



Gauging the impact of the strength of patent systems on renewable energy consumption

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ABSTRACT

In recent years, renewable energy consumption has been at the centre stage of academic debate. Little is however known about the potential impact of the strength of patent systems (IPRs) and renewable consumption. This study addresses this issue using a GMM methodological framework for a panel of 47 developed and developing economies over the period 1998–2017. To the best of our knowledge this is the first study where two alternative indices that measure differences in strength of patent systems are employed to explore the underlying relationship whilst at the same time controlling for other potential determinants of renewable energy consumption. We find that protection of intellectual property rights across nearly all estimated models and country groups tends to have a negative impact on renewable energy consumption whilst a convex relationship is established when nonlinearities are explored. Finally, the global financial crisis is found to have a negative impact on renewable energy in both developed and developing economies. Further probing indicates that in a depressed economic environment the strength of IPRs might have a significant role to play in encouraging more renewable energy consumption.

1. Introduction

In the realm of international business, a comparison of the strength of patent systems indices across countries are vital to our understanding of intellectual property management. The heterogenous nature of legal institution across different countries suggests that economic values arising from the introduction of new products or technologies depend to a great extent on the efficacy and enforcement of intellectual property rights [1]. As such, varying degrees of strength and enforcement of national patent and intellectual property (IP) protection systems are of paramount importance in the international business literature.

In this context, the location and nature of technology development across countries as well as changes in patent systems affect firm decisions particularly in developing economies [2–6]. According to WTO protection of Intellectual property rights (IPRs) is vital as intellectual property rights (IPR) promote innovation and economic development (Article 7 TRIPS Agreement).

Given the unfolding debate on how to mitigate the disastrous effects of the climate change on socioeconomic sustainability, growing research is set to explore the impact of intellectual property on climate change mitigation. As such, the development of climate-friendly technologies and renewable energy such as solar and wind has been recognised as

essential to dealing with the adverse effects of climate change [7].

The asymmetry however in resource endowment, level of economic development and state of technological innovation among countries, calls for a transfer of technological know-how from technologically advanced countries to those that are lagging [8]. Indicatively, 90% of all technological advancements is taking place in the United States, European Union, Japan and China whilst 80% of all patented innovations in carbon capture, geothermal, solar and wind energy technologies are owned by companies from France, Germany, Japan, South Korea, United Kingdom and the United States [9,10]. The observed disparities in technological innovation between countries is explicitly acknowledged by the TRIPS Agreement which grants the least developed country members more flexibility in meeting their obligations under TRIPS to adopt a stronger technological base.

On the empirical front, the evidence on the impact of IPR protection on climate change and clean energy is rather mixed, with some studies arguing that IPR protection are vital in incentivizing and transferring innovative practices in clean energy technologies, whilst others claim that IPR protection might act as a hindrance to emerging countries' access to clean technologies due to higher costs [11,12].

This lack of agreement in academic research on the impact of IPR protection might be to a certain extent ascribed to the nature of data,

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data limitations or the nature of the methodological frameworks used in the field [13,14]. It might additionally be that research on the impact of IPR protection on clean technology innovation and transfer is still at its infancy with the preponderance of those studies use legal and case studies perspectives [7,12,15].

Currently, the bulk of the extant studies on renewable energy development and adoption are concerned with its technical and economic aspects. Whilst the existing literature lacks a comprehensive empirical investigation of the impact of IPR protection on renewable energy, studies of the impact of IPR enforcement that track differences in patent enforcement across countries are conspicuous by their absence.

This study addresses this gap by focusing on patent systems and the legal and institutional frameworks with respect to renewable energy. More specifically, the main contributions of this study are as follows: a) to the best of our knowledge this is the first study that offers novel empirical evidence on the impact of patent systems strength on renewable energy consumption by employing two recently developed indices that measure differences in the strength of patent systems whilst at the same time controlling for other potential determinants of renewable energy consumption. In this direction we use a Generalized Method of Moments (GMM) approach for a panel of 47 developed and developing economies over the period 1998–2017. GMM provides a powerful tool for analysing panel data that allows for flexible modelling, bidirectional causality, efficient estimation as well as accounting for potential endogeneity; b) by utilizing the same methodological approach as Papa-georgiadis, Cross and Alexiou [16] we provide a comprehensive update of the existing IP index which spanned the period 1998–2011. This innovation is undoubtedly of immense significance as, in our context, the six additional IP estimates, for the period 2012 to 2017, allow for the two indices to be comparable and used symmetrically in the estimation process that takes place in the study; and c) we assess the persistent impact of the recent global financial crisis (GFC) on renewable energy consumption.

The rest of the paper is organized as follows: Section 2 touches on the relevant literature whilst section 3 elaborates on the empirical investigation adopted. Section 4 presents and discusses the results and finally section 5 concludes.

2. Relevant literature

The impact of IPR protection on developing economies has been at the forefront of academic debate with one school of thought arguing that IPR protection enhances innovation, economic growth and development hence encouraging more foreign direct investment [17], whilst another school sustains that strong IPRs impedes economic activity [18] through empowering monopolies of innovators, distorting prices and limiting the ability of developing countries to access imported technology [19].

A national patent system consists of three key elements that are designed to protect ownership rights. First the legal framework which sets out the rules that patent owners can use to defend and uphold their rights i.e., regulations set out in book-law, secondly, the practical procedures which enforce these rights, and thirdly, the efficient control of public and private organizations involved in the operations of the patent system [20]. In this context, enforcement-related operations involve the existence appropriate facilitators such as police forces, customs officials as well as private enforcement agencies who ensure that economic agents comply with the respective patent system [21,22].

For innovative firms, patents are thought to be a source of competitive advantage and any misappropriation of the patent technology is subject to penalties enshrined within the legal framework of each country [23,24]. In this sense, protection of intellectual property rights safeguards innovations from being unlawfully used by other entities that did not actively participate in their development [25]. As such, the extent to which innovations are protected determines the actual benefit accrued to the innovators, their future behaviour towards innovation as well as their decisions to transfer innovations to other countries [1]. The

fact that innovators prefer transferring their innovations or technology to countries with a strong IPR protection suggest that IPR protection serves as both a stimulator of innovation and technology transfer [26]. On the other, there is also the argument that strong IPR protection prevents the diffusion of key technologies and inventions by creating a natural monopoly and increasing the costs of access to such inventions [27].

In the extant literature the significant role of IPR protection as a promoter of technological innovation, renewable energy development, transfer and diffusion can be found in several studies and reports [15, 28]. Higher economic returns in conjunction with strong IPR protection can potentially attract more investment in renewable energy technology with positive spill-over effects in renewable energy development.

When however, IPR protection is considered in the context of a developing country the argument becomes more complex as they rely heavily on advanced economies for the development, transfer, and diffusion of innovation on renewable energy technologies [11,12]. It would therefore appear that stronger IPR protection could make it harder or more expensive for developing countries to access these technologies [10].

2.1. Empirical literature

Intellectual property rights have assumed a centre stage in the debate about clean energy technological transfer and innovation. Policy debate revolving around the role of IPR protection in relation to clean energy and climate mitigation technologies emerges in academic literature. At the same time, however, whilst technology transfer and innovation are key themes in the agenda of United Nations Conference on Sustainable Development, IPRs are hardly mentioned [28].

Despite the fact that much of the research in the field is approached from a legal perspective there is some emerging evidence that sheds light on the relationship of patent systems on economic growth trade, FDI, innovation and technology transfer and diffusion [16,29–33].

Several of those studies that focus on the impact of IPR protection on innovation and technology transfer, have produced contrasting results. More specifically, evidence points to a strong positive relationship between patent rights and firm's propensity to invest in innovative technology [25]. Amongst the industries considered the greatest impacts was observed in the scientific instruments and industrial chemicals industries. On the other hand, there is also evidence suggesting that there is a relatively small lagged positive effect of IPR protection and domestic innovation which turns negative after an optimal level of IPR protection has been reached [34].

Moreover, it has also been argued that IPR's protection impact on economic growth and technology transfer in low-income and industrialised countries is positive, whilst for middle-income countries the impact is marginal and negative [35]. Additional findings suggest that having sufficient capacity to innovate is a key mediating factor that conditions the relationship between IPR protection, technology innovation and diffusion in developing countries [35]. In particular, the evidence suggests that such a relationship is strong and positive in developing countries with sufficient capacity to innovate, whilst it is negligible and negative for developing countries without such capacity. In view of the above one can infer that the impact of IPR protection on technology transfer and innovation may differ across industries or will very much depend on the level of economic development and innovation capacity [11].

Whilst a few studies suggest that IPR protection does not impede adoption of climate change mitigation technologies, additional factors such as geography, renewable technology type [36], innovation policies and adoptive capacities [37], as well as political economy factors [8] should also be considered. A similar conclusion has also been drawn by Copenhagen Economics [7] in the case of developing countries whereby invoking the Chinese experience it is argued that strengthening the IPR regime fosters indigenous innovations in clean technology [38–40].

In view of the lack of consensus in the extant empirical literature we now proceed to the empirical exploration of the relationship between the strength of patent systems and renewable energy consumption using two recently developed indices that measure differences in the strength of patent systems. As such, this study assumes a significant role in the area as it purports to offer comprehensive insights and conclusions that can inform policy decisions and contribute to the advancement of renewable energy technologies.

3. Empirical investigation

Existing studies on the factors affecting renewable energy are typically split into those that focus on renewable energy consumption and those that focus on renewable energy production.

The key factors driving the supply and demand of renewable energy are well documented in the literature [41]. In this study, we approach renewable energy technology by focusing on renewable energy generation/use. Given that renewable energy technologies are either a product of domestic innovation or technology transfer, we infer that the strength and most importantly the enforcement of intellectual property rights may affect them significantly. We therefore argue that countries with higher and improving levels of IPR enforcement might be more inclined to adopt renewable energy technology. In this context we would expect that countries on different economic trajectories will be affected differently.

3.1. Methodology

For the empirical investigation, an econometric model is formulated and estimated for a pool of 29 developed and 18 developing economies spanning the period 1998–2017. In exploring the link between patent enforcement and consumption of renewable energy additional control variables have also been used. The 47 countries used in the empirical analysis are presented in Table A4 in the Appendix.

The specification of the econometric model is expressed as follows:

$$RENC_{i,t} = \alpha_i + \beta_1 IPR_{i,t} + \gamma_1 CONTROLS_{i,t} + v_i + \varepsilon_{i,t} \quad (1)$$

where $RENC_{i,t}$ denotes renewable energy consumption. $IPR_{i,t}$ is a measure of IP protection, $CONTROLS_{i,t}$ is a set of control variables and v_i and $\varepsilon_{i,t}$ are the error terms; i denotes a country (where $i = 1, 2, \dots, N$) and t the time period (where $t = 1, 2, \dots, T$); ε is a white noise error with zero mean and v a country-specific component of the error term that does not necessarily have a zero mean; α_i is a parameter reflecting a variant country-specific intercept.

3.2. The variables

The dependent variable is renewable energy which is sourced from World Development Indicators and defined as the share of renewable energy in total final energy use.

3.2.1. Patent system indices

Despite the significant attention the study of intellectual property rights has received, developing an acceptable IPR measurement has been really challenging [25]. Whilst some studies use dummy variables to capture the impact of IPRs [42,43] others have tried to develop measures for the strength of IPR [44,45]. Allred and Park [25] however, argue that these approaches are exposed to significant limitations because the measures of IPR used are mostly developed for only one time period. Instead, an index should be developed that is based on continuous values that capture variations among countries. Ginarte and Park [46], produced an index for over 100 developed and developing countries over the period 1960–2005 at five-year intervals which captures the strength of IPR protection based on the following five categories – extent of coverage, membership in international patent agreements,

provisions for loss of protection, enforcement mechanisms, and duration of protection.

More recently, novel research has emerged producing two composite indices - an index developed by Papageorgiadis, Cross and Alexiou in 2014 (henceforth IPRA) and an index developed by Papageorgiadis and Sofka in 2020 (henceforth IPRP) - that measure differences in strength of patent systems across 49 and 51 countries respectively. Both patent enforcement indices, can be decomposed into three topical sub-indices i. e. servicing costs, property rights protection costs, and monitoring costs, reflect volatility in patent enforcement. One key difference however between these two patent enforcement indices is that the most recent one (i.e. IPRP) takes in to account firm-level patent litigation data with broad country coverage. “A major source of differences and dynamism in the strength of patent systems originates from the degree to which patents do not just confer rights to their holders but how effectively and efficiently they can be enforced” ([47] p.1).

Given that the IP index developed by Papageorgiadis Cross and Alexiou only spanned the period 1998–2011, by using the same methodological framework we have updated the existing index which now provides estimates for up to 2017.¹ This innovation is of great significance as it allows for the two indices to be comparable and used symmetrically in the estimation process that follows in this study. The updated index is presented in Table A4 in the Appendix. It should be noted that the score of both indices used in this study ranges from 0 to 10, with 0 indicating a weak patent system and 10 indicating a stronger patent system. In the context of our study both indices will serve as our core independent variables.

3.2.2. Control variables

In the literature there are several variables that can be potentially used as key determinants of renewable energy. In our study, GDP per capita, trade openness and research and development are featured as key economic factors that influence renewable energy adoption. In particular, GDP per capita is expected to positively influence renewable energy as the higher the level of development the higher the propensity and resources to develop renewable energy [48]; Trade openness (TROP) is used as a measure of the level of globalization and economic integration that intends to capture the channel of diffusion of technological innovations and know-how [49]. The expectation is that such knowledge transfer will facilitate the adoption of renewable energy technologies [50]. In the extant literature R&D is also found to be a significant driver of innovation and therefore a key factor in the global quest for cleaner energy [51].

Furthermore, it has also been suggested that the recent global financial crisis (GFC) in 2007/8 might have adversely affected the trends in investment flows for renewable energy technologies as the cost of capital rose dramatically thereby making it more difficult to access credit [52]. To gauge the persistent impact of the GFC we have introduced a dummy variable that takes the value of 0 before 2008 and 1 for the period after. We have also decided to investigate potential non-linearities between IPRs and renewable energy by including a square term of IPRs. Potential non-linearities would imply that IPR could increase innovation, but stronger patent systems beyond a certain level could undermine innovation [34,35]. The main source of our dataset that spans the period 1998–2017 was the World Development Indicators database of the World Bank. (See table A3 in the appendix for definition of variables).

3.3. Model specification

A dynamic panel data model approach using the GMM framework is adopted along the lines developed by Holtz-Eakin, Newey, and Rosen

¹ For a comprehensive account of how the index has been constructed see Ref. [16].

and further advanced by Arellano and Bond and Arellano and Bover [53–55]. The main reason why we have selected this particular methodology is the several advantages it possesses when it comes to panel data analysis. More specifically, GMM allows for flexible modelling of the distribution of the error terms in panel data models especially when the assumptions of traditional linear regression models, such as homoscedasticity and normality of errors, are violated. Furthermore, GMM provides a way to estimate panel data models efficiently by using the moment conditions derived from the model to construct the estimation function hence producing more efficient estimates than traditional methods whilst at the same time it accounts for endogeneity in panel data models by using instrumental variables (IV) to identify the causal effects of the explanatory variables on the dependent variable. Finally, GMM can also be used to estimate dynamic panel models as well as deal with the incidental parameters problem that arises in these models, which can lead to biased estimates in traditional methods.

In a nutshell, the GMM approach is well suited for dealing with the bidirectional causality between variables; the possible endogeneity of explanatory variables, as well as omitted variable biases; time invariant country characteristics (fixed effects) that may be correlated with the explanatory variables; and the presence of autocorrelation [56,57]. As such, we employ the two-step procedure and obtain robust standard errors with Windmeijer's finite sample correction [58].

The dataset used covers the period 1998 to 2017 and consists of N cross-sectional units, denoted $i = 1, \dots, N$ observed at T time periods, denoted $t = 1, \dots, T$. More specifically, y is a $(TN \times 1)$ vector of endogenous variables, and x is a $(TN \times k)$ matrix of exogenous variables, which does not include a column of units for the constant term. In this context, we collect data for a cross section of 47 economies ($N = 47$), over a period of 20 years ($T = 20$). We initially estimate equations for the entire dataset, and then we split the dataset into two groups, that is, developed and developing countries. In doing so, we estimate various specifications, and the explicit form of which is expressed as follows:

$$RENC_{i,t} = a_0 + a_1 RENC_{i,t-1} + a_2 IPR_{i,t} + a_3 IPR_{i,t}^2 + a_4 GDPpc_{i,t} + a_5 R\&D_{i,t} + a_6 TROP_{i,t} + a_7 GFCDUM_i + GFCDUM_i * IPR_{i,t} + u_{i,t} \quad (2)$$

$$u_{i,t} = v_i + e_{i,t} \quad (3)$$

The fixed-country specific effect is removed by taking the first difference of the regressors as long as it does not vary with time. From equation (3), we get:

$$\Delta u_{i,t} = \Delta v_i + \Delta e_{i,t} \quad (4)$$

where $RENC$ denotes renewable energy use and is measured as the share of renewable energy in total energy use; IPR consists of the two composite indices – i.e., the updated IPRA and IPRP, that measure differences in strength of patent systems across countries; $GDPpc$ denotes GDP per capita; $TROP$ stands for trade openness and defined as the share of the sum of nominal imports and exports in GDP; $R\&D$ is research and development expenditure as a percentage of GDP; $GFCDUM$ is a dummy that captures the persistent/protracted impact of the global financial crisis; and $GFCDUM * IPR$ is the interaction term that attempts to capture the impact of the strength of patent systems over the period after the global financial crisis broke out. The lags of the independent variables were used as instruments during the estimation process.

Prior to estimating the model we test our series for unit roots to establish the order of integration. In this study, we utilize both common root tests - Levin, Lin, Chu - and individual root tests - Im, Pesaran, Shin and ADF, Fisher. The tests² suggest that the null hypothesis of a unit root is rejected in all cases hence implying that although a short run

relationship might exist, there is no need to explore cointegrating relationships [59].

4. Discussion of results

The consistency of the estimators were tested using Arellano and Bond's proposition i.e. testing the hypothesis that there is no second-order serial correlation for the disturbances of the first-differenced equation, as well as a Sargan's test of over-identifying restrictions [53]. An additional test for over-identifying restrictions is the J-statistics of Hansen. Roodman argues that if "non-sphericity is suspected in the errors, as in robust one-step GMM, the Sargan test statistic ... is inconsistent. In that case, a theoretically superior over-identification test for the one-step estimator is that based on the Hansen statistic from a two-step estimate" ([60], p. 12). As such, the robustness of our GMM-SYS estimates are tested by means of the AR(2) and Hansen tests on the basis of which the null hypothesis of no serial correlation and instrument validity cannot be rejected. Our results support the validity of the over-identifying restrictions and the absence of second-order serial correlation in all regressions, hence rendering reliable estimates.

The summary statistics and the correlation matrix are presented in tables A1 and A2 in the appendix. The low correlation coefficients between pairs of the variables suggests that multicollinearity has been kept at bay.

Table 1 presents the results of the baseline regression for the entire sample of 47 countries. In model 1, IPRA is found to be highly significant suggesting that the strength of patent systems positively affects energy consumption. In models 2 and 3 however when the quadratic term is inserted in the equation the sign of IPRA is reversed whilst the significance drops to 10% and 5% levels respectively. The quadratic term is positive and significant in both models bearing a positive sign. The latter suggests that whilst stronger IP protection leads to lower energy consumption there is a threshold after which stronger IP protection leads to higher renewable energy consumption. When IPRP is used as an alternative measure of IP protection the picture is more or less the same. The only difference is that in models 5 the IPRP is found to be weakly significant whereas in model 6 the effect of IP protection is found to be insignificant. The quadratic terms in both models have turned out to be significant bearing a positive sign as previously when IPRA was used.

Surprisingly, GDP per capita is found to have a significant negative relationship with renewable energy adoption hence suggesting that economic development is associated with a lower share of renewables in total energy use. The fact that we have included both developed and developing countries in the estimation process might have distorted the effect of GDP per capita on renewable energy adoption. Trade openness ($TROP$) appears to have a significant positive impact on the adoption of renewable energy which is in line with the literature hence confirming the role of trade in transferring technology to the countries in need [50]. $R\&D$ is found to exert no significant impact on renewable energy consumption across all estimated models. The GFC dummy is found to be insignificant whereas the interaction dummy is highly significant suggesting that strong protection of IPRs during the global financial crisis will exert a positive impact on renewable energy adoption. When IPRP is considered (models, 4, 5 and 6) the results are akin to the ones established previously with the only difference the insignificant coefficient of IPRP in model 4.

Table 2 reports the results for the cluster of the developed countries. In model 1, IPRA is significant and positively associated with renewable energy consumption whilst in model 2 when nonlinearities are considered IPRA is significant bearing a negative sign. The quadratic term is found to be positive and significant which is akin to the estimations presented in Table 1. In model 3, IPRA is insignificant whilst the quadratic term is positive and weakly significant.

GDP per capita is consistently negative and significant whilst $R\&D$ is found to be only positive and weakly significant in model 3. $TROP$ is found to positively affect renewable energy adoption in models 2, 3, 4

² For economy of space, we do not report the unit root tests but these are available upon request.

Table 1

GMM-SYS regression estimates - Entire Dataset. Dependent variable: Renewable Energy Consumption.

Explanatory Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
RENC _{t-1}	0.952(0.007)***	0.938(0.012)***	0.945(0.014)***	0.956(0.007)***	0.094(0.013)***	0.947(0.014)***
IPRA	0.125(0.01)***	−0.442(0.202)**	−0.357(0.212)*			
IPRA ²		0.045(0.015)***	0.038(0.016)**			
IPRP				0.064(0.018)***	−0.138(0.07)*	−0.107(0.070)
IPRP ²					0.019(0.005)***	0.015(0.006)***
GDPpc	−0.041(0.003)***	−0.044(0.003)***	−0.035(0.004)***	−0.046(0.002)***	−0.047(0.003)***	−0.036(0.004)***
R&D	−0.052(0.03)	−0.074(0.043)*	−0.039(0.048)	−0.009(0.041)	−0.070(0.05)	−0.032(0.055)
TROP	−0.002(0.0007)***	0.004(0.000)***	0.003(0.001)***	0.002(0.000)***	0.003(0.001)***	0.002(0.001)***
GFCDUM			0.260(0.555)			0.322(0.246)
GFCDUM*IPRA			0.024(0.001)***			
GFCDUM*IPRP						0.162(0.002)***
AR(2) p-value ⁽¹⁾	0.520	0.546	0.531	0.517	0.515	0.504
Sargan p-value ⁽²⁾	0.897	0.962	0.989	0.872	0.892	0.901

Note: ⁽¹⁾ Test for second order serial correlation; ⁽²⁾ Tests the null hypothesis of the appropriate set of instruments; (*), (**) and (***) denote significance at 10%, 5% and 1% level respectively; robust standard errors are given in parenthesis. We also control for time effects using period dummies.

Table 2

GMM-SYS regression estimates -Developed countries. Dependent variable: Renewable Energy Consumption.

Explanatory Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
RENC _{t-1}	0.978(0.031)***	0.871(0.031)***	0.984(0.031)***	0.910(0.024)***	0.909(0.024)***	0.917(0.025)***
IPRA	0.043(0.017)**	−1.257(0.605)**	−0.983(0.609)			
IPRA ²		0.088(0.038)**	0.069(0.039)*			
IPRP				−0.001(0.022)	−0.676(0.374)*	−0.955(0.327)***
IPRP ²					0.052(0.025)**	0.071(0.021)***
GDPpc	−0.049(0.007)***	−0.046(0.006)***	−0.023(0.013)*	−0.050(0.007)***	−0.051(0.007)***	−0.020(0.012)*
R&D	0.238(0.350)	0.303(0.350)	0.059(0.034)*	0.393(0.345)	0.400(0.345)	0.402(0.347)
TROP	0.001(0.445)	0.001(0.007)*	0.001(0.0007)*	0.001(0.0006)*	0.001(0.0006)**	−0.001(0.008)
GFCDUM			−0.508(0.202)**			−0.393(0.204)**
GFCDUM*IPRA			0.225(0.123)*			
GFCDUM*IPRP						0.132(0.016)***
AR(2) p-value ⁽¹⁾	0.487	0.473	0.478	0.486	0.489	0.488
Sargan p-value ⁽²⁾	0.730	0.786	0.801	0.804	0.799	0.793

Note: ⁽¹⁾ Test for second order serial correlation; ⁽²⁾ Tests the null hypothesis of the appropriate set of instruments; (*), (**) and (***) denote significance at 10%, 5% and 1% level respectively; robust standard errors are given in parenthesis. We also control for time effects using period dummies.

(at the 10% level of significance) and 5 (at the 5% level). The GFC dummy unlike previously when the entire sample was considered, is found to have a negative effect on renewable energy adoption whilst the interaction term is positive and highly significant.

In the case of the developing countries (Table 3) the results appear to be more fragmented as only in the case where the IPRA measure is considered; there appears to be a negative and significant association with renewable energy adoption (models 2 and 3) as well as a positive nonlinear relationship.

GDP per capita is still surprisingly negative and highly significant but in line with previous studies [10]. Both R&D and TROP are found to be insignificant across all specifications. The results for both the GFC

dummy and the interaction dummy are in line with our results for developed economies, i.e., negative, and significant in the case of the additive dummy and negative and significant in the case of the interaction term. It should also be stressed that the lagged independent variable of energy consumption was found to be positive and significant across all clusters of countries and across all estimated equations.

5. Concluding remarks

The business activity of multinational enterprises (MNEs) is greatly affected by the quality of a host country's patent system. A firms' ability to appropriate returns for their investment in areas such as R&D and

Table 3

GMM-SYS regression estimates -Developing countries. Dependent variable: Renewable Energy Consumption.

Explanatory Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
RENC _{t-1}	0.981(0.012)***	0.986(0.012)***	0.982(0.0313)***	0.979(0.012)***	0.986(0.012)***	0.984(0.012)***
IPRA	0.008(0.050)	−0.513(0.291)*	−0.590(0.300)**			
IPRA ²		0.051(0.027)*	0.058(0.028)**			
IPRP				−0.001(0.022)	0.676(0.974)	−0.055(0.327)
IPRP ²					0.052(0.225)	0.271(0.021)
GDPpc	−0.058(0.011)***	−0.058(0.011)***	−0.055(0.011)***	−0.050(0.007)***	−0.051(0.007)***	−0.059(0.011)***
R&D	0.238(0.350)	0.215(0.164)	0.212(0.167)	0.393(0.345)	0.400(0.345)	0.402(0.347)
TROP	0.001(0.445)	0.001(0.021)	0.001(0.002)	0.001(0.061)	0.001(0.061)	0.001(0.008)
GFCDUM			−0.192(1.050)*			−1.481(0.608)**
GFCDUM*IPRA			0.519(0.251)**			
GFCDUM*IPRP						0.546(0.187)***
AR(2) p-value ⁽¹⁾	0.694	0.893	0.791	0.905	0.872	0.917
Sargan p-value ⁽²⁾	0.899	0.863	0.889	0.832	0.799	0.881

Note: ⁽¹⁾ Test for second order serial correlation; ⁽²⁾ Tests the null hypothesis of the appropriate set of instruments; (*), (**) and (***) denote significance at 10%, 5% and 1% level respectively; robust standard errors are given in parenthesis. We also control for time effects using period dummies.

innovation very much depends on the existence of patent-related legislation in the legal framework of countries, as well as the ability and willingness of government officials and institutional actors to enforce it.

This study explores empirically the impact of the strength of patent systems on renewable consumption using a GMM methodological framework for a panel of 47 developed and developing economies over the period 1998–2017. We find that protection of intellectual property rights across nearly all estimated models tends to have a negative impact on renewable energy consumption when other potential determinants of renewable energy consumption are considered. As such, the main conclusion of this study is that the strength of intellectual property rights within a country might stifle renewable energy consumption. Of interest is also the result of the nonlinearities which indicate a convex relationship i.e. as renewable energy consumption goes down with more enforcement of IPRs there is a point after which stronger patent systems will have a positive impact on renewable energy consumption.

What is surprising however is the result pertaining to the relationship between GDP per capita and renewable energy consumption. The counter-intuitive sign (i.e., negative) that was established throughout all estimations might suggest that revenue from fossil fuels has had a positive impact on GDP per capita across many countries, which in turn has discouraged investment in renewable energy technologies. It can also be argued that as economies develop further total energy use increases at a greater rate than that of renewable energy.

In the extant literature it is widely held that in high R&D capability countries, stronger patent systems may increase competition among inventors, which to an extent limits innovation. In our study R&D was found to have an insignificant impact on renewable energy consumption. Furthermore, the fact that openness of trade turned out to be a significant determinant of renewable energy in the case of the developing countries but not in the case of the developed economies might indicate the disproportionate transfer of technological know-how from technologically advanced countries to those that are lagging.

This study goes further to gauge the impact of the global financial crisis 2007/8 which undoubtedly impacted nearly every sector in the global economy. Our findings suggest that the negative impact of the GFC on renewable energy adoption might be due to the attitude of the banks over that period i.e., banks might have almost stopped lending altogether whilst fresh money found its way to corporations with strong balance sheets with whom the banks have very close relationships. The interactions term however suggests that the strength of IPPs might have a significant role to play in encouraging more renewable energy consumption.

The impact of the strength of patent systems on renewable energy consumption is a very complex issue with significant policy implications. Patents may be a crucial mechanism for incentivizing innovation through granting exclusive rights to inventors for a limited period, hence allowing them to recover their investment in R&D. In our context, the strength of patent systems can also have significant implication that affect renewable energy consumption, which is critical for mitigating climate change.

On the one hand, strong patent systems can encourage R&D development of new renewable energy technologies which can lead to significant advances in renewable energy. This, in turn, can have positive spill over effects, as these technologies become more efficient and cost-effective, making them more competitive with traditional energy sources. On the other hand, however, strong patent systems can also lead to barriers to innovation and technology transfer, stifling the development of similar technologies, which may undermine competition and inhibit innovation. This can lead to higher prices for renewable energy technologies, which can slow down the adoption of renewable energy and

reduce the overall consumption.

Moreover, strong patent systems can also make it difficult for developing countries to access renewable energy technologies as many renewable energy technologies are developed in developed countries and are protected by patents. Developing countries may not have the resources to develop their own technologies or to license existing technologies, which can limit their access to renewable energy sources. This can exacerbate global inequalities in access to clean energy and slow down the transition to a more sustainable energy system.

In view of the above, policymakers must balance the benefits and costs of strong patent systems in the context of renewable energy consumption. One approach could be to promote open innovation and collaboration among inventors, researchers, and companies to share knowledge and accelerate the development and adoption of renewable energy technologies. This could include measures such as open licensing agreements or government funding for collaborative research and development.

Another approach could be to strengthen patent systems' flexibility, allowing for exceptions to exclusive rights to address public interest concerns such as access to renewable energy. This could include measures such as compulsory licensing, which allows governments to grant licenses to use patented technologies in certain circumstances, or limitations on patent rights in cases where patents have the potential to stifle competition or inhibit innovation.

In view of our novel results policy makers must carefully balance the benefits and costs of strong patent systems and consider measures to promote innovation, collaboration, and access to renewable energy technologies. By doing so, they can help accelerate the transition to a more sustainable energy system and mitigate the effects of climate change.

Strong patent systems might disproportionately benefit large firms as they are more likely to use patents to entrench their position in the market or threaten other inventors with litigation whilst on the other hand, small- and medium-sized firms are more likely to use patents to accumulate revenue and enhance their reputation within their sector. We feel that a strategic adjustments of intellectual property rights can either encourage more or less innovation, depending on how strong or weak the existing patent systems are.

This study might be subject to several limitations that emanate from the relatively short span of the dataset due to data availability as well as the limited generalization of the results due to variations in policies, regulations, and economic conditions permeating different economies. In view of such potential limitations, we propose future direction that can, in all likelihood, produce more holistic and insightful results. We feel that a combination of mixed (both qualitative and quantitative) research methods, including *inter alia* case studies, and interviews with experts in the field will provide better insight into the perspectives of different stakeholders on policy considerations surrounding patent protection for renewable energy technologies.

CRediT authorship contribution statement

Constantinos Alexiou: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

APPENDIX

Table A1
Summary statistics

Variable	Mean	STD	Min	Max
<i>IPRA</i>	7.68	1.41	4.07	9.9
<i>IPRP</i>	7.36	1.60	3.7	9.7
<i>RENC</i>	16.0	17.0	0.09	77.4
<i>R&D</i>	2.0	0.92	0.42	4.81
<i>TROP</i>	102.6	80.2	18.1	442.6
<i>GDPpc</i>	1.74	2.83	10.0	23.9

Table A2
Cross correlation matrix

Variable	<i>IPALEX</i>	<i>IPPAP</i>	<i>ENER</i>	<i>RD</i>	<i>TRD</i>	<i>GDPpc</i>
<i>IPRA</i>	1					
<i>IPRP</i>	0.95	1				
<i>RENC</i>	0.29	0.24	1			
<i>R&D</i>	0.03	0.04	0.14	1		
<i>TROP</i>	0.07	0.06	−0.24	−0.23	1	
<i>GDPpc</i>	−0.01	0.01	−0.11	−0.08	0.20	1

Table A3
Definition of variables and sources

Variable	Definition	Source
<i>RENC</i>	Renewable energy consumption (% of total final energy consumption) [EG.FEC.RNEW.ZS]	World Development Indicators
<i>GDPpc</i>	GDP per capita (constant 2010 US\$) [NY.GDP.PCAP.KD]	World Development Indicators
<i>TROP</i>	Imports and exports (% of GDP) [NE.TRD.GNFS.ZS]	World Development Indicators
<i>R&D</i>	Research and development expenditure (% of GDP) [GB.XPDRSDV.GD.Zs]	World Development Indicators
<i>IPRA</i>	IPI index/updated from 2011 to 2017	Papageorgiadis, N., Cross, A. R., and Alexiou, C. (2014)/updated by author.
<i>IPRP</i>	IPI index (account firm-level patent litigation)	Papageorgiadis, N. and Sofka, W. (2020)
<i>GFCDUM</i>	Global Financial Crisis dummy – 2007/8	Generated by the author

Table A4
IPR Index by Papageorgiadis, Cross and Alexiou (2014) and Updated index – IPRA

Country Name	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
<i>Existing index developed by Papageorgiadis, Cross and Alexiou (2014)</i>															UPDATED INDEX - IPRA					
Argentina	4.2	4.2	4.6	4.5	3.8	3.6	3.6	3.9	3.9	3.9	3.9	3.9	3.9	4	3.8	3.7	3.7	3.6	3.6	3.7
Australia	8.9	8.9	8.7	8.8	8.9	9	9	8.9	8.9	8.8	8.9	8.9	8.8	8.9	8.5	8.2	8.1	8.2	8.2	8.1
Austria	8.1	8.2	8.3	8.4	8.3	8.3	8.7	8.8	8.8	8.5	8.6	8.4	8.3	8.2	7.1	7.1	7.4	7.3	7.4	7.4
Belgium	6.4	6.4	7	7.3	7.6	7.9	7.9	7.7	7.8	7.7	7.8	7.6	7.6	7.8	7.6	7.6	7.7	7.7	7.6	7.7
Brazil	4.9	5.1	5	5	5	4.9	4.9	4.6	4.3	4.4	4.5	4.6	4.6	4.7	4.6	4.6	4.6	4.6	4.6	4.6
Canada	9.3	9.3	9.3	9.1	9.1	8.8	8.8	8.6	8.7	8.9	8.9	8.8	9	8.8	8.5	8.2	8.2	8.3	8.3	8.2
Chile	7.1	7.3	7.6	7.6	7.5	7.5	7.5	7.3	7.4	7.2	7.1	7	7.3	7.4	7.2	7.1	7.3	7.1	7.1	7.3
China	4.7	4.5	4.3	4.5	4.7	4.6	4.6	4.4	4.5	4.7	4.8	4.8	4.7	4.8	4.3	4.4	4.1	4.2	4.3	4.1
Colombia	3.5	4	4.2	4.6	4.6	4.6	4.6	4.8	4.9	4.8	4.8	4.6	4.5	4.4	4.0	4.0	4.0	4.1	4.1	4.0
Czech Republic	5.6	5.4	5.3	5.1	5	5	5.2	5.3	5.7	5.9	5.9	5.7	5.5	5.4	5.2	5.1	5.4	5.4	5.4	5.4
Denmark	9.8	9.8	9.7	9.6	9.5	9.5	9.6	9.5	9.6	9.5	9.4	9.4	9.3	9.4	9.0	9.0	9.1	9.2	9.3	9.1
Finland	9.5	9.7	9.9	9.8	9.7	9.7	9.6	9.5	9.6	9.5	9.2	9.1	9.3	9.5	9.0	8.9	9.0	8.9	8.8	9.0
France	7.4	7.4	7.4	7.5	7	7.5	7.6	7.9	7.9	7.8	7.6	7.5	7.5	7.6	7.2	7.3	7.1	7.1	7.2	7.1
Germany	8.3	8.5	8.2	8.1	7.9	8.2	8.6	8.6	8.5	8.4	8.3	8.3	8.3	8.3	8.0	7.9	8.0	8.2	8.1	8.0
Greece	5.7	5.7	5.8	5.3	5.2	5.4	5.4	5.3	5.5	5.6	5.6	5	4.8	4.6	4.1	4.4	4.7	4.6	4.7	4.7
Hong Kong	8	7.8	7.9	8	8.5	8.2	8.2	8.3	8.5	8.5	8.3	8.4	8.5	8.5	7.8	7.8	7.6	7.7	7.6	7.6
Hungary	6	6.2	6.1	6.2	5.9	5.8	5.8	5.9	6.1	6.1	5.9	5.9	5.6	5.5	5.7	5.6	5.6	5.5	5.5	5.6
Iceland	–	–	–	–	–	–	–	9.5	9.5	9.2	9	8.8	8.5	8.4	8.2	7.9	7.9	7.8	7.9	7.9
India	4.2	4.3	4.3	4.1	4.2	4.2	4.2	4.5	4.9	4.9	4.7	4.7	4.6	4.5	4.2	4.2	4.4	4.4	4.4	4.4
Indonesia	3.4	3.1	3.2	3.2	3.1	3.3	3.5	3.5	3.7	3.6	3.8	4.1	4.1	4.2	3.7	3.8	4.0	3.9	3.9	4.0
Ireland	8.5	8.1	7.8	8	7.6	7.9	8	8	8	8	8.2	8.4	8.4	8.1	7.3	7.5	7.7	7.8	7.6	7.7
Israel	7.6	7.4	7.3	8	7.8	7.7	7.1	7.1	6.9	6.9	6.8	6.7	6.8	6.7	6.4	6.5	6.4	6.5	6.4	6.4
Italy	5.7	5.7	5.7	6.4	6.1	6.1	5.6	5.8	5.7	5.9	5.6	5.2	4.9	5	4.6	4.6	4.6	4.7	4.6	4.6
Japan	6.8	7	7.2	7.7	7.4	7.4	7.5	7.7	8.1	8	7.8	8.1	8.1	8.3	7.6	7.6	7.8	7.9	7.9	7.8
Jordan*	–	–	–	–	–	5.7	6.1	6.4	6.1	5.7	6	5.9	5.6	5.5	5.2	4.9	5.3	5.3	5.3	5.3
Korea (South)	5.2	4.9	5.1	5.2	5.6	5.4	5.5	5.9	6	6.2	6.4	6.2	6.1	6.1	6.0	5.7	5.7	5.7	5.8	5.7

(continued on next page)

Table A4 (continued)

Country Name	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
Existing index developed by Papageorgiadis, Cross and Alexiou (2014)															UPDATED INDEX - IPRA					
Malaysia	6.2	5.8	5.6	5.6	5.8	6.1	6	6.1	6.1	6.2	6	5.5	5.6	5.5	5.4	5.5	5.7	5.7	5.8	5.7
Mexico	4.5	4.6	4.5	4.7	4.5	4.6	4.6	4.5	4.5	4.6	4.6	4.3	4.2	4.1	3.9	3.9	3.9	3.8	3.7	3.9
Netherlands	9	9	9.2	9.1	9.2	9	8.9	8.8	9	9.2	9.1	9.1	8.9	9	8.5	8.4	8.4	8.4	8.4	8.4
New Zealand	9.4	9.3	9.3	9.3	9.4	9.4	9.5	9.4	9.5	9.4	9.3	9.4	9.3	9.4	9.0	9.1	9.1	9	9	9.1
Norway	9.1	8.9	9	8.7	8.6	8.8	9.1	8.9	9	8.8	8.3	8.8	8.8	9.1	8.6	8.6	8.6	8.7	8.7	8.6
Philippines	4.4	4.7	4.2	4.1	3.8	3.8	3.8	3.7	3.8	3.8	3.7	3.7	3.7	3.8	3.8	4.0	4.2	4.2	4.2	4.2
Poland	5.5	5.2	5.1	5.2	4.9	4.7	4.4	4.5	4.7	5.1	5.4	5.7	5.9	6.1	6.0	6.2	6.2	6.1	6.2	6.2
Portugal	6.9	7.1	6.9	6.8	6.8	7.1	6.8	7	7.1	7	6.7	6.5	6.5	6.5	6.3	6.3	6.4	6.2	6.2	6.4
Romania	—	—	—	—	—	3.9	4	4	4.1	4.6	4.7	4.7	4.6	4.5	4.6	4.5	4.6	4.5	4.6	4.6
Russia	3.6	3.5	3.4	3.4	3.7	3.7	3.9	3.5	3.6	3.5	3.4	3.4	3.4	3.5	3.2	3.3	3.2	3.4	3.4	3.2
Singapore	9.1	9.1	9.1	9.1	9.2	9.3	9.2	9.3	9.3	9.3	9.3	9.2	9.3	9.2	8.7	8.6	8.4	8.5	8.6	8.4
Slovakia	—	—	—	4.8	4.7	4.7	5	5.2	5.5	5.6	5.7	5.3	5.1	4.9	4.8	4.8	5.1	5.2	5.1	5.1
S. Africa	6	5.9	6	5.8	5.9	5.6	5.8	5.6	5.8	6.1	6	5.8	5.6	5.4	4.9	4.8	5.0	4.8	4.8	5.0
Spain	6.8	7.2	7.5	7.5	7.4	7.2	7.3	7.2	7.1	7.1	6.9	6.6	6.6	6.6	6.5	6.8	6.0	6.1	6.1	6.0
Sweden	9.4	9.4	9.3	9.1	9.3	9.3	9.3	9.1	9.3	9.3	9.4	9.3	9.3	9.4	8.8	8.9	8.7	8.8	8.9	8.7
Switzerland	9.1	9.1	8.9	8.8	8.8	8.9	9.2	9.2	9.2	9.2	9.2	9.1	8.9	9	8.7	8.5	8.6	8.7	8.8	8.6
Taiwan (ROC)	6	6.2	6.1	6.3	6.1	6.3	6.2	6.4	6.4	6.3	6.3	6.2	6.4	6.6	6.4	6.3	6.3	6.3	6.3	6.3
Thailand	4.4	4.5	4.6	4.5	4.6	4.6	4.8	4.9	4.8	4.6	4.7	4.5	4.6	4.5	4.3	4.0	4.2	4.3	4.4	4.2
Turkey	4.6	4.7	5	4.6	4.2	4.2	4.3	4.6	4.8	5	5.3	5.1	5	4.9	5.1	5.2	4.7	4.8	4.7	4.7
Ukraine*	—	—	—	—	—	—	—	—	—	3.8	3.6	3.4	3.5	3.4	3.1	2.9	3.0	3.1	3.2	3.0
United Kingdom	8.9	8.9	9	8.7	9	8.9	8.8	8.8	8.8	8.6	8.1	8.1	8.1	8.3	7.6	7.8	8.0	7.8	7.7	8.0
USA	8.22	8.22	8.42	8.31	8.36	8.18	8.17	8.23	8.01	7.93	8.03	8.12	7.86	7.88	7.0	7.0	7.1	7.2	7.2	7.1
Venezuela, RB	3.4	3.7	3.7	3.8	3.4	3.2	3.3	3.3	3.2	3	2.9	2.9	2.9	2.9	2.3	2.3	2.2	2.1	2.2	2.2

Note: * Ukraine and Jordan were the only countries that were left out of the estimation due to data limitations.

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