Energy Policy 62 (2013) 887–897

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Do renewable electricity policies promote renewable electricity generation? Evidence from panel data

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HIGHLIGHTS

- We evaluate the effects of renewable electricity policies using the PPML technique.
- The panel dataset covers 122 countries over 1980–2010.
- The policy effects diminish as the number of policies increases.
- The effects are more pronounced before 1996 as well as in developed and emerging market countries.
- Policy effectiveness varies by the type of policy and energy source.

ARTICLE INFO

Article history:
Received 15 November 2012
Accepted 15 July 2013
Available online 7 August 2013

Keywords:
Policy effectiveness
Renewable electricity
PPML

ABSTRACT

Using the Poisson pseudo-maximum likelihood estimation technique, this paper evaluates the effects of renewable electricity policies on renewable electricity generation using a large panel dataset that covers 122 countries over the period of 1980–2010. The results suggest that renewable electricity policies play a crucial role in promoting renewable electricity generation, but their effectiveness is subject to diminishing returns as the number of policies increases. There is also evidence that the effects of renewable electricity policies are more pronounced before 1996 as well as in developed and emerging market countries, and the negative policy interaction effect fades with the stage of economic development. Lastly, policy effectiveness varies by the type of renewable electricity policy and energy source. Only investment incentives and feed-in tariffs are found to be effective in promoting the development of all types of renewable energy sources for electricity considered in this paper.
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1. Introduction

The global economy has experienced a remarkable period of rapid growth in recent decades till the onset of the Global Financial Crisis. As a consequence, global energy demand has been increasing rapidly and is expected to be about 33% higher in the year 2035 compared to 2010 (IEA, 2011). In most countries, conventional fossil fuels, such as coal, oil and natural gas, have been the primary sources for meeting global energy demand. However, the supply constraint of fossil fuel and concerns over greenhouse gas emissions have led to a worldwide effort to diversify to renewable energy sources such as solar, wind, biomass and geothermal power.

Renewable electricity (RE) sources, can create substantial environmental and socio-economic benefits, such as minimizing greenhouse gas emissions, using local resources, increasing energy access and improving energy security (IPCC, 2011; Omer, 2009; REN, 2012). However, despite the enormous potential benefits, RE is still a relatively minor contributor to total energy supply. In 2010, the total net electricity power generated from renewable sources in the world was 4154 billion kilowatt hours (kwh), less than 21% of global final net electricity generation.[1]

The main barrier for RE development is its high fixed costs compared to non-renewable electricity (Beck and Martinot, 2004; Sawin, 2004; Verbruggen et al., 2010). Most RE projects have large initial costs, long lags in generating revenues and even longer lags in making any profits. As a result, government policies like feed-in tariffs, tax credits, tradable certificates, investment incentives, and production quotas play an important role in promoting innovation in the RE sector, and in reducing the costs and accelerating market penetration of green energy. While it is expected that these policies will assist the RE sector to develop, the extent to which

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[1] Author's calculation based on the EIA data.

0301-4215/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enpol.2013.07.072

this policy assistance has led to greater production of RE power has received limited attention in the existing literature.

The majority of the literature on the effectiveness of RE policies relies on exploratory analyses and case studies (Berry and Jaccard, 2001; Bird et al., 2005; Gan et al., 2007; Zarnikau, 2011). Only a handful of studies have attempted to quantify the impacts of RE policies on the development of its target sector. In a cross-country study, Johnstone et al. (2010) find that public policies play a significant role in encouraging patent applications, but the effects on different renewable sources vary greatly by the type of policy instrument. Nicolli and Vona (2012a) and Vona et al. (2011) explore this issue further by tackling the problem of policy endogeneity. They also find evidence that renewable policies positively affect green energy innovations. In addition, there are some cross-country studies investigating the relative effectiveness of different policy mechanisms. For instance, Dong (2012) shows that feed-in tariffs increase total wind energy production capacity above the renewable portfolio standards.

There are also empirical papers analyzing the effectiveness of RE policies at the state level, using mainly U.S. data. While some state level studies reach a firm and positive conclusion (Adelaja and Hailu, 2008; Menz and Vachon, 2006; Yin and Powers, 2010), others find mixed results (Carley, 2009; Kneifel, 2008). Against this background, researchers have started to question whether the effectiveness of RE policies is conditional on natural, social and institutional environment. For instance, Delmas and Montes-Sancho (2011) argue that a large presence of non-governmental organizations, green residential customers and democratic representatives facilitate the transmission of RE policies.

This paper aims to contribute to this literature using a large panel dataset. Our analysis extends previous research in three ways. First, empirical analysis on the effectiveness of RE policies remains scarce; the few cross-country studies like Johnstone et al. (2010) mainly focus on renewable patent counts rather than RE generation. In this paper we use a more direct proxy for RE sector development, namely the share of electricity generation from non-hydro renewable energy sources (Brunnschweiler, 2010; Carley, 2009). Second, although many previous studies (Azuela and Barroso, 2011; Blyth et al., 2009; Fischer and Preonas, 2010) mention that interaction of RE policies would affect the effectiveness of RE policies, the assertion remains untested. In this paper, we empirically investigate whether there are policy interaction effects in RE generation. Third, most previous studies lump different countries together in their analyses regardless of their state of development, and do the same to different periods, different policy instruments and different energy sources. In this paper, we allow for heterogeneity amongst countries, periods, policy instruments, and energy sources, respectively.

The remainder of the paper is structured as follows. Section 2 describes the data and methodology used to examine the effects of RE policies on RE generation. Section 3 presents and discusses the empirical findings. Section 4 concludes.

2. Data and the methodology

Our dataset covers 122 countries for 31 years from 1980 to 2010 and is unbalanced. The dataset is compiled using data from three different sources: the Energy Information Administration (EIA) of the United States, the World Development Indicators of the World Bank, and the International Energy Agency (IEA). Data descriptions and summary statistics are provided in Appendix A.

To assess the effects of RE policies on RE generation, we specify our estimation regression as follows.

$$Y_{it} = a + \mathbf{X}_{it}\delta + \beta Policy_{it} + u_i + v_t + \omega_{it} \qquad (1)$$

where Y_{it} is a measure of electricity generation from non-hydro renewable sources as a share of total electricity generation in country i at year t, $Policy_{it}$ is the RE policy variable, $\mathbf{X}_{it}$ denotes the vector of control variables, a is the constant, δ is the vector of coefficients of control variables, β is the coefficient of policy variable, u_i is country fixed effects used to capture time-invariant country heterogeneity, v_t is time fixed effects used to capture time-variant global shocks, and ω_{it} is the random error, representing the net effect of all other unobservable factors that might influence Y_{it}. δ and β measure the influence (i.e. marginal effect) of their associated explanatory variable on the dependent variable, keeping other explanatory variables constant.

It should be pointed out that, this modeling framework allows for the possibilities that some control variables (e.g. income) may affect RE policies. At the same time, RE policies may also be affected by factors not included in the control variables set (e.g. policymakers' preference). However, as our interest is the total effect of RE policies on RE generation, not what is driving RE policies, the current modeling framework is appropriate.

Our measurement of RE generation, Y_{it}, excludes a key player in the sector – hydropower. This is because large hydropower projects often bring about serious negative environmental and social externalities and therefore regarded by many as a non-viable renewable source (Brunnschweiler, 2010).[2] In addition to the aggregate measure, we also consider different types of renewable sources for electricity, including (i) biomass and waste; (ii) solar, tide and wave; and (iii) wind energy. The share of these three sources in overall non-hydro RE generation was 91% in the year 2010.[3] All electricity generation data is obtained from the EIA.

The RE policy variable, $Policy_{it}$, is our key explanatory variable. A database on public policies for RE compiled by the IEA is used to construct alternative RE policy indicators. In this paper, we consider the following six policy instruments: (1) investment incentives such as risk guarantees and capital grants that aim at reducing the capital cost of RE production; (2) tax incentives used to encourage RE production; (3) feed-in tariffs, which are a form of price regulation designed to guarantee producers of RE power a cost-based price; (4) voluntary programs, in which members agree to undertake socially beneficial actions, such as buying RE; (5) production quotas, which place a requirement on the minimum amount of electricity supply that comes from renewable sources; and (6) tradable certificates, which provide a tool for trading and meeting RE obligations among consumers and producers, and a mechanism for tracking and verifying RE sources.

Following Carley (2009) and Johnstone et al. (2010), dummy variables are first created to record the implementation of different policy instruments. For each of the six policy instruments, a dummy variable takes a value of 0 prior to implementation of the policy and 1 thereafter.[4] Three separate measures of aggregate RE policy are then constructed from the six policy dummy variables to provide a representation of the overall policy support of RE generation for a given country. The first aggregate RE policy variable, *poldum*, is also a dummy variable. For a given year and a given country, the variable takes a value of 1 if the country adopts any of the six policies described above, and 0 otherwise. The second variable, *polavg*, is a simple average of all the six policy dummies and normalized to lie within the range of 0 to 1. The last aggregate policy variable, *polpca*, is constructed using the principal components method in order to reduce the dimensionality of the set of individual policy variables. As the first principal component

[2] Some examples are the giant Three Gorges Dam in China and Illisu Dam project in Turkey.

[3] Author's calculation based on the EIA data.

[4] Any policy that becomes effective after October in a given year is coded as effective the following year.

accounts for as much as 71% of the variance of its underlying variables, we choose to use only the first component as an aggregate policy variable, and normalize its value to lie within the range of 0–1. In the regression analysis, the three aggregate RE policy measures are used alternatively as the RE policy variable, $Policy_{it}$.

One limitation of our RE policy measures is that they only indicate whether a specific RE policy is deployed, but not its intensity. We do not consider policy intensity because accurate data are scarce, especially given the large number of countries and long periods considered in this paper. In fact, similar RE policy measures have been used in the literature, including Carley (2009), Johnstone et al. (2010), and Nicolli and Vona (2012a, 2012b).

One possible reason why different countries may implement RE policies with different intensities is that they have different natural, social and institutional environments. For instance, people are more environmentally conscious if they are more vulnerable to natural disasters and, as a result, their representative government is likely to implement RE policies more forcefully. Also, the intensity of RE policies may also be affected by global environment standards. The use of fixed effects to control for the unobserved country and time heterogeneity goes some way in mitigating biases due to the omission of intensity measures in our estimation.

Figs. 1 and 2 show the scatter plots of the share of non-hydro RE power against respectively *polavg* and *polpca*. In both figures there is an unmistaken inverse-U shape relationship between the share of non-hydro RE generation and either policy variable. This suggests that, as by Fischer and Preonas (2010), in the case that not all RE policies are coherent, implementing more RE policies does not necessarily result in better development of the RE sector. We will test this policy interaction effect in the empirical section.

The control variables to be included in $\mathbf{X}_{it}$ are discussed as follows.

(1) Income: measured by real GDP per capita in 2000 year USD. The variable is used to control for the possibility that richer countries will have a higher percentage of RE production because they have the ability to invest more heavily in the RE sector (Carley, 2009; Dong, 2012; Sapat, 2004);
(2) CO_2 intensity: measured by CO_2 emissions per GDP. It is difficult to predict a priori effect of CO_2 intensity on RE development. It is possible that greater CO_2 emissions bring out more incentives towards RE development, yet it is also possible that greater pollution is accompanied with larger economic investment, which will reduce the propensity to invest in renewable sources for electricity (Marques et al., 2010; Romano and Scandurra, 2011). Considering the potential endogeneity of the variable,[5] 1 year lagged CO_2 intensity is used in the regression;
(3) Energy imports: measured by the ratio of net energy imports to total energy consumption. The variable captures the degree of energy dependence on foreign countries. We expect higher energy dependence on foreign markets to spur domestic RE development (Dong, 2012);
(4) Financial development: measured by domestic credit to the private sector as a proportion of GDP. The variable controls for the impacts of financial sector development on the share of RE in the power sector. Considering the relatively higher fixed costs of RE, access to finance can create more opportunities for RE deployments (Brunnschweiler, 2010; Huang, 2009; Waldhier, 2010);
(5) Human capital: measured by secondary school enrollment as a percentage of gross enrollment. Human capital is believed to facilitate the adoption of renewable innovative technologies (Benhabib and Spiegel, 2005);
(6) Foreign direct investment (FDI): measured by FDI net inflows as a proportion of GDP. As a composite bundle of capital, knowledge and technology, FDI contributes to RE growth via various ways such as alleviating credit constraint, improving technical progress and facilitating the diffusion of RE technologies (De Mello, 1999; Del Rio Gonzalez, 2009; Sawhney and Kahn, 2011);
(7) Demographic structure: measured by the share of female and the share of working-age population (aged from 15 to 64 years) in the total population respectively. As there is evidence that women have stronger preferences for environmental quality due to their tendency to be caregivers, to be cooperative, and to feel compassion (Torgler and Garcia-Valinas, 2007; Torgler et al., 2008; Vona et al., 2011); as a result, a higher

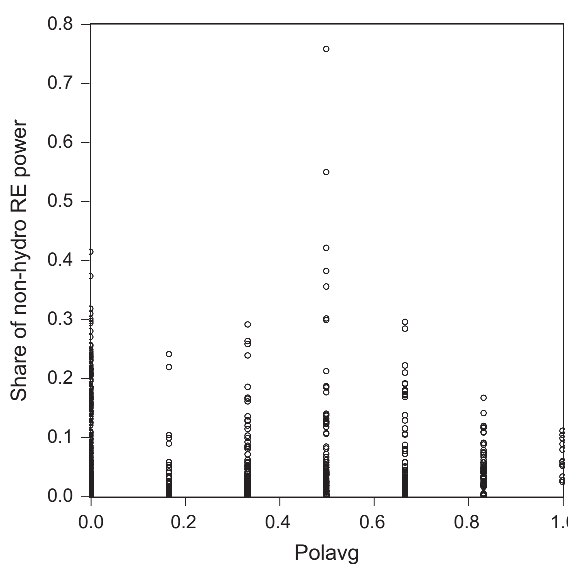

Fig. 1. Scatter plot of share of non-hydro RE power against *Polavg.*

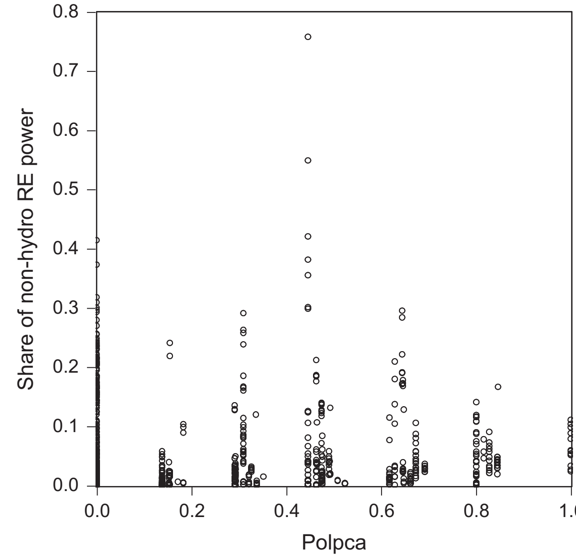

Fig. 2. Scatter plot of share of non-hydro RE power against *Polpca.*

[5] Generally speaking, the more electricity is generated using renewable sources, the lower the CO_2 emission will be. However, when the emissions are capped by the emissions trading scheme such as the European Emission Trading System and the cap-and-trade policy in the U.S., the CO_2 emission could also be constant or even increase as the price of CO_2 emission falls with the increase in the RE generation.

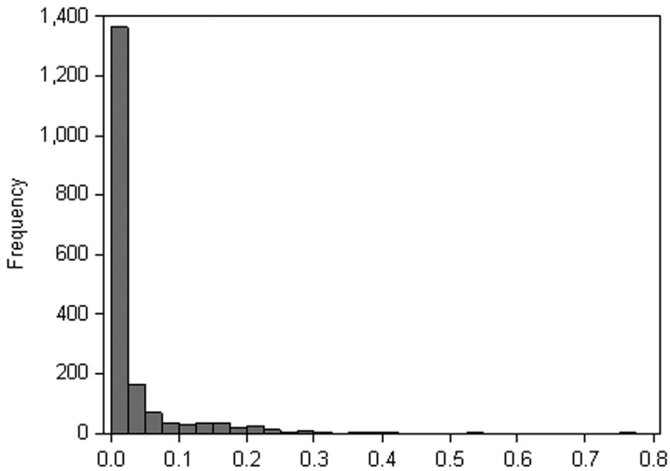

Fig. 3. Histogram of the share of non-hydro RE power.

proportion of females in the population is expected to lead to a larger share of RE. With respect to the share of working-age population, it could impact RE through two channels. Firstly, working-age people's preference for good environmental quality has previously been found to be relatively weaker than retirees (Vona et al., 2011);[6] as such, a larger ratio of working-age population is expected to result in a smaller share of RE. Secondly, the activities of the working-age population are likely to be more energy intensive than those of the elderly or children. Therefore, a larger proportion of working-age population is expected to put more pressure on energy supply, which may promote more energy development. However, whether it will promote more RE or fossil energy development is unclear.

Fig. 3 shows the histogram of the share of non-hydro RE production. It can be seen that a larger proportion of observations cluster at the very low end of the distribution. In fact, 39 countries in our dataset do not produce non-hydro green electricity over the whole sample period, and some others only produce non-hydro green electricity over part of the sample period. Due to this, 36.1% of the observations have a zero value for the dependent variable. This could create potentially large biases in parameter estimates when using traditional ordinary least squares (OLS) estimation techniques (Helpman et al., 2008; Santos Silva and Tenreyro, 2006). To address this issue, our main estimations are performed using the Poisson pseudo-maximum likelihood (PPML) estimation technique. Details on the Poisson regression could be found in Winkelmann (2008) and Arvis and Shepherd (2011). Furthermore, when the error term is heteroskedastic, the OLS estimates are inconsistent. This can also be handled by the PPML estimator with a robust covariance matrix. The PPML approach gives consistent estimates regardless of how the data are distributed. Results from simulation show that the PPML performs well compared with other estimators (Santos Silva and Tenreyro, 2011). Nevertheless, we also provide OLS estimates for the purpose of comparison. As the PPML estimator fails to converge when the model includes too many dummies, we use region fixed effects instead of country fixed effects. The set of countries in the data are divided into five regions — the Americas, Europe, Asia, Africa and Oceania. For consistency, we also use region fixed effects in the OLS estimations.

[6] Similar results are also confirmed by a survey conducted by ICOM Information and Communications in 2008. According to this survey, consumers over 55 years old are the most prolific users of green products in the U.S., while those aged 25–34 years old are among the least likely to use environmentally friendly goods.

3. Results and discussion

3.1. Baseline results

Table 1 presents the estimation outcomes resulting from the two techniques for the baseline model as expressed in Eq. (1). Columns (1)–(3) report the OLS estimates and columns (4)–(6) show the PPML results.

The coefficients for the RE policy variables are positive and statistically significant at above the 5% level in all estimations. This indicates that the implementation of RE policies on average has positive effects on the RE sector's development, and this finding is robust to the two estimation techniques and to these policy measures. However, there are substantial quantitative differences between the OLS and PPML estimations. The coefficients for all three policy variables are much larger in the PPML estimations than in the OLS ones, confirming the OLS estimator's severe bias due to a large number of zero observations.

Since the PPML model is a non-linear model, for a dummy variable like *poldum* that can only take on the value of either 0 or 1, it is inappropriate to interpret its coefficient as the marginal effect, as in the case of linear models. As such, it is better to focus on its qualitative results, which support the aforementioned conclusion. For the other two policy variables, since they are continuous, their coefficients can be interpreted as a linear approximation of the marginal effect.[7] The quantitative results from these two policy variables are quite comparable. A one standard deviation increase in *polavg* and *polpca* is expected to increase the share of non-hydro RE generation by approximately 3.8 and 3.5 standard deviations, respectively.[8]

Regarding the control variables, most of them are significant at above the 10% level and give consistent results in different estimations, vindicating their inclusion. In all cases the coefficients of energy imports, financial development and human capital are significant and positive. This shows that increase in foreign energy dependence, improvement in financial market quality and accumulation of human capital could contribute to the RE sector's development. The coefficient of lagged CO_2 intensity is significant and negative, suggesting that CO_2 emissions play a negative role in encouraging RE generation. This finding accords well with Marques et al. (2010) who argue that social pressure for better environment does not always weigh in the decision process of choosing amongst renewable and nonrenewable energy sources. If the CO_2 intensity reflects the demand for energy and such demand leads to a faster investment in the non-RE sector than in the RE sector, then it is plausible for the CO_2 intensity variable to be negatively related to the share of RE generation. Furthermore, the coefficient of working age population variable is also negative, reflecting that economic growth prompted by a larger working age population raises the demand for traditional fossil energy. The significance of the coefficients of per capita income and FDI are not consistent across the OLS and PMLL estimations, and the coefficients of the ratio of females to total population changes sign between the OLS and PPML estimates. The PPML estimations, which are not biased by the piling up of zero observations, confirm the positive relationship between RE generation and the proportion of females. Although the proportion of females and the proportion of working age population seems have a much larger coefficient than other control variables, it should be read against the background that the two variables are also of much smaller standard deviations (see Table A1). Finally, the positive relationship between RE generation and expansion

[7] The unit of the marginal effect is the share of non-hydro RE generation per extra RE policy instrument.

[8] The calculation is based on the standard deviation figures from Table A1 of the Appendix. For instance, for *polavg*, 0.935*0.25/0.061 = 3.83. This is only a linear approximation because the Poisson model is a non-linear model.

Table 1
Baseline regression results.

Estimator		OLS			PPML		
		(1)	(2)	(3)	(4)	(5)	(6)
Policy variable	Poldum	0.00887**			0.465***		
		(0.00366)			(0.130)		
	Polavg		0.0202***			0.935***	
			(0.00712)			(0.197)	
	Polpca			0.0187**			0.889***
				(0.00734)			(0.192)
Control variable	Ln (income)	0.00538***	0.00502***	0.00518***	0.0848	0.0659	0.0714
		(0.00188)	(0.00189)	(0.00189)	(0.0577)	(0.0576)	(0.0584)
	Ln (CO_2 intensity)	−0.0183***	−0.0185***	−0.0185***	−0.789***	−0.850***	−0.848***
		(0.00286)	(0.00286)	(0.00286)	(0.0787)	(0.0808)	(0.0806)
	Energy imports	0.00539***	0.00540***	0.00543***	0.565***	0.563***	0.560***
		(0.000940)	(0.000939)	(0.000940)	(0.0943)	(0.0930)	(0.0923)
	Ln (financial development)	0.0108***	0.0106***	0.0107***	0.269***	0.272***	0.274***
		(0.00233)	(0.00233)	(0.00233)	(0.0769)	(0.0757)	(0.0759)
	Ln (human capital)	0.0210***	0.0221***	0.0220***	0.962***	1.083***	1.080***
		(0.00462)	(0.00463)	(0.00463)	(0.207)	(0.204)	(0.206)
	Ln (FDI)	0.00159*	0.00166*	0.00165*	0.0649	0.0734	0.0739
		(0.000933)	(0.000933)	(0.000934)	(0.0560)	(0.0573)	(0.0578)
	Ln (female)	−0.0973***	−0.0974***	−0.0959***	6.882**	6.577**	6.480**
		(0.0318)	(0.0316)	(0.0316)	(2.934)	(2.920)	(2.889)
	Ln (working age population)	−0.364***	−0.358***	−0.358***	−11.83***	−11.68***	−11.67***
		(0.0255)	(0.0255)	(0.0255)	(0.860)	(0.850)	(0.849)
Constant	1.692***	1.671***	1.664***	10.11	10.48	10.78	
	(0.170)	(0.169)	(0.169)	(10.48)	(10.56)	(10.47)	
Year fixed effects		Yes	Yes	Yes	Yes	Yes	Yes
Region fixed effects		Yes	Yes	Yes	Yes	Yes	Yes
R^2		0.218	0.219	0.219	0.272	0.272	0.271
Observations		1812	1812	1812	1812	1812	1812

Note: Numbers in parentheses are standard errors.
* indicates statistical significance at the 10% level.
** indicates statistical significance at the 5% level.
*** indicates statistical significance at the 1% level.

of economic power and inflows of FDI as suggested by the literature is not empirically conclusive.

3.2. Heterogeneous effects of different energy sources and policy instruments

Different policy instruments generally produce different policy outcomes (Johnstone et al., 2010). In this section, we test whether the effectiveness of RE policy varies by policy instrument and by energy source. To save space, Table 2 presents the PPML results for the policy variables only. Each policy variable enters the regression as a dummy variable. Columns (1)–(3) show the results when all the individual policy variables are introduced into the same regressions together, while columns (4)–(6) present the results when the six policy variables are introduced into the regressions one by one.

Investment incentives and feed-in tariffs are found to have significant and positive effects for all renewable energy sources for electricity, regardless of whether other policy variables are included or excluded. Tax incentives and production quotas are found to have significant and positive effects on the biomass and waste electricity generation only. In addition, we find that the effects of some policy instruments are sensitive to the inclusion of other variables. For example, voluntary programs seem to be effective in promoting solar, tide and wave energy when other policy instruments are excluded as in column (5), but not so when other policy instruments are controlled for as in column (2). This could be a consequence of the correlation between the policy variables.[9]

One unexpected finding is the significant but negative effect of production quotas on the wind RE production, and voluntary programs on the wind, the biomass and waste RE production.[10] A possible explanation comes from Johnstone et al. (2010), who argue that RE policies are often concurrent with energy efficiency policies, and given the level of energy consumption, increasing energy efficiency can alleviate the lack of fossil energy sources, and thus reduce demand for RE.

3.3. The more RE policies, the better?

Many RE policies have overlapping objectives and interact with each other to a degree. For example, investment incentives for capital goods may be accompanied by tax incentives for final goods. As a consequence, the effects generated by a RE policy may be affected by other coexisting policies (Azuela and Barroso, 2011; De Jonghe et al., 2009; Fischer and Preonas, 2010; Philibert, 2011). Specifically, the effectiveness of an RE policy will be enhanced by complementary policies but diminished by overlapping or uncoordinated policies.[11] That is, if there is policy complementarities,

[9] The correlation coefficients of different policy instrument variables are provided in the appendix.

[10] Delmas and Montes-Sancho (2011) find that the renewable portfolio standard policy also has a negative impact on investments in RE capacity. They attribute this to the key role of social and economic conditions in determining policy effectiveness.

[11] IEA (2008) finds that the combination of federal production tax credits and state level policies such as incentives and production quotas promote wind power growth significantly, while "neither federal nor state support has been sufficient in isolation". Regarding uncoordinated policies, a recent case is from South Africa. In 2009, while the finishing touches to RE feed-in tariffs were being made by the national energy regulator of South Africa, the then Department of Minerals and Energy Affairs introduced a requirement for independent power projects to launch

Table 2
PPML test results for individual policy.

Dependent variable	All-together introduction results			One-by-one introduction results		
	Biomass and waste (1)	Solar, tide and wave (2)	Wind (3)	Biomass and waste (4)	Solar, tide and wave (5)	Wind (6)
Investment incentives	0.446***	0.755***	0.935***	0.694***	0.766***	0.945***
	(0.127)	(0.261)	(0.244)	(0.134)	(0.219)	(0.255)
Feed-in tariffs	0.297**	0.746***	0.729***	0.421***	0.818***	0.857***
	(0.136)	(0.279)	(0.166)	(0.152)	(0.172)	(0.177)
Tax incentives	0.478***	−0.724	0.0546	0.735***	−0.382	0.194
	(0.128)	(0.452)	(0.199)	(0.117)	(0.409)	(0.209)
Voluntary programs	−0.758***	0.216	−0.293*	−0.546***	0.414*	−0.288*
	(0.112)	(0.202)	(0.160)	(0.120)	(0.212)	(0.160)
Production quotas	0.253*	0.310	−0.584***	0.483***	0.203	−0.403***
	(0.153)	(0.249)	(0.146)	(0.135)	(0.260)	(0.140)
Tradable certificates	−0.0603	−0.300	0.0276	0.279**	−0.309	−0.255*
	(0.148)	(0.573)	(0.161)	(0.117)	(0.534)	(0.153)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: numbers in parentheses are standard errors.

* indicates statistical significance at the 10% level.
** indicates statistical significance at the 5% level.
*** indicates statistical significance at the 1% level.

then one would expect to see the RE policy effect increase faster than the number of policies being put in place. On the other hand, if there is policy conflict, then one may observe the policy effect decreasing as more policies are launched.[12] Lastly, if different policies are largely duplicating each other, then the RE policy effect would stay the same or increase at a decreasing rate with the number of policies. To test which of these scenarios dominate, we modify the baseline model by including a squared term of the policy variable to investigate the non-linear effects of RE policies. Empirical test results based on the OLS and PPML estimator are presented in Table 3.

The results for all control variables are very similar to those in Table 1. Therefore, we focus on the RE policy variables and their squared terms only. Since *Poldum* is a dummy variable, we do not consider it in this non-linear specification. When *polavg* is used as the policy variable, the coefficients of the policy variables are significant and positive, and the coefficients of the policy-squared variables are negative and significant, regardless of which estimation method is used. Similar results are found for *polpca* in that its coefficient is significant and positive while that of its squared term is significant and negative in all regressions. The results indicate that the inverse-U shape relationship between the two policy variables and the share of non-hydro RE generation as depicted in Figs. 1 and 2 remain robust after controlling for other factors.

The findings confirm a diminishing or even conflicting effect of RE policies on renewable electricity generation. When RE policies are scarce, their adaption bears a strong incentive for RE generation. However, as the number of policy instruments increases, especially when the strength of policy instruments reaches a certain level, the policy effects plateau or even decline. In other words, a greater number of policy instruments do not always bring about stronger policy effects, and the consideration of policy overlapping and interaction is very important in designing multiple RE policies.

3.4. Does the stage of economic development matter?

Some studies have pointed out that local economic conditions, natural endowment, and institutional environment are important factors in determining the effectiveness of RE policies (Delmas and Montes-Sancho, 2011; Klein et al., 2008). Hence, it could be hypothesized that the effects of RE policies on RE generation may vary across different groups of countries. In this section, we empirically test this hypothesis by separating our sample into three mutually exclusive subsamples for developed countries, developing countries, and emerging market countries respectively. The summary statistics for RE generation and RE policy variables for each of these three groups are provided in Appendix A. As expected, on average RE generation makes up a larger proportion of total electricity generation in developed countries than in emerging market countries, which in turn is larger than in developing countries. Also, the number of RE policy instruments

(*footnote continued*)
a tender process to obtain permits and licenses to produce RE. The latter may create red tape that mitigates the effect of the feed-in tariff policies.

[12] In addition to the interactions between RE policies and other environmental and climate policies, such as emissions trading system in European countries (Abrell and Weigt, 2008; De Jonghe et al., 2009; Philibert, 2011), there are also policy conflicts among RE policies. In the late 1990s and early 2000s, many states in the U.S. adopted the renewable energy portfolio standards (RPS), which rely on a competitive framework and aim to meet renewable energy targets at a minimum cost. However, after the installment of the RPS, many new RE policies have also been deployed, seeking to achieve other objectives such as environmental benefits, supporting emerging RE technologies and promoting specific renewable energy resources. This however results in tension amongst different policy objectives (Grace et al., 2011). For example, driven by the aim to benefit the local, more in-state RE generations have been used despite their higher cost. Furthermore, some less mature and costly technologies have been prompted as they are expected to become lower-cost RE resources in the future. Another example of policy conflict comes from Australia. The Queensland solar bonus scheme (QSBS) and the small-scale renewable energy scheme (SRES) are the two major policies promoting the implementation of small-scale RE technologies in Queensland, Australia. A difference between these two schemes is that the QSBS is restricted to supporting only solar photovoltaic(PV) rooftop systems, whereas the SRES fosters a wider variety of technologies including small-scale wind and solar hot water systems. In 2009, the solar credit multiplier system commenced in Queensland, which awarded five renewable electricity certificates (REC) per Megawatt hour (MWh) to each small residential solar PV, wind or hydro system instead of the usual one REC/MWh. The solar credit multiplier had made the QSBS more attractive, promoting a massive growth in solar PV. However, the growth of solar PV bring about a crowding-out effect on other RE technologies supported within the SRES policy such as wind and solar hot water system. Based on the data from the Australia Government Clean Energy Regulator, while the quantity of installation of solar PV increased about 96 percentages from 2010 to 2011 in Queensland, the quantity of solar water heater installation decreased around 11 percentages during this period, and there was even no new wind installation in 2011.

Table 3
Test results of policy interaction effects.

Estimator		OLS		PPML	
		(1)	(2)	(3)	(4)
Policy variable	Polavg	0.0644***		2.571***	
		(0.0189)		(0.601)	
	Polavg-squared	−0.0621**		−1.996***	
		(0.0246)		(0.592)	
	Polpca		0.0731***		2.842***
			(0.0192)		(0.623)
	Polpca-squared		−0.0766***		−2.383***
			(0.0250)		(0.632)
Control variable	Ln (income)	0.00490***	0.00498***	0.0399	0.0387
		(0.00189)	(0.00189)	(0.0555)	(0.0556)
	Ln (CO_2 intensity)	−0.0180***	−0.0180***	−0.803***	−0.799***
		(0.00286)	(0.00286)	(0.0828)	(0.0824)
	Energy imports	0.00544***	0.00545***	0.578***	0.576***
		(0.000938)	(0.000937)	(0.0940)	(0.0935)
	Ln (financial development)	0.0106***	0.0106***	0.264***	0.266***
		(0.00233)	(0.00233)	(0.0742)	(0.0739)
	Ln (human capital)	0.0212***	0.0211***	1.036***	1.037***
		(0.00464)	(0.00463)	(0.203)	(0.202)
	Ln (FDI)	0.00158*	0.00155*	0.0669	0.0667
		(0.000932)	(0.000933)	(0.0546)	(0.0545)
	Ln (female)	−0.104***	−0.104***	7.510**	7.573**
		(0.0317)	(0.0317)	(3.095)	(3.093)
	Ln (working age population)	−0.364***	−0.365***	−11.89***	−11.92***
		(0.0256)	(0.0256)	(0.873)	(0.874)
Constant	1.722***	1.725***	8.020	7.884	
	(0.170)	(0.170)	(10.99)	(10.98)	
Year fixed effects		Yes	Yes	Yes	Yes
Region fixed effects		Yes	Yes	Yes	Yes
R^2		0.222	0.223	0.280	0.282
Observations		1812	1812	1812	1812

Note: numbers in parentheses are standard errors.

* indicates statistical significance at the 10% level.

** indicates statistical significance at the 5% level.

*** indicates statistical significance at the 1% level.

being implemented increases with the state of development, with developed countries on average having 1.62 RE policy instruments in place, compared to 0.84 in emerging market countries and 0.17 in developing countries. There is no clear evidence that certain country groups favor certain policy instruments, in that the order of popularity of the six policy instruments is roughly the same across the three countries groups. Investment incentives are the most popular RE policy instrument, followed by tax incentives, then equally by feed-in tariffs and voluntary programs, then by production quotas, and finally by tradable certificates.

Table 4 reports the PPML estimation results only, to save space. Columns (1) and (3) exclude the squared term of the policy variable, while columns (2) and (4) include it. Starting with the developed countries, we find that the coefficient of the policy variable (represented by *polavg* or *polpca*) is significant and positive in all estimations, indicating that public RE policies are very effectual in this country group. Furthermore, the squared term of the policy variable in columns (2) and (4) is significant and negative. For emerging market countries, the coefficient of the policy variable is also significant and positive in all estimations, and that of its squared term is negative and highly significant. Lastly, for developing countries, the policy variable is positive but insignificant by itself in columns (1) and (3), but becomes negative in columns (2) and (4) when its squared term is also included, and both the policy variable and its squared term are insignificant, regardless of which measure of policy variable is applied.

A comparison of the results for the three country groups is revealing. First of all, while the policy variable is positive for all three country groups, it is significant only for emerging market and developed countries. This finding indicates that the effects of RE policy are discernable in the developed and emerging market country groups, but not in developing countries. Furthermore, there is also evidence of policy interaction effects in developed and emerging market countries, and the magnitude of the coefficient for the policy squared term relative to that for the policy term (in absolute terms) is increasing as it moves from developed countries to emerging market countries. These findings mean that the negative policy interaction becomes smaller in magnitude as the level of development increases. A possible explanation is that developed countries have better institutions and, as the first adapter of RE, richer experience to formulate coherent RE policies. This is consistent with the finding of IEA (2008) that “those EU–OECD countries which, overall, have a longer history of RE policies, feature among the countries with the highest policy effectiveness for all new renewable electricity generation technologies”.

3.5. *Does the effectiveness of RE policies change over times?*

In this section, we test whether the effect of RE policies varies over time by separating our sample into two subsamples for, respectively, 1980–1995 and 1996–2010. The timespan of the two subsamples is roughly the same. The summary statistics for the key variables for each of the two periods are provided in Appendix A. More RE policies have been implemented after the mid-1990s. Specifically, 1.44 RE policy instruments for one country are in place on average in 1996–2010, compared to 0.14 in 1980–1995. This finding is consistent with the development of RE policies. The energy crisis of the 1970s triggered the first wave of RE policy

Table 4
PPML test results for different country groups.

Country group	Policy variable	(1)	(2)	(3)	(4)
Developed countries	Polavg	0.855***	2.377***		
		(0.323)	(0.684)		
	Polavg-squared		−1.552**		
			(0.632)		
	Polpca			0.762**	2.591***
				(0.328)	(0.706)
	Polpca-squared				−1.858***
					(0.655)
	R^2	0.411	0.420	0.405	0.417
	Observations	623	623	623	623
Emerging market countries	Polavg	0.540*	2.605***		
		(0.282)	(0.961)		
	Polavg-squared		−2.997**		
			(1.344)		
	Polpca			0.520*	2.742***
				(0.295)	(0.953)
	Polpca-squared				−3.231**
					(1.339)
	R^2	0.847	0.846	0.847	0.847
	Observations	475	475	475	475
Developing countries	Polavg	0.160	−0.523		
		(0.609)	(2.393)		
	Polavg-squared		1.064		
			(3.333)		
	Polpca			0.209	−0.544
				(0.634)	(2.495)
	Polpca-squared				1.171
					(3.467)
	R^2	0.519	0.518	0.519	0.518
	Observations	771	771	771	771
Year fixed effects		Yes	Yes	Yes	Yes
Region fixed effects		Yes	Yes	Yes	Yes

Note: numbers in parentheses are standard errors.

* indicates statistical significance at the 10% level.
** indicates statistical significance at the 5% level.
*** indicates statistical significance at the 1% level.

responses in most part of the developed world, whereas these policies stopped expanding when oil prices started falling in the early 1980s (Nicolli and Vona, 2012b). In 1982, only 20 countries had adopted policies to support RE production, and most of the spending on RE in these countries focused on research and development, and demonstration rather than actual generation. In response to increasing world energy demand and concern for climate change mitigation, a number of RE policies especially market-based instruments like taxes and incentives were enacted in the 1990s to promote RE power generation, and the adoption of new policies and targets accelerated further in the 2000s. The number of countries with RE policies in 1994 was 25, more than doubled to 55 in 2005, and to over 120 in 2012.

Table 5 reports the PPML estimation results only, to save space. Columns (1)–(3) present the results for 1980–1995, while columns (4)–(6) give the results for 1996–2010.

The magnitudes of the coefficients of policy variables are larger for the period 1980–1995 than for the period 1996–2010, regardless of how the aggregate RE policy variable is constructed. This finding suggests that although RE policies play an important role in promoting RE deployment in both periods, the effects of RE policies are more pronounced for the period 1980–1995. For instance, the results of columns (2) and (3) indicate that a one standard deviation increase in *polavg* and *polpca* is associated with 5.5 and 5.3 standard deviations increase in the share of non-hydro RE generation, respectively, while the results of columns (5) and (6) indicate that a one standard deviation increase in *polavg* and *polpca* is expected to increase the share of non-hydro RE generation by only 3.0 and 2.6 standard deviations, respectively. A possible explanation for this finding is that in the 1980s and the early 1990s, both the non-hydro RE generation and the number of RE policies are at low level of bases, therefore RE policies have a greater marginal effect on RE generation. In addition in 1980–1995, countries that have adopted RE policies are mostly developed countries, and RE policies are more likely to have greater effectiveness in these countries as they have better institutions to carry out the policies. Finally, one unexpected result that requires further investigation is the sign of financial development changing over the two periods.

4. Conclusions

In this paper, we investigate the effectiveness of renewable electricity (RE) policies in promoting RE generation, using a much larger dataset than in previous studies. Our dataset covers 122 countries over the period of 1980–2010. Overall, the empirical results suggest that RE policies have significant positive impacts on the development of the RE sector, and the conclusion is robust to various techniques and policy measures. Furthermore, there is evidence of a negative effect of ‘policy crowdedness’ in that the effect of RE policy diminishes or even reveres as more and more RE policies are put in place. The positive effects of RE policy are found to have bigger marginal effect on RE production before 1996 than after, and there are less negative policy interaction effects in more

Table 5
PPML test results for different periods.

Estimator		1980–1995			1996–2010		
		(1)	(2)	(3)	(4)	(5)	(6)
Policy variable	Poldum	0.616^{**}			0.416^{***}		
		(0.288)			(0.157)		
	Polavg		3.564^{***}			0.671^{***}	
			(1.057)			(0.215)	
	Polpca			3.750^{***}			0.606^{***}
				(1.130)			(0.210)
Control variable	Ln (income)	0.145	0.121	0.126	0.0683	0.0511	0.0572
		(0.0979)	(0.0960)	(0.0960)	(0.0775)	(0.0778)	(0.0793)
	Ln (CO_2 intensity)	-0.917^{***}	-0.928^{***}	-0.930^{***}	-0.631^{***}	-0.689^{***}	-0.680^{***}
		(0.131)	(0.128)	(0.128)	(0.0993)	(0.105)	(0.105)
	Energy imports	0.668^{***}	0.670^{***}	0.675^{***}	0.551^{***}	0.543^{***}	0.538^{***}
		(0.124)	(0.106)	(0.106)	(0.115)	(0.113)	(0.112)
	Ln (financial development)	-0.185^{*}	-0.207^{*}	-0.204^{*}	0.433^{***}	0.438^{***}	0.442^{***}
		(0.109)	(0.110)	(0.110)	(0.0987)	(0.0979)	(0.0980)
	Ln (human capital)	1.595^{***}	1.671^{***}	1.662^{***}	0.704^{**}	0.844^{***}	0.845^{***}
		(0.300)	(0.259)	(0.262)	(0.321)	(0.319)	(0.320)
	Ln (FDI)	0.200^{**}	0.197^{**}	0.198^{**}	−0.0162	−0.00281	−0.00274
		(0.0932)	(0.0828)	(0.0842)	(0.0803)	(0.0834)	(0.0837)
	Ln (female)	36.39^{***}	37.62^{***}	37.49^{***}	−1.867	−2.120	−2.057
		(4.054)	(4.114)	(4.094)	(2.869)	(2.814)	(2.778)
	Ln (working age population)	-17.21^{***}	-17.65^{***}	-17.60^{***}	-10.75^{***}	-10.75^{***}	-10.75^{***}
		(1.148)	(1.168)	(1.158)	(1.191)	(1.208)	(1.206)
Constant	-85.62^{***}	-88.78^{***}	-88.46^{***}	42.07^{***}	42.68^{***}	42.38^{***}	
	(15.33)	(15.50)	(15.47)	(10.90)	(10.78)	(10.66)	
Year fixed effects		Yes	Yes	Yes	Yes	Yes	Yes
Region fixed effects		Yes	Yes	Yes	Yes	Yes	Yes
R^2		0.462	0.488	0.486	0.253	0.248	0.249
Observations		849	849	849	963	963	963

Note: numbers in parentheses are standard errors.

* indicates statistical significance at the 10% level.
** indicates statistical significance at the 5% level.
*** indicates statistical significance at the 1% level.

Table A1
Variable definitions and summary statistics, $N=1812$.

Variable	Definition	Source	Mean	Std. dev	Min.	Max.
Non-hydro RE	Electricity generation produced from non-hydro renewable energy as a proportion of total electricity generation.	EIA	0.029	0.061	0	0.76
Biomass and waste	Electricity generation produced from biomass and waste energy as a proportion of total electricity generation.	EIA	0.012	0.033	0	0.71
Solar, tide and wave	Electricity generation produced from solar, tide and wave energy as a proportion of total electricity generation.	EIA	0.00012	0.00077	0	0.021
Wind	Electricity generation produced from wind energy as a proportion of total electricity generation.	EIA	0.0033	0.016	0	0.19
Investment incentives	Dummy variable, coded as 1 if investment incentives are adopted, 0 otherwise.	IEA	0.26	0.44	0	1.0
Feed-in tariffs	Dummy variable, coded as 1 if feed-in tariffs are adopted, 0 otherwise.	IEA	0.12	0.32	0	1.0
Tax incentives	Dummy variable, coded as 1 if tax incentives are adopted, 0 otherwise.	IEA	0.17	0.37	0	1.0
Voluntary programs	Dummy variable, coded as 1 if voluntary programs are adopted, 0 otherwise.	IEA	0.11	0.32	0	1.0
Production quotas	Dummy variable, coded as 1 if production quotas are adopted, 0 otherwise.	IEA	0.10	0.30	0	1.0
Tradable certificates	Dummy variable, coded as 1 if tradable certificates are adopted, 0 otherwise.	IEA	0.057	0.23	0	1.0
Poldum	Dummy variable, coded as 1 if any of renewable electricity policies are adopted, 0 otherwise.	IEA	0.29	0.46	0	1.0
Polavg	Average of all policy dummies and normalized as to range from 0 to 1	IEA	0.14	0.25	0	1.0
Polpca	First component and normalized as to range from 0 to 1	IEA	0.13	0.24	0	1.0
Income	Real GDP per capita in 2000 year USD	WDI	9435	10979	102	56389
CO_2 intensity	CO_2 emissions per GDP	WDI	2.15	0.88	0.11	6.14
Energy imports	Ratio of net energy imports to total energy consumption	WDI	−0.18	1.68	−16.79	1.0
Financial development	Domestic credit to private sector as a proportion of GDP	WDI	0.57	0.45	0.015	3.19
Human capital	Secondary school enrollment as a proportion of gross enrollment	WDI	0.74	0.31	0.043	1.62
FDI	FDI net inflows as a proportion of GDP	WDI	0.047	0.26	0	5.24
Female	Ratio of female to total population	WDI	0.50	0.024	0.31	0.54
Working age population	Working-age population a proportion of total population	WDI	0.62	0.061	0.47	0.81

EIA: Energy Information Administration. WDI: World Development Indicators. IEA: International Energy Agency.

developed countries. Finally, the effectiveness of RE policy varies by policy instrument and by renewable sources for electricity. Only investment incentives and feed-in tariffs are found to have positive effects on all three types of renewable sources for electricity considered in this paper; other policy instruments like tax incentives, voluntary programs, production quotas and tradable certificates have effects only on specific sources of RE.

Our empirical investigations have strong policy implications. Since RE policies are major driving forces of RE development, it is feasible for developing countries to learn the best policy practice from successful countries to promote their RE deployment. Furthermore, due to the policy interaction effects, to further improve the effectiveness of RE policy, governments should make special efforts to assess the compatibility among RE policies and other regulatory mechanisms. If some RE policies are given first consideration and a longer-term role, other policies should be adjusted to take the existing policies into account. This would help reduce policy overlapping and incoherence and improve the overall policy effectiveness. Lastly, considering the fact that some policy instruments are effective only for specific renewable sources for electricity, it is also vital for governments to incorporate specific goals of RE production outcomes and local social, institutional and economic conditions into the policy design.

Acknowledgments

This paper is funded by the Fundamental Research Funds for the Central Universities and the Research Funds of Renmin University of China (No. 12XNK021). The authors would like to thank the anonymous reviewer and Liam Wagner for their comments and suggestions.

Table A2
Summary statistics of selected variables by country groups.

Country group	Developed countries				Emerging market countries				Developing countries			
	Mean	Std. dev	Min.	Max.	Mean	Std. dev	Min.	Max.	Mean	Std. dev	Min.	Max.
Non-hydro RE	0.038	0.065	0	0.76	0.021	0.047	0	0.26	0.025	0.062	0	0.41
Biomass and waste	0.021	0.046	0	0.71	0.0062	0.011	0	0.070	0.0082	0.024	0	0.16
Solar, tide and wave	0.00030	0.0013	0	0.021	0.000010	0.000070	0	0.0013	0.000030	0.00019	0	0.0019
Wind	0.0085	0.026	0	0.19	0.00060	0.0022	0	0.020	0.00065	0.0035	0	0.034
polavg	0.27	0.30	0	1	0.14	0.24	0	0.83	0.028	0.12	0	0.83
polpca	0.26	0.30	0	1	0.13	0.23	0	0.82	0.026	0.11	0	0.83
Investment incentives	0.49	0.50	0	1	0.29	0.45	0	1	0.067	0.25	0	1
Tax incentives	0.33	0.47	0	1	0.16	0.36	0	1	0.039	0.19	0	1
Feed in tariffs	0.24	0.43	0	1	0.13	0.33	0	1	0.023	0.15	0	1
Voluntary programs	0.23	0.42	0	1	0.12	0.33	0	1	0.016	0.12	0	1
Production quotas	0.22	0.41	0	1	0.11	0.31	0	1	0.014	0.12	0	1
Tradable certificates	0.13	0.34	0	1	0.027	0.16	0	1	0.010	0.10	0	1

Table A3
Summary statistics of selected variables by different periods.

Sub-Period	1980–1995				1996–2010			
	Mean	Std. dev	Min.	Max.	Mean	Std. dev	Min.	Max.
Non-hydro RE	0.021	0.052	0	0.41	0.036	0.067	0	0.76
Biomass and waste	0.0081	0.022	0	0.35	0.016	0.039	0	0.71
Solar, tide and wave	0.000033	0.00021	0	0.0021	0.00019	0.0010	0	0.021
Wind	0.00030	0.0025	0	0.032	0.0060	0.021	0	0.19
Polavg	0.024	0.080	0	0.50	0.24	0.30	0	1
Polpca	0.021	0.074	0	0.52	0.22	0.29	0	1
Investment incentives	0.068	0.25	0	1	0.43	0.49	0	1
Tax incentives	0.028	0.17	0	1	0.29	0.45	0	1
Feed in tariffs	0.024	0.15	0	1	0.20	0.40	0	1
Voluntary programs	0.0071	0.084	0	1	0.21	0.41	0	1
Production quotas	0.0094	0.097	0	1	0.19	0.39	0	1
Tradable certificates	0.0047	0.069	0	1	0.10	0.31	0	1

Table A4
Correlation Coefficient of Six Policy Instrument Variables.

Correlation coefficient	Investment incentives	Tax incentives	Feed-in tariffs	Voluntary programs	Production quotas	Tradable certificate
Investment incentives	1.00					
Tax incentives	0.65	1.00				
Feed in tariffs	0.53	0.45	1.00			
Voluntary programs	0.56	0.49	0.33	1.00		
Production quotas	0.51	0.47	0.42	0.38	1.00	
Tradable certificate	0.38	0.47	0.17	0.34	0.41	1.00

Appendix A

Please see Table A1–A4.

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