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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ARTICLE INFO
Keywords:
Dynamic panel model
1997 Asian financial crisis
2008 global financial crisis
Renewable energy
CO₂ emissions

ABSTRACT
This paper examines whether the 1997 Asian financial crisis affected the renewable energy/carbon dioxide (CO₂) 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 CO₂ 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 (CO₂) 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), Zouaighi and Sánchez (2016), and Zouaighi 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/CO₂ 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 CO₂ emissions (but not statistically significantly) post-2008 crisis vs 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 CO₂ 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 - CO₂ 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.

https://doi.org/10.1016/j.heliyon.2022.e08931
Received 22 September 2021; Received in revised form 26 September 2021; Accepted 7 February 2022
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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. 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/CO2 emissions literature

A vast body of literature examining the links between renewable energy consumption and CO2 emissions for many countries provides mixed results. Research indicates that increased use of renewable energy is associated with a subsequent reduction in CO2 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 (Shafiee 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 CO2 emissions for their high-income country subsample and not for the middle/low-income subsamples. Dong et al. (2020) also find 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 CO2 emissions. Menyah and Wolde-Rufael (2010) find no significant relationship for the high-income subsample and negative (but not significant) relationship for lower-income countries in their study.

### 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 | CO2 | Renewable Energy | FDI | Export | Import | GDP |
|-------------|-----|------------------|-----|--------|--------|-----|
| Mean        |     |                  |     |        |        |     |
| 1987–2018   | 492.23 | 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   | 1006.649 | 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   | 1006.649 | 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          | 20.092 | 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 crises, and period 3 as the period following the 2008 crisis.

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.
2.2. The gross domestic product/CO₂ emissions literature

Clearly, extant results are mixed and seem to indicate that the links may be income and development level specific. For instance, independent variables like gross domestic product (GDP) per capita and FDI inflows have been shown to influence CO₂ emissions. In some studies, GDP per capita has been documented to positively (negatively) influence CO₂ 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). Others have found a positive relationship between the variables of interest in low, middle, and high-income countries in the sample (Youssef et al., 2016). In addition, the literature finds evidence of a mixed set of results on the international trade/CO₂ emissions link. Some studies document a positive relationship between trade openness and CO₂ emissions for 24 transition countries (Tamazian and Rao, 2010) and ten Middle East and North Africa (MENA) countries (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/CO₂ emissions link for 9 of 12 MENA countries (Omri, 2013). Others analyze separately the impact of exports and imports on CO₂ emissions. Again, evidence on both the export and import relationships are mixed. Studies

![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.](image)

| Time Period | CO₂ | 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 | -0.866 | -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 |

2.3. The foreign direct investment/CO₂ emissions literature

Next, the relationship between FDI inflows and CO₂ 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 CO₂ emissions (Birdsall and Wheeler, 1993; Zhang and Zhou, 2016; Liu et al., 2017). 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).

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.
document a positive (negative) exports/CO2 emissions relationship in lower-middle income (high and low income) 65 belt and road initiative countries (Muhammad et al., 2020). Similarly imports were documented lower-middle income (high and low income) 65 belt and road initiative to be positively related to CO2 emissions in 189 countries (Al-mulali and 2016; Zouaghi and 2018; Sadorsky, /C19 financial crises in 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 CO2 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 CO2 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. They also show that countries switching to renewable energy sources reduced CO2 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. 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/CO2 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 CO2 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 CO2 emissions immediately following the crisis induced by rapid economic recoveries of global economies, especially in developed countries (Peters et al., 2012).

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?

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Dong et al., (2020) and Sadowsky (2020) show that CO2 emission levels increased post 2008 crisis.
suggests preliminary evidence that the 1997 crisis impacted macroeconomic variables (for example, CO2 emissions, GDP, and energy usage levels) differently than the 2008 crisis. To the best of our knowledge, no other paper focuses on the 1997 crisis and controlled for differences in sample country levels) differently than the 2008 crisis. To the best of our knowledge, no other paper focuses on the 1997 crisis and controlled for differences in sample country levels. We believe that these relationships may have been altered 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 CO2 emissions and adoption of renewable energy by sample countries. The basic elements of the model are described below:

\[ y_{it} = \alpha y_{i,t-1} + \beta x_{it} + \eta_i + \nu_t \]

(1)

where \( y_{it} \) is the dependent variable and is defined as the annual rate of CO2 emission of country i at year t. Since CO2 emissions (and other variables) evolve cumulatively over time, we include a lagged CO2 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 \( x_{it} \). \( \eta_i \) is the unobserved country specific and time invariant effect with \( \text{Var}(\eta_i) = \sigma^2_\eta \). \( \nu_t \) are assumed to be independently distributed across

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**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 | CO2 | 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 | 487.853 | 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 | 2.328 |
| 1998-2007 | 5.533 | 6.558 | 10.419 | 3.287 | 3.206 | 3.515 |
| 2009-2018 | 5.773 | 6.102 | 2.702 | 2.782 | 0.546 | 0.573 |
| 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 |

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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-Zumáquero 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).
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     | CO2   | 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 | 1.53         | 5.53       |
|                 | 1987–1996 | 1.53         | 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:

\[ \Delta y_{it} = \alpha \Delta y_{it-1} + \beta \Delta x_{it} + \nu_{it} = \gamma W_{it} + \Delta \nu_{it} \]  

(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 (CO2). Next, the explanatory variables include renewable energy consumption (Renewable Energy), FDI inflows (FDI), exports (Export), import (Import), and GDP (GDP).15 Sample data definitions, descriptive statistics and sources (list of countries) are presented in Table 1, 2, 3, 4.(6).

Carbon dioxide (CO2) emissions, measured in million tons, are attributed to the country in which they physically occur. The CO2 emissions data are from the “Our World in Data” database derived from the Global Carbon Project.16 Renewable energy consumption, measured in terawatt-hours (TWH), data are from the Our World in Data database.17 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.18 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.19

Finally, results are computed for the overall time period 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 CO2 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 CO2 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 CO2 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 (CO2 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 CO2 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 CO2 emissions and renewable energy, the relationships depend on country income levels and the specific crisis under consideration. CO2 emissions have only recorded statistically

14 To properly examine the influence of exports and imports on CO2 emissions, we subtract net exports from GDP, and examine the simultaneous impact of GDP, exports, and imports on CO2 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?SChosenLang=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.
significant increases for the full/high income samples and only for post-1997 data versus pre-1997 data. For the upper/lower middle-income countries, both crises seem not to have affected CO2 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.

These results affirm the Peters et al. (2012) conclusion that the 1997 crisis was fundamentally different than the 2008 crisis insofar as CO2 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 CO2 emissions increased for the world, it has decreased for the much narrower sample used in this study.

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 |
|--------------|--------------------|----------|----------|----------|-----------------------------|-----------------------------|-----------------------------|
| CO2          | Full sample        | 359.641  | 478.110  | 638.918  | 118.469**                   | 160.809                     | 279.277                     |
|              | High income        | 432.889  | 503.757  | 463.276  | 70.869*                     | -40.481                     | 30.387                      |
|              | Upper middle income| 378.365  | 598.386  | 1097.406 | 220.021                     | 499.021                     | 719.042                     |
|              | Lower middle income| 131.404  | 219.490  | 395.181  | 88.086 (0.19)               | 175.691                     | 263.777                     |
| Renewable energy | Full sample     | 45.893   | 59.370   | 106.474  | 13.477**                    | 60.818**                    | 74.295                      |
|              | High income        | 56.761   | 63.636   | 91.422   | 6.875**                     | 27.786**                    | 34.661**                    |
|              | Upper middle income| 45.958   | 75.502   | 175.628  | 29.544*                     | 100.126                     | 129.670                     |
|              | Lower middle income| 16.293   | 22.441   | 38.659   | 6.148*                      | 16.218                      | 22.366                      |
| FDI          | Full sample        | 1.563    | 3.490    | 2.698    | 1.927***                    | 0.791***                    | 1.135***                    |
|              | High income        | 1.729    | 4.571    | 3.321    | 2.842***                    | 1.250**                     | 1.592**                     |
|              | Upper middle income| 1.706    | 2.734    | 2.315    | 1.029**                     | 0.419                       | 0.610                       |
|              | Lower middle income| 0.887    | 1.740    | 1.610    | 0.853**                     | -0.131                      | 0.722***                    |
| Export       | Full sample        | 24.116   | 24.977   | 25.790   | 0.861***                    | 0.813***                    | 1.674***                    |
|              | High income        | 24.835   | 25.605   | 26.255   | 0.770***                    | 0.649***                    | 1.420***                    |
|              | Upper middle income| 23.762   | 24.760   | 25.755   | 0.988***                    | 0.995***                    | 1.993***                    |
|              | Lower middle income| 22.721   | 23.613   | 24.584   | 0.892***                    | 0.971***                    | 1.863***                    |
| Import       | Full sample        | 24.173   | 24.993   | 25.828   | 0.820***                    | 0.835***                    | 1.655***                    |
|              | High income        | 24.845   | 25.586   | 26.208   | 0.743***                    | 0.620***                    | 1.364***                    |
|              | Upper middle income| 23.735   | 24.701   | 25.751   | 0.966***                    | 1.050***                    | 2.016***                    |
|              | Lower middle income| 23.036   | 23.835   | 24.915   | 0.800                       | 1.080***                    | 1.879***                    |
| GDP          | Full sample        | 25.612   | 26.191   | 26.947   | 0.579***                    | 0.756***                    | 1.334**                     |
|              | High income        | 26.099   | 26.622   | 27.136   | 0.523***                    | 0.514***                    | 1.037**                     |
|              | Upper middle income| 25.437   | 26.067   | 27.055   | 0.629***                    | 0.989***                    | 1.618**                     |
|              | Lower middle income| 24.565   | 25.217   | 26.262   | 0.652***                    | 1.045***                    | 1.697**                     |

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.
These preliminary results suggest that partitioning the data by crisis and by income levels may be justified insofar as the CO2 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/CO2 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 CO2 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               | CO2 Emissions | Renewable Energy | FDI    | Export  | Import  | GDP    |
|--------------------|---------------|------------------|--------|---------|---------|--------|
| Breusch-Pagan LM   | 100.39,55***  | 1279.11,55***    | 2413.29*** | 19025.02*** | 18535.63*** | 17127.50*** |
| (0.00)             | (0.00)        | (0.00)           | (0.00) | (0.00)  | (0.00)  | (0.00) |
| Pesaran scaled LM  | 255.81,55***  | 301.22,55***     | 46.86*** | 502.02*** | 488.61*** | 450.03*** |
| (0.00)             | (0.00)        | (0.00)           | (0.00) | (0.00)  | (0.00)  | (0.00) |
| Pesaran CD         | 46.84,55***   | 111.22,55***     | 31.65*** | 137.91*** | 136.10*** | 130.58*** |
| (0.00)             | (0.00)        | (0.00)           | (0.00) | (0.00)  | (0.00)  | (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.

For the overall period, results suggest that renewable energy consumption is significantly positively correlated with CO2 emissions for the entire sample and significantly positively correlated with CO2 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 CO2 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

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21 However, and unlike Peters et al. (2012), we find that CO2 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.
middle-income 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 CO₂ 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 CO₂ emissions and CO₂ emissions are significantly positive for the overall data. Finally, the relationships between CO₂ 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 CO₂ emissions. First, the impact of renewable energy consumption on CO₂ 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. These differential findings on the impact of the crisis on the renewable energy/CO₂ emissions relationship have not been previously reported in the literature.

In addition, based on the reported negative relationship between renewable energy consumption and CO₂ emission in selected sample countries/periods and the relationships reported for other control variables (FDI, imports, exports, and GDP), we conclude that increased consumption of renewable energy in these countries can reduce CO₂ 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). 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 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

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

| Pesaran’s CADF test | CO₂       | Renewable Energy | FDI       | Export    | Import    | GDP       |
|--------------------|-----------|------------------|-----------|-----------|-----------|-----------|
| Constant           |           |                  |           |           |           |           |
| Level, lag(0)      | -1.945**  | -5.086***        | -12.333***| -3.580*** | -3.897*** | -4.532*** |
|                    | (0.03)    | (0.00)           | (0.00)    | (0.00)    | (0.00)    | (0.00)    |
| Level, lag (1)     | -0.370    | -3.787***        | -4.811*** | -4.529*** | -4.813*** | -4.806*** |
|                    | (0.36)    | (0.00)           | (0.00)    | (0.00)    | (0.00)    | (0.00)    |
| 1st difference, lag(0) | -21.803***| -24.076***       | -26.372***| -18.982***| -17.800***| -18.072***|
|                    | (0.00)    | (0.00)           | (0.00)    | (0.00)    | (0.00)    | (0.00)    |

Constant & trend

| Level, lag(0)      | 0.089     | -5.988***        | -12.227***| -0.179    | 0.062     | 0.394     |
|                    | (0.54)    | (0.00)           | (0.00)    | (0.43)    | (0.53)    | (0.65)    |
| Level, lag(1)      | 2.898     | -5.492***        | -3.825*** | -0.837    | -0.790    | -0.815    |
|                    | (1.00)    | (0.00)           | (0.00)    | (0.20)    | (0.22)    | (0.21)    |
| 1st difference, lag(0) | -25.697***| -25.377***       | -38.672***| -17.264***| 0.062     | -16.405***|
|                    | (0.00)    | (0.00)           | (0.00)    | (0.53)    | (0.00)    | (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.

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 CO₂ emissions also changed because of the crises.
sign of the relationship did not change following the 2008 crisis for this income group. 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

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25 However, the significance changed from strongly negative to insignificantly negative.
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/CO2 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 relationship and significance remained unchanged for the lower middle-income subsample through the two crises. Fourth, reduction of CO2 emissions may not always encourage adoption of renewable energy sources. 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.

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.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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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