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Research article

The impacts of the 1997 Asian financial crisis and the 2008 global financial crisis on renewable energy consumption and carbon dioxide emissions for developed and developing countries

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ABSTRACT

This paper examines whether the 1997 Asian financial crisis affected the renewable energy/carbon dioxide (CO_2) emissions relationship differently when compared to the 2008 global financial crises. Using the Dynamic Panel Data Model, we examine separately the impact of the 1997 crisis and the 2008 crises on the stated relationship for annual data between the 1987–2018 period for a group of high, upper-middle, and lower middle-income countries. Our findings suggest that the results were crisis and country specific. For the overall sample, the relationship between the two variables was positive (and significant post-1997 and pre-2008 crises) but negative post-2008 crisis. In contrast, the positive relationship remained unchanged for the lower middle-income subsample through the two crises. We also find evidence that the 1997 Asian crisis altered the relationship differently than the 2008 financial crisis especially for the upper and middle-income groups. Clearly, reduction of CO_2 emissions may not be guaranteed even if host countries adopt renewable energy sources since country income levels and the nature of the crisis may matter. Future research may consider how the degree of pollution controls and differential costs of renewable energy adoption in countries may alter this relationship.

1. Introduction

Research examining the renewable energy consumption/carbon dioxide (CO_2) emission links for developing countries are extensive and generally recommend policies to ratchet up the local renewable energy infrastructure to encourage renewable energy consumption (Pao and Tsai, 2011; Shahbaz et al., 2013; Zhu et al., 2016), particularly for lower income countries to allow them to attract foreign direct investment (FDI) aimed at inflows of technology transfer (Omri and Kahouli, 2014; Doytch and Narayan, 2016). Extant literature also documents links between global financial crises and the transmission of technological innovation to recipient countries. For instance, Colombo et al. (2016), Zouaghi and Sánchez (2016), and Zouaghi et al. (2018) show the firms devise survival and growth strategies designed to overcome global financial crises by developing innovation products. Although there is extensive work on the factors that affect the renewable energy adoption/CO_2 emissions relationship, there is scant work (with few recent exceptions) on how a crisis will alter this relationship. The exception includes recent work by Dong et al. (2020) who show that countries switching to renewable energy sources reduced CO_2 emissions (but not statistically significantly) post-2008 crisis[1] versus pre-2008 crisis levels for a sample of 120 countries.

In this paper, we add to the emerging literature by examining whether the renewable energy/pollution links were also similarly altered during the 1997 crisis. We conjecture that the impact of the 2008 crisis affected global economies differently than the 1997 crisis. Hence, we conjecture that the differential effects on country macroeconomic variables can imply differences in the relationship between renewable energy adoption and CO_2 emissions pre and post each crisis. If the pre/post link changes were different for the 1997 crisis versus the 2008 crisis, then policy prescriptions useful for one crisis may not work for other crises. We don't believe that this issue has been investigated in the extant literature. Specifically, we conjecture that the renewable energy consumption - CO_2 emission relationship was altered differently by the 1997 crisis than by

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[1] Henceforth, we will refer to the 1997 Asian crisis as the 1997 crisis and to the 2008 financial crisis as the 2008 crisis.

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Table 1. Descriptive statistics, sample variables for the entire period (1987–2018), and for each subperiod: 1987–1996 (period 1), 1998–2007 (period 2), and 2009–2018 (period 3). Overall sample.

	Time Period	CO_2	Renewable Energy	FDI	Export	Import	GDP
Mean	1987–2018	492.223	70.579	2.584	24.961	24.998	26.250
	1987–1996	359.641	45.893	1.563	24.116	24.172	25.612
	1998–2007	478.110	59.370	3.490	24.977	24.993	26.191
	2009–2018	638.918	106.474	2.698	25.790	25.828	26.947
Median	1987–2018	97.051	19.769	1.558	24.979	24.995	26.251
	1987–1996	72.623	12.277	0.984	24.114	24.160	25.514
	1998–2007	114.081	18.608	2.390	25.035	24.992	25.989
	2009–2018	165.797	28.359	1.813	25.927	25.735	26.617
Maximum	1987–2018	10064.690	1836.653	31.721	28.606	28.772	30.685
	1987–1996	5625.042	416.184	14.331	27.470	27.586	29.732
	1998–2007	6861.751	500.720	31.721	28.134	28.489	30.350
	2009–2018	10064.690	1836.653	24.304	28.606	28.772	30.685
Minimum	1987–2018	1.839	0.003	-12.284	21.005	21.290	22.433
	1987–1996	1.839	0.003	-0.511	21.005	21.290	22.433
	1998–2007	2.635	0.020	-4.263	21.779	21.863	22.839
	2009–2018	3.462	0.099	-12.284	22.578	22.379	23.209
Std. Dev.	1987–2018	1332.833	156.007	3.560	1.555	1.500	1.500
	1987–1996	921.093	82.629	2.168	1.423	1.362	1.435
	1998–2007	1201.536	103.096	4.153	1.429	1.378	1.419
	2009–2018	1734.202	231.648	3.776	1.340	1.280	1.338
Skewness	1987–2018	4.637	5.433	3.630	-0.120	-0.046	0.221
	1987–1996	4.341	2.612	3.400	-0.033	0.028	0.277
	1998–2007	4.008	2.373	3.266	-0.150	0.019	0.387
	2009–2018	4.171	4.266	3.471	-0.091	-0.031	0.332
Kurtosis	1987–2018	25.991	45.090	20.992	2.469	2.619	3.230
	1987–1996	21.775	9.107	16.531	2.371	2.533	3.155
	1998–2007	18.216	7.428	16.381	2.272	2.510	3.247
	2009–2018	20.150	24.775	19.683	2.357	2.726	3.773
Observations	1987–2018	1110	1110	1110	1110	1110	1110
	1987–1996	370	370	370	370	370	370
	1998–2007	370	370	370	370	370	370
	2009–2018	370	370	370	370	370	370

Notes: 1. Periods are defined as the following. The entire sample period includes annual data from 1987 to 2018 (inclusive) but excludes data for 1997 (the year of the 1997 crisis and for 2008 (the year of the 2008 crisis). Period 1 includes date from 1987 through 1996, period 2 (1998–2007), and period 3 (2009–2018). Period 1 can be viewed as the period before the 199 crisis, period 2 as the period between the two crisis, and period 3 as the period following the 2008 crisis.

the 2008 crisis and may also be a function of the level of economic development of host countries. Using the Dynamic Panel Data Model (DPDM), we examine separately the impact of the 1997 and the 2008 crises on the stated relationship for annual data between the 1987–2018 period collectively and separately for a group of high, upper middle, and lower middle-income countries.[2] Conducting tests using the same set of countries over two different types of crises allows us to compare our findings across crises and derive appropriate policy implications.

2. Literature review and rationale for this study

2.1. The renewable energy consumption/CO_2 emissions literature

A vast body of literature examining the links between renewable energy consumption and CO_2 emissions for many countries provides mixed results. Research indicates that increased use of renewable energy is associated with a subsequent reduction in CO_2 emissions in developed countries, namely the European Union (Bölük and Mert, 2014; Dogan and Seker, 2016) and the Organization for Economic Co-operation and Development (OECD) countries (Shafiei and Salim, 2014; Bilgili et al., 2016), and African countries (Zoundi, 2017). Similar findings are also reported for a group of global countries (Dong et al., 2018), China (Chen et al., 2019), and for India (Sinha and Shahbaz, 2018), Pakistan (Waheed et al., 2018), and Malaysia (Sulaiman et al., 2013).

Evidence also indicates that the relationship may depend on sample country income levels. For instance, Jebli et al. (2020) show that renewable energy consumption significantly reduces CO_2 emissions for the selected sample of global countries except for lower-middle income sample countries. Similarly, Le et al. (2020) suggest a negative link only for their high-income country subsample and not for the middle/low-income subsamples. Dong et al. (2020) also affirm a significant negative relationship for the high-income subsample and negative (but not significant) relationship for lower-income countries in their study.

In contrast, other researchers have found no evidence of a clear relationship between the use of renewable energy resources and a subsequent reduction in CO_2 emissions. Menyah and Wolde-Rufael (2010) using United States (US) data, and Pata (2018) using Turkey data, and Charfeddine and Kahia (2019) using data from select Middle East countries, document no (or a weak) relationship between the variables of interest.

[2] Using World Bank country classifications, we separate out sample countries into four income groups, namely, low, lower-middle, upper-middle, and high. Lack of adequate sample size prevented us from including countries in the low-income group.

Table 2. Descriptive statistics, sample variables for the entire period (1987–2018), and for each subperiod: 1987–1996 (period 1), 1998–2007 (period 2), and 2009–2018 (period 3). High-income subsample.

	Time Period	CO_2	Renewable Energy	FDI	Export	Import	GDP
Mean	1987–2018	466.641	70.606	3.207	25.565	25.547	26.619
	1987–1996	432.889	56.761	1.729	24.835	24.845	26.099
	1998–2007	503.757	63.636	4.571	25.605	25.588	26.622
	2009–2018	463.276	91.422	3.321	26.255	26.208	27.136
Median	1987–2018	68.490	23.240	1.665	25.716	25.601	26.466
	1987–1996	62.146	13.579	1.085	24.970	24.950	26.033
	1998–2007	68.673	20.771	2.868	25.825	25.678	26.375
	2009–2018	74.902	31.164	1.844	26.669	26.612	26.963
Maximum	1987–2018	6130.552	747.231	31.721	28.548	28.772	30.685
	1987–1996	5625.042	416.184	14.331	27.470	27.586	29.732
	1998–2007	6130.552	391.287	31.721	28.134	28.489	30.350
	2009–2018	5700.108	747.231	24.304	28.548	28.772	30.685
Minimum	1987–2018	1.839	0.003	-12.284	21.375	21.290	22.433
	1987–1996	1.839	0.003	-0.511	21.375	21.290	22.433
	1998–2007	2.635	0.020	-4.263	21.779	21.863	22.839
	2009–2018	3.462	0.099	-12.284	22.578	22.379	23.209
Std. Dev.	1987–2018	1213.487	119.287	4.635	1.424	1.418	1.541
	1987–1996	1132.359	99.315	2.508	1.341	1.324	1.531
	1998–2007	1309.690	105.613	5.352	1.319	1.317	1.490
	2009–2018	1197.152	145.409	5.065	1.245	1.276	1.430
Skewness	1987–2018	3.889	2.603	2.793	-0.617	-0.493	-0.039
	1987–1996	3.872	2.239	3.457	-0.593	-0.588	-0.042
	1998–2007	3.864	2.219	2.399	-0.804	-0.499	0.134
	2009–2018	3.851	2.547	2.452	-0.787	-0.686	-0.085
Kurtosis	1987–2018	16.649	9.791	12.579	3.272	3.399	3.511
	1987–1996	16.472	6.717	15.462	3.136	3.469	3.296
	1998–2007	16.344	6.530	9.391	3.718	3.575	3.516
	2009–2018	16.277	8.934	10.589	3.658	3.863	4.143
Observations	1987–2018	570	570	570	570	570	570
	1987–1996	190	190	190	190	190	190
	1998–2007	190	190	190	190	190	190
	2009–2018	190	190	190	190	190	190

2.2. The gross domestic product/CO_2 emissions literature

Clearly, extant results are mixed and seem to indicate that the links may be income and development level specific,[3] For instance, independent variables like gross domestic product (GDP) per capita and FDI inflows have been shown to influence CO_2 emissions. In some studies, GDP per capita has been documented to positively (negatively) influence CO_2 emissions if sample countries are at the early (advanced) stage of economic growth (Grossman and Krueger, 1995; Acaravci and Ozturk, 2010; Sarkodie and Strezov, 2019; Hove and Tursoy, 2019).[4] Others have found a positive relationship between the variables of interest in low, middle, and high-income countries (Tucker, 1995). Support also exists for an inverted U-shape relationship for Japan and Korea (developed countries), an N-shape curve for sample developing countries (Brazil, China, Egypt, Mexico, Nigeria and South Africa (Onafowora and Owoye, 2014), an inverted U-shape curve for 12 of 15 developed countries (Apergis, 2016), and an inverted U shape curve for 56 sample countries that contain high, middle, and low income countries in the sample (Youssef et al., 2016).

2.3. The foreign direct investment/CO_2 emissions literature

Next, the relationship between FDI inflows and CO_2 emissions is also empirically mixed. Host countries able to attract FDI inflows from global firms with higher technology and superior production processes can expect a reduction in local CO_2 emissions (Birdsall and Wheeler, 1993; Zhang and Zhou, 2016; Liu et al., 2017).[5] Other studies show that global firms from strict pollution regulations tend to export pollution to countries with lax pollution regulations (Bommer, 1999; Nasir et al., 2019; Rana and Sharma, 2019; Shen et al., 2019; and Wang et al., 2019).[6]

2.4. The international trade/CO_2 emissions literature

In addition, the literature finds evidence of a mixed set of results on the international trade/CO_2 emissions link. Some studies document a positive relationship between trade openness[7] and CO_2 emissions for 24 transition countries (Tamazian and Rao, 2010) and ten Middle East and North Africa (MENA) countries[8] (Farhani et al., 2014). Others find evidence of a negative relationship for low/high-income OECD countries (Al Mamun et al., 2014) and upper middle-income countries (Sohag et al., 2017). Still others find evidence of no significant trade openness/CO_2 emissions link for 9 of 12 MENA countries (Omri, 2013). Others analyze separately the impact of exports and imports on CO_2 emissions. Again, evidence on both the export and import relationships are mixed. Studies

[3] In addition, choice of sample period may affect the findings and conclusions.
[4] This relationship is referred to as the environmental Kuznets curve.

[5] This relationship is often referred to as the pollution halo hypothesis.
[6] This relationship is often referred to as the pollution haven hypothesis.
[7] Trade openness is defined as imports plus exports/GDP.
[8] MENA countries include Algeria, Bahrain, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, and Lebanon.

Table 3. Descriptive statistics, sample variables for the entire period (1987–2018), and for each subperiod: 1987–1996 (period 1), 1998–2007 (period 2), and 2009–2018 (period 3). Upper middle-income subsample.

	Time Period	CO_2	Renewable Energy	FDI	Export	Import	GDP
Mean	1987–2018	691.386	99.029	2.252	24.759	24.729	26.186
	1987–1996	378.365	45.957	1.705	23.762	23.735	25.437
	1998–2007	598.386	75.502	2.734	24.760	24.701	26.067
	2009–2018	1097.406	175.628	2.315	25.755	25.751	27.055
Median	1987–2018	199.949	26.388	2.032	24.687	24.720	26.203
	1987–1996	124.319	18.343	1.043	24.018	23.908	25.492
	1998–2007	197.646	31.058	2.652	24.913	24.848	25.909
	2009–2018	279.175	41.243	2.114	25.944	25.924	26.702
Maximum	1987–2018	10064.690	1836.653	8.686	28.606	28.566	30.255
	1987–1996	3408.347	272.524	8.686	25.869	25.761	27.485
	1998–2007	6861.751	500.720	7.803	27.860	27.579	28.807
	2009–2018	10064.690	1836.653	6.119	28.606	28.566	30.255
Minimum	1987–2018	13.539	0.146	-0.220	21.616	21.507	23.257
	1987–1996	13.539	0.146	-0.220	21.616	21.507	23.257
	1998–2007	20.563	0.923	-0.128	22.334	22.160	23.577
	2009–2018	31.851	1.564	0.238	23.480	23.550	24.877
Std. Dev.	1987–2018	1790.277	232.544	1.687	1.397	1.389	1.338
	1987–1996	756.575	70.175	2.036	1.003	1.026	1.077
	1998–2007	1328.624	121.737	1.472	1.205	1.169	1.181
	2009–2018	2657.530	366.273	1.317	1.195	1.162	1.226
Skewness	1987–2018	4.039	4.562	1.072	0.185	0.155	0.373
	1987–1996	2.873	1.917	1.909	-0.425	-0.370	-0.147
	1998–2007	3.270	1.872	0.461	-0.070	-0.019	0.210
	2009–2018	2.857	2.854	0.603	0.481	0.448	0.806
Kurtosis	1987–2018	19.102	27.346	4.358	3.108	3.024	3.325
	1987–1996	9.808	5.307	5.948	2.337	2.278	2.195
	1998–2007	12.896	5.090	3.886	2.667	2.516	2.292
	2009–2018	9.262	10.777	2.683	3.097	3.016	3.320
Observations	1987–2018	330	330	330	330	330	330
	1987–1996	110	110	110	110	110	110
	1998–2007	110	110	110	110	110	110
	2009–2018	110	110	110	110	110	110

document a positive (negative) exports/CO_2 emissions relationship in lower-middle income (high and low income) 65 belt and road initiative countries (Muhammad et al., 2020). Similarly imports were documented to be positively related to CO_2 emissions in 189 countries (Al-mulali and Sheau-Ting, 2014), 102 countries (Liddle, 2018), and low income countries of the 65 belt and road initiative countries (Muhammad et al., 2020) and negatively related to CO_2 emissions in middle and high-income countries of the 65 belt and road initiative countries (Muhammad et al., 2020).

It seems that the various relationships between key variables of interest are extremely complex and are influenced by a variety of factors. Even here, there seems to be no consensus on the exact nature of the relationship. To this, we add a new wrinkle: Could the stated relationship also be influenced by financial crises? Will the relationship pre/post crisis be sensitive to the crisis? Are the relationships robust to any crisis?

2.5. Why should we expect the renewable energy/CO_2 emissions relationship to be different depending on crisis?

Prior empirical evidence suggests that there may be a strong basis for expecting the relationship of interest to behave differently based on the crisis. First, renewable energy industry capacity growth rates and technology efficiencies were less developed during the 1997 crisis than during the 2008 crisis (Bilgili et al., 2015; Gielen et al., 2019). These growth rates were relatively lower post-1997 crisis, and higher post-2008 crisis, especially for those using solar thermal and geothermal power (Bilgili et al., 2015). In addition, post-2008 crisis, many commercialized renewable energy costs were comparable to fossil fuel costs (Gielen et al., 2019). Second, Peters et al. (2012) document significant differences on impact to global economies as a result of each crisis. They show evidence that decreases in CO_2 emissions after the 1997 crisis was induced by economic downturns and not by energy consumption structural changes. In contrast, the 2008 crisis led to significant increases in CO_2 emissions immediately following the crisis induced by rapid economic recoveries of global economies, especially in developed countries (Peters et al., 2012). Finally, even though economies recovered rapidly post-2008 crisis, the strength of this recovery may depend on country income levels. Next, while both Jebli et al. (2020) and (Dong et al. (2020) document evidence of country income level links, only the Dong et al. (2020) study suggests a possible link between the 2008 crisis and the relationship of interest. Dong et al. (2020) find evidence that the 2008 crisis did not affect the relationship.[9] They also show that countries switching to renewable energy sources reduced CO_2 emissions (but not statistically significantly) post-2008 crisis from pre-crisis levels for a sample of 120 countries. However, they did not examine whether the 1997 crisis affected this relationship. Since the world has witnessed two major financial crises in recent times, the 1997 crisis, and the more recent 2008 crisis (Colombo et al., 2016; Zouaghi and Sánchez, 2016; Zouaghi et al., 2018; Sadorsky, 2020), it seems important to understand whether the crises differently influenced the relationship of interest. Literature cited in this section

[9] Dong et al., (2020) and Sadorsky (2020) show that CO_2 emission levels increased post 2008 crisis.

Table 4. Descriptive statistics, sample variables for the entire period (1987–2018), and for each subperiod: 1987–1996 (period 1), 1998–2007 (period 2), and 2009–2018 (period 3). Lower middle-income subsample.

	Time Period	CO_2	Renewable Energy	FDI	Export	Import	GDP
Mean	1987–2018	248.692	25.798	1.413	23.639	23.928	25.348
	1987–1996	131.404	16.293	0.887	22.721	23.035	24.565
	1998–2007	219.490	22.441	1.740	23.613	23.835	25.217
	2009–2018	395.181	38.659	1.610	24.584	24.915	26.262
Median	1987–2018	70.185	11.722	1.081	23.556	23.860	25.200
	1987–1996	45.883	9.935	0.635	22.731	23.024	24.492
	1998–2007	70.260	13.422	1.111	23.457	23.724	25.146
	2009–2018	98.920	14.853	1.468	24.295	24.675	26.191
Maximum	1987–2018	2654.101	261.170	9.321	27.009	27.189	28.667
	1987–1996	878.827	80.784	3.986	24.436	24.730	26.732
	1998–2007	1390.254	141.758	9.321	26.204	26.354	27.859
	2009–2018	2654.101	261.170	3.797	27.009	27.189	28.667
Minimum	1987–2018	3.447	0.372	-0.209	21.005	21.598	22.719
	1987–1996	3.447	0.372	0.001	21.005	21.598	22.719
	1998–2007	7.736	0.749	0.256	22.439	22.622	23.539
	2009–2018	12.944	0.448	-0.209	22.918	23.184	24.525
Std. Dev.	1987–2018	497.853	44.552	1.294	1.196	1.162	1.208
	1987–1996	229.216	22.401	0.884	0.850	0.772	0.972
	1998–2007	375.372	32.072	1.769	0.901	0.878	0.992
	2009–2018	721.611	64.892	0.857	1.017	0.957	1.004
Skewness	1987–2018	3.014	3.007	2.782	0.546	0.573	0.495
	1987–1996	2.146	1.807	1.616	-0.040	0.121	0.521
	1998–2007	2.060	2.067	2.648	0.884	0.810	0.734
	2009–2018	2.119	2.125	0.624	1.205	1.113	1.006
Kurtosis	1987–2018	11.767	12.399	14.906	3.693	3.457	3.299
	1987–1996	6.016	4.923	5.740	2.369	2.328	3.289
	1998–2007	5.533	6.558	10.419	3.287	3.206	3.515
	2009–2018	5.773	6.102	2.702	3.692	3.653	3.408
Observations	1987–2018	210	210	210	210	210	210
	1987–1996	70	70	70	70	70	70
	1998–2007	70	70	70	70	70	70
	2009–2018	70	70	70	70	70	70

suggests preliminary evidence that the 1997 crisis impacted macroeconomic variables (for example, CO_2 emissions, GDP, and energy usage levels) differently than the 2008 crisis. To the best of our knowledge, no study has examined the validity of this relationship separately for the 1997 and the 2008 crises and controlled for differences in sample country income levels. We believe that these relationships may have been altered differently by the crises and is the subject matter for this research.[10] Based on extant literature, we also add several control variables to the study.

The paper is organized as follows. In Section 3, we describe the basic research methodology adopted in the paper. In Section 4, sample data used in the study is presented, followed by a presentation of empirical results and discuss our empirical findings in Section 5 while section 6 presents the conclusions.

3. Research methodology

In this paper, following the leads of other researchers (Dritsaki and Dritsaki, 2014; Li et al., 2016; Lv and Xu, 2019; González et al., 2019)[11], we adopt the Dynamic Panel Data Model (DPDM) to investigate the relationship between CO_2 emissions and adoption of renewable energy by sample countries. The basic elements of the model are described below:

$$y_{it} = \alpha y_{i,\,t-1} + \beta' x_{it} + \eta_i + \nu_{it} \quad (1)$$

where y_{it} is the dependent variable and is defined as the annual rate of CO_2 emission of country i at year t. Since CO_2 emissions (and other variables) evolve cumulatively over time, we include a lagged CO_2 emissions variable as a control variable for each country i as $y_{i,\,t-1}$.[12] Next, the list of explanatory (renewable energy consumption) and control variables (FDI, imports, exports, and GDP) are captured under x_{it}.[13] η_i is the unobserved country specific and time invariant effect with $E(\eta_i) = \eta$ and $Var(\eta_i) = \sigma^2_\eta$. ν_{it} are assumed to be independently distributed across

[10] While extant literature suggests that major macroeconomic factors (output, investment, and industrial production) decline significantly pursuant to both the 1997 and the 2008 crises (Claessens et al., 2010; Morales-Zumaquero and Sosvilla-Rivero, 2016) they also do not examine whether the nature of the key relationship of interest changed differently following the onset of a crisis.

[11] Earlier researchers using the DPDM methodology include Arellano and Bond (1991); Blundell and Bond (1998); and Arellano (2003). The DPDM model is preferred over other methods because of its ability to accommodate unobserved country heterogeneity problems, omitted variable biases, measurement errors, potential endogeneity issues, potential biases, and imprecision problems (Arellano and Bond, 1991; Blundell and Bond, 1998; Arellano, 2003).

[12] Environmental quality evolves cumulatively over time: the environmental quality of today is likely to be linked to that of yesterday, rendering it appropriate to consider a dynamic EKC specification that includes lagged dependent variable on the right-hand side (Li et al., 2016).

[13] Variable definitions and sources to operationalize these variables are provided in the next section.

Table 5. Descriptive statistics, sample variables for the entire period (1987–2018), and for each subperiod: 1987–1996 (period 1), 1998–2007 (period 2), and 2009–2018 (period 3). Standard Deviation per unit of Output, Overall subsample.

	Time Period	CO_2	GDP (billion)
Mean	1987–2018	492.22	866
	1987–1996	359.64	420
	1998–2007	478.11	757
	2009–2018	638.92	1420
Median	1987–2018	97.05	257
	1987–1996	72.62	120
	1998–2007	114.08	197
	2009–2018	165.80	369
Maximum	1987–2018	10064.69	20600
	1987–1996	5625.04	8070
	1998–2007	6861.75	14500
	2009–2018	10064.69	20600
Minimum	1987–2018	1.84	5.53
	1987–1996	1.84	5.53
	1998–2007	2.64	8.21
	2009–2018	3.46	13.20
Std. Dev.	1987–2018	1332.83	2250
	1987–1996	921.09	1070
	1998–2007	1201.54	1910
	2009–2018	1734.20	3150
Std. Dev. per unit of output	1987–2018	2.71	2.60
	1987–1996	2.56	2.54
	1998–2007	2.51	2.53
	2009–2018	2.71	2.21

Note: Data presented in other tables use natural logs, here we use raw data.

Table 6. Lower-middle, upper-middle, and high-income countries.

Income group	Country	Count
High	Canada, Chile, Denmark, Finland, France, Greece, Iceland, Israel, Italy, Netherlands, Norway, Portugal, Singapore, South Korea, Spain, Sweden, Switzerland, United Kingdom, United States of America	19
Upper middle	Argentina, Brazil, China, Colombia, Ecuador, Malaysia, Mexico, Peru, South Africa, Thailand, Turkey	11
Lower middle	Bangladesh, Egypt, India, Morocco, Pakistan, Philippines, Sri Lanka	7

countries with zero mean, but arbitrary forms of heteroscedasticity across units and time are possible. The first differences from Eq. (1) are used to avoid country specific bias effects from OLS estimates:

$$\Delta y_{it} = \alpha \Delta y_{i,\,t-1} + \beta' \Delta x_{it} + \Delta \nu_{it} = \gamma' W_{it} + \Delta \nu_{it} \tag{2}$$

4. Sample data, sources, and characteristics

The selected sample consists of annual balanced panel data from 37 (19 high income, 11 upper middle-income and 7 lower middle-income) countries and spans the 1987 to 2018 period. The sample data covers two crisis periods – the 1997 and the 2008 crises. The dependent variable proxies pollution captured by carbon dioxide emissions (CO_2). Next, the explanatory variables include renewable energy consumption (Renewable Energy), FDI inflows (FDI), exports (Export), import (Import), and GDP (GDP').[14] Sample data definitions, descriptive statistics and sources (list of countries) are presented in Table 1, 2, 3, 4(6).

Carbon dioxide (CO_2) emissions, measured in million tons, are attributed to the country in which they physically occur. The CO_2 emissions data are from the "Our World in Data" database derived from the Global Carbon Project[15]. Renewable energy consumption, measured in terawatt-hours (TWH), data are from the Our World in Data database[16]. The inflow of foreign direct investment (FDI) is measured as a percentage of gross domestic product for the year. The FDI data are from United Nations Conference on Trade and Development website[17]. Exports are exports of goods and services. The Exports data are in current U.S. dollars using natural logarithms. Imports are imports of goods and services. The Imports data are in current U.S. dollars using natural logarithms. Gross domestic product per capita (GDP') is defined as gross domestic product minus net export. The Exports, Imports, and GDP data are from the World Bank website[18].

Finally, results are computed for the overall time period[19] and for each of three subperiods, periods 1, 2, and 3. Period 1 only includes data spanning the 1987–1996 (inclusive) period. Period 2 (3) spans data for the 1998–2007 (2009–2018) time frame. Next, Table 5 presents standard deviations per unit of output for CO_2 emissions and GDP output for the full time period and for each of periods 1–3. These results clearly document that the standard deviation per unit of output of CO_2 emissions are larger than corresponding estimates for GDP for all time periods except for the post-1997 crisis period. These results are generally consistent with the findings of Peters et al. (2012).

Next, data availability by country and time periods also allows us to conduct a pairwise t-test to determine whether variable means have changed across both crises. The pairwise t-test is a preliminary test to determine if the variable means for CO_2 emissions and for renewable energy differ for each category of high income, upper-middle and lower-middle income countries and across time periods delineated by the crises. If there are no statistically significant differences in each variable mean (CO_2 emissions and renewable energy) across time periods and across countries, then there may be no basis to conduct formal tests on the nature of these relationships. If there are significant differences in mean values for CO_2 emissions and renewable energy across countries and time periods delineated by the crises, then we can proceed with the formal tests to examine the relationship between the two variables of interest (see Table 5, 6).

Table 7 presents these results for differences between pairwise values between periods 2 (post-1997 crisis) and 1 (pre-1997 crisis) for all variables for the overall sample and for each subsample. Similarly, the difference in pairwise values between period 3 (post-2008 crisis) and period 2 (post-1997 crisis but pre-2008 crisis) are presented for all variables and samples. Table 8 presents the paired test results in summary form for ease of interpretation.

These results provide some interesting findings. First, with some exceptions, sample variables have recorded statistically significant increases across all periods for the overall sample and for each subsample. However, for key variables like CO_2 emissions and renewable energy, the relationships depend on country income levels and the specific crisis under consideration. CO_2 emissions have only recorded statistically

[14] To properly examine the influence of exports and imports on CO_2 emissions, we subtract net exports from GDP, and examine the simultaneous impact of GDP, exports, and imports on CO_2 emissions (Haug and Ucal, 2019). This variable is labelled as GDP'.

[15] http://www.globalcarbonatlas.org/en/content/project-overview. Updated from Peters et al. (2011).

[16] https://ourworldindata.org/renewable-energy.

[17] https://unctadstat.unctad.org/wds/ReportFolders/reportFolders.aspx?sCS_ChosenLang=en.

[18] http://www.worldbank.org/.

[19] We include all data between 1987 and 2018 (inclusive) for the overall period statistics and subsequent computations. However, we exclude data for the crisis years, namely for years 1997 and 2008.

Table 7. Paired difference t-test for period, by sample country and variables.

Variable	Sample composition	period 1	period 2	period 3	Difference: period2-period1	Difference: period3-period2	Difference: period3-period1
CO_2	Full sample	359.641	478.110	638.918	118.469** (0.04)	160.809 (0.24)	279.277 (0.14)
	High income	432.889	503.757	463.276	70.869* (0.12)	-40.481 (0.18)	30.387 (0.23)
	Upper middle income	378.365	598.386	1097.406	220.021 (0.21)	499.021 (0.28)	719.042 (0.26)
	Lower middle income	131.404	219.490	395.181	88.086 (0.19)	175.691 (0.25)	263.777 (0.23)
Renewable energy	Full sample	45.893	59.370	106.474	13.477** (0.02)	47.104* (0.06)	60.581** (0.04)
	High income	56.761	63.636	91.422	6.875*** (0.00)	27.786*** (0.02)	34.661*** (0.01)
	Upper middle income	45.958	75.502	175.628	29.544* (0.11)	100.126 (0.23)	129.670 (0.20)
	Lower middle income	16.293	22.441	38.659	6.148* (0.14)	16.218 (0.27)	22.366 (0.23)
FDI	Full sample	1.563	3.490	2.698	1.927*** (0.00)	-0.791*** (0.01)	1.135*** (0.00)
	High income	1.729	4.571	3.321	2.842*** (0.00)	-1.250** (0.02)	1.592*** (0.01)
	Upper middle income	1.706	2.734	2.315	1.029** (0.03)	-0.419 (0.19)	0.610 (0.26)
	Lower middle income	0.887	1.740	1.610	0.853*** (0.01)	-0.131 (0.52)	0.722*** (0.04)
Export	Full sample	24.116	24.977	25.790	0.861*** (0.00)	0.813*** (0.00)	1.674*** (0.00)
	High income	24.835	25.605	26.255	0.770*** (0.00)	0.649*** (0.00)	1.420*** (0.00)
	Upper middle income	23.762	24.760	25.755	0.998*** (0.00)	0.995*** (0.00)	1.993*** (0.00)
	Lower middle income	22.721	23.613	24.584	0.892*** (0.00)	0.971*** (0.00)	1.863*** (0.00)
Import	Full sample	24.173	24.993	25.828	0.820*** (0.00)	0.835*** (0.00)	1.655*** (0.00)
	High income	24.845	25.588	26.208	0.743*** (0.00)	0.620*** (0.00)	1.364*** (0.00)
	Upper middle income	23.735	24.701	25.751	0.966*** (0.00)***	1.050*** (0.00)	2.016*** (0.00)
	Lower middle income	23.036	23.835	24.915	0.800 (0.00)	1.080*** (0.00)	1.879*** (0.00)
GDP	Full sample	25.612	26.191	26.947	0.579*** (0.00)	0.756*** (0.00)	1.334*** (0.00)
	High income	26.099	26.622	27.136	0.523*** (0.00)	0.514*** (0.00)	1.037*** (0.00)
	Upper middle income	25.437	26.067	27.055	0.629*** (0.00)	0.989*** (0.00)	1.618*** (0.00)
	Lower middle income	24.565	25.217	26.262	0.652*** (0.00)	1.045*** (0.00)	1.697*** (0.00)

Notes:1. Period 1: 1987–1996 (pre-crisis); period 2:1998–2007 between the 1997 and the 2008 crises); period 3: 2009–2018 (post-2008 crisis).
2. ***, **, and * denote two tailed significances at the 1%, 5%, and 10% levels, respectively.
3. The corresponding p values are reported in parentheses.

significant increases for the full/high income samples and only for post-1997 data versus pre-1997 data.[20] For the upper/lower middle-income countries, both crises seem not to have affected CO_2 output. Similarly, consumption of renewable energy has increased significantly over both crises for full/high income samples, the upper/middle income have recorded significant increases only post-1997 crisis and not post-2008 crisis. Next, exports, imports and GDP have increased significantly across both crises and seem not to depend on country income levels. Finally, the 2008 crisis (and not the 1997 crisis) seems to be impacting FDI inflows generally for sample groups. FDI inflows have recorded statistically significant decreases post-2008 versus pre-2008 levels for the overall and the high-income samples but not the upper/middle-income samples.

These results affirm the Peters et al. (2012) conclusion that the 1997 crisis was fundamentally different than the 2008 crisis insofar as CO_2

[20] These results are at variance with those reported by Peters et al. (2012) who show that CO_2 emissions *increased* for their sample countries following the 1997 crisis. Our sample represents a small subset of the global sample used by Peters et al. (2012). Hence, it is possible that while CO_2 emissions increased for the world, it has *decreased* for the much narrower sample used in this study.

Table 8. Paired difference t-tests: Summary results.

Period	Sample Variables	Overall Sample	High Income Sample	Upper Middle-Income Sample	Lower Middle-Income Sample
Period 2 – Period 1	CO_2 Emissions	**S+**	**S+**	NS +	NS+
	Renewable Energy	**S+**	**S+**	**S+**	**S+**
	FDI	**S+**	**S+**	**S+**	**S+**
	Export	**S+**	**S+**	**S+**	**S+**
	Import	**S+**	**S+**	**S+**	**S+**
	GDP	**S+**	**S+**	**S+**	**S+**
Period 3 – Period 2	CO_2 Emissions	NS+	NS-	NS+	NS+
	Renewable Energy	**S+**	**S+**	NS+	NS+
	FDI	**S-**	**S-**	NS-	NS-
	Export	**S+**	**S+**	**S+**	**S+**
	Import	**S+**	**S+**	**S+**	**S+**
	GDP	**S+**	**S+**	**S+**	**S+**
Period 3 – Period 1	CO_2 Emissions	NS+	NS+	NS+	NS+
	Renewable Energy	**S+**	**S+**	NS+	NS+
	FDI	**S+**	**S+**	NS+	**S+**
	Export	**S+**	**S+**	**S+**	**S+**
	Import	**S+**	**S+**	**S+**	**S+**
	GDP	**S+**	**S+**	**S+**	**S+**

Notes: 1. Period 1: 1987–1996 (pre-crisis); period 2:1998–2007 between the Asian and the Global financial crisis); period 3: 2009–2018 (post crisis).
2. A '+' ('-') represents an increase (decrease) over the stated periods; 'S' represents significance at the ≤ 10% level. 'NS' implies no significant differences between the two stated periods. Significant relationships are bolded.

These preliminary results suggest that partitioning the data by crisis and by income levels may be justified insofar as the CO_2 emissions/renewable energy relationship is concerned. There are differences in some sample variable and crises defined time periods across country income groups. In the next section, we formally investigate whether the renewable energy/CO_2 emissions link has been altered by the crises and whether these links are country income group specific.

We first conduct the Pesaran's cross-sectional dependence CD test to ensure that sample variables are cross sectionally independent and that the sample variables are stationary. After ensuring variable stationarity, we conduct Dynamic Panel Data Model regressions to determine the relationship between the variables separately for each time period before and after each crisis.

5. Empirical results

We first examine whether the sample variables are independent cross-sectionally with each other. Table 9 presents the results of the Pesaran's cross-sectional dependence CD tests and indicate that the null hypothesis of no cross-sectional dependence between sample variables is rejected at the 1% level. To rectify this problem, we conduct the second-generation panel unit root test (Pesaran, 2007). Results documented in Table 10 show that all sample variables are stationary at level. This finding enables us to use the variables to examine the relationships between CO_2 emissions and the explanatory variables for the overall sample and for each subsample.

As indicated earlier, we adopt the Dynamic Panel Data Model (DPDM) to examine the relationship between the dependent variable and stated explanatory variables. These results are presented in Table 11 for the entire sample and for each subsample, prior to and after each crisis. Table 11 contains the parameter estimates while Table 12 contains the tests for significance of generated estimates. Table 12 shows that all the regression models are significant at the 1% level, with the exception of the results for the high-income sample, post 2008 crisis, using the joint test.

Table 9. Cross-sectional dependence tests for the entire sample period.

Test	CO_2	Renewable Energy	FDI	Export	Import	GDP
Breusch-Pagan LM	10039.35*** (0.00)	12791.55*** (0.00)	2413.29*** (0.00)	19025.02*** (0.00)	18535.63*** (0.00)	17127.50*** (0.00)
Pesaran scaled LM	255.81*** (0.00)	331.22*** (0.00)	46.86*** (0.00)	502.02*** (0.00)	488.61*** (0.00)	450.03*** (0.00)
Pesaran CD	46.34*** (0.00)	111.22*** (0.00)	31.65*** (0.00)	137.91*** (0.00)	136.10*** (0.00)	130.58*** (0.00)

Notes: 1. Null hypothesis: No cross-section dependence (correlation). Cross-section means were discarded for correlation computations.
2. ***, ** and * denotes significance at the 1%, 5%, and 10% levels, respectively.
3. The corresponding p-values are reported in parentheses.

emissions are concerned.[21] However, we find evidence that CO_2 emissions showed significant increases *only* for the high-income sample and not for the other income groups. Renewable energy adoption increased for all income groups post-1997, but only for high-income countries post-2008. Their conclusions that focus on economic recovery post-2008 persuaded countries to forgo presumably costly renewable energy consumption after the 2008 crisis is supported by the results presented here. In addition, consistent with their findings, we find (Table 1) that variations in CO_2 emissions across countries exceed the variations in GDP for the overall time period and for each subperiods.

[21] However, and unlike Peters et al. (2012), we find that CO_2 emissions increased after the 1997 crisis. Again, we believe that our sample size restrictions dictated by availability of data on all sample variables may account for the differences.

For the overall period, results suggest that renewable energy consumption is insignificantly positively correlated with CO_2 emissions for the entire sample and significantly positively correlated with CO_2 emissions for the lower middle-income country subsample. In addition, a significant negative relationship is observed between the stated variables for the high income and the upper middle-income subsamples. Next, we review results for each time period (before/between/and after/each crisis).

For the period prior to the 1997 crisis, the stated relationship of renewable energy consumption and CO_2 emissions is positive and significant for the entire sample, the high income and the upper middle-income country subsamples, and positive (but not significant) for the lower middle-income country subsample. When we examine the period post-1997 crisis, significant differences start to emerge: the stated relationship is significantly negative for the high income and the upper

Table 10. Second generation panel unit root test, full sample time period.

Pesaran's CADF test	CO_2	Renewable Energy	FDI	Export	Import	GDP
Constant						
Level, lag(0)	-1.945** (0.03)	-5.086*** (0.00)	-12.333*** (0.00)	-3.580*** (0.00)	-3.897*** (0.00)	-4.532*** (0.00)
Level, lag (1)	-0.370 (0.36)	-3.787*** (0.00)	-4.811*** (0.00)	-4.529*** (0.00)	-4.813*** (0.00)	-4.806*** (0.00)
1st difference, lag(0)	-21.803*** (0.00)	-24.076*** (0.00)	-26.372*** (0.00)	-18.982*** (0.00)	-17.800*** (0.00)	-18.072*** (0.00)
Constant & trend						
Level, lag(0)	0.089 (0.54)	-5.988*** (0.00)	-12.227*** (0.00)	-0.179 (0.43)	0.062 (0.53)	0.394 (0.65)
Level, lag(1)	2.898 (1.00)	-5.492*** (0.00)	-3.835*** (0.00)	-0.837 (0.20)	-0.790 (0.22)	-0.815 (0.21)
1st difference, lag(0)	-25.697*** (0.00)	-25.377*** (0.00)	-38.672*** (0.00)	-17.264*** (0.00)	0.062 (0.53)	-16.405*** (0.00)

Notes: 1. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.
2. The corresponding p values are reported in parentheses.
3. first differences, lag(0) serials will be used in subsequent regressions.

middle-come subsample and significantly positive for the overall sample and the lower middle-income subsample. For the period post-2008 crisis, significant divergence in results emerge: the relationship between renewable energy consumption and CO_2 emissions is significantly positive *only* for the lower middle-income subsample, significantly negative for the entire sample and the upper middle-income subsample, and negative (but not significant) for the high income subsample. As expected, the relationships between the lagged CO_2 emissions and CO_2 emissions are significantly positive for the overall data. Finally, the relationships between CO_2 emissions and control variables (FDI, Export, Import, and GDP), are significant in most cases as presented in Table 11.

From the results presented in Table 11, several key conclusions can be made with respect to the relationship between renewable energy use and CO_2 emissions. First, the impact of renewable energy consumption on CO_2 emissions varies across sample countries classified by income levels. Second, we document evidence that the stated relationship has been altered separately by the two crises and that the degree of impact depends on the income level of sample countries.[22] From a policy perspective, our results show that increased use of renewable energy is associated with a reduction in CO_2 emissions for the full sample: the relationship becomes significantly negative post-2008 (−0.351) from significantly positive values pre-2008 crisis (0.666, pre-1997 crisis, and 0.250, period between crises). Clearly, it seems difficult to conclude that increased renewable energy usage reduced pollution, especially if two crises are thrown in. We also find that this favourable result post-2008 crisis is not obtained for all subsamples and depend on the crises. For the high-income and upper middle-income subsamples, while the relationship is significantly negative for the full sample period (coefficient = -0.851), the relationship only turned negative post-1997 crisis (from 0.841 to -0.331). However, the relationship becomes statistically insignificant post-2008.[23] Results seem to be comparatively better for the upper middle-income subsample. Here the overall results present a significant negative relationship (coefficient = -0.170), a significantly positive relationship pre-1997 crisis (2.52) which then turns into a significantly negative relationship post each crisis (−0.916 for the period between crisis, and -0.492 post-2008 crisis). These results may suggest that the collective renewable energy policies of the governments of upper middle-income countries may have been more effective post-1997 crisis.

Unfortunately, the renewable energy usage/CO_2 was positive (mostly significantly) across crises for the lower middle-income sample of countries. The relationship is significantly positive for the overall period (1.512) and for the period between the crisis (1.709) and post crisis (2.041). Surprisingly, for this group, the relationship was negative (but insignificant) pre-1997 crisis. Our results (for the upper and the lower middle-income subsamples) and the negative relationship (where observed) is consistent with those presented by Jebli et al., (op. cit.) who show that the consumption of renewable energy negatively impacts CO_2 emissions in the upper middle-income countries but not in lower-middle income countries. In contrast, we document a significantly positive relationship for most periods for the lower-income group whereas Jebli et al. (op. cit.) find no relationship for this subgroup. Finally, our findings documented above also demonstrate that the stated relationship is sensitive to the income level of countries. These differential findings on the impact of the crisis on the renewable energy/CO_2 emissions relationship have not been previously reported in the literature.

In addition, based on the reported negative relationship between renewable energy consumption and CO_2 emission in selected sample countries/periods and the relationships recorded for other control variables (FDI, imports, exports, and GDP), we conclude that increased consumption of renewable energy in these countries *can* reduce CO_2 emissions. These results are consistent with those of Thangavelu et al. (2009), De Haas, and Van Horen (2013), Ersoy and Erol (2016), and Ghosh et al. (2016).[24]

Next, we examine whether the relationship changed differently following the 1997 crisis versus the 2008 crisis. Results presented in Table 11 suggests that for the full sample, the 1997 crisis did not alter the positive and significant relationship between renewable energy and pollution emissions, but the 2008 crisis changed a positive relationship pre-crisis to a negative one post-crisis. However, analysis of results for sample country groups presents a different picture. For the high-income subsample, a significantly positive relationship pre-1997 crisis changed to a significantly negative relationship post-1997 crisis. However, the

[22] Our findings that the relationship is depends on country income levels is consistent with those reported by Dong et al., (2020) and with the Dong et al., (2020). However, our results differ from these in the sense that we find evidence of relationship *differences* across two crises and country income levels. In other words, the two crises altered the relationship of interest.

[23] The relationship, while negative post 2008, was not significant for the high-income subsample.

[24] While these authors find that FDI inflows changed because of the crises, we find the relationship between renewable energy and CO_2 emissions also changed because of the crises.

Table 11. Dynamic Panel Data Model regression results. Parameter estimates.

Variable	Time Period	Full sample	High income	Upper middle income	Lower middle income
CO_2(-1)	1987–2018	0.517*** (0.00)	-0.200*** (0.00)	0.823*** (0.00)	0.182*** (0.00)
	1987–1996	0.026 (0.61)	-0.318*** (0.00)	0.426*** (0.00)	0.676*** (0.00)
	1998–2007	0.740*** (0.00)	-0.368*** (0.00)	0.935*** (0.00)	0.510*** (0.00)
	2009–2018	0.489*** (0.00)	0.001 (0.98)	0.489*** (0.00)	0.270*** (0.00)
Const	1987–2018	-0.343 (0.80)	0.849 (0.52)	-1.797 (0.51)	11.422*** (0.00)
	1987–1996	7.287*** (0.00)	9.518*** (0.00)	-2.100 (0.54)	1.985 (0.17)
	1998–2007	-8.698*** (0.00)	1.446 (0.46)	-13.583** (0.01)	-0.528 (0.73)
	2009–2018	3.664* (0.09)	-2.799 (0.16)	9.102* (0.10)	12.672** (0.01)
Renewable Energy	1987–2018	0.057 (0.34)	-0.851*** (0.00)	-0.170** (0.03)	1.512*** (0.00)
	1987–1996	0.666*** (0.00)	0.841*** (0.00)	2.520*** (0.00)	0.179 (0.47)
	1998–2007	0.250** (0.04)	-0.331*** (0.00)	-0.916*** (0.01)	1.709*** (0.00)
	2009–2018	-0.351*** (0.00)	-0.172 (0.14)	-0.492*** (0.00)	2.041*** (0.00)
FDI	1987–2018	-0.518 (0.15)	-0.474* (0.07)	-0.702 (0.61)	1.047 (0.36)
	1987–1996	0.724 (0.46)	-0.897 (0.45)	1.935 (0.29)	1.192 (0.41)
	1998–2007	-0.624 (0.15)	-0.243 (0.41)	-1.302 (0.49)	-0.357 (0.45)
	2009–2018	-0.072 (0.92)	-0.246 (0.61)	1.672 (0.70)	-5.075 (0.23)
Export	1987–2018	-13.125 (0.35)	-64.917*** (0.00)	12.551 (0.55)	-61.168*** (0.00)
	1987–1996	-5.484 (0.71)	-42.481 (0.17)	17.153 (0.45)	-7.754 (0.50)
	1998–2007	49.564** (0.02)	-20.982 (0.34)	69.382 (0.13)	33.506** (0.02)
	2009–2018	-61.458* (0.09)	-29.714 (0.55)	-90.492 (0.22)	-88.503* (0.10)
Import	1987–2018	129.138*** (0.00)	180.605*** (0.00)	117.384*** (0.00)	52.743** (0.01)
	1987–1996	28.502** (0.04)	95.682** (0.02)	31.366** (0.03)	27.294** (0.01)
	1998–2007	155.147*** (0.00)	81.466*** (0.00)	268.156*** (0.00)	-23.997* (0.05)
	2009–2018	146.147*** (0.00)	58.108 (0.27)	235.143*** (0.00)	101.110* (0.08)
GDP	1987–2018	-42.997*** (0.00)	-79.625*** (0.00)	-46.098*** (0.01)	-17.497 (0.34)
	1987–1996	2.399 (0.85)	-42.996 (0.16)	-2.628 (0.84)	-12.401 (0.29)
	1998–2007	-110.469*** (0.00)	-36.422* (0.06)	-191.876*** (0.00)	33.437*** (0.00)
	2009–2018	-39.693 (0.23)	-50.853 (0.21)	14.081 (0.84)	-55.677 (0.26)
Count		37	19	11	7

Notes: 1. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.
2. The corresponding p values are reported in parentheses.

sign of the relationship did not change following the 2008 crisis for this income group.[25] More stark differences are noted for the upper/lower middle-income groups. The 1997 crisis changed a significantly positive relationship into a significantly negative relationship for the upper middle-income group, but the 2008 crisis did not influence the sign or significance levels. Similarly, the lower middle-income group results changed from no relationship pre-1997 crisis to a significantly positive

[25] However, the significance changed from strongly negative to insignificantly negative.

Table 12. Dynamic Panel Data Model regression results. Tests for significance of estimates.

Test	Time Period	Full sample	High income	Upper middle income	Lower middle income
Sargan over-identification	1987–2018	2643.01*** (0.00)	1702.13*** (0.00)	992.247*** (0.00)	567.653*** (0.00)
	1987–1996	220.049*** (0.00)	197*** (0.00)	111.646*** (0.00)	79.3192*** (0.00)
	1998–2007	510.424*** (0.00)	247.125*** (0.00)	146.574*** (0.00)	109.968*** (0.00)
	2009–2018	439.335*** (0.00)	439.481*** (0.00)	144.381*** (0.00)	144.8*** (0.00)
Wald (joint) test	1987–2018	1393.47*** (0.00)	334.414*** (0.00)	2356.09*** (0.00)	73.3171*** (0.00)
	1987–1996	39.753*** (0.00)	39.414*** (0.00)	188.519*** (0.00)	78.2691*** (0.00)
	1998–2007	1127.48*** (0.00)	63.4866*** (0.00)	1171.79*** (0.00)	446.761*** (0.00)
	2009–2018	337.875*** (0.00)	4.46436 (0.61)	200.868*** (0.00)	37.5771*** (0.00)

Notes: 1. ***">***, **">**, and *">* denote significance at the 1%, 5%, and 10% levels, respectively.
2. The corresponding p values are reported in parentheses.

relationship post-1997 crisis. However, the relationship and significance levels remained unchanged post-2008 crisis.

6. Conclusions

The paper offers some major contributions. First, this paper has examined an area that has not yet been explored – whether the 1997 and the 2008 crises impacted the renewable energy/CO_2 emissions relationship differently for a select sample of countries arranged by income levels. Second, using the Dynamic Panel Data Model, we examine collectively and separately the impact of the 1997 and the 2008 crises on the stated relationship for annual data between the 1987–2018 period for a group of high, upper-middle, and lower middle-income countries. Our results suggest that the two financial crises significantly altered the examined relationship post-1997 crisis for both the high-income and the upper middle-income subsamples. Third, for the overall sample, the relationship between the two variables was positive (and significant post-1997 and pre-2008 crises) but negative post-2008 crisis. In contrast, the positive relationship remained unchanged for the lower middle-income subsample through the two crises. Fourth, reduction of CO_2 emissions may not be guaranteed even if host countries adopt renewable energy sources. In addition, country income levels and the two crises seem to alter the stated relationship. Finally, the renewable energy/pollution links were altered differently following the 1997 crisis than after the 2008 crisis for the upper and the lower middle-income groups. These last set of findings, to the best of our knowledge, have not been reported in the literature.[26]

If the goal of any government is to reduce CO_2 emissions, then policy that encourages adoption of renewable energy sources may not always work. In addition, any future crisis may also alter this relationship. However, for lower middle-income countries, CO_2 emissions do not seem to be correlated with renewable energy adoption and the crises. Governments may need to consider the income levels of their countries to select the best possible policy method to reduce emissions while adopting renewable energy resources. Our research indicates that policy prescriptions may depend on a clear understanding of the nature of the crisis and the income levels of countries.

One acknowledged limitation of this paper is that since the 2008 financial crisis occurred over 10 years ago, the findings of this study may not easily transport to future crises. However, while the data is old, the examined linkages may still be robust.

We provide several avenues for further research in this area. From an academic perspective, we suggest the addition of other key variables (for example, the degree of enforcement, cost of access to renewable energy sources, etc.) to determine whether these additional variables further influence the examined relationships. The study can also be extended to include other countries depending on data availability. Future research could also examine the robustness of our findings for newer crises. For instance, one can argue that the recent pandemic is a crisis of sorts. Once more recent data becomes publicly available, research can be undertaken on whether the links examined here are still valid post pandemic.

[26] We also acknowledge that it is possible that renewable energy sources were less available around the 1997 crisis than around the 2008 crisis and could partially account for the observed results.

Declarations

Author contribution statement

Chi-Hui Wang: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Prasad Padmanabhan, Chia-Hsing Huang: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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