roadmaps are focusing on developing the relevant R&D, infrastructure, workforce, and policy frameworks to leverage this potential. For example, the Sarawak Hydrogen Roadmap and the National Energy Transition Roadmap (NETR, 2023) set out key goals and strategies to foster hydrogen growth. By 2050, hydrogen could add RM1.7 trillion to the GDP of Malaysia and create 200,000-300,000 jobs (NETR, 2023). The main drivers of hydrogen growth are the investment in R&D to optimize production technologies, investment in new and improved infrastructure (such as refueling stations and production facilities), clear policies and regulatory frameworks, as well as the development of partnerships at the international level, while development of relevant skills and increasing public awareness are also important aspects to take into consideration.

2.3 Hydrogen Production Growth in Malaysia

Malaysia has entered several billion-dollar hydrogen deals, with US$4.2 billion allocated in Sarawak. A Hydrogen Economy & Technology Roadmap has been set for 2040 (NETR, 2023) to create policy certainty. By 2050, the country will be targeting 70% of its energy mix to come from renewable sources, of which green hydrogen will be a significant part (MIDA, 2021). Issues facing the nation include high capital expenditure and uncertain policy frameworks, intermittency of renewables and market immaturity. Overcoming these will require significant political support and investment in technology.

2.4 Factors Affecting Hydrogen Growth

2.4.1 Research and Development

Innovation in hydrogen technology is needed in order to reduce costs and ensure sustainability. Reports (IEA, 2019; 2023) suggest that hydrogen innovation is crucial in order to reach Paris Agreement targets. Malaysia is in need of advanced technologies such as power-to-gas technology as well as a collaborative research and development effort with universities, industries and government (Conte, 2001). Funding and policy initiatives will encourage quicker commercialisation and enable Malaysia to compete effectively in the future (Ahmad et al., 2021).

2.4.2 Infrastructure Development

Infrastructure is a key facilitator. Malaysia requires centralized production plants, fueling stations, high-tech storage (metal hydrides, caverns) and integration into smart grids (Khzouz & Gkanas, 2020). Making use of its existing gas pipelines and building export terminals will bolster Malaysia's global presence. Models can be learned from international experiences: Japan's massive production plants, Germany's refueling stations, EU's SoutH2 Corridor, U.S.'s underground storage, South Korea's blended hydrogen fuels (IEA, 2019; Shine, 2023; Wood, 2022). The use of PPPs and innovation centers can facilitate rapid infrastructure deployment.

2.4.3 Policy and Regulatory

Policies will play a crucial role in driving hydrogen adoption. Malaysia's policy to diversify its energy mix will be important; there should be inclusion of environmental controls and financial support, along with the establishment of clear hydrogen guidelines (Foo, 2015; Riera et al., 2023). A strong regulatory framework coupled with supportive market conditions would draw more investments into sustainable adoption.

2.5 Theoretical Justification

The framework of Hydrogen Economy is applied in this research, focusing on hydrogen as the clean carrier on low-carbon development. The framework is driven by three pillars (R&D, infrastructure and policy). Malaysia's demand on hydrogen (50k tons in 2023, CAGR 3.88% in until 2034) would lead to contribution of RM 49-61 billion of GDP by 2030. Malaysia's major markets for hydrogen are China, Japan, South Korea and Singapore (Malaysia Hydrogen Market, 2024; Ibrahim, 2023; Hutchinson, 2023). Such framework is consistent with the concept of sustainable development where it combine economic development, environmental protection and social equity.

2.6 Hypothesis Development

The study aimed to test this hypothesis:

- H1: R&D positively affects hydrogen growth (Conte, 2001; Martnez-Burgos et al., 2021).
- H2: Infrastructure positively affects hydrogen growth (Khzouz & Gkanas, 2020; Xiao Fei Tian & Pei, 2023).
- H3: Policy and regulation positively affects hydrogen growth (Ahmad et al., 2021).

2.7 Theoretical Framework

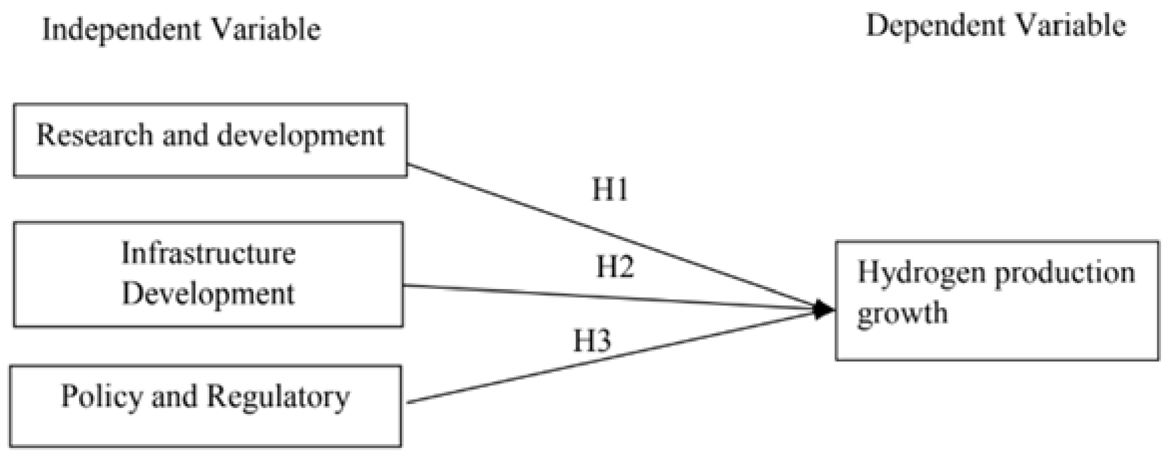

Figure 1: Research Framework

(Source: Self-created)

3 Research Methodology

3.1 Research Design

A quantitative design incorporating both descriptive and explanatory aspects was utilized. Descriptive analysis shows the panorama of Malaysia's hydrogen industry on production capacity, infrastructures and market development (Philip et al., 2022; Hannan et al., 2018). Explanatory analysis explores interrelations between driving factors of hydrogen development via regression, time series and scenario analysis (Tseng et al., 2005; Ahmad et al., 2021).

3.2 Purpose of Study

The objectives of this study are:

1. To explore the present status of hydrogen production in Malaysia.
2. To evaluate the various technological, economic and policy factors contributing to this expansion.
3. To make recommendations for future advancement and interactions with other interested parties.

3.3 Types of Investigation

- Descriptive: Existing production, distribution, market situation.
- Explanatory: Statistical modeling for hypothesis testing (Green hydrogen opportunities, 2022).

3.4 Extent of Researcher Interference

Mixed methods were used, in the form of surveys (quantative) and findings from interviews (qualitative) (Wong et al., 2021). Using interviews, surveys and secondary data means that this approach is triangulated. Respondents were given freedom, as opposed to having to choose answers, to remove any bias.

3.5 Study Settings

Non-contrived setting, a non-contrived context that data are gathered from hydrogen experts with real points of view (Dikilita & Griffiths, 2017).

3.6 Time Horizon

This study employs a cross-sectional approach where data were collected over 4 weeks, using surveys (Johannesson & Perjons, 2014).

3.7 Unit of Analysis

The main actors are companies and suppliers that are involved in the hydrogen industries, especially the semiconductor companies located in Kulim, Kedah in the north of Malaysia. The departments which answer this questionnaire are Facilities, Engineering, Finance, R&D, procurement and logistics.

3.8 Sampling Design

3.8.1 Target Population

This paper is about researching Malaysian hydrogen production industry, concerning companies, supplier stakeholders and the energy industry. The case study area used is Kulim, Kedah as a semiconductor manufacturing area. Respondents were selected according to knowledge and experience with regards to hydrogen production industry and energy industry. 316 respondents, comprising both company workers and suppliers, participated in questionnaire survey. The population is defined as a full collection of people whose study matter the collected information supports better decisions making.

3.8.2 Sample Size

Slovin's formula was used in order to compute for the sample size. The samples would then give an unbiased reflection of the population. Taking into consideration the confidence level to be at 5%, the following was the computed sample size:

$$n = \frac{N}{1 + Ne^2} = \frac{1500}{1 + 1500(0.05)^2} \approx 316$$

In which n is the sample size, N is the population size and e is the sampling error. Using this formula, the sample size calculated was 316 respondents with the population size being 1,500, guaranteeing a statistically significant and reliable result from the survey. Minimising potential sampling error, (Ellen, 2020).

3.9 Measurements and Measures

The survey uses items of Nominal & Likert scale (Bhandari & Nikolopoulou, 2023). Each independent variable uses 5 Likert-scale items for its measurement. The construction of the questionnaire is presented below:

Table 1: Questionnaire Design

Section	Variables	No of Item	Source	Adapt/ Adopt	Measurement scale
I	Demographic	5	1. Age 2. Gender 3. Occupation 4. Working experience 5. Education Level	-	-
II (Dependent Variable)	Hydrogen production growth	5	(IBRAHIM, 2023) (Hutchinson, 2023) (Azhar, 2021)	Adopted	Likert scale
III	Research and development	5	(Ananth, 2020)	Adopted	Likert scale
(Independent Variables)	Infrastructure Development	5	(Mills,2024)	Adopted	Likert scale
	Policy and Regulatory	5	(Martin, 2020)	Adopted	Likert scale

3.10 Data Collection Method

Questionnaires were sent through confidential online surveys. Response rate was maximized through the use of explicit directions and survey distribution to a diverse range of positions with the use of reminders through emails or phone calls. The responses can be exported directly to an excel spreadsheet.

3.11 Data Analysis Methodology

Data was analyzed using descriptive statistics, correlation and regression. Qualitative content analysis will be also used for open-ended questions (Mohajan, 2020). Pilot test, factor analysis, reliability tests and hypothesis testing will be also conducted. The unit of analysis was clearly identified whether individuals, groups, organization, event. Sampling design described how participants will be selected including sample size, sampling frame and technique. Data collection method described tools used for example, survey questionnaire, interview, observations etc. Measurement and measure explained about measures or scales that will be used, focusing on its validity and reliability. Last, the data analysis described methods for statistics analysis and used software.

4 Data Analysis

4.1 Pilot Test

Prior to conducting the actual survey, a pilot test was administered to check for reliability and validity of the questionnaire. The pilot test comprised of 50 respondents in a manufacturing company in Kulim, Kedah that falls under the study's respondents' profile. The respondents received their questionnaires via Microsoft Teams by utilizing the inter-company network.

4.1.1 KMO and Bartlett Test (Pilot Test)

The value for KMO shown in Table 2 is 0.775, which is categorized as a "good" measure for sample adequacy and an appropriate dataset to be used for factor analysis (Glen, 2016). The Chi-Square value is 103.141 with a degree of freedom of 6 and a p-value of < 0.001; this implies that variables are significantly correlated to one another, hence suitable for factor analysis with good common variance.

Table 2: KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.775
Bartlett's Test of Sphericity	Approx. Chi-Square	103.141
	Df	6
	Sig.	< 0.001

4.1.2 Pilot Testing: Reliability Test

Results from the pilot test found that the questionnaire was easily understood by the respondents. The Cronbach's Alpha value were all greater than 0.8 as shown in Table 3, which can be deemed as a good indicator of the survey instrument's reliability and internal consistency (Frost, 2022).

Table 3: Reliability Test

	Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	No of Items
Hydrogen Production Growth	0.918	0.919	5
Research and Development	0.909	0.908	5
Infrastructure Development	0.864	0.862	5
Policy and Regulation	0.846	0.844	5

4.2 Response Rate

The number of questionnaires issued and returned is summarized in Table 4. The number of questionnaires issued was 400 and 381 were returned while 19 questionnaires were returned unfinished yielding a response rate of 95.25%. The extremely high response rate indicates that the respondents were interested in the survey topic, thereby enhancing the validity and reliability of the data collected, which can be used for more effective interpretation and analysis.

Table 4: Summary of responses received

Description	Result
Total questionnaires distributed	400
Total number of respondents received	381
No response to the questionnaires	19
Percentages of response rate	95.25%

4.3 Demographic Profile of Respondents

Figure 2 shows the demographic characteristics, which include gender, age, education, occupation and work experience of respondents.

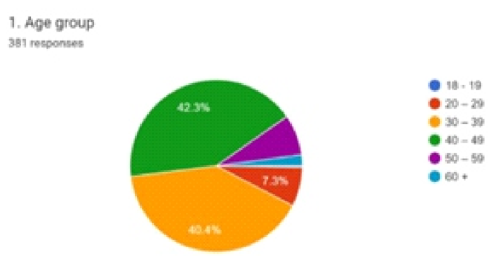

Figure 2: Descriptive analysis (Age)

The majority of those who participated were middle-aged, aged between 30 and 49 (40.4% between 30-39 and 42.3% between 40-49), younger adults represented the next largest group (7.3% of which were 18-19, followed by other groups ranging from 20-29, 50-59 and 60+ in progressively smaller amounts).

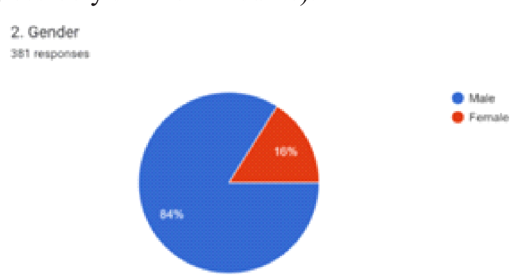

Figure 3: Descriptive analysis (Gender)

The data received from the survey exhibits an obvious gender distribution. Of all the respondent, 84% of them were men and only 16% of them were women. Figure 3 illustrates that the majority of respondents were men, which corresponds to the composition of male and female in the scope being surveyed.

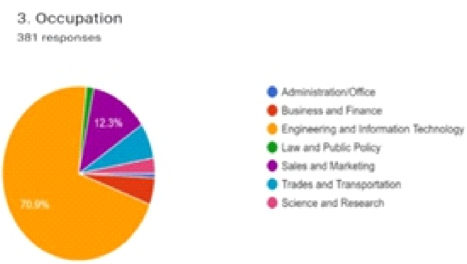

Figure 4: Descriptive analysis (Occupation)

As reported in the survey, the largest group consists of employees in Administration/Office (70.9%), followed by Business and Finance (12.3%), while the remainder of jobs are evenly distributed among Engineering, IT, Law and Public Policy, Sales and Marketing, Trades and Transportation, and Science and Research. The Figure 4 indicates a significant tendency of participants in Administration/Office and thus may reflect the structure of employment or people's tendency to work in this field.

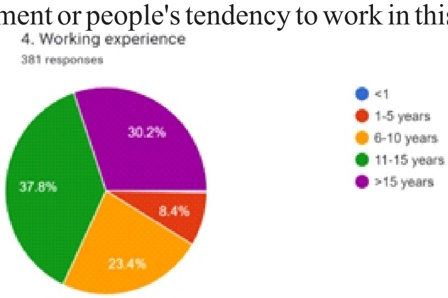

Figure 5: Descriptive analysis (Work Experience)

In Figure 5, we see that most of the participants are relative newcomers to the field. While 37.8% have under one year of experience, and 30.2% have 1-5 years of experience, 23.4% have 6-10 years of experience, and 8.4% have over 15 years of experience. The industry has a young workforce, giving an interesting perspective on what the experiences of the relative newcomers are.

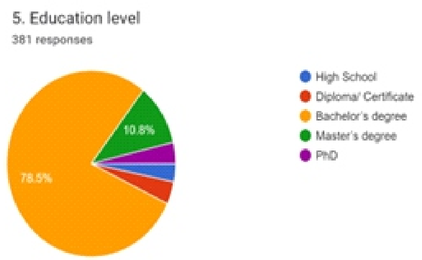

Figure 6: Descriptive analysis (Work Experience)

From Figure 6, the most of the respondent is High School holder which account for 78.5% in the largest group followed by Diploma/ Certificate holder which count for 10.8%, and Bachelor degree holder, Master degree holder, and PhD holder which count for 7.4%, 2.6% and 0.8% respectively. Thus the highest number of participants are having secondary education background, and the number decreases proportionally to higher education holder.by Business and Finance (12.3%), while the remainder of jobs are evenly distributed among Engineering, IT, Law and Public Policy, Sales and Marketing, Trades and Transportation, and Science and Research. The Figure 4 indicates a significant tendency of participants in Administration/Office and thus may reflect the structure of employment or people's tendency to work in this field.

The respondents' demographic information is as follows: Table 5 shows the summary profile of respondents:

Table 5: Respondents' demographic profile

Group	Sub-group	Frequency	Percent
Age group	18-19	1	0.3
	20-29	28	7.3
	30-39	154	40.4
	40-49	161	42.3
	50-59	29	7.6
	60+	8	2.1
Gender	Male	320	84.0
	Female	61	16.0
Occupation	Administration/Office	3	0.8
	Business and Finance	19	5.0
	Engineering and Information Technology	270	70.9
	Law and Public Policy	6	1.6
	Sales and Marketing	47	12.3
	Science and Research	11	2.9
Working experience	<1	1	0.3
	1-5	32	8.4
	6-10	89	23.4
	11-15	144	37.8
	>15	115	30.2
Education level	Bachelor's degree	299	78.5
	Diploma/ Certificate	15	3.9
	High School	12	3.1
	Master's degree	41	10.8
	PhD	14	3.7

4.4 Actual Data Analysis

To estimate how well the data could be used to test hypotheses a number of initial analyses were run on responses collected from 381 participants. All statistical analyses were run using SPSS version 20.

4.4.1 Factor Analysis

The KMO value of 0.729, which is shown in Table 6, indicates that the sample size is adequate for factor analysis, falling within the "middling" category of suitability. Bartlett's Test of Sphericity produced a Chi-Square value of 596.422 with 6 degrees of freedom and a significance level below 0.001, confirming that correlations between variables are significantly different from zero. Together, the high survey response rate, KMO result, and Bartlett's test demonstrate that the dataset is reliable and well-suited for factor analysis, providing a solid basis for identifying and interpreting underlying factors.

Table 6: KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.729
Bartlett's Test of Sphericity	Approx. Chi-Square	596.422
	df	6
	Sig.	< 0.001

4.4.2 Reliability Test

From the reliability test displayed in table 7 it can be seen that the scales of measurement used are more or less reliable. It can be seen that the dependent variable which is Hydrogen Production Growth has a fairly good internal reliability with a Cronbach's alpha of 0.742 over 5 items.

Table 7: Reliability Test

Variables	Cronbach's Alpha	No. of items
Hydrogen production growth (Dependent Variable)	0.742	5
Research and development (Independent Variable)	0.714	5
Infrastructure Development (Independent Variable)	0.739	5
Policy and Regulatory (Independent Variable)	0.645	5

Research and development and Infrastucture development recorded acceptable to good withCronbach's Alpha of 0.714 and 0.739 respectively. However the Policy and Regulatory variable recorded fairly low Cronbach's Alpha of 0.645.

4.5 Hypothesis Testing

This section is going to be based on the hypothesis testing, which measures how dependent variable and independent variable are related through the use of multiple regression and regression ANOVA. The following are the hypotheses set in the study:

- H1: Research and Development positively and significantly affects hydrogen production growth.
- H2: Infrastructure positively and significantly affects hydrogen production growth.
- H3: Policy and Regulation positively and significantly affects hydrogen production growth.

4.5.1 Results of Multiple Regression Analysis

The regression analysis result gives a value for R to be 0.314 which implies a moderate positive linear relationship exists between observed and predicted value of Hydrogen Production Growth (HPG). The R square value of 0.099 shows that 9.9% of variability within HPG can be accounted for by the independent variables (Research and Development, Infrastructure Development and Policy/Regulatory). This explains the model accounts for some variation but the largest percentage of variation is not accounted for implying there are other explanatory factors involved which were not accounted for in the model (Frost, 2019). Lower values of R square can be observed in social sciences due to the complex and unpredictable nature of human and organizations behavior (Zach, 2019). As reported in Table 8 Adjusted R square is 0.091 it adjusts the R square value based on the number of predictors used sample size, showing that the model explains approximately 9.1% of the variance in HPG, while the Durbin-Watson statistic of 0.948 indicates the presence of positive autocorrelation in the It follows that the positive residuals tend to be followed by other positive residuals, which implies a tendency of the error term not to occur randomly.

Table 8: Model Summary Result

Model Summary [b]					
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.314[a]	0.099	0.091	0.72806	0.948

a) Predictors: (Constant), Policy and Regulation, Research and development, Infrastructure Development
b) Dependent Variable: hydrogen production growth

4.5.2 Correlation analysis

The correlation matrix indicates several statistically significant relationships among the variables Hydrogen Production Growth (HPG), Research and Development (RND), Infrastructure Development (INF), and Policy and Regulatory (PNR).

- HPG shows moderate positive correlations with RND (0.286), INF (0.274), and PNR (0.266).
- RND demonstrates a strong positive correlation with INF (0.782) and a moderate positive correlation with PNR (0.583).
- INF and PNR are also strongly correlated, with a coefficient of 0.622.

As tabulated in Table 9, all correlations are significant at the 0.01 level, confirming that these relationships are unlikely to have occurred by chance. This suggests that while each independent variable is positively associated with hydrogen production growth, there are also strong interrelationships among the independent variables themselves.

Correlations

		HPG_A	RND_A	INF_A	PNR_A
Hydrogen Production Growth	Pearson Correlation	1	0.286**	0.274**	0.266**
	Sig. (1-tailed)		<0.001	<0.001	<0.001
	N	381	381	381	381
Research and Development	Pearson Correlation	0.286**	1	0.782**	0.583**
	Sig. (1-tailed)	<0.001		<0.001	<0.001
	N	381	381	381	381
Infrastructure Development	Pearson Correlation	0.274**	0.782**	1	0.622**
	Sig. (1-tailed)	<0.001	<0.001		<0.001
	N	381	381	381	381
Policy and Regulation	Pearson Correlation	0.266**	0.583**	0.622**	1
	Sig. (1-tailed)	<0.001	<0.001	<0.001	
	N	381	381	381	381

Table 9: Correlations Analysis

**. Correlation is significant at the 0.01 level (1-tailed).
Where,
HPG = Hydrogen Production Growth
RND = Research and Development
IFD = Infrastructure Development
PNR = Policy and Regulation

4.5.3 Regression ANOVA

The ANOVA results confirmed that the regression model is statistically significant. As shown in Table 10, the regression sum of squares is 21.843 with 3 degrees of freedom, producing a mean square of 7.281. The residual sum of squares is 199.835 with 377 degrees of freedom, yielding a mean square of 0.530. The model produced an F-statistic of 13.736 with a significance level below 0.001. These findings indicate that the overall regression model significantly predicts the dependent variable. This means that at least one of the independent variables—Research and Development, Infrastructure, or Policy and Regulation—has a statistically significant effect on the growth of hydrogen production (Bevans,2020).

Table 10: ANOVA

ANOVA a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	21.843	3	7.281	13.736	< 0.001b
	Residual	199.835	377	0.530		
	Total	221.678	380			

a) Predictors: (Constant), Policy and Regulation, Research and development, Infrastructure Development

b) Dependent Variable: hydrogen production growth

4.5.4 Multicollinearity and Beta Coefficient

Table 11 shows the result of hypothesis testing. The test showed that Research and Development($p = 0.059$) and Infrastructure ($p = 0.376$) has not statistically positive relationship on the increase of hydrogen production growth. Policy and Regulation has the positive relationship ($p = 0.039$) and it is statistically significant. The regression test also showed the same result, and policy and Regulation has beta value 0.132 and p value is 0.039. So Policy and Regulation has a positive relationship for the hydrogen production growth (Nieminen, 2022). Correlation matrix also demonstrates a considerable relation between R&D, Infrastructure and policy & regulation, implying that all factors may not have a direct effect on growth but are inter-related and likely to have synergy. The collinearity test, indicated by Variance Inflation Factors (VIFs) are less than the threshold of 10 thus it indicates no severe collinearity among the variables (Frost, 2017). But the considerably higher VIFs for the variables, Research and development and policy and regulation indicated some degree of multicollinearity to keep an eye on. Overall, the results highlight that policy & regulation would play an crucial role in stimulating the growth of hydrogen production. And the research & development and infrastructure are inter-linked.

Table 11: Coefficients and Collinearity Result

Coefficients a								
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	2.856	0.187		15.279	< 0.001	0.374	2.677
	Research and development	0.134	0.071	0.152	1.894	0.059	0.347	2.883
	Infrastructure	0.063	0.071	0.074	0.886	0.376	0.588	1.699
	Policy and Regulation	0.130	0.063	0.132	2.068	0.039	0.374	2.677

Dependent Variable: hydrogen production growth

4.6 Summary of Hypothesis Testing

This experiment was conducted to investigate the following hypothesis:

H1: Research and Development has a positive effect on hydrogen production growth, but this is not statistically significant.

H2: Infrastructure has a positive effect on hydrogen production growth, but this is not statistically significant.

H3: Policy and Regulation has a positive effect on hydrogen production growth, and this is statistically significant.

5 Discussion, Recommendation, and Conclusion

5.1 Discussion of the Research Findings

Three dominant drivers: R&D, Infrastructure and Policy and Regulation determines the sustainable development of hydrogen production in Malaysia. The findings of the research discovered that both R&D and Infrastructure are positively impacting on hydrogen production, however, there is no statistical significant relationship on both variables. Contrary to the findings on the other two variables, policy and regulation has a significant and positive impact on hydrogen production development which is the key driving factor for hydrogen production in Malaysia. R&D has been crucial in enhancing the hydrogen technology, increasing efficiency and lowering the cost. The findings revealed that current R&D is not strong enough to bring tangible results. This is mainly due to underinvestment, dispersed and lack of focused effort in the development, as well as an inequitable regional progress, in which Sarawak is favored with their hydropower production, the results showed a strong case for more funding to be injected as well as closer coordination between public, industry and academia to speed up innovation and commercialization. The infrastructure is also vital component in the development and growth of hydrogen production. Without adequate pipeline, refueling station and distribution facilities the production of hydrogen cannot be adequately consumed by other industries and services. However, infrastructure development is still at pilot stage where most of the projects (e.g. Hydrogen plant in Sarawak) are too small in scale to produce a detectable impact nationwide. A greater sum of investment is needed along with long-term strategic planning beyond pilot projects in developing the hydrogen network. Amongst the three drivers discussed, it seemed that policy and regulation has the most deciding power to determine hydrogen production in Malaysia. The research confirms that effective policies greatly affect hydrogen production development by attracting investment, facilitating R&D and promoting infrastructural development. Policies like National Energy Transition Roadmap (NETR), Hydrogen Economy and Technology Roadmap (HETR) also revealed government's commitment to green hydrogen production and the goal of achieving net-zero by 2050 with international cooperation through the platform of APEC Low Carbon Hydrogen Policy had paved the path for Malaysia to attract investment and boost economic development. However, clear incentives, regulatory guidelines and certifications were not adequately established to secure sustained private sector participation.

The study also indicates that R&D and infrastructure play significant roles in the expansion of hydrogen but it plays minimal role in the present Malaysian context. The most critical factor identified in the study is policy and regulation as a solid regulation is required for the adoption of hydrogen to accelerate. Malaysia need to enhance its investments in R&D, pace up the deployment of infrastructure, further improve its policy frameworks to promote sustained hydrogen growth in the country. Combined efforts will allow the country to move towards low carbon future and to meet its net-zero targets for 2050.

5.2 Recommendations

5.2.1 Demographic Profile

In order to increase the generalizability and robustness of studies on hydrogen production in Malaysia, improvements have to be made with regard to the demographic profile of the respondents. The present sample profile, with a majority being in the 30-49 age bracket, suggests a need for more diversity in age groups, with representation being required from young adults (18-29) and older adults (50+). A balance of genders also needs to be addressed, considering that 84% of the respondents were males. Effort has to be made to aim for equal distribution of genders to include perspectives specific to each gender. It is also crucial to have a mixture of job backgrounds. Engineering and IT accounted for the largest number of respondents and left minimal space for responses from sectors such as Administration, Business and Finance, Law and Public Policy, Sales and Marketing, as well as Science and Research. Inclusion of a greater number of people from these fields would allow for varied responses on hydrogen production. Finally, variation across different parts of Malaysia and various industries should also be considered. While inclusion of people from various regions in Malaysia may present different views on hydrogen production at the regional level, the diverse nature of industries, including energy, manufacturing, transport, and government agencies, can provide a clear understanding on sector specific perceptions towards hydrogen production. To meet these demands, appropriate sampling and recruitment strategies such as collaboration with various professional associations, collaborations with academic institutions, and advertising through the use of social media could be implemented. Various incentives could also be provided to attract and encourage respondents to partake in studies on hydrogen production, with an effort to ensure inclusivity.

5.2.2 Result Analysis

Given the outcome of the findings, some recommendations could be proposed to ensure that the hydrogen production in Malaysia can develop sustainably. The first recommendation that need to be put into action is the boost of research and development investment. Although it had started, more is needed for it to produce significant outcome. More funding are to be allocated into the R & D of cutting-edge production of hydrogen production such as electrolysis of water splitting, thermochemical water splitting by utilizing the energy of renewble source. Second, the partnership of the government, the industries, and the universities will have to be developed for increasing the rate of progress of technologies development and knowledge transfer between the organizations.

Secondly, Malaysia needs to increase its infrastructure for hydrogen so that wider implementation can be done. A network of pipelines, distribution hubs and fueling stations are essential for proper storage, transportation and distribution of hydrogen to effectively manage its use. The provision of these infrastructures should be strategically mapped to cater for all rural and urban regions enabling easier accessibility to hydrogen energy. Nevertheless, research has proven that financial investment is at an infancy level and more support needs to be given to move beyond the pilot projects. There is an essential and continuous funding to develop a nationwide robust system of hydrogen infrastructure.

Finally, the policy and regulatory landscape needs to be enhanced to provide a predictable and enabling environment for hydrogen growth. Financial mechanisms like subsidies, tax incentives, and grants will draw in private sector involvement, while regulations will increase investor confidence. The development of a separate regulatory authority overseeing hydrogen ventures and compliance with international standards will bolster Malaysia's global standing. Stable and predictable policy support will also attract investment, spur R&D, and support infrastructure development.

6.0 Conclusion

This research analyzed the sustainable growth of hydrogen production in Malaysia by analyzing the R & D, infrastructure and policy & regulation factors. The research concludes that the effect of R&D and infrastructure on hydrogen growth in Malaysia is positive but small as the investment and projects are still minimal. Policy and regulation is the most effective factor, motivating hydrogen growth by incentive and regulations. The research points out the role of public awareness, international cooperation and robust infrastructure development for a strong hydrogen economy. The limitation such as the data reliability, geographic coverage, methodology and the insufficient engagement of stakeholder suggests that the future research need to adopt better data quality, comparative and long-term study and engage stakeholders extensively. In sum, this research provides valuable information that can be used to devise strategies toward a competitive and robust Malaysian hydrogen production, and lead it as a competitive power house in clean energy in the future.