energies

Article

Lock-In Effects on the Energy Sector: Evidence from Hydrogen Patenting Activities

Francesca Pantaleone * and **Roberto Fazioli**

Department of Economics, University of Ferrara, 44121 Ferrara, Italy; roberto.fazioli@unife.it
* Correspondence: francesca.pantaleone@edu.unife.it

Abstract: The aim of the paper is to analyze how regulatory design and its framework's topics, other than macroeconomic factors, might impact green innovation by taking into consideration a brand-new renewable source of energy that is becoming more and more important in recent years: hydrogen and fuel cell patenting activities. Such activities have been used as a proxy for green technological change in a panel data of 52 countries over a 6-year period. A series of sectorial, energy regulation, and macroeconomic variables were tested to assess their impact on that technological frontier of green energy transition policy. As might have been expected, the empirical analysis carried out with the model that was prefigured confirms significant evidence of lock-in effects on fossil fuel policies. The model confirms, however, another evidence: countries already investing in renewables might be willing to invest in hydrogen projects. A sort of reinforcement to the further development of green sustainable strategies seems to derive from having already concretely undertaken this direction. Future research should exploit different approaches to the research question and address the econometric criticalities mentioned in the paper, along with exploiting results of the paper with further investigations.

Keywords: hydrogen; energy; environmental innovation; renewables; patents; panel data

check for updates

Citation: Pantaleone, F.; Fazioli, R. Lock-In Effects on the Energy Sector: Evidence from Hydrogen Patenting Activities. *Energies* **2022**, *15*, 3006. https://doi.org/10.3390/en15093006

Academic Editors: Amine Lahiani and Salma Mefteh-Wali

Received: 27 March 2022
Accepted: 18 April 2022
Published: 20 April 2022

1. Introduction

For many decades, the idea of being able to exploit the small but efficient hydrogen atom has animated the action of scientists and researchers and beyond. Today, hydrogen is gaining the interest of academics, governments, and the industrial sector. Such renewed interest does not derive only from the objective chemical-energetic appeal of that element: its flexibility and efficiency indeed may well allow for sighting sustainable goals of 2030 and 2050. Indeed, the dream of a new hydrogen economy is well defined: an industrial system in which the dominant role of the energy carrier and fuel is performed by hydrogen, together with electricity, and that is thought of as a sunrise industry that would contribute to reducing energy consumption and emissions, as well as stimulating economic growth. These are certainly ambitious objectives, but they leave the main issues of energy policies uncovered, such as: the security of energy availability in a manner consistent with the quantities and types of requests of the demand side of each country, the concrete reliability of the energy generative chain with respect to national needs, and the cost-effectiveness of energy sources. The prospect of the "hydrogen economy" could, however, even become a risk for those who already have sufficient, competitive primary sources and an element of strength of their economic policies, or, on the contrary, an objective of necessary hope for those countries that find themselves in precursor conditions, that is of ineluctable dependence on primary sources that are scarce in their own area of jurisdiction.

Despite the many technical articles on hydrogen structure and its possible outcomes, there is not much evidence of macroeconomic spillovers linked to hydrogen innovation. The aim of this paper is to fill part of this gap and analyze the relationship between innovation on hydrogen and fuel cells with respect to regulatory framework. The first part of this paper will consist in a brief introduction of recent policies on energy mix, an overview of investment trends in renewables, and the increasing number of hydrogen strategies on governments' agendas. The second part of the paper will consist in an empirical analysis, trying to estimate the linkage between hydrogen innovation and eventual spillover effects under the macroeconomic point of view. Following the literature's approach, patents on hydrogen and fuel cells have been used as a proxy for innovating activities. The aim of the paper is to assess whether countries investing in renewable energies or still dependent on fossil fuel supply are most likely to invest in hydrogen activities. To do so, a panel data model has been structured considering 52 countries over a 6-year period, including hydrogen patenting activities in relationship with several macroeconomic control variables. The Poisson-fixed effect model estimation led to statistically significant correlation with renewable policy instruments—in positive—and fossil fuel support—in negative—along with GDP, government's debt, and entrepreneurship control variables. Results highlighted strong evidence of lock-in effects but also a positive sort of path dependency in renewable policies. Results are discussed in the final part of the paper.

1.1. Hydrogen Strategy: An Overview

After years focused on power and eolic energy sources, hydrogen is becoming more and more the main character of a new sustainable development scenario all over the world. Simply incomparable energy yields compared to the so-called discontinuous renewable sources (wind and photovoltaic), generating serious systemic management problems (from the necessary and onerous revision of the electricity transmission networks generated to the duck-curve effects) [1], in addition to its widespread presence worldwide and flexibility of use both as an energy source and as an energy vector make hydrogen the real and serious objective for an effective global energy transition. Even the general objective of the decarbonization of world economies, albeit chimerical, can and should be based on the diffusion of innovative technologies based on hydrogen as a primary source. The common idea is to meet the expectations of the Paris Agreement—the 1.5° climate goal and climate neutrality by 2040 [2], with the overall scope of reducing greenhouse gas emissions. In particular, Europe has developed a dedicated policy framework for renewable hydrogen, with major milestones to achieve step-by-step [3]:

- Reducing fossil fuel consumption in the aviation and shipping sector, and the transport system in general, through an increasing and pervasive carbon tax system implementation.
- Balancing electricity grid and mitigating the duck-curve effect of power generation, at least in early phases of the new energy mix scenario.
- Building a solid, well-defined infrastructure system based on electrolyzers, pipelines, compressors, refueling stations, and grid capacity to make the hydrogen infrastructure "marketable" for competitors.
- In the short term, blending hydrogen into gas pipelines to mitigate the dependence on natural gas supply and mitigate emissions so that hydrogen will be one of the major key players in energy supply.

Hydrogen is becoming important also outside Europe, as more and more countries are currently investing in hydrogen technologies. As IEA reports, in 2020, ten governments introduced their hydrogen strategy, such as Canada [4], which has formed a national non-profit sector association of industry, academia, research agencies, and other stakeholders to focus on developing clean hydrogen and fuel cell technologies. However, China's goal for carbon neutrality [5] is far from European ones, relying on 2060 as the final target for achieving all the objectives. Hydrogen has been declared one of the priority topics in the country's latest five-year plan. Hydrogen, combined with new technologies, such as energy storage, will have the role of improving the energy mix in the country. About the United States, despite the fact that it has clearly stated its intent on developing a hydrogen infrastructure, it has also stated that it will not stop investing in fossil fuel: the current strategy relies on carbon capture and storage to reduce emissions of natural gas supply and increase the development of a renewable hydrogen supply [6].

The number of countries investing in hydrogen is constantly rising, with an increasing number of companies joining the International Hydrogen Council. The aim of the council is to push research and development in hydrogen technologies and identify any eventual criticality that should be mitigated through government support [7]. Hydrogen is particularly interesting for governments and any firm's strategy map since it can be applied to many different sectors: on the energy supply side, current hydrogen strategies are producing a positive effect on hydrogen development, reaching 70 MW of electrolysis capacity installations and meeting 51 Mt of demand in the industrial sector; however, these numbers are still far from the expectations of meeting 44% of total hydrogen demand from the industrial sector.

Hydrogen and other clean energy systems can also be applied to the refining and chemical sector through ammonia and methanol production: expectations for 2030 are a total demand of 9 Mt, but current strategies only forecast a total supply of about 3 Mt. Germany, Austria, and United Arab Emirates are mostly investing in the steel and iron sector through hydrogen blending, which is another important outcome of hydrogen innovation. As of today, the most relevant hydrogen use remains hydrogen use in electricity generation through blue and gray hydrogen, usually associated with a carbon-capture and storage system to absorb the CO_2 emitted from natural gas inputs or green hydrogen obtained through water electrolysis. Another important hydrogen usage that has been developing in recent years is in the automotive sector through the fuel cell system. The transport system is the most impactful sector in terms of CO_2 emissions and, therefore, is under the eye of European Commission for the carbon-neutrality goal [8]. For this reason, many incentives for automotive innovation have been deployed by countries over the years. To reduce emissions, achieve energy efficiency, and optimize the noise of vehicles, fuel cells can be implemented in electric vehicles, since they act as batteries, producing electricity through an electrochemical reaction of hydrogen combined with oxygen [9].

So far, forecasts show that only 18% of this demand will be achieved considering current strategies. This is because, despite all the important outcomes deriving from eventual hydrogen technological change, research and development is still expensive and risky. The hydrogen infrastructure is highly intensive and complex, which requires huge capital investments and government support. According to the European Commission's July Hydrogen Strategy [3], the actual indicative costs for hydrogen production today are: 38 EUR/MWh for current high-carbon production; 50 EUR/MWh for "blue" hydrogen; and 65–135 EUR/MWh for "green" hydrogen. It is important to remark that these costs—especially those related to blue hydrogen—are merely indicative because they are location specific. Moreover, because there are some difficulties in finding the right metal hydrides to match with the necessary criteria, the possibility of a storage system of hydrogen is still uncertain.

To reach the overall targets, it is essential to build national hydrogen strategies and road maps to create market demand and mobilize investment in production, infrastructure, and factories. The objectives of the regulator, or rather of the Independent Regulatory Authorities in the Industry and Energy Markets, can only be oriented toward the purpose: from the neutral search for maximum allocative efficiency indifferent to the characterizations of the supply-dice to a new season of sustainable regulatory design with the aim of stimulating, favoring, and encouraging one trajectory rather than another (i.e., from technological neutrality to the clear representation of explicit technological preferences of the policy maker and the regulator). Already, from these considerations, the radical paradigm shift of energy regulation should be deduced with the assumption of the exogenous direction from the superiority of the green and sustainable trajectories in the formation of relative prices and, therefore, of the choices of operators on the competitive energy markets.

1.2. Literature Review

Taking into consideration innovation mechanisms in theory, we know from examples of previous literature research that there are several factors that might be linked with technological transitions, in a positive or negative way. The topic has been widely addressed on micro, macro, and meso levels.

Policy intervention indeed plays a crucial role in promoting hydrogen innovation. We already know from previous literature examples that the regulatory framework can significantly affect technological change [10]. Some studies have shown a positive correlation between regulation and growth, especially if considering "green" innovation models [11], whereas some others [12] have discovered small effects of regulation on productivity, employment, and competitiveness. Nevertheless, the debate is still ongoing and examples from the literature show that there are many factors that might compete to spur innovation. Some authors have suggested that renewable energy deployment policies can lead to the premature lock-in of the current dominant technology, leading eventually to long-term inefficiencies [13]. Popp and Newell [14] analyzed eventual crowding-out effects in the energy sector, discovering that an increase in alternative energy patents does result in fewer patents of other types, since it converges research and development and profit maximization goals.

Cross-country analysis helps to understand the degree to which environmental policy strategies lean toward green growth and innovation boost. In addition, country-level analysis might confirm what has been discovered at the micro level; however, there are some cases when patents have underestimated innovative activities in large firms, as well as R&D do in small ones. [15]. Systematic differences in countries are expressed through different specialization in green technologies [16].

Karaduman [17] examined the impact of technological innovation on emerging countries, finding a positive relationship between foreign direct investment, patent applications, and human capital, even though some others discovered a lower probability of success of the innovative entrepreneur due to restrictions of the rate of technical progress in the industry [18]. Blind and Jungmittag [19] analyzed the impact of patenting activities on macroeconomic growth in Europe and discovered a positive relationship between the two, highlighting the importance of patents in R&D-intensive industries.

About education, it has been shown by several authors that technological innovation has a significant impact on the educational system at all levels [20,21].

However, its impact on employment and inequality is still controversial due to different research outcomes from the literature. Employment impacts usually depend on institutional settings, and they are often linked to other macroeconomic metrics [22], but innovation might either lead to a net positive effect on employment [23] or lead to the so-called technological unemployment, without any compensation mechanisms. Innovation positively affects employment growth [24]. This happens because technological change, as a direct effect of innovation, usually leads to the optimization of capital and labor; it also enhances know-how, which might be linked to the necessity to focus on a few, well-remunerated high-skilled workers [25]. This latest element is indirectly linked to entrepreneurship, whose relationship with innovation is still trivial. Some results show that technological change attracts entrepreneurship based on the block chain method through disruptive product innovation over adoptive one [26].

Vona and Patriarca [27] addressed inequality by analyzing its relationship with the environmental quality of technologies. They started by assuming that environmental technology is mostly driven by the demand for green products and regulation—or the direct demand for green goods and political pressure. Overall, they concluded that inequality has a negative impact on the final outcome of technology transition, even though at the first stage of innovation, i.e., at the beginning of its life cycle, inequality seems to have a smaller impact.

Hydrogen and green energy transition should not act differently from any other kind of innovation activity. In particular, despite blue hydrogen requiring a fossil fuel input, for its impact on carbon reduction and energy efficiency, it is classified as "green" technology. What is more trivial, though, is to detect whether there are any significant differences and lock-in effects between "green" and "brown" technologies. Noailly and Smeets [28] analyzed patenting activities splitting between "brown" and "green" firms, discovering that there are no significant differences between the two in terms of research and development smoothing, even though renewable firms are more willing to use cash stock as buffer to smooth R&D over time since they are more sensitive to financial constraints, implying that investing in renewable is considered more risky than investing in fossil fuel projects. Barbieri et al. [29] discovered that green technologies usually involve a more radical innovation activity and are more complex to perform.

It seems that hydrogen policy strategies lead to a significant increase in the government's public debt, showing the importance of public intervention, since most of the financing is provided at the national level rather than by outsiders or international investors [30].

2. Materials and Methods

The aim of the paper is to analyze hydrogen projects to detect any eventual lock-in effect on other renewable and fossil fuel energy sectors by examining the relationship between hydrogen innovation and the regulatory framework. As pointed out earlier, the radical paradigm shift in energy regulation should be deduced with the assumption of the exogenous direction from the superiority of the green and sustainable trajectories in the formation of relative prices and, therefore, of the choices of operators on the competitive energy markets. As a consequence, we expected evidence of lock-in effects on fossil fuel policies in countries that make their leadership in the fossil fuel industry a reason for credible strength. At the opposite end, countries already investing in renewables might be willing to invest in hydrogen projects as a sort of self-reinforcement to the further development of green sustainable strategies. To do so, we will include two proxies of policy instruments for both renewables and fossil fuel. In addition, we have included control variables to determine their relationship with variables of interest. Following the literature's approach, we will include macroeconomic factors, such as GDP, unemployment, entrepreneurship, government debt, interest rates, and inequality.

Finding the right proxy for innovation might be trivial. Some authors suggest that surveys are the most suitable indicators of innovation performances at a firm's level. As Lerner and Seru stated [31], microeconomic analysis through patent counts can lead to interferences in the estimation, since "when aggregated at the firm level, these patent and citation biases can survive popular adjustment methods and are correlated with firm characteristics" [32]. Therefore, a macroeconomic approach will be used for this analysis. Research and development expenditure has been used to address the link between innovation and productivity, which most of the times leads to finding a positive relationship between the two [33]. Patents are often used as a proxy for innovation and might mitigate financing constraints, especially for small firms [34]; taking granted patents instead of filed ones might lead to more consistent results [35]. However, it is important to underline that they do not contain information about market transactions or the real use of the patented technologies: not all patents might be directly linked to innovation. Moreover, it is important to consider the differences in licensing process, patenting rates, and patent propensity, which might impact the results of estimation. It is also important to remark that not all inventions are patented, since not every invention satisfies the requirement of novelty, inventive step, and industrial purposes; another reason is that firms might deliberately choose not to patent the technology to protect the secrecy of the invention [36].

Despite all the limitations mentioned so far, patents on hydrogen and fuel cells will be used as a proxy for innovation activities in this paper. One reason is the availability of patent data on a global scale, which has been increasing over time. Additionally, it has been shown that patent count is positively correlated with both research and development input and output, marking it as a valid proxy for innovation [37].

2.1. Data

We have created a panel data of 52 countries over 6 years, from 2014 to 2019, to detect cross-sectional differences and time series variations during years. Tables 1 and 2 report a summary of data used in the model estimation.

Table 1. Variable summary.

Variable Name	Storage Type	Display Format	Variable Label
PatH2FC	int	%10.0 g	Patents on hydrogen and fuel cells
FEEDintariff	double	%14.2 g	Mean feed in tariff for power gen
FFsupport	double	%10.0 g	Total fossil fuel support, % of total tax revenues
GDPppp	double	%10.0 g	GDP per capita, purchasing power parity
Unempl	double	%10.0 g	Unemployment rate
entrep	double	%10.0 g	Costs of starting a business, % of income per capital
INT	double	%10.0 g	Interest rates on bank credit to the private sector
GOVdebt	double	%10.0 g	Government debt as percent of GDP
GINI	double	%10.0 g	Gini income inequality index

Source: Own elaboration.

Table 2. Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
PatH2FC	312	78.95192	239.329	0	1682
FEEDinTariff	312	0.0724468	0.1282538	0.01	0.8474
FFsupport	312	0.7442305	1.187694	0.0080258	10.36747
GDPppp	312	37693.71	21188.6	6912.18	113940.2
Unempl	312	7.645962	4.86156	2.01	28.47
entrep	312	5.741987	6.719382	0	42.6
INT	175	9.443086	9.940587	0	67.25
GOVdebt	310	63.1089	41.23614	0.05	223.81
GINI	199	35.2804	7.652283	24	63

Source: own elaboration.

The main variable of interest is the number of patents in hydrogen and fuel cell activities, retrieved from the Fuel Cells and Hydrogen Observatory [38]. We also considered years and countries where those patent activities are not evident. If we consider the period between 2014 and 2020, the most impactful country is China, with more than 11,000 patents, followed by the United States—almost 10,000—and Europe—slightly above 6000. A recap of the data can be found in the Table A2 in Appendix B.

As a proxy for renewable energy instrument policy, we retrieved mean feed in tariff from power generation from OECD statistics [39]. It represents a policy instrument aimed at accelerating investments in renewable technologies through long-term contracts to renewable energy producers. It differentiates price depending on the type of technology considered. The final aim is to achieve a gradual decrease in the price of the tariff to trigger a decrease in marginal costs of production for green technologies.

Similarly, we considered fossil fuel support as a percentage of tax revenues. This variable more directly addresses the presence of governments' intervention in brown energy technologies. This variable has been built not to include any reference of first goals of incentives or their environmental effects in order to have a more neutral interpretation of the outcome. The education proxy variable has been omitted due to collinearity issues.

From TheGlobalEconomy database [40], we have retrieved control variables as non-Intellectual Property Right factors that might influence patenting activities: GDP per capita in terms of purchasing power parity; unemployment rate; cost of starting a business in percentage of income per capita as a proxy for entrepreneurship, which refers to all official fees required by law, excluding bribes; government debt as a percentage of GDP; interest rates on bank credit to the private sector as a proxy for financing constraints, and the Gini index as a proxy for inequality.

Usually, variables are converted into logarithms to normalize highly skewed variables. In this case, we did not find any particular evidence on the high skewness of data and the variance is not particularly high. Overall, the panel is quite balanced despite the fact that there are many missing pieces of information on some variables.

2.2. Model Framework

There are several ways to work with patenting activities and innovation in terms of the model framework. Considering that the dependent variable represents the number of patents, the model used usually is a Count Panel Data (CPD) one. One main problem of panel data is to detect unobserved heterogeneity. At the firm level, it would be difficult to detect variations in the dependent variables across individual entities, such as the sector or the firm's characteristics. A good model framework in the presence of data dispersion would be a negative binomial model. In this case, the model assumes a dispersion parameter ϕ that allows variance to be greater than its mean [41].

At the macroeconomic level, the fixed or random effect model slightly mitigates this issue since it works with cross-sectional and time series features in order to obtain time-invariant variables. The main difference is to detect whether the unobservable characteristics are systematic or not between countries. In the first case, the fixed effect model would be appropriate, while the random effects model considers random influence on the outcome. Usually, to embody cross-sectional information coming from different regions, fixed effect seems to be the most suitable model [42].

$$y_{it} = a_i + B_1 x1_{it} + B_2 x2_{it} + \ldots + B_n xn_{it} + u_{it},\ i = 1,2\ldots N,\ t = 1,2\ldots t \tag{1}$$

where i and t represent individual and time effects, respectively, on the explanatory variables; a and B represent intercept and regression coefficient, respectively; and u is the error term.

To confirm our assumption and following the literature's approach, the Hausman test has been performed [43]. This test controls whether individual effects are uncorrelated with regressors in the model; if so, the random effect model violates the Gauss–Markow assumption since in this case, individual effects are embodied in error term. Therefore, it would not provide the best linear unbiased estimate (BLUE) estimation. On the contrary, in the fixed effect model, individual effects are a part of the intercept and the correlation between intercept and variables does not violate the Gauss–Markow assumption. In our case, Hausman confirmed that the fixed effect model better suits our estimation. Results of the test can be found in the Appendix A.

Considering the non-negative value of the dependent variable, the model would then become a fixed effect Poisson model. The Poisson model considers that the dependent variable assumes a Poisson distribution with a probability density function:

$$f(y_{it};\lambda_{it}) = \frac{[\exp(-\lambda_{it})](\lambda_{it})^{y_{it}}}{y_{it}!},\ i = 1,2\ldots N; t = 1,2\ldots T \tag{2}$$

where $\lambda_{it} = \exp\left(x'_{it}B\right)$, i.e., it is an exponential function of the linear index of explanatory variables, and it is positive for all combinations of parameters. All characteristics that are not time-varying are captured by the intercept α_i expressing individual heterogeneity.

Parameter estimation can be obtained by the conditional maximum likelihood method developed by Hausman et al. [44]. The Poisson fixed effect model is:

$$y_{it}|x_{it},\ B,\ \alpha_i \sim Poiss\left[\alpha_i \exp\left(x'_{it}B\right)\right] \sim Poiss\left[\exp\left(ln\alpha_i + x'_{it}B\right)\right] \tag{3}$$

where α_i is unobserved and might be correlated with x_{it}. This allows consistent estimates of B since α_i can be eliminated by quasi-differencing the regression.

Stata 17 has been used for computing the estimation. Heteroskedasticity has been checked by performing Wald test [45]. Since these tests are sensitive to model assumptions, the assumption of normality, for example, is a common practice to combine the tests with diagnostic plots to make a judgment on the severity of the heteroscedasticity and to decide if any correction is needed for heteroscedasticity [46]. In our case, we eventually decided to correct heteroskedasticity by performing "robust" estimation on Stata.

3. Results and Discussion

Table 3 reports the results of the empirical analysis.

Table 3. Results from estimation—the Poisson fixed effect model.

Path2fc	Coefficient	Robust Std. Err.	Z	P > |Z|	[95% Confidence Intervals]	
FEEDintariff	9.749774	3.452031	2.82	0.005	2.983918	16.51563
FFsupport	−1.085871	0.3747343	−2.90	0.004	−1.820336	−0.351405
GDPppp	0.0003607	0.0001409	2.56	0.010	0.0000845	0.0006368
Unempl	−0.1524892	0.1533309	−0.99	0.320	−0.4530122	0.1480338
GOVdebt	0.111188	0.029431	3.78	0.000	0.0535042	0.1688717
entrepr	0.4173129	0.0747734	5.58	0.000	0.2707597	0.563866
INT	0.0110372	0.0246116	0.45	0.654	−0.0372006	0.0592751
GINI	0.0400765	0.1520688	0.26	0.792	−0.2579727	0.3381258
Observations	98					
Groups	21					

Source: Own elaboration.

When drafting the fixed effect model first, the interclass correlation rho and the standard deviation of within-group residuals showed the presence of strong individual effects, but overall, the likelihood ratio chi-square test showed that the full set of predictors fits significantly better than an intercept-only model, implying that the model quite fits the data.

Variables highlighting policy instruments toward fossil fuel or renewable activities are statistically significant at 1% level, along with government's debt and entrepreneurship. So is GDP, at the 5% level. On the contrary, unemployment, interest rate, and Gini index did not turn out to be statistically significant. Poisson regression coefficient interpretation is not straightforward: it can be interpreted as the difference in logs of expected counts and the relative regression coefficient, taking the other variables as constant.

Results confirmed previous literature approaches on environmental innovation. In particular, a hydrogen-like green technological change enhances a country's profitability. Statistically speaking, for a 1 unit increase in GDP per purchasing power parity, the difference in the logs of expected counts would be expected to increase by about 0.0004. However, in this paper, we are not focusing on the magnitude of coefficients, which might vary according to the chosen dataset, but on the sign of the estimation. A broader interpretation of the coefficient seems to suggest that innovation-driven strategies have a positive effect on green development, even though different innovation-driven indicators contribute differently to the promotion of green growth [47].

An increase in patenting activities in hydrogen and fuel cell also leads to an increase in entrepreneurship. This is also confirmed by the literature: R&D activities affect green growth and enhance entrepreneurial potential by increasing the value added by economic activities on a large scale. This relates to an indirect effect on the significant change in per capita income, which also explains the variable "GDP" in our model [48]. The growth in entrepreneurship should also explain a potential growth in population and employment change, but it goes beyond the scope of this analysis.

The results also confirmed the literature that hydrogen patenting activities are positively correlated with public debt. Public debt plays a major role in hydrogen policy investment decisions, also led by the scarcity of foreign direct investments in this sector [49]. Therefore, it confirms the strong importance of a regulatory framework and national agenda in driving innovation, especially for hydrogen policy strategies: hydrogen strategies are profitable if incentivized. Therefore, more incentives in the public sector lead to more liquidity in the incentivized sectors, which leads in its own way to an increase in public debt.

A separate comment should be made on the first two variable outcomes. As expected, there is a strong correlation between renewable and fossil fuel policies, in an opposite way. Results confirmed a lock-in effect, which might be due to learning effects, economies of scale, network externalities, power differentiation, or many other factors. Overall, environmental innovation is impacted by the socio-economic context, which is impacted by the socio-technical regime and regulatory frameworks [50]. It seems that countries that maintain a sustainable fossil fuel supply through policy instruments might not be willing to invest in hydrogen. This underlines the fact that there is a huge portion of countries that still depend on oil and gas to create and supply power demand at both national and international levels and will not be able to change their energy mix anytime soon [51].

However, there seems to be a positive trend in countries already investing in renewables, which might be willing to focus on hydrogen strategies. What is important to remark is that previous policies on renewables might also impede a possible strategy since all major investments are already addressed to another green technology.

There are also some criticalities related to the model framework chosen for the estimation. A stationarity test has been computed through the Hadri [52] Lagrange multiplier (LM) test. It turns out that for all variables considered in the model, the null hypothesis has been rejected, so all the panels are (trend) stationary. Stationarity might be a problem because of risks in spurious regression. One way to solve it is by first-differencing the variables, and this might be the best-case scenario for short-run models, such as this one. Another econometric-related problem is regarding cross-sectional dependence. In studies such as this one, when estimating variables within regions, we expect some serious cross-sectional dependence in the variables. This might lead to inconsistent parameter and incorrect inferences [53]. It is also important to remark that a marginal effect on the nonlinear fixed effect Poisson model depends on α, which might be unknown. Lastly, impure heteroskedasticity has been corrected through robust estimation, but omitted variable bias remains an unsolved issue for many econometric evaluations. This is also suggested by the within-R-squared difference in the model result: there might be impure heteroskedasticity led by an omitted variable bias that causes the non-constant variance: if the effect of the omitted variable varies throughout the observed range of data, it can produce telltale signs of heteroskedasticity in the residual plots.

4. Conclusions

This paper analyzed the relationship between hydrogen patenting activities at the national level and some key variables to detect lock-in effects. Combining results from the analysis and recent trends in hydrogen strategies for developed countries, it seems that hydrogen acts in a manner similar to other renewable energies in terms of environmental innovation. It might spur green growth and requires huge government intervention in terms of subsidies and regulation.

Results of the analysis confirmed the existence of a path dependency in both trajectories. Countries that are highly dependent on fossil fuel find difficulties in switching to renewable energies, either hydrogen or other ones. As expected, therefore, the empirical analysis confirms significant evidence of lock-in effects on fossil fuel policies for countries whose model of affordable development is based on such energy source dominions. Furthermore, the model confirms another expected different evidence: policies that have been designed for explicit paradigm shifts toward sustainability logics will end up self-reinforcing over time; the consequence is believed to lead to intertemporal self-support.

For green and sustainable strategies for countries already investing in renewables, they might be willing to invest in hydrogen projects as some sort of reinforcement to the further development of green sustainable strategies stemming from having already concretely undertaken this direction.

The real challenge for policy makers would be to find a way to shift from the existing path dependence and avoid new, sub-optimal lock-in effects on the new technological change.

Hydrogen could be the key for achieving this target. Even though, theoretically speaking, it acts similar to a renewable source of energy, hydrogen strategies so far allow a blended mechanism of gray and green technologies. Blue hydrogen, the main vector for energy transition in the European hydrogen strategy and other non-European countries, only shifts the emission issue at the basis of the life cycle; to eliminate the problem, carbon-capture and storage technologies are essential to achieve net zero emission targets of next-generation EU and broader zero-emission strategies. Therefore, fossil-fuel-dependent countries can use natural gas to achieve clean energy as the final output. This strategy is particularly efficient in a short-term period since costs for hydrogen electrolysis are still not marketable. Future phases of energy transition require reducing hydrogen costs of production from industrial recesses with low greenhouse gas emissions, along with the costs of generating renewable power—which include reducing capital expenditures of electrolyzers. Additionally, all synergies with existing and potential infrastructures for the diffusion of hydrogen supply must be exploited. After 2040, green hydrogen should reach economic sustainability and become competitive so that natural gas would become less important for the overall energy supply mix [54].

Even though this strategy seems profitable and appealing in a theoretical way, it is important to remind ourselves about where we are currently. Energy supply nowadays depends on three main factors: performance of primary sources on the renewable technology; competitive costs and usage of inputs in the same life cycle; and reliability and accessibility of supply, including efficiency in optimization and security of the capacity. The duck curve is a clear example of how current renewable technologies cannot exclusively be relied on because they still cannot provide the energy necessary to address a country's demand. Moreover, though investments in renewables have been increasing over the years, in 2018, CO_2 emissions reached their peak with respect to previous years. What is certain is that energy transition cannot start from private investments or companies and require huge regulatory support and subsidies, which will help to reduce the levelized cost of energy for power generation. What is not certain, though, is whether these policies should disband fossil fuel installations. Recent policies at European and international levels have brought the spotlight on energy transition, but in reality, it represents only a small part of the entire energy system: the share of electricity in the final consumption of energy from RES is only 20% [55]. Most of the investments so far have been addressed to photovoltaic and eolic power generation, which were not able to eradicate fossil fuel production due to scarcity of energy efficiency capacity in power supply. [56]

In addition to this, the COVID-19 SARS-CoVe crisis will inevitably lead governments and much of the energy sector into heavy debts. Some companies have already declared bankruptcy—see most of the major B2B companies in the UK [57]. Those that stood up are revisiting their costs, considering that natural gas reached price peaks never seen before. For all the reasons mentioned so far, it may take several years to return to pre-COVID-19 SARS-CoV solidity. However, even before the crisis, the flow of investments was misaligned with the needs of energy transition.

The crisis could be an opportunity to change pace and reallocate all financing sources to focus on defined and consistent policies. To achieve the sustainability goals of 2030, 2040, and 2050, investments in energy efficiency—including CO_2-efficient fuels for transport and industries—will be crucial, but more importantly, the target of those investments. The path-dependance chain must be broken to focus policy instruments on development and optimization of hydrogen infrastructure, technologies, and energy supply.

Future research should exploit different approaches to the research question and address the econometric criticalities mentioned in the paper. Moreover, it should examine the real forecast trajectories of current hydrogen strategies, considering the impacts deriving from COVID-19 and the current natural gas price shock.

Author Contributions: Conceptualization, methodology, software, resources, data curation, writing-original draft preparation, project administration: F.P.; validation, formal analysis, investigation, writing—review and editing, visualization, supervision: R.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: [DATABASE] Fuel Cells and Hydrogen Observatory, 2021, Total patent registration, Available online: https://www.fchobservatory.eu/index.php/observatory (accessed on 31 December 2021). [DATABASE] OECD, 2021, Database. Available online: https://www.oecd.org/ (accessed on 31 December 2021). [DATABASE] Global economy, world economy. (n.d.)—Available online: https://www.theglobaleconomy.com/ (accessed on 31 December 2021).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Hausmann Test.

Test of H0: Difference in coefficients not systematic.

Table A1. Hausmann Test.

	(*b*) Fixed	**(*b*) Random**	**(*b* − *B*) Difference**	**Sqrt (Diag(*V_b* − *V_B*)**
FEEDinTariff	434.079	273.0139	161.0651	26.70799
FFsupport	−145.9811	−103.1045	−42.8766	17.12198
GDPppp	0.0696954	0.0008366	0.0688588	0.0183012
Unempl	28.95821	−9.275583	38.2338	15.29532
GOVdebt	5.257046	2.787475	2.469572	2.819364
entrepr	10.03169	−3.429052	13.46074	9.406153
INT	−2.949113	−3.949316	1.000203	2.828978
GINI	4.086443	13.3064	−9.219959	18.96064

chi2(9) = $(b - B)'[(V\_b - V\_B)^{-1}](b - B)$ = 24.62. Prob > chi2 = 0.0018. Source: own elaboration.

In this case, the p-value is less than 0.05. Therefore, we do reject the null hypothesis that errors are not systematic.

Appendix B

Table A2. Fuel cell and hydrogen patents, overview.

Country	Overall Patents, Fuel Cell & Hydrogen, 2014–2020
Africa	11
Argentina	38
Australia	884
Austria	109
Belgium	6
Brazil	527
Bulgaria	3
Canada	1587
Chile	78
China	11,726
Colombia	6
Costa Rica	8
Croatia	8
Cyprus	4
Czech Republic	16
Denmark	338
Ecuador	2
Egypt	2
Eurasia	137
Europe	6216
Finland	15
France	450
Germany	982
Greece	15
Hong Kong	76
Hungary	28
Iceland	1
India	72
Ireland	2
Israel	108
Italy	47
Japan	5768
Korea	4497
Lithuania	5
Luxembourg	8
Malaysia	18
Mexico	155
Moldova	3
Morocco	8

Table A2. *Cont.*

Country	Overall Patents, Fuel Cell & Hydrogen, 2014–2020
Netherlands	36
New Zeland	18
Nicaragua	2
Norway	21
Patent Cooperation Treaty	3737
Peru	29
Philippines	26
Poland	121
Portugal	50
Romania	11
Russia	501
Saudi Arabia	1
Serbia	5
Singapore	178
Slovakia	2
Slovenia	10
South Africa	118
Spain	394
Sweden	18
Switzerland	6
Taiwan	588
Tunisia	1
Turkey	10
Ukraine	12
United Kingdom	536
United States of America	9817
Uruguay	1

Source: Fuel Cells and Hydrogen Observatory, 2021; total patent registration.

References

1. Fazioli, R. *Obiettivo Sostenibilità. Il Difficile Cammino della Transizione Energetica*; Tab Edizioni: Roma, Italy, 2021; 388p.
2. United Nations Environment Programme. *Global Trends in Renewable Energy Investment 2020*; BloombergNEF; School of Finance and Management: Frankfurt, Germany, 2020.
3. European Commission. A Hydrogen Strategy for a Climate-Neutral Europe. In *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Com-Mittee and the Committee of the Regions*; Global Status of CCS 2020; Global CCS Institute: Melbourne, VIC, Australia, 8 July 2020.
4. Climate Action Network. *Can Europe's Position on Hydrogen*; Climate Action Network: Bonn, Germany, February 2021. Available online: www.caneurope.org (accessed on 31 December 2021).
5. Meidan, M. *China's Emerging Hydrogen Strategy, Commentary*; Italian Istitute for International Political Studies (ISPI): Milan, Italy, 2021.
6. Runyon, J. Major Hydrogen Initiatives Underway at US Department of Energy. Renewable Energy World. 2021. Available online: www.renewableenergyworld.com (accessed on 31 December 2021).
7. Global CCS Institute. *Global Status of CCS 2020, November Report*; Global Carbon Capture and Storage Institute: Melbourne, VIC, Australia, 2021.
8. IEA. *Hydrogen Projects Database*; IEA: Paris, France, 2020.
9. European Science Hub. *Hydrogen and Fuel Cells*; Research Topics; European Science Hub: Westerduinweg, The Netherlands, 2021. Available online: https://ec.europa.eu/jrc/en/research-topic/hydrogen-and-fuel-cells (accessed on 31 December 2021).

10. Ambec, S.; Cohen, M.A.; Elgie, S.; Lanoie, P.; Canada, B.; Chabot, R.; Thornton, G. The porter hypothesis at 20: Can environmental regulation enhance innovation and competitiveness? *Rev. Environ. Econ. Policy* **2013**, *7*, 2–22. [CrossRef]
11. Van Leeuwen, G.; Mohnen, P. Revisiting the Porter hypothesis: An empirical analysis of Green innovation for the Netherlands. *Econ. Innov. New Technol.* **2017**, *26*, 63–77. [CrossRef]
12. Dechezleprêtre, A.; Misato, S. The Impacts of Environmental Regulations on Competitiveness. *Rev. Environ. Econ. Policy Assoc.* **2017**, *11*, 183–206. [CrossRef]
13. Kim, J.E.; Tang, T. Preventing early lock-in with technology-specific policy designs: The Renewable Portfolio Standards and diversity in renewable energy technologies. *Renew. Sustain. Energy Rev.* **2020**, *123*, 109738. [CrossRef]
14. Popp, D.; Newell, R. Where does energy R&D come from? Examining crowding out from energy R&D. *Energy Econ.* **2012**, *34*, 980–991. [CrossRef]
15. Pavitt, K. R&D, patenting and innovative activities: A statistical exploration, Res. *Policy* **1982**, *11*, 33–51. [CrossRef]
16. François Perruchas, Davide Consoli, Nicolò Barbieri, Specialisation, diversification and the ladder of green technology development. *Res. Policy* **2020**, *49*, 103922. [CrossRef]
17. Karaduman, Ç. Technology diffusion towards emerging markets: A comparative panel data analysis. *Iktis. Idari Ve Siyasal Arastırmalar Derg.* **2020**, *5*, 287–304. [CrossRef]
18. Rocha, L.A.; Cardenas, L.Q.; Reis, F.A.; Silva NG, A.; De Almeida, C.A.S. Inflation and innovation value: How inflation acfects innovation and the value strategies across firms. *Estud. Econ.* **2021**, *38*, 147–195. [CrossRef]
19. Blind, K.; Jungmittag, A. The impact of patents and standards on macroeconomic growth: A panel approach covering four countries and 12 sectors. *J. Product. Anal.* **2008**, *29*, 60. [CrossRef]
20. McMeen, G.R. The Impact of Technological Change on Education. *Educ. Technol.* **1986**, *26*, 42–45. Available online: http://www.jstor.org/stable/44425172 (accessed on 31 December 2021).
21. Bonilla, S. Connecting High School, College and the Labor Market: Evidence on the Scale-up of Career Pathways in California (CEPA Working Paper No.19-03). 2019. Available online: http://cepa.stanford.edu/wp19-03 (accessed on 31 December 2021).
22. Allen, J.P.; Badillo-Amador, L.; van der Velden, R.K.W. *Wage Effects of Job-Worker Mismatches: Heterogeneous Skills or Institutional Effects?* Research Memorandum 071; Graduate School of Business and Economics (GSBE), Maastricht University: Maastricht, The Netherlands, 2013.
23. Nickell, S.; Kong, P. *Demand and Employment*; Papers 367; London School of Economics—Centre for Labour Economics: London, UK, 1989.
24. Meriküll, J. The Impact of Innovation on Employment. *East. Eur. Econ.* **2010**, *48*, 25–38. [CrossRef]
25. Vivarelli, M. Innovation, Employment and Skills in Advanced and Developing Countries: A Survey of Economic Literature. *J. Econ. Issues* **2014**, *48*, 123–154. [CrossRef]
26. Zheng, L.J.; Xiong, C.; Chen, X.; Li, C.S. Product innovation in entrepreneurial firms: How business model design influences disruptive and adoptive innovation. In *Technological Forecasting and Social Change*; Elsevier: Amsterdam, The Netherlands, 2021; Volume 170.
27. Vona, F.; Patriarca, F. Income inequality and the development of environmental technologies. *Ecol. Econ.* **2011**, *70*, 2201–2213. [CrossRef]
28. Smeets, J.; Noailly, R. Financing Energy Innovation: Internal Finance and the Direction of Technical Change. No 69-2021, CIES Research Paper series, Centre for International Environmental Studies, The Graduate Institute. *Environ. Resour. Econ.* **2021**, 1–25. [CrossRef]
29. Barbieri, N.; Marzucchi, A.; Rizzo, U. Knowledge sources and impacts on subsequent inventions: Do green technologies differ from non-green ones? *Res. Policy* **2020**, *49*, 103901. [CrossRef]
30. Bosch, M.; Lederman, D.; Maloney, W.F. *Patenting and Research and Development: A Global View*; Policy Research Working Paper No. 3739; World Bank: Washington, DC, USA, 2005. Available online: https://openknowledge.worldbank.org/handle/10986/8500 (accessed on 31 December 2021).
31. Lerner, J.; Seru, A. The Use and Misuse of Patent Data: Issues for Finance and Beyond. *Rev. Financ. Stud.* **2021**, hhab084. [CrossRef]
32. Hall, B.H.; Thoma, G.; Torrisi, S. *The Market Value of Patents and R&D: Evidence from European Firms*; Working Paper Series; National Bureau of Economic Research: Cambridge, MA, USA, 2007. [CrossRef]
33. Baumann, J.; Kritikos, A.S. The link between R&D, innovation and productivity: Are micro firms different? *Res. Policy* **2016**, *45*, 1263–1274. [CrossRef]
34. Czarnitzki, D.; Hall, B.H.; Hottenrott, H. *Patents as Quality Signals? The Implications for Financing Constraints on R&D*; Working Paper Series 19947; National Bureau of Economic Research: Cambridge, MA, USA, 2014. [CrossRef]
35. Burhan MSingh, A.K.; Jain, S.K. Patents as proxy for measuring innovations: A case of changing patent filing behavior in Indian public funded research organizations. *Technol. Forecast. Soc. Chang.* **2017**, *123*, 181–190. [CrossRef]
36. Nagaoka, S.; Motohashi, K.; Goto, A. Patent Statistics as an innovator indicator. In *Handbooks in Economics*; Elsevier: Amsterdam, The Netherlands, 2010; Volume 2, pp. 1084–1112. [CrossRef]
37. Dang, J.; Motohashi, K. Patent statistics: A good indicator for innovation in China? Patent subsidy program impacts on patent quality. *China Econ. Rev.* **2015**, *35*, 137–155. [CrossRef]

38. [DATABASE] Fuel Cells and Hydrogen Observatory. Total Patent Registration. 2021. Available online: https://www.fchobservatory.eu/index.php/observatory (accessed on 31 December 2021).
39. [DATABASE] Oecd. Database. 2021. Available online: https://www.oecd.org/ (accessed on 31 December 2021).
40. [DATABASE] Global Economy, World Economy. (n.d.). Available online: https://www.theglobaleconomy.com/ (accessed on 31 December 2021).
41. Polus, A.; Cohen, M. A new, non-canonical Poisson regression model for the prediction of crhases on low-volume rural roads. *IATSS Res.* **2012**, *35*, 98–103. [CrossRef]
42. Youssef, A.H.; Abonazel, M.R.; Elsayed, G. Ahmed Estimating the Number of Patents in the World Using Count Panel Data Models. *Asian J. Probab. Statistics.* **2020**, *6*, 24–33. [CrossRef]
43. Giambona, F.; Jacono, V.; Scuderi, R. The IPAT Model: An Empirical Evidence Il modello IPAT: Un'evidenza empirica. In *Statistics and Environment—Statistica e Ambiente—Sessioni Spontanee*; CLEUP: Padova, Italy, 2005.
44. Hausman, J. Specification Tests in Econometrics. *Econometrica* **1978**, *46*, 1251–1272. [CrossRef]
45. Hausman, J.A.; Hall, B.H.; Griliches, Z. Econometric models for count data with an application to the patents-R&D relationship. *Econometrica* **1984**, 52. [CrossRef]
46. Harrell, F.E., Jr. *Regression Modeling Strategies*; Sections 9.2 and 10.5; Springer: Berlin/Heidelberg, Germany, 2001.
47. Baum, C.F. *XTTEST3: Stata Module to Compute Modified Wald Statistic for Groupwise Heteroskedasticity*; Statistical Software Components S414801; Boston College Department of Economics: Boston, MA, USA, 2000; revised 5 July 2001.
48. Klitkou, A.; Bolwig, S.; Hansen, T.; Wessberg, N. The role of lock-in mechanisms in transition processes: The case of energy for road transpor. *Environ. Innov. Soc. Transit.* **2015**, *16*, 22–37. [CrossRef]
49. Cao, W.; Zhang, Y.; Qian, P. The Effect of Innovation-Driven Strategy on Green Economic Development in China—An Empirical Study of Smart Cities. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1520. [CrossRef] [PubMed]
50. Fazioli, R.; Pantaleone, F. Macroeconomic Factors Influencing Public Policy Strategies for Blue and Green Hydrogen. *Energies* **2021**, *14*, 7938. [CrossRef]
51. Jensen, P.; Webster, E. Another look at the relationship between innovation proxies. *Aust. Econ. Pap.* **2009**, *48*, 252–269. [CrossRef]
52. Elgouacem, A. *Designing Fossil Fuel Subsidy Reforms in Oecd and G20 Countries: A Robust Sequential Approach Methodology*; Environment Working Paper No. 168; OECD: Paris, France, 2020.
53. Hadri, K. Testing for stationarity in heterogeneous panel data. *Econom. J.* **2000**, *3*, 148–161. [CrossRef]
54. Kapetanios, G.; Pesaran, M.H.; Yamagata, T. Panels with non-stationary multifactor error structures. *J. Econom.* **2011**, *160*, 326–348. [CrossRef]
55. Rasool, F.; Gulzar, A.; Naseer, S. Drivers of Entrepreneurship: Linking With Economic Growth and Employment Generation (A Panel Data Analysis). *Pak. Dev. Rev.* **2012**, *51*, 587–605. Available online: http://www.jstor.org/stable/23734789 (accessed on 31 December 2021). [CrossRef]
56. Alverà, M. *Rivoluzione Idrogeno. Edizione Mondador*; Mondadori Electa: Milan, Italy, 2021; ISBN 978-88-918-2811-8.
57. Morison, R. Two More U.K. Energy Suppliers Collapse in Avalanche of Failures. Bloomberg Markets. 2021. Available online: https://www.bloomberg.com/news/articles/2021-11-25/two-more-u-k-energy (accessed on 31 December 2021).