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Renewable Energy Pathways toward Accelerating Hydrogen Fuel Production: Evidence from Global Hydrogen Modeling

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Abstract: Fossil fuel consumption has triggered worries about energy security and climate change; this has promoted hydrogen as a viable option to aid in decarbonizing global energy systems. Hydrogen could substitute for fossil fuels in the future due to the economic, political, and environmental concerns related to energy production using fossil fuels. However, currently, the majority of hydrogen is produced using fossil fuels, particularly natural gas, which is not a renewable source of energy. It is therefore crucial to increase the efforts to produce hydrogen from renewable sources, rather from the existing fossil-based approaches. Thus, this study investigates how renewable energy can accelerate the production of hydrogen fuel in the future under three hydrogen economy-related energy regimes, including nuclear restrictions, hydrogen, and city gas blending, and in the scenarios which consider the geographic distribution of carbon reduction targets. A random effects regression model has been utilized, employing panel data from a global energy system which optimizes for cost and carbon targets. The results of this study demonstrate that an increase in renewable energy sources has the potential to significantly accelerate the growth of future hydrogen production under all the considered policy regimes. The policy implications of this paper suggest that promoting renewable energy investments in line with a fairer allocation of carbon reduction efforts will help to ensure a future hydrogen economy which engenders a sustainable, low carbon society.

Keywords: energy policy; hydrogen; global hydrogen model; random effect model; renewable energy

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1. Introduction

An adequate energy supply is associated with a satisfactory quality of life in today's society; yet, it remains a pressing need for some consumers around the globe. Global industrialization and ever-rising living standards have made energy security a priority issue [1]. Worldwide energy demands are constantly increasing, at a rate faster than that at which the global population is growing. Global energy production primarily relies on fossil fuels, and their continued use has a negative impact on the environment while hastening their depletion. The dependence upon fossil fuels in addressing the global challenge of energy security is concerning and requires redress. If fossil-based resources are used into the future at the same rate as they are currently, they will be depleted within the next 100 years. This implies that global energy demands must be met, including by a much higher contribution from renewable energy sources in order to engender a sustainable energy system. According to the International Energy Agency (IEA), global energy consumption will rise by 53% by 2030, posing a significant threat to energy security in the near future [2,3]. As illustrated in Figure 1, fossil fuels have met more than 80% of global energy demands over the last decade. The transition away from fossil-derived fuels will necessitate their substitute with renewable sources, some of which are intermittent in nature, necessitating electrical grid augmentation and storage measures to ensure stability [4]. To achieve such a transition and meet the Paris Agreement goals, international investment in renewable energy resources and parallel technologies, including distribution networks and storage, are required to exceed the current commitment levels [5]. Between 2010 and 2020, there was a slight decrease in fossil fuel and nuclear power usage due to the increased use of renewable energy sources. Within renewables, in 2010 hydropower contributed most of the entire 8% consumption of renewable energy sources, and while this remains the case in 2020, wind and solar sources of renewables have increased their share significantly. These statistics demonstrate that while global efforts to increase the use of renewable energy sources are moving in the right direction, much more needs to be done to further decrease the global share of fossil fuel-based energy generation and to move toward a sustainable energy system (see Figure 1b,c).

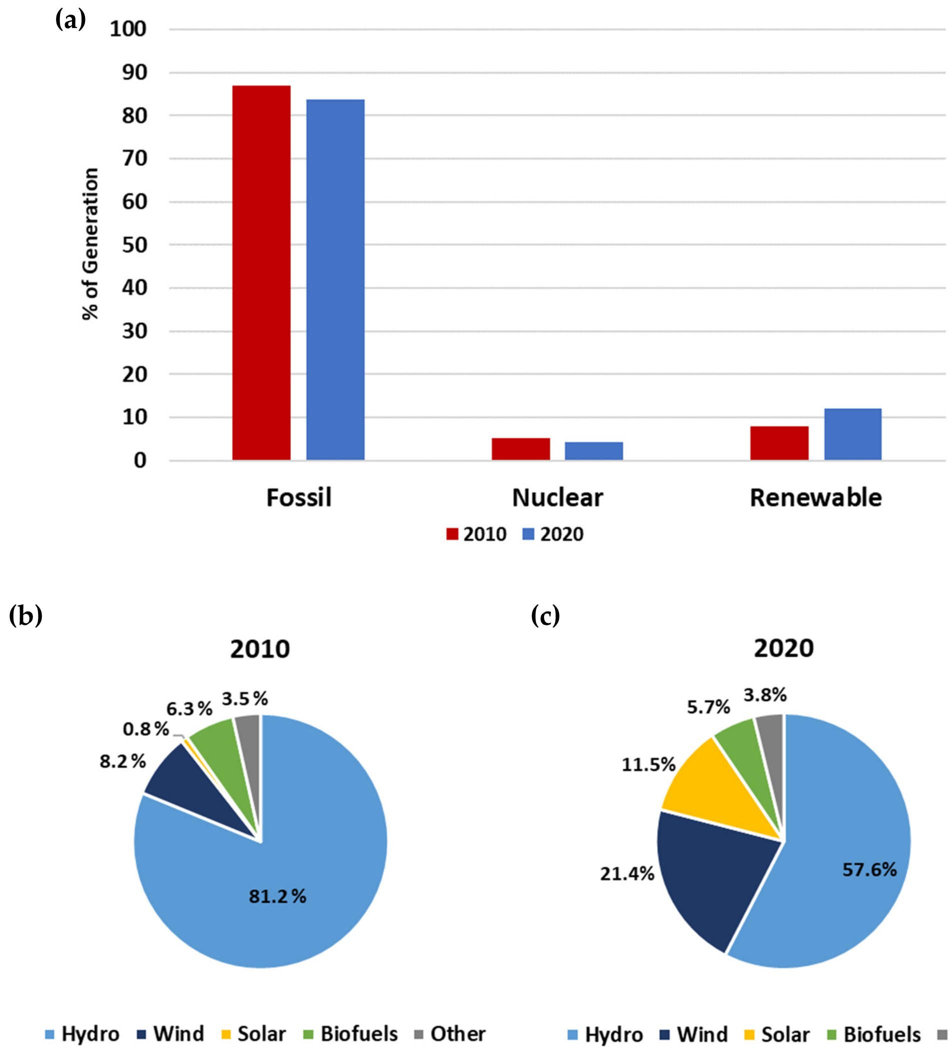

Figure 1. (**a**) Global energy mix comparison from 2010 to 2020 and the contributions of different renewable energy sources for (**b**) 2010 and (**c**) 2020 [6].

In addition to the direct utilization of renewable sources of energy, the synthesis and utilization of renewable fuels are also critical for slowing the rate of depletion of fossil fuels and creating a stable energy system. In moving toward this goal, hydrogen represents a clean fuel option as its combustion produces no carbon dioxide or harmful emissions. Hydrogen used as a substitute for hydrocarbon-based fuels in sectors such as power generation, industrial production, and transport could substantially reduce our reliance on fossil fuels to fulfill global energy needs [7,8]. Furthermore, hydrogen can be blended with natural gas to reduce emissions without the impact on lifestyle convenience [9,10]. In addition, hydrogen has the potential to be an efficient energy carrier and can be easily transformed into electricity using fuel cell technologies [11,12]. Currently, however, a considerable portion of hydrogen is produced utilizing fossil fuels, implying that clean fuel is synthesized via environmentally harmful source materials. In 2019, nearly 98% of global hydrogen was produced utilizing methane and coal, either as pure hydrogen or as synthesis gas (SYNGAS), with only 1% of the hydrogen produced from fossil fuels utilizing carbon capturing and storage systems (see Figure 2).

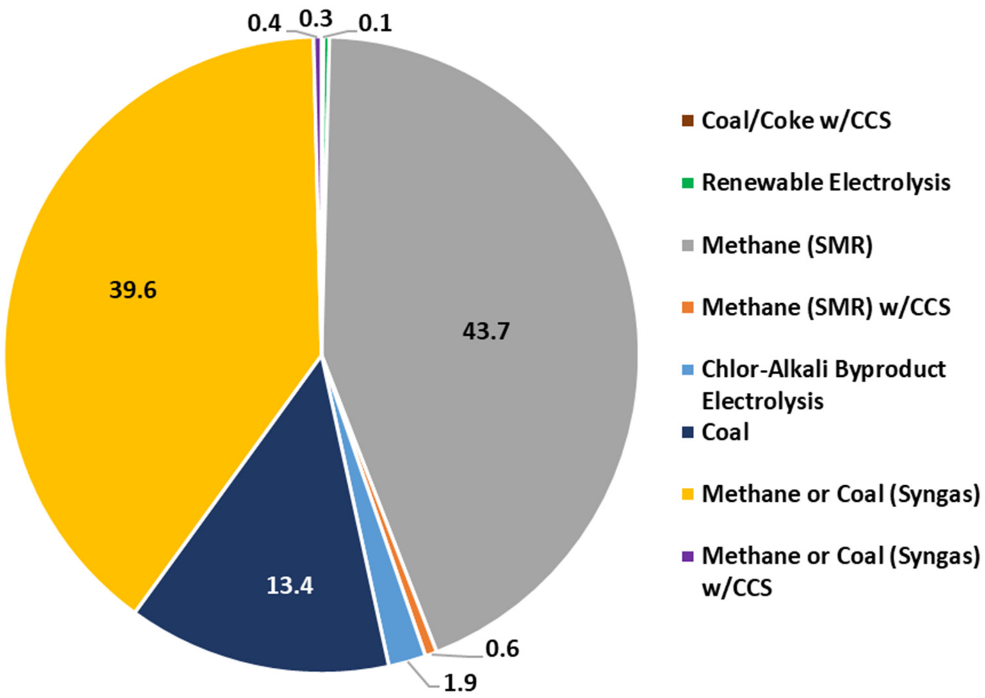

Figure 2. Global hydrogen production breakdown by source in 2019 [13].

Bearing these facts in mind, it is essential to increase the percentage of hydrogen production via the thermochemical, electrochemical, and electrolysis routes, for example, ideally utilizing renewable energy. An integrated approach that includes the continued use of nuclear power, fossil fuels, carbon capture and storage (CCS), renewables, and, conceivably, negative emission innovations [14] is the most likely combination of technologies to engender a sustainable and cost-effective energy system.

Environmental and health benefits can be achieved through increasing hydrogen production if it is derived from low- or zero-emission sources, such as solar, wind, and nuclear energy. To ensure clean and efficient energy for society, it is therefore imperative to look into the role that renewable energy plays in the production of hydrogen fuel.

The purpose of the current study is to utilize the comprehensive findings of a global energy system optimization model to identify the impact of renewable energy in hydrogen fuel production applying a random effects regression model. In addition, we investigate the indirect effects of hydrogen-related policies, including region-specific nuclear restrictions, equal carbon dioxide mitigation obligations for developed and developing nations, and the blending of hydrogen gas with city gas (methane and natural gas).

2. Literature Review

This study deals with the leverage of a global energy model toward understanding, through robust statistical analysis, which policy and technology interventions will best enable the production of hydrogen and therefore engender the hydrogen economy. Our literature review seeks to establish the current understanding in these areas by reviewing the literature which considers global hydrogen modelling approaches, the statistical and economic evaluation of the hydrogen economy, and, critically, the provenance of hydrogen generation. Through targeted keyword searches, these three critical areas are evaluated by considering the recent, relevant scholarship and by establishing the gap dealt with in the present study.

Currently, there are a limited number of such global considerations of the future hydrogen system, such as a study identifying the roadblocks to the emergence of a hydrogen economy, including the resistance both politically and economically and the potential stifling of hydrogen-based research and development [15]. Some of the positive flow on aspects of an emerging hydrogen economy has been highlighted in global evaluations, such as the emergence of fuel cell vehicles (FCV) and the benefits in the direction of energy security [16], as well as hydrogen's ability to contribute toward carbon reduction in a number of sectors [17]. A study on the potential penetration of hydrogen and the required infrastructure for storage and distribution in North and Central America identified that the emergence of a hydrogen economy will drive FCV deployment and has the potential to engender energy security benefits, while concerns remain surrounding the storage and distribution approaches [18]. In the case of Vietnam, the government approved the National Strategy of Renewable Energy Development by 2030 and its vision for 2050 in order to lessen reliance on fossil fuels, ensure domestic energy security, and help mitigate global climate change. This strategy set goals to increase the proportion of power produced using renewable sources to 35% of the total amount by 2015, 38% by 2020, and 43% by 2050. The government has recently released a number of effective regulations that support the growth of solar, wind, biomass, and waste-to-energy technologies [19,20]. Considering the cross-regional consumption of renewable energy, hydrogen storage is proposed as a potential solution to overcome uneven renewable energy spatial distribution. A modeled approach in South China suggests that hydrogen energy storage systems can improve economic feasibility and reduce network losses [21]. Furthermore, it considers the use of hydrogen as an enabler in renewable-based energy systems in urban–industrial settings. Hydrogen is shown to be able to play a conducive role in enabling energy distribution and the realization of a robust system incorporating aspects of heating and cooling, electricity, and energy storage [22,23] Of course, it is important to also understand that the timeline for the transition to a hydrogen society or a renewables-led low-carbon energy system will be dependent on the progression of technological learning curves and the cost of the deployment of these technologies along the transition timeline [24,25].

In terms of the body of research that deals with the statistical and economic evaluation of future hydrogen production and hydrogen-incorporating energy systems, there are some pertinent examples. For example, in Japan, the economic feasibility of hydrogen production from excess renewables was investigated, identifying the necessary capacity factors and capital cost barriers in order to engender economically feasible hydrogen production in Japan [26]. A statistical analysis of wind-based hydrogen production was undertaken using response surface methodology (RSM), suggesting that appropriate plant sizing (wind farm capacity) can be undertaken utilizing model approaches, with the modeled outcomes matching well with the actual data [27]. Similarly, using a combination of RSM and artificial neural network approaches, the production yield of bio-hydrogen from wastewater was analyzed and accurately predicted, identifying the potential for non-traditional sources of hydrogen in the future [28]. Furthermore, a statistical analysis of the critical factors which underpin hydrogen production via fermentation was undertaken, identifying the optimal conditions and production rates [29]. Within the field of the fermentative generation of hydrogen, a literature review of 55 studies and 339 experiments was undertaken by Moussa et al. [30], identifying potential hydrogen yields, productivity, and content in biogas feedstocks, which are complicated by the scattered nature of feedstocks and the conditions used in the experiments.

Recently, the issues surrounding the provenance of hydrogen have become an international concern, and the debate surrounding grey hydrogen (which is produced from fossil fuels), blue hydrogen (from fossil fuels with CCS), turquoise hydrogen (from renewable heat and methane pyrolysis), and green hydrogen (from renewable sources) and the best way to engender a hydrogen economy have come to the fore [31]. For example, the European Union is seeking to promote green hydrogen produced via water electrolysis using renewable-based electricity, with blue hydrogen used as a transitionary step toward this goal. However, a study focusing on Germany showed that unless carbon prices are above 480 EUR/ton or significant subsidies are not in place, electrolysis is unlikely to be competitive with blue hydrogen production techniques [32]. A similar study conducted in Colombia showed that the most likely pathway for Colombia toward a hydrogen economy is the use of coal as a feedstock. In order to achieve blue hydrogen, a significant investment in CCS will be required, above and beyond the initial government estimates, and green hydrogen is not discussed [33]. Green hydrogen production appears feasible in Latin America, where abundant hydropower is available, and where spilled flows can be captured (i.e., in Colombia and Venezuela) and utilized for electrolysis. Depending on the scenario outcomes, including the amount of wasted energy that could be used to produce hydrogen, the cost of producing and storing hydrogen in Venezuela could be as low as ~22.4 US cents per kg [34]. In a study in Oman, green hydrogen production to supply hydrogen refueling stations utilizing grid-connected mega-solar was investigated, suggesting that hydrogen could be produced at a levelized cost of 5.5 EUR/kg, with excess energy sold back to the grid [35]. Blue hydrogen as a bridging technology is likely to be driven by steam methane reforming (SMR) using natural gas. SMR with 85% carbon capture was explored as an option for hydrogen production, showing promise from an economic standpoint at 2.36 USD/kgH_2; however, from an environmental standpoint, the emission of 6.66 kgCO_2/kgH_2 of blue hydrogen production from SMR is not ideal compared to the green hydrogen approaches [36]. In a study in Vietnam, a few promising criteria for the steam gasification process of producing hydrogen-enriched gases were discussed, including reaction conditions, different types of gasifiers, reaction catalysts, etc. In terms of manufacturing costs, the perfect application of the biomass gasification innovation may be one of the most promising routes for the synthesis of hydrogen obtained from biomass [37].

However, the COVID-19 economic impact that each nation has gone through has had a significant impact on the development of the clean energy transition. It would be ideal if policies could be resilient and shield investments in renewable energy from significant setbacks and dangers. There would be a greater vision of the supporting policies and legal frameworks meant for the low-carbon economy with the deployment of new renewable generation resources and production facilities. In order to define short-term policy objectives that will help both the recovery effort and the development of sustainable energy sources, governments must identify the appropriate tactics in their reactions to the epidemic [38].

A comparison of potential hydrogen production approaches suggests that biomass-based hydrogen production may play a role, subject to advances in technological approaches and the application of CCS, while renewable-based electrolysis approaches, while good in terms of pure hydrogen production, remain comparatively expensive [39]. Intermittent sources of renewable energy such as wind and solar are considered well-matched with hydrogen as an energy storage medium [40]. Hydrogen production in this study considers fossil fuels with CCS, nuclear, and renewable pathways, including biomass, whilst being cognizant of the strict carbon dioxide reduction targets.

Based on the global hydrogen model, in the present study the following three policy regimes are considered to assess the hydrogen fuel production through renewable energy sources. A detailed conceptual framework of the study is depicted in Figure 3.

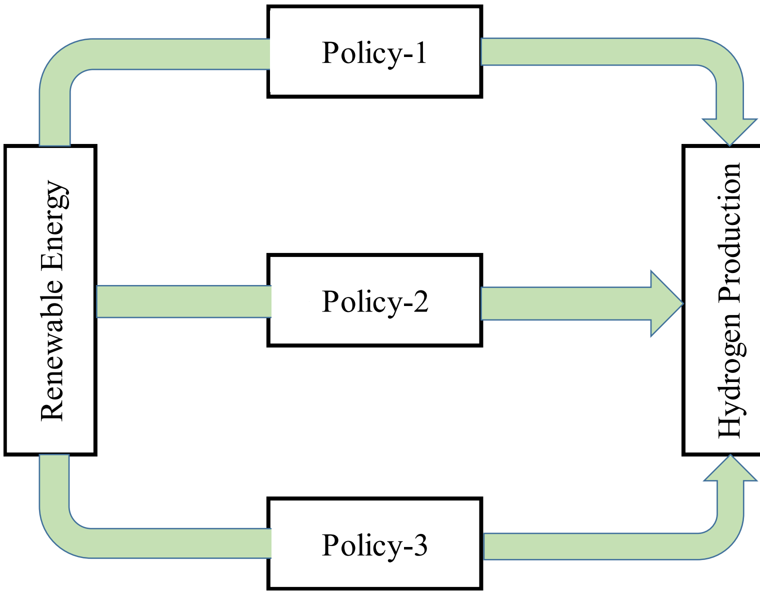

Figure 3. Conceptual framework.

1. Nuclear restrictions (restricting the deployment of new nuclear facilities in nations with these policies in place or proposed [41]) and a hydrogen to city gas blend ratio of 5% by volume.
2. Equal mitigation obligations for both the Organization for Economic Co-operation and Development (OECD) and the non-OECD nations of 65% carbon dioxide reductions, in order to achieve the same rate of reduction as the current regime which seeks an 80% reduction from OECD, and a 60% reduction from non-OECD nations.
3. Nuclear restrictions, as was the case in policy 1, with an increased hydrogen to city gas blend ratio of 30%, the theoretical maximum for the existing infrastructure and utilities [42].

3. Data and Methodology

The model developed in this study is applied to the disaggregated world energy model known as Dynamic New Earth (DNE) 21, which has been utilized extensively to evaluate the strategies for reducing worldwide carbon dioxide emissions [43], the long-term environmental and energy system scenarios [44], and the social and environmental benefits of electric and fuel cell vehicle deployment [45]. The application investigated in this study is an application of DNE 21 to a global linear optimization of future energy system regimes examining the effect of renewable energy on hydrogen fuel production from 2000 to 2050. The model is intended to take into account both the technological and the policy constraints, as follows:

(1) The analysis includes 82 global regions, each of which is classified as a production or consumption 'node' based on its unique characteristics. Pipelines and grids connect the production and consumption nodes in geographically adjacent regions, and maritime pathways connect those separated by oceans.

(2) The greenhouse gas emission reduction targets for 2050 are determined in accordance with Representative Concentration Pathways 2.6 (RCP2.6) [46], to meet the Paris Agreement's target of two degrees or less. Under these conditions, OECD countries must lower emissions by 80% and non-OECD countries by roughly 60% by 2050 compared to the 2020 levels [47].

(3) The energy system is optimized for cost and carbon dioxide reductions in 10-year time periods from 2000 to 2050, using IBM ILOG CPLEX Optimization Studio, which is aware of the variables and takes into account the supply and demand aspects of the global energy system.

(4) Hydrogen created under model constraints can be used in the transport, industry, energy generation, and city gas distribution sectors, as well as for secondary chemical production as a feedstock.

The model results include the change in the cost of the overall energy system, the energy supply and consumption, the CCS use levels, the energy system framework, the quantum of hydrogen introduced into the energy system, the production techniques, the end uses, and the geographic roots. A detailed model flow from primary energy to final demand is presented in Figure 4.

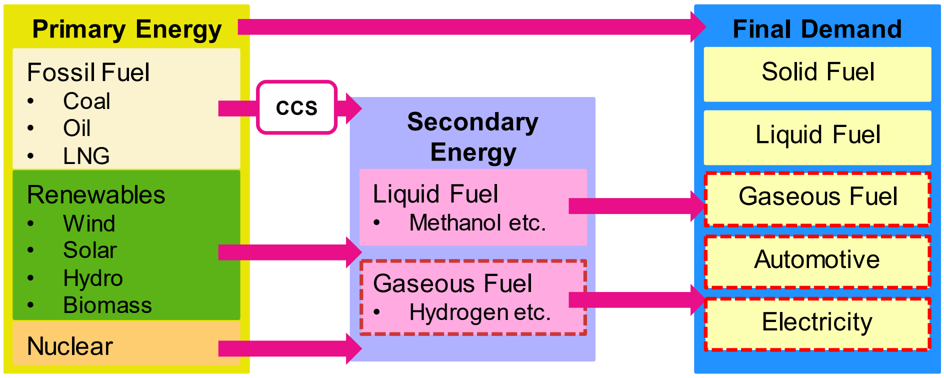

Figure 4. Primary and secondary energy sources consideration along with model final demand.

The primary sources of energy involve traditional fossil fuels such as coal, oil, and natural gas, as well as unconventional fossil fuels such as heavy crude oil, oil sands, shale oil, and unconventional natural gas. Wind, solar photovoltaic (PV), geothermal, hydropower, and biofuels are all examples of renewable energy sources. Several biomass sources are considered, including energy crops, forestry biomass, log residues, black liquor, wastepaper, sawmill residues, crop harvest residues, sugar cane residue, bagasse, and household wastes. Light water and light water mixed oxide fuel (MOX) reactors, fast breeder reactors (FBR), and high-temperature gas-cooled reactors (HTGR) and HTGR MOX reactors are examples of nuclear power plants.

Hydrogen, methane, methanol, dimethyl ether (DME), oil products, and carbon monoxide are all considered secondary energy sources. The total energy demand takes into account daily load curves and seasonal fluctuations and includes solid fuels, liquid fuels, gaseous fuels, and electricity.

Based on the above-described model constraints, a random effects regression model is used to assess the effect of renewable energy on hydrogen fuel production considering the three aforementioned hydrogen-related policy regimes.

Statistical Modeling

The ordinary least square (OLS) estimation technique is used to estimate the parameters of linear regression equations, but this method can give misleading results for clustered or grouped data. Generally, the variation of the response variable is not constant among the clusters (regions). Therefore, to address the regional (cluster) variation or heterogeneous effects of the clusters in a panel setting, we utilize a random effect model in this study. The hydrogen production response variable is not the same among the selected regions. The random effect model is constructed as follows:

$$y_{it} = f(x_{it},\ u_i, \epsilon_{it}) \tag{1}$$

where y_{it} is the response variable, x is the vector of the covariates or independent variables, u_i is the random effect term for the clusters, and ϵ is the random error term. As hydrogen production (HP) is the outcome variable, and renewable energy (RE), nuclear energy (NE), fossil fuel (FF), and carbon capture storage (CCS) are the independent variables in the study, the random effect model (Equation (1)), after transforming the variables into logarithmic form, can be written as follows:

$$\ln(HP_{it}) = \beta_0 + \beta_1 \ln(RE_{it}) + \beta_2 \ln(NE_{it}) + \beta_3 \ln(FF_{it}) + \beta_4 \ln(CCS_{it}) + u_i + \epsilon_{it} \quad (2)$$

where β_1 is the constant (intercept), the β's are the regression coefficients that measure the effects of the independent variables on the hydrogen production, and u_i is considered as the random effect to account for the cluster (regions) variation, where each region has been considered as a cluster, while ϵ is the random error term [48].

4. Results and Discussion

This section describes the results of our study. The temporal trends of various energy sources, including hydrogen, renewable, nuclear, fossil fuel, and CCS, along with the net emissions under the three different energy policy regimes, are presented in Figure 5.

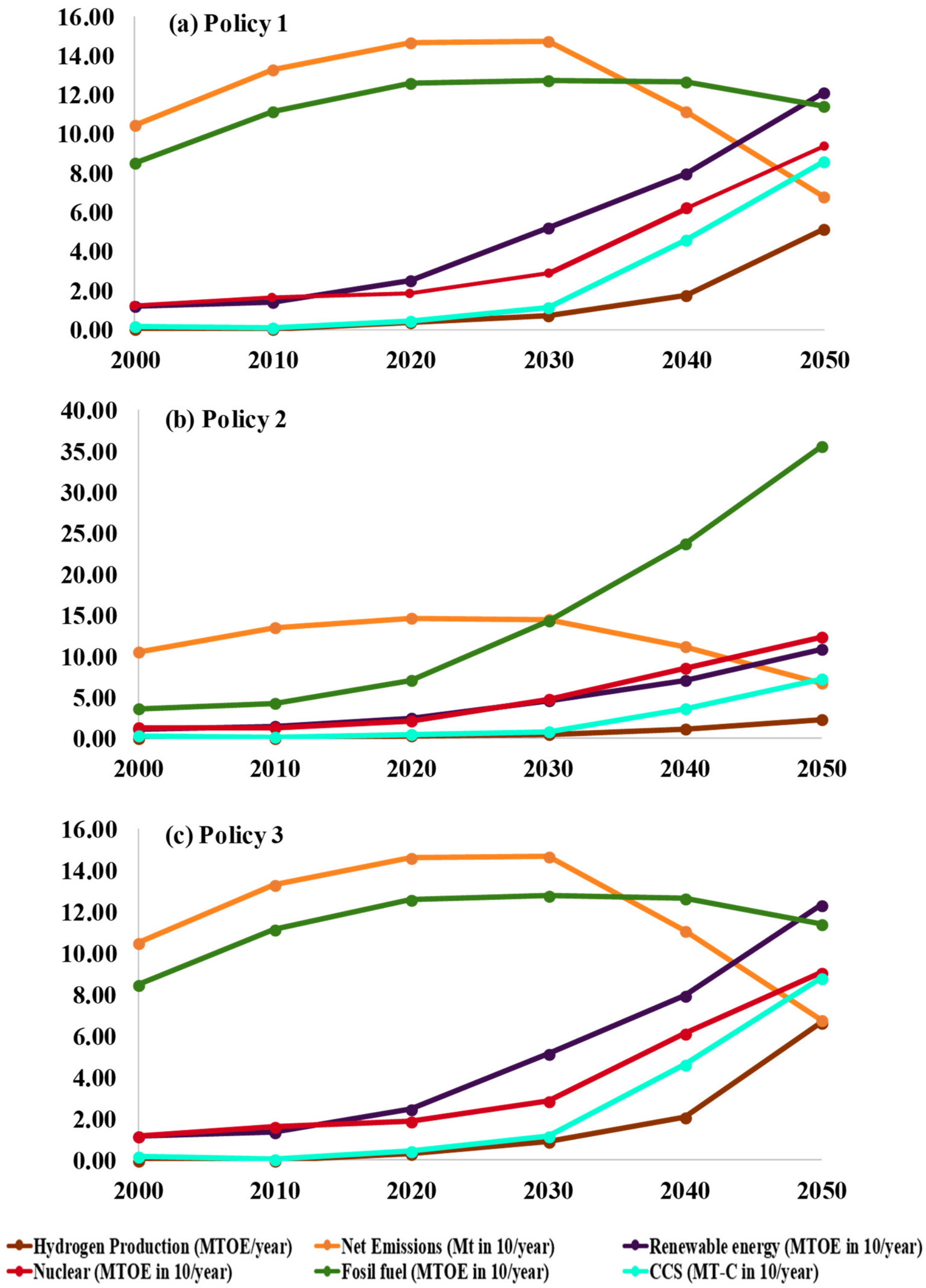

Figure 5. Trend of various energy sources in three different hydrogen-related policies.

These results show that all three energy policy regimes increase the hydrogen production, renewable energy, and nuclear power contribution levels over time. Hydrogen production is higher under policies 1 and 3 (nuclear restrictions and hydrogen/city gas blend of 5–30%), while under policy 2 (equal carbon dioxide mitigation obligations for both OECD and non-OECD countries) the hydrogen production increases are relatively muted. Here, it is possible to conclude that nuclear restrictions enhance hydrogen fuel production. During the period from 2000 to 2050, fossil fuel consumption decreased under policies 1 and 3 but increased under equal mitigation obligations (policy 2), while the net emissions reduced over time for all the policies.

To understand the adjusted effect of renewable energy generation on hydrogen fuel production under the three considered energy policy regimes, a random effects model is used. As the data used in this study are collected from different regions across different countries, there may be regional variation in the data. For example, some regions may have a low level of hydrogen production while others have a high level of hydrogen production. Fixed effect regression models do not take into account regional variation, i.e., this type of model assumes that all the regions have the same level of hydrogen fuel production. Therefore, this model may give misleading results. To overcome this problem, the random effects regression model has been used in the present study and takes into account the regional variation. The detailed results (the adjusted effect) of renewable energy on hydrogen fuel production using a random effects regression model, taking into account the relevant control variables, are presented in Table 1.

Table 1. Random effect model for estimating the effect of renewable energy on hydrogen fuel production.

Policy Scenario	Variable	Estimates	*p*-Value	95% Confidence Interval	
Policy 1 (Nuclear restriction and 5% city gas blending)	ln(renewable)	1.929	0.000	1.369	2.489
	ln(nuclear)	0.067	0.008	0.018	0.116
	ln(fossil)	−0.010	0.836	−0.108	0.087
	ln(ccs)	0.243	0.000	0.161	0.325
Policy 2 (Equal mitigation obligation)	ln(renewable)	2.225	0.004	0.696	3.753
	ln(nuclear)	0.177	0.000	0.087	0.267
	ln(fossil)	−0.795	0.342	−2.438	0.847
	ln(ccs)	0.2086	0.000	0.126	0.291
Policy 3 (Nuclear restriction and 30% city gas blending)	ln(renewable)	1.901	0.000	1.343	2.458
	ln(nuclear)	0.063	0.006	0.018	0.107
	ln(fossil)	−0.012	0.800	−0.102	0.079
	ln(ccs)	0.255	0.000	0.173	0.337

The results suggest that renewable energy has a positive and statistically significant relationship with the hydrogen fuel production under all the considered policies. The contribution of renewable energy toward hydrogen fuel production is higher under policy 2 when compared to policies 1 and 3, where it is at a similar level. For instance, a one-unit increase in renewable energy production increased the average hydrogen fuel production by 1.9 percent in the selected regions under policies 1 and 3, whereas for policy 2 the average hydrogen fuel production increased by approximately 2.2 percent for each unit increase in renewable energy production. Nuclear energy also has a positive and statistically significant effect on hydrogen fuel production. As policy 2 does not include any nuclear restrictions, the average hydrogen production increased by 0.18 percent due to a one-unit increase in nuclear energy. In addition, carbon capture and storage (CCS) has a positive and statistically significant effect on hydrogen fuel production under all the hydrogen-related policies in the selected regions. For example, a one-unit increase in CCS increased average hydrogen fuel production by 0.26 percent under policy 3. For a clearer understanding of these results across the policy regimes, the multivariate results are presented in Figure 6.

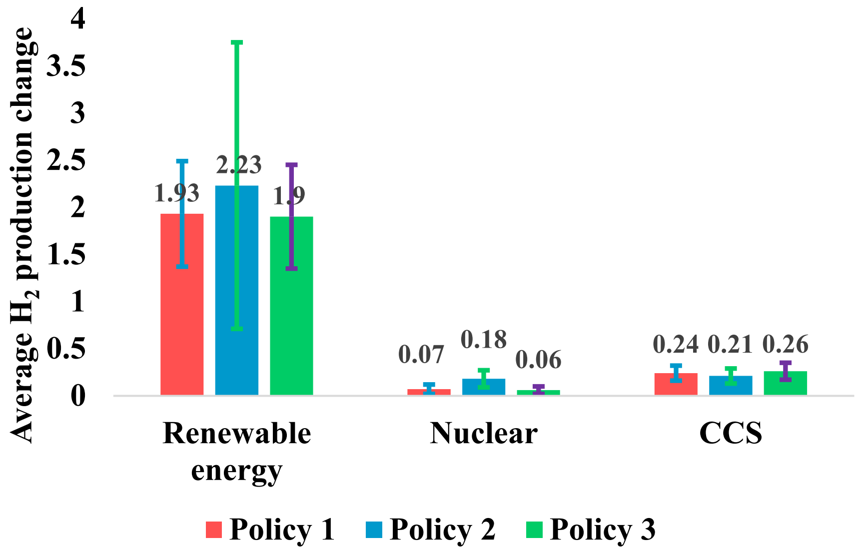

Figure 6. Estimates of renewable energy on hydrogen fuel production according to policy.

In addition, hydrogen derived from renewable sources has no emissions and serves as a clean substitute for fossil fuels. For instance, Europe may represent a good location for the large-scale deployment of renewable-based hydrogen generation since it has a plentiful supply of renewable electricity from offshore wind. Compared to a fossil fuel economy, a hydrogen economy based on renewable energy sources is likely to greatly lessen the effects of global warming. In the near future, renewable-based hydrogen will be used in at least three different ways: it will completely replace all fossil-based hydrogen-based applications; it will be used in fuel cells for medium- to heavy-duty land vehicles; and it will be used in aviation and shipping via e-fuels. Therefore, we believe that hydrogen derived from renewable sources is a promising source of clean fuel and has the potential to be crucial to the transition to a green economy.

5. Conclusions and Policy Implications

At present, hydrogen energy as a sustainable energy source is superior to other energy sources in terms of technological efficiency and economic and environmental impacts [49,50]. However, approximately 96% of the hydrogen produced in world markets is supplied via fossil fuels. Considering the devastating effect of fossil fuels on the environment, advanced nations with limited fossil fuel reserves are increasing investment in renewable energies for generating hydrogen fuel. Hence, this paper investigated the role of renewable energy in promoting the future hydrogen economy and considered different energy policy regimes, including the restriction of nuclear power generation, ensuring that both OECD and non-OECD nations are required to mitigate carbon emissions at the same level, and the quantity of hydrogen allowed to be blended with city gas. The empirical findings specify that increasing renewable energy could significantly accelerate the growth of the future renewable-based hydrogen economy. It was also found that large-scale future investment in renewable energy and the deployment of CCS technology to fossil fuel generation plants, along with the restriction of new nuclear plant deployment, as well as the implementation of an equal carbon mitigation obligation, will play the most important role in promoting a hydrogen economy not reliant on fossil fuels. Utilizing renewable energy has both environmental and financial advantages, such as the ability to produce energy with no greenhouse gas emissions from fossil fuels and to reduce some forms of air pollution, thus increasing economic development and employment opportunities in manufacturing, installation, etc., while diversifying the energy source and lowering the reliance on imported fuels.

Hydrogen will be a critical component of future society's decarbonization, as well as a potential source of long-term revenue from renewable energy deployment. Hydrogen as an energy carrier is subject to a number of uncertainties, including global climate and energy policies, technological advancement, social acceptance, and the ability to develop markets for hydrogen's use in the transportation and industry sectors. To succeed with the accelerating of the global future hydrogen economy, national and international coordination is needed not only to realize the benefits of a hydrogen economy but also to achieve a carbon-neutral society. In order to do so, it is important to assess how an increase in renewables or other energy sources will impact upon hydrogen production, particularly with regard to the eventual, desirable transition from grey to blue and finally to green hydrogen in a future hydrogen society. While this study investigates the potential for renewable energy to drive the emergence of the hydrogen economy, the learning curves of the emerging technologies may impact this analysis in the future. Future research can focus on the cost-effectiveness of renewable-based hydrogen production in regional and global contexts.

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