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A panel data analysis of policy effectiveness for renewable energy expansion on Caribbean islands

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ABSTRACT

Accelerating the rate of renewable energy deployment in Small Island Developing States is critical to reduce dependence on expensive fossil fuel imports and meet emissions reductions goals. Though many islands have now introduced policy measures to encourage RE development, the existing literature focuses on qualitative recommendations and has not sought to quantitatively evaluate and compare the impacts of policy interventions in the Caribbean. After compiling the first systematic database of RE policies implemented in 31 Caribbean islands from 2000 to 2018, we conduct an econometric analysis of the effectiveness of the following five policy interventions in promoting the deployment of RE: investment incentives, tax incentives, feed-in tariffs, net-metering and net-billing programs, and regulatory restructuring to allow market entry by independent power producers. Using a fixed effects model to control for unit heterogeneities between islands, we find evidence that net-metering/net-billing programs are strongly and positively correlated with increases in installed capacity of renewable energy - particularly solar PV. These findings suggest that the RE transition in the Caribbean can be advanced through policies targeting the adoption of small-scale, distributed photovoltaics.

1. Introduction

Fighting global warming by reducing greenhouse gas (GHG) emissions is one of the most challenging and urgent tasks of the 21st century. It is the consensus of thousands of scientists that GHG emissions from human behaviors are producing clear and worsening impacts on global climate systems (IPCC, 2014). The energy sector is one of the major contributors to global GHG emissions, and this trend is likely to continue as growing global demands for electricity further entrench reliance on fossil fuels (EIA, 2019). The rapid deployment of renewable energy (RE) is critical to decarbonize electricity generation systems and thereby mitigate the impacts of climate change.

Small island developing states (SIDS) and island nations are disproportionately vulnerable to climate change impacts, which include an increase in the frequency and intensity of extreme weather events such as hurricanes, flooding and sea level rise (Monioudi et al., 2018; Reyer et al., 2017; Rhiney, 2015; UNFCCC, 2005). This reality was driven home by the historic 2017 Atlantic hurricane season, where Hurricanes Harvey, Irma and Maria battered the Caribbean in short succession leading to several hundred deaths, year-long power outages and billions in damages to infrastructure (Blake, 2018). More recently, in 2019, Category 5 Hurricane Dorian caused damages in the Bahamas estimated at $3.4 billion and impacted the homes and properties of over 70,000 Bahamians (IDB, 2020).

However, while the small size and remoteness of islands leave them vulnerable to climate change, these same traits also position them to be leaders in the energy transition by showcasing the feasibility of high levels of RE penetration to the grid (Soomauroo et al., 2020). Though they contribute less than 1% of total annual GHG emissions, islands could have a global influence by providing successful examples of energy transitions (UN-OHRLLS, 2015). Recognizing this, many Caribbean islands have established ambitious renewable energy targets. Aruba, Dominica, Grenada, and Montserrat are among several islands that have pledged to meet 100% of energy needs with renewables between now and 2030. Furthermore, islands' discrete, well-defined geographic and political boundaries render them powerful as research subjects to understand policy intervention and system transformation. The 31 island nations of the Caribbean are particularly instructive because there has been wide variation in how aggressive and successful the islands have been in promoting RE deployment.

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While vulnerability is certainly a motivating factor for Caribbean islands to adopt RE, there are also economic factors at play. The generation portfolios of most Caribbean utilities are poorly diversified and dependent on centralized diesel generation assets. Over 87% of primary energy needs are currently met with imported petroleum, leaving the islands vulnerable to price shocks in the global oil market. As most utilities are allowed to pass these volatilities directly to customers through a fuel surcharge, tariffs in the region commonly exceed $0.30 per kilowatt-hour (Mcintyre et al., 2016) which is more than twice as large as the average world residential tariff of $0.13 per kilowatt-hour (IEA, 2018). These expenses have far-reaching consequences for island economies, rendering them uncompetitive in international trade and even tourism (Scobie, 2019).

Despite considerable abundant renewable resources, Caribbean islands have been slow to adopt RE (Shirley and Kammen, 2013). A number of technical, economic, political and social barriers, prominently financial resource shortages, monopolistic utility structures, and fossil lock-in dilemmas, among others, have been identified and analyzed to better understand the lack of RE deployment on these islands (Betzold, 2016; Dornan and Shah, 2016; Haraksingh, 2001). Among those barriers, a lack of supportive policies and regulatory frameworks are identified as most important challenges for RE implementation (Blechinger, 2015, 2016; Ince et al., 2016). This challenge of supportive policy design is underlined by Romano et al. (2016), who through an econometric analysis of macroeconomic, demographic, and institutional factors find that under resource constraints policy-makers prefer to focus on policies targeting economic growth rather than environmental management.

New policies and regulatory regimes are crucial to capitalize on the substantial RE potential on Caribbean islands, reduce GHG emissions locally, improve affordability and sustainability of the local power supply, and set a global example for promoting RE development (Dornan and Shah, 2016). As Borång et al. (2016) point out, such policies need to be designed for each island's specific institutional and political context. Though there is a wealth of quantitative studies describing RE policy effectiveness for non-island regions (Carley, 2009; Dong, 2012; Shrimali and Kniefel, 2011; Yin and Powers, 2010; Johnstone et al., 2010; Zhao et al., 2013), it is not sufficient to rely on global recommendations on RE policy effectiveness for this region. RE policies have proliferated in Caribbean SIDS throughout the past decade and Caribbean-specific quantitative analysis are now possible.

Our paper supplements the existing qualitative literature by providing the first quantitative analysis of RE policy effectiveness which focuses exclusively on Caribbean islands. We also provide a unique database of RE policies implemented in 31 Caribbean islands between 2000 and 2018. We begin by asking questions regarding the makeup and timeline of policy implementation in the Caribbean: what types of RE policies have been most popular in the Caribbean? When did most islands begin implementing policies? How does implementation of RE capacity in the Caribbean compare with global figures? Using a fixed effects model, we then evaluate the strength of the correlation between these policies and growth in RE capacity. This addresses the guiding question of our paper: which policy instruments are the most effective in encouraging RE deployment on Caribbean islands? We conclude by discussing why these policies were effective in terms of the technical, political or economic barriers they helped to overcome, and derive recommendations for policymakers to select and prioritize policy interventions.

We have structured the remainder of the paper as follows. Section 2 dives further into literature for RE policies on islands and measuring policy effectiveness and describes the econometric methodology and data sources. Section 3 presents our empirical results. Section 4 discusses the results in the larger context of Caribbean RE development and provides recommendations based on our findings. Sections 5 and 6 conclude and describe important areas for future research.

2. Background, methodology and data

2.1. Background

SIDS have been a focus for RE researchers given their high vulnerability, leadership in climate change negotiations, and clearly defined system boundaries which allow for transparent analyses (Ourbak and Magnan, 2017; Soomauroo et al., 2020; Blechinger et al., 2016). Barriers to RE deployment in the Caribbean and the importance of policy to overcome them has been well-documented since the early 2000s. Haraksingh (2001) underlined the importance of policy support for RE to reduce the dependency on fossil fuels on Caribbean islands. Contreras et al. (2010) confirmed this in an extensive report ten years later and Shirley and Kammen (2013) elaborated on recommendations on island-specific policies studied by Blechinger and Shah (2011) for Trinidad and Tobago. Shah and Niles (2016) underline again the importance of policies and regulatory frameworks for RE deployment. They propose an institutional analysis and design framework in order to ease effective implementation of policies, but remain vague in the distinct recommendations on which policy instruments should be implemented.

In terms of specific policy instruments, feed-in tariffs have been recommended for larger Caribbean island states by Jacobs et al. (2013). Blechinger (2016) suggests a mix of regulatory and financial instruments, including feed-in tariffs and net-billing, to push RE development by utilities, independent power producers, and other private entities. The instruments are structured for different size classes of Caribbean islands, but their effectiveness is not quantified (Blechinger et al., 2016). Timilsina and Shah (2016) recommend allowing the involvement of IPPs, the establishment of net-metering and billing programs, and fiscal incentives such as tax exemptions to accelerate RE adoption, but again do not provide any quantitative evidence of effectiveness. Regarding non-policy factors, Dornan and Shah (2016) have identified ODA as a driver for RE development but only if accompanied by necessary policy reforms.

We find from this literature survey a confirmed consensus on the crucial role of policies and regulatory frameworks for RE deployment on Caribbean islands. However, there is less consensus on which reforms and policy incentives are most effective and an exploration of why due to the lack of statistical modeling and quantitative analyses. Furthermore, there are few recent data sources on RE policy implementation in the Caribbean of which none are inclusive of smaller island dependencies. With our paper we aim to close this research gap with a detailed empirical study to parse the lessons offered by the Caribbean's experience with RE policy and deployment – lessons which can be instructive not only for the Caribbean, but for SIDS in other regions and remote communities at large.

A growing body of literature has used econometric modeling to test the effectiveness of policy on RE deployment in non-island contexts. Carley (2009), Dong (2012), Shrimali and Kniefel (2011), and Yin and Powers (2010) use fixed effects models to examine the effectiveness of policies on RE development in the US and EU. However, their applicability to non-OECD and developing nations is limited. Most of these studies focus on policies such as renewable portfolio standards (RPS), green power purchasing programs and clean energy funds which have not been widely used in the Caribbean.

Johnstone et al. (2010) and Zhao et al. (2013) provide the mostly relevant empirical studies of RE policy. Johnstone et al. (2010) demonstrate via a fixed effects model and a panel of 25 countries from 1978 to 2003 that tax incentives had a strong influence on RE patent counts across all technology types. They also found that policies had disparate effects based on technology type; while investment incentives were effective for solar technology, renewable obligations and tradable certificates better supported wind technology. Zhao et al. (2013) demonstrated using a Poisson pseudo-likelihood estimation technique and a panel of 122 countries over a 30-year period that feed-in tariffs and investment incentives were effective for all renewable energy types, but that the effects are more pronounced prior to the late 1990s.

2.2. Methodology

The primary objective of our empirical analysis is to estimate the effectiveness of five policy instruments – investment incentives, tax incentives, feed-in tariffs, net-metering/net-billing programs, and regulatory restructuring to allow independent power producers (IPPs) – on the development of RE in the Caribbean. After capturing these policy interventions as dummy variables, we regress them against cumulative renewable energy capacity in a fixed effects model which controls for unobservable heterogeneities between islands and macro time trends. The following sections provide further detail on variable and model specification.

2.2.1. Definition of policy variables

Though there are dozens of potential policy options available to policymakers to encourage renewable energy, we limit the policies examined in this study to the following five instruments which our policy survey identified as the most frequently implemented among the 31 islands. These policy instruments are similar to those studied by Zhao et al. (2013) but are modified to fit the Caribbean environment where tradable certificate schemes, RPS, auction mechanisms, and voluntary programs have not been widely used:

1. Investment incentives (InvestmentInc): grants or low-cost loans to reduce the capital cost of RE development. An example is Puerto Rico's use of a Green Energy Fund to subsidize up to 50% of wind or PV systems through a competitive grant process (DSIRE, 2015).
2. Tax incentives (TaxInc): policies designed to leverage the tax system to provide incentives for RE, including import reductions or exemptions, tax deductions for companies involved in the RE sector, property tax exemptions, and value-added tax reductions or incentives. An example is Antigua and Barbuda's 2015 Renewable Energy Act which provides for exemptions of import duties on plants, machinery, and parts imported for RE, waivers for customs duties, and corporate tax relief (*Renewable Energy Act, 2015*).
3. Feed-in tariffs (FiT): a policy mechanism used to stimulate RE development by offering favorable price regimes for RE relative to carbon-intensive generation (Benitez, 2012). In the Caribbean context, FiTs are oriented towards utility-scale RE production from independent power producers (IPPs).
4. Net-metering and net-billing schemes (NMNB): net-metering functions in a similar manner to FiTs by ensuring a favorable price for RE generation, usually through customer "prosumers" who receive credit for every net unit of energy which is fed into the grid.[1]
5. Regulatory restructuring to allow IPPs (IPP): this policy captures the deregulation of the electricity sector to require utilities to accept interconnections from independent power producers (IPPs), often by amending previous legislation to allow the government to grant licenses directly to IPPs. Given the monopolistic nature of most Caribbean utilities and their historical reluctance to integrate RE, we exclude policy interventions which are intended to attract IPPs but designate the utility as the decision-maker in granting generation licenses. For example, though IPPs are legally allowed in St. Vincent and the Grenadines IPPs, we exclude this policy given that the power to grant generation licenses rests with the monopoly utility VINLEC opposed to an external government regulator (IDB, 2013).

2.2.2. Definition of outcome variable

We quantify our outcome variable as the cumulative capacity of non-hydro RE including solar PV, onshore wind power, geothermal, and biomass. Capacity is chosen instead of generation as capacity is not sensitive to the impacts of weather and equipment performance and is a reliable indicator of deliberate investment decisions. Though we acknowledge that generation of RE is the appropriate indicator of progress towards climate goals, the present study is interested in the linkages between policy and development of renewable infrastructure. The forces which affect the capacity factors of infrastructure are outside the scope of this study. We also opt to use an absolute measure of RE capacity instead of normalizing it as a percentage of total installed capacity. Since the total capacity of island grids is relatively small, an RE measure normalized by total installed capacity will be subject to fluctuations from weather impacts, equipment failures, and similar events unrelated to RE development and can bias the results of our analyses. This experimental design mirrors the empirical work of Carley (2009), Delmas and Montes-Sancho (2011), and Dong (2012) who use cumulative capacity as their outcome variable in econometric analyses of RE policy.

To provide further clarity on the impacts of RE policy on specific technology types, we conduct separate regressions for solar and wind development in addition to the aggregated RE regression. Though we include geothermal and biomass generation in our measure of RE, we do not include them as separate regressions given the limited growth in capacity of these technologies over the study period and the lack of targeted policies to encourage development of these resources.

Much of the hydropower capacity in this region was constructed prior to the period of interest. As these legacy assets decline in capacity or come offline, they can skew the measure of RE capacity and make it difficult to ascertain the effects of recent RE policies. For these reasons we omit hydropower from our measure of installed RE capacity.

2.2.3. Model selection and description

A key concern in the selection of the estimation model for applied policy research is the ability to account for unobservable differences between islands resulting from the diversity of socioeconomic, demographic, geographic, historical, and political circumstances of Caribbean islands. A pooled regression model will produce biased estimates as it cannot control for this unobserved heterogeneity between islands. An F-test to verify the suitability of a variable intercept model over a pooled regression model returned a p-value < 0.01, indicating that a pooled regression model is inappropriate for this use case (Schaffer and Stillman, 2016).

A fixed effects model is a form of variable intercept model which can produce unbiased estimates with efficient standard errors by controlling for unobserved heterogeneity between groups that is correlated with explanatory variables. A random effects model, in contrast, assumes no correlation between the unobserved and observed variables. A fixed effects model is theoretically more appropriate, as the types of heterogeneities between islands we seek to control for likely also influence the types of policies that they are predisposed to implement. To test this formally, we employ a Hausman test, which rejects the null hypothesis that there is no correlation between the error term and the fixed effects terms with a p-value < 0.01. As Liu et al. (2019) identify, the traditional Hausman test assumes that the individual fixed effects and disturbance term are independently and identically distributed, which may not be applicable in the presence of heteroskedasticity and within-group correlation. To verify the results of the Hausman test, we use a method developed by Schaffer and Stillman based on approaches by Arellano (1993) and Wooldridge (2002) to compute a statistic which is robust to heteroskedasticity and autocorrelation (Schaffer and Stillman, 2016). This test again confirms the significance of correlation between the

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[1] Net-billing programs and feed-in tariffs both function by allowing interconnection with the utility grid and providing per kWh compensation to the owner of the generation unit. Given this similarity, the terms are used interchangeably in some islands. Here, a policy is designated as net-metering/net-billing if its intended beneficiaries are small-scale residential or commercial consumers who do not generate electricity as a primary business model. In contrast, we categorize a policy as a feed-in tariff if its objective is to encourage the participation of IPPs in the generation market.

individual fixed effects and error terms with a p-value < 0.01. Given this, the results of the F-test, Hausman test, and overidentification statistic, and the methodological precedent set by Carley (2009), Yin and Powers (2010), Marques et al. (2010), Shrimali and Kniefel (2011), and Groba (2013), we conclude that a variable intercept fixed effects model is appropriate.

Our fixed effects model takes the following form:

$$Y_{i,t} = \beta_0 + \sum_{k=1}^{k} \beta_k X_{i,\,k,t} + \sum_{j=1}^{j} \beta_j Policy_{i,j,t-t_{lag}} + u_i + v_t + \varepsilon_{i,t}$$

where the outcome variable $Y_{i,t}$ measures the cumulative capacity of non-hydropower renewables in island i during year t, $X_{i,\,k,t}$ is a vector of control variables, u_i is the fixed-effect term capturing island individual heterogeneity, v_t is a time fixed effects term to control for larger regional trends, and $\varepsilon_{i,t}$ is an idiosyncratic disturbance term which captures all variation in the outcome variable not accounted for by island and time fixed effects or explanatory variables. $Policy_{i,j,t-t_{lag}}$ is a vector of RE policy variables at time $t - t_{lag}$. Since it can take several years for a policy to take full effect after its enactment date, we follow the example of Carley (2009), Delmas and Sancho (2011), Liu et al. (2019), and Johnstone et al. (2010) and introduce a lag term, in this case equivalent to two years, into the RE policy vector. Though only two-year lag results are reported here, regression results were robust across sensitivity test scenarios with zero, one, two, three, and four-year lags.

Following Carley (2009), Johnstone et al. (2010), and Zhao et al. (2013), we capture policy interventions as dummy variables which assume a value of 1 in the year of implementation and following years, and 0 before implementation or if not implemented. A necessary limitation of treating policy implementation as dummy variables is that all policies within a category are treated equally in the regression. There is no measure of the aggressiveness of each policy or of how well it was written, enacted, or enforced.

Within the general framework of a fixed effects model, it is important to choose an estimation method which is robust to violations of regression model assumptions. A Wooldridge test rejected the null hypothesis of no autocorrelation in our panel data (Wooldridge, 2002; Drukker, 2003). A modified Wald test rejected the null hypothesis of groupwise homoscedasticity in the residuals of a fixed effects regression model (Baum, 2001). Finally, we tested the residuals of the fixed effects specification for cross-sectional dependence using the testing procedures methods proposed by De Hoyos and Sarafidis (2006) which are preferable for panel datasets where the cross-sectional dimension is larger than the time dimension. Given these nonidealities (heteroscedasticity, cross-sectional dependence, and autocorrelation), we choose the Driscoll and Kraay (1998) covariance matrix estimator for use with a fixed effects regression. To test the robustness of the results under this fixed effects (FE) specification, we also include a specification using a Prais-Winston estimation with panel corrected standard errors (PCSE). Time and island dummy variables are maintained within the PCSE specification for reasons discussed in Section 2.2.4. Per Hoechle (2007) both estimation methods produce standard errors which are robust to heteroscedasticity, cross-sectional correlation, and autocorrelation.

2.2.4. *Control variables*

The inclusion of island and year dummy variables in the regression controls for static heterogeneities between islands and for dynamic macro trends. The island dummy variables control for time-invariant differences such as renewable resource abundancy or land area, precluding the need for their explicit inclusion as control variables. Year dummy variables account for time-dependent macro trends, such as economic shocks, which affect all islands. The remaining control variables are therefore chosen to account for trends which are both time-variant and non-homogenous across the group of islands. Table 1 shows summary statistics for the outcome, policy, and control variables.

$X_{i,\,k,t}$ is a vector of covariates which controls for economic, social, and geographic differences between islands and minimizes variable endogeneity. It is composed of the following variables for which we provide summary statistics in Table 2:

1. Gross domestic product (GDP) per capita: measured in 2019 USD and included to control for the possibility explored by Andreas et al. (2017) that "sustainability is a luxury" and that wealthier countries have the resources to more heavily invest in RE technology. This is a standard control variable which has precedent in the empirical study of RE policies by Carley (2009), Yin and Powers (2009), Marques et al. (2010), Shrimali and Kniefel (2011), Dong (2012), Jenner et al. (2013), and Zhao et al. (2013), among others.
2. Official development assistance (ODA): measured in 2019 USD as a percent of GDP. It has become increasingly clear in the past decade that access to finance is a critical barrier to RE development in small islands. ODA flows to Caribbean islands for energy sector reform and RE investments has accordingly increased in recent years (Niles and Lloyd, 2013; Atteridge and Savvidou, 2019). We include ODA to control for temporal variations in unequal allocation of development aid across the 31 islands throughout the 19-year study period.
3. Foreign direct investment (FDI): measured in 2019 USD as a percent of GDP. FDI inflows are often associated with transfer of knowledge and technology and have been demonstrated to be correlated with energy consumption (Doytch and Narayan, 2015).
4. Average fuel cost: measured in USD per thermal kWh of imported hydrocarbon fuels. This variable is intended to control for the difference in fossil fuel costs across islands. The economic environment in islands with high average fuel costs will be more supportive of RE than islands with low fossil fuel costs (Blechinger, 2015).
5. Renewable patent count: the cumulative number of yearly global solar and wind patents. This variable is included as a proxy for the rapid technological innovation and knowledge dissemination which occurred during the study period. The use of patent data as a proxy for innovation is well-established in the literature (Johnstone et al., 2010; Brunnermeier and Cohen, 2003).

A potential risk of explicitly including control variables is that they could absorb some of the effects of the explanatory variables if they lie in the causal pathway of RE development. For example, if international donors allocate additional aid for RE development because of the enactment of favorable RE policies, and this in turn further increases RE deployment, the control variable will absorb some of the explanatory power which should be attributed to our explanatory policy variables. This would lead to an underestimation of policy effectiveness.

All control variables except FDI and ODA are modeled as logarithms, as this can help eliminate heteroscedasticity without obscuring the underlying relationship to the outcome variable. FDI and ODA are normalized as a percent of GDP. ODA and FDI data for the Dutch islands of Bonaire, Saba, and St. Eustatius was not available. To avoid biasing our coefficients we exclude these three islands in all regressions except where otherwise stated.

2.3. *Data*

Our dataset covers 31 Caribbean islands over the 19-year period from 2000 to 2018, resulting in 569 observations. We use the term island rather than state because 17 of the 31 islands are political dependencies of France, the United Kingdom, the Netherlands, or the United States. We present a list of the islands included in our study and relevant characteristics in Table 2.

IRENA's yearly renewable energy statistics is our source for renewable installed capacity (IRENA, 2019). For islands where data is not available, figures were triangulated from alternate sources such as government statistics (CBS, 2018; Commission de Régulation de

Table 1
Variable definitions and summary statistics.

Variable	Description	Source	Variable type[a]	Min.	Max.	Mean	SD	Obs.
RECapacity	Non-hydro cumulative RE capacity	IRENA	Cont	0	679	26.8	92.7	589
SolarCapacity	Cumulative solar PV capacity	IRENA	Cont	0	166	5.09	18.9	589
WindCapacity	Cumulative onshore wind capacity	IRENA	Cont	0	183	6.15	20.3	589
InvestmentInc	Investment incentive policies	Author	Bin	0	1	0.0951	0.294	589
TaxInc	Tax incentive policies	Author	Bin	0	1	0.261	0.440	
FiT	Feed-in tariff implemented	Author	Bin	0	1	0.168	0.374	589
NMNB	Net-metering or net-billing policy implemented	Author	Bin	0	1	0.226	0.418	589
IPP	Regulatory restructuring to allow IPPs to power market	Author	Bin	0	1	0.255	0.436	589
Income	Gross domestic product in USD per person	World Bank	Cont	334	107,997	21,732	18,515	589
ODA	Official development assistance as percent of GDP	OECD	Cont	−0.00267	4.34	0.0501	0.283	532
FDI	Foreign direct investment as percent of GDP	World Bank	Cont	−8.75	119	1.72	9.57	532
FuelCost	Fuel cost in USD per thermal kWh	Blechinger (2015)	Cont	0.00574	0.887	0.130	0.983	589
PatentCount	Number of filed solar and wind patents	IRENA	Cont	7705	442,846	208,110	163,693	589

[a] Bin = binary variable, Cont = continuous variable.

Table 2
Summary characteristics of the 31 islands in the study.

Island Name	Political Status	Area (km^2)	GDP (2018 USD/person)	Population (1,000s)	2018 RE %[a]
Anguilla	BOT	91	$23,899	15	3.2
Antigua & Barbuda	Sovereign	443	$16,728	96	6.3
Aruba	Netherlands CC	180	$27,015	106	12.6
Bahamas	Sovereign	10,010	$32,218	386	0.2
Barbados	Sovereign	430	$17,949	287	9.2
Bermuda	BOT	54	$107,997	66	0.0
Bonaire	Netherlands SM	288	$22,952	20	55.1
British Virgin Islands	BOT	151	$35,155	30	1.5
Cayman Islands	BOT	264	$86,856	64	5.9
Cuba	Sovereign	109,820	$8,822	11,338	9.1
Curaçao	Netherlands CC	444	$19,219	163	21.2
Dominica	Sovereign	751	$7,691	72	1.9
Dominican Republic	Sovereign	48,320	$8,051	10,627	7.4
Grenada	Sovereign	344	$10,641	111	5.1
Guadeloupe	France ROM	1,629	$22,024	400	25.2
Haiti	Sovereign	27,560	$868	11,123	0.7
Jamaica	Sovereign	10,831	$5,354	2,935	16.9
Martinique	France ROM	40	$31,834	376	21.7
Montserrat	BOT	102	$36,211	5	0.0
Puerto Rico	US UOT	8,959	$33,271	3,040	4.1
Saba	Netherlands SM	13	$22,877	2	45.8
St. Barthelemy	France COM	25	$37,898	10	0.1
St. Eustatius	Netherlands SM	21	$32,406	3	77.9
St. Kitts & Nevis	Sovereign	261	$19,277	52	6.0
St. Lucia	Sovereign	606	$10,566	182	4.2
St. Maarten	Netherland CC	34	$9,987	42	0.0
St. Martin	France COM	54	$23,309	37	0.2
St. Vincent & the Grenadines	Sovereign	389	$7361	110	2.3
Trinidad & Tobago	Sovereign	5,128	$17,130	1,390	0.1
Turks & Caicos	BOT	948	$27,141	38	0.5
US Virgin Islands	US UOT	346	$38,066	105	1.4

[a] RE capacity as percent of total installed capacity IEA, 2018; BOT = British Overseas Territory, CC = Constituent Country, SM = Special Municipality, COM = Overseas Collectivity (Collectivités d'outre-mer), ROM = Overseas Region (Régions d'outre-mer), UOT = Unincorporated Organized Territory.

l'Energie, 2018, CIA, n.d., Barbados Fair Trading Commission, 2019; Commonwealth of Dominica, 2015; Development Bank of Jamaica Limited, 2020; Government of Bermuda, local utility reports (BELCO, n.d.), and studies from credible international organizations (IRENA, 2018; Latin American Energy Organization, 2019; Nexant, 2010; NREL, 2015a, 2015b; WorldData, n.d.).[2]

While several sources provide information on RE policy implementation for the larger sovereign islands, there are no existing datasets that comprehensively cover the 31 islands in our study. To fill this gap, we compiled a database of policies intended to encourage development of RE through a systematic review of relevant documents. The primary information source was legislative documents such as acts or laws from national legal databases and environmental legal databases such as ECOLEX. Policies and program announcements from local electric utilities were also a rich data source, as were filings and reports from government regulators where they existed. Government energy policies, roadmaps, integrated resource plans, and other strategy documents provided another source of information. Findings from these primary documents were cross-checked with the National Renewable Energy Laboratory's (NREL) Energy Snapshots publications, Renewable Energy and Energy Efficiency Partnership (REEEP) annual reports, Energy Dossiers from the Inter-American Development Bank (IDB), Bloomberg NEF's Climatescope database, the Database of State Incentives for Renewables & Efficiency (DSIRE) and other various gray literature documents from organizations such as the Rocky Mountain Institute, Green Climate Fund, and IRENA. As a final step, this database was reviewed by local energy sector experts for islands where there were remaining data gaps.

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[2] RE data was not available from IRENA for Bermuda, Bonaire, Monserrat, Saba, St. Martin, St. Barthelemy, St. Eustatius, and St. Martin.

3. Results and discussion

3.1. An overview of policy implementation and RE growth in the Caribbean

In 2000, the islands had on average less than 0.5% RE as a fraction of total installed capacity of renewable and non-renewable generating assets. The French island of Guadeloupe was an early leader with just under 10% of total installed capacity coming from wind and biomass sources. Curacao and Jamaica were the only other islands at this time with more than 1% RE penetration.

Between 2000 and 2018, total RE capacity in the 31 islands grew over 1,600% from 82 MW to an estimated 1417 MW.[3] As Fig. 1 demonstrates, strong growth in solar PV and onshore wind drove this dramatic increase, with solar and wind accounting for 54% and 38% of growth in capacity, respectively. Modest growth in geothermal and bioenergy accounted for the remainder. The overall growth in the region is impressive considering, as Fig. 2 shows, that most islands had zero or negligible RE in 2000. By 2018, most islands had RE penetration on the order of 2–10%, with an average of 5.3% RE penetration. This regional figure compares unfavorably with global figures which the International Energy Agency estimated to be around 26% in early 2019 (IEA, 2020).

The Dutch islands of St. Eustatius and Bonaire are remarkable outliers among the 31 islands, with 77.8% and 55.1% installed capacity RE by 2018 respectively. According to data from the Dutch government, RE penetration as a percent of total generation is more moderate but still the highest in the region at 45.5% for St. Eustatius and 32.8% in Bonaire (CBS, 2018). In contrast, the Bahamas, Bermuda, Haiti, Monserrat, St. Barthelemy, St. Maarten, St. Martin, Trinidad and Tobago and Turks and Caicos had less than 1% RE penetration IEA, 2018.

RE policy implementation grew precipitously over the 19-year study period. As our policy survey revealed, the most widely implemented policies were investment incentives, tax incentives, feed-in tariffs, net-metering/net-billing programs, and regulatory restructuring to allow IPPs. Though renewable portfolio standards and RE auctions were also utilized on some of the islands, the five aforementioned policies were selected as the focus of the study given the high frequency of implementation.

As Fig. 3 shows, prior to 2000 none of the islands had implemented any of the five policies. By 2018, this figure had grown to 76. Policy implementation took off around 2006 – coinciding with a one-year lag with the entrance of the Kyoto Protocol into force (United Nations, 1997) – and grew steadily through 2018. Overall, regulatory restructuring to allow independent power producers was the most frequently used of the five policies, with 19 of 31 islands passing some sort of legislation revoking the status of the utility as the sole licensed electricity generator. Net-metering/net-billing and tax incentives were also widespread, with just over half of the islands having implemented these measures by 2018. Investment incentives were the least frequently used, likely because of the significant financial resources necessary to leverage this particular policy.

Table 3 presents policy evolution over time disaggregated by island. It demonstrates France's early activism in promoting renewables in their overseas departments and territories by implementing feed-in tariffs and regulatory restructuring in the early 2000s. The Dominican Republic (DR) is also noteworthy as an early adopter of RE policies. By 2007, when most islands in the study were just beginning to implement RE policies, the Dominican Republic had already completed a regulatory restructuring and introduced a feed-in tariff, tax incentives, investment incentives and a renewable portfolio standard.

3.2. A conceptual framework of policy effectiveness

Existing studies by Shirley and Kammen (2013), Blechinger (2016), Blechinger et al. (2016), Dornan and Shah (2016), Ince et al. (2016), Timilsina and Shah (2016), Khan and Kahn (2017), provide a rigorous understanding of the technological, economic, and political barriers to RE development in the Caribbean and strategies that have been used to counteract them. Building from this work, Fig. 4 shows the conceptual framework underpinning this analysis which theorizes the linkages between the key barriers to RE development identified in the literature, strategies which have been used to overcome them, and finally the specific policy instruments through which these strategies are deployed. Though this framework of barriers, strategies, and policies is far from exhaustive, it is instructive in understanding the impact pathways of the policy mechanisms assessed in this study.

Blechinger (2015) reports a lack of a legal and regulatory framework for private investors as the most important barrier as identified by experts in local utilities, governments, and the private sector. This would suggest that feed-in tariffs and net-metering/net-billing programs, which must define clear rules of interconnection and compensation for non-utility generators, would be particularly effective in the Caribbean. High initial investment costs are also ranked as highly important which suggests that well-planned investment incentives would be effective policy instruments to encourage project development. Finally, a lack of legal framework for IPPs and utility monopoly rank in the top ten most important barriers, leading us to hypothesize that regulatory reform to allow IPPs to enter the generation sector would be effective in stimulating RE deployment. In the following sections we present our empirical results and interpret their relevancy to policymakers.

3.3. Evidence of policy effectiveness

Our empirical analysis is structured in three separate regressions. The first, which we designate RE 1, tests the impacts on policy to cumulative total RE capacity, inclusive of solar, wind, biomass, and geothermal. As a robustness check we include RE 2, which shows the same regression as RE 1 with insignificant variables omitted. The second and third regressions follow the same framework but are technology specific. Solar 1 and Wind 1 test the impacts of policy on cumulative solar PV and onshore wind capacity, respectively. Solar 2 and Wind 2 are again robustness checks which mirror Solar 1 and Wind 1 but with insignificant variables omitted. This framework is repeated for the alternate PCSE specification. We present these estimation results in Table 4.

Given the log nature of the outcome variable, we interpret the regression coefficients of the policy variables as follows: the total RE capacity (or solar or wind capacity for the technology-specific regressions) on an island that implemented the policy will, on average, be $100 \cdot X$ percent larger than the counterfactual case in which the policy was not adopted, where X is equivalent to the regression coefficient. For a control variable in log form with regression coefficient Y, a 1 percent increase in the control variable will on average produce a Y percent increase in the cumulative renewable capacity.

Net-metering/net-billing policies, which have become increasingly popular price instruments in Latin America and the Caribbean, were positive and significant across all three outcome variables in both regression specifications. Feed-in tariffs had a significant and positive correlation with total RE capacity across both regressions, although to a lesser extent (1.306) in the PSCE specification than in the FE specification (2.962). Interestingly, the impact of feed-in tariffs on solar installed capacity was only found to be significant in the FE specification, which overall yielded consistent but more optimistic results than the PCSE specification.

For total renewable capacity, feed-in tariffs had the largest effect in both specifications, followed closely by net-metering/net-billing. Investment incentives, tax incentives and regulatory restructuring to allow

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[3] Excluding biomass RE from Cuba, for which the data is inconsistent.

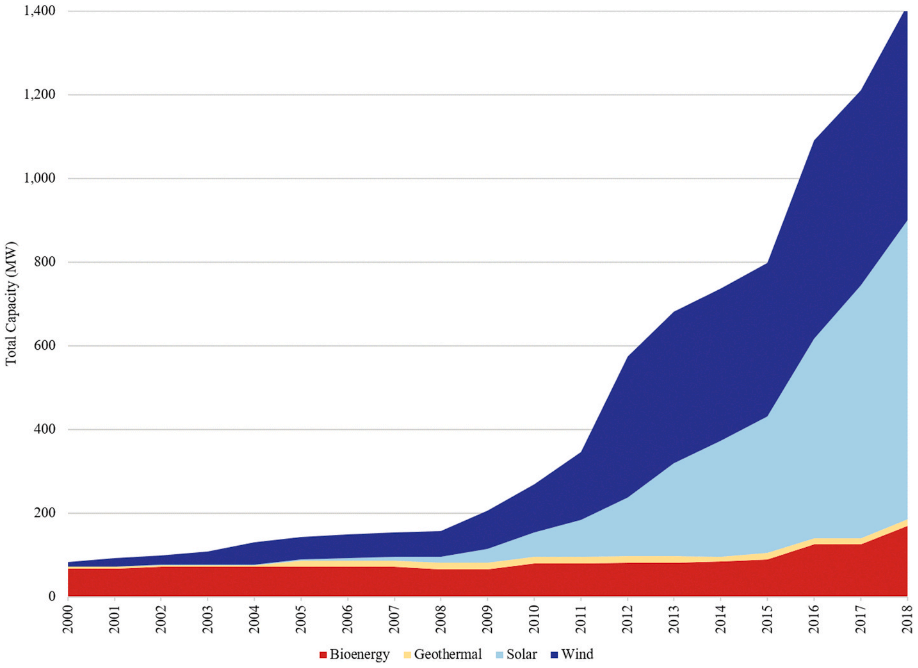

Fig. 1. RE growth in the 31 study islands over time by renewable type.

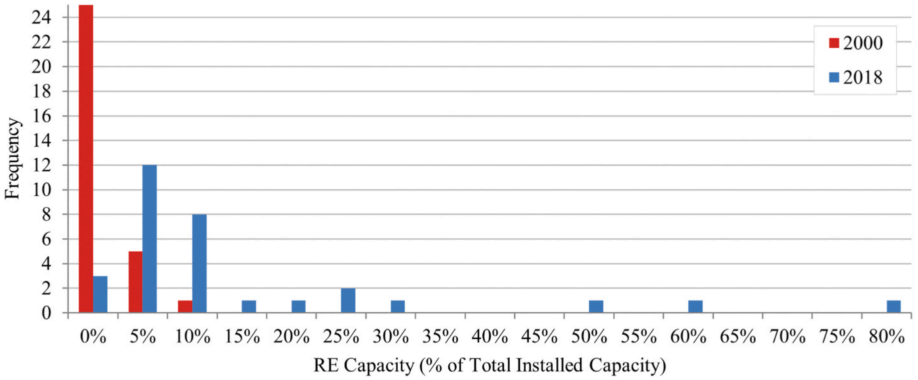

Fig. 2. Histograms comparing RE penetration in 2000 and 2018.

IPPs were not significantly correlated with total RE growth. The lack of correlation of total RE with regulatory restructuring was not unexpected given that this measure is an enabling policy which does not directly incentivize RE development. This will be discussed further in section 4.3. These results remained stable across both specifications when insignificant variables were omitted from the regression.

In the solar-specific regression, net-metering/net-billing was the only policy which was positively and significantly correlated with growth in solar installed capacity across both FE and PCSE specifications. Interestingly, both specifications also found investment incentives to be significantly correlated with growth in solar capacity, but with a relatively large negative coefficient. We will explore possible explanations for this counter-intuitive result in section 5. These results also remained stable in Solar 2 when insignificant variables were omitted.

For the wind-specific regressions, tax incentives, feed-in tariffs, and net-metering/net-billing programs were positively and significantly correlated with growth in wind installed capacity. Net-metering/net-billing had the strongest correlation, followed by feed-in tariffs and tax incentives. However, when insignificant variables were omitted in the PCSE specification, feed-in tariffs and net-metering/net-billing policies lost statistical significance above the 10% level, likely due to correlation between policy variables. Wind was the only model in which tax incentives were significant. Investment incentives and allowing IPPs were not significant in any of the wind-specific regressions.

The control variables were more sensitive to model specification than the policy variables. Only ODA and patent count were found to be significantly correlated with RE capacity growth across both FE and PCSE specifications. ODA was negatively correlated with growth in wind energy for both specifications. A patent count for RE technologies, used as a proxy for technological innovation, was significant across all regressions except Wind 2 under the FE specification. This result would appear to reflect the remarkable innovation which occurred in renewable technology over the past two decades, particularly in solar PV technology. The implications of these results will be discussed in the following section.

3.4. Caribbean policy and RE deployment in perspective

Despite ambitious RE targets and a nearly 20-fold increase in the number of policies implemented between 2000 and 2018, RE growth in the Caribbean has been sluggish (Dornan and Shah, 2016; Scobie, 2019). As Fig. 5 demonstrates, while global RE capacity grew rapidly from 2.0% to 20% of total installed capacity, RE in the Caribbean islands grew from 0.4% to only 5.3%. The slow growth in the Caribbean likely reflects a

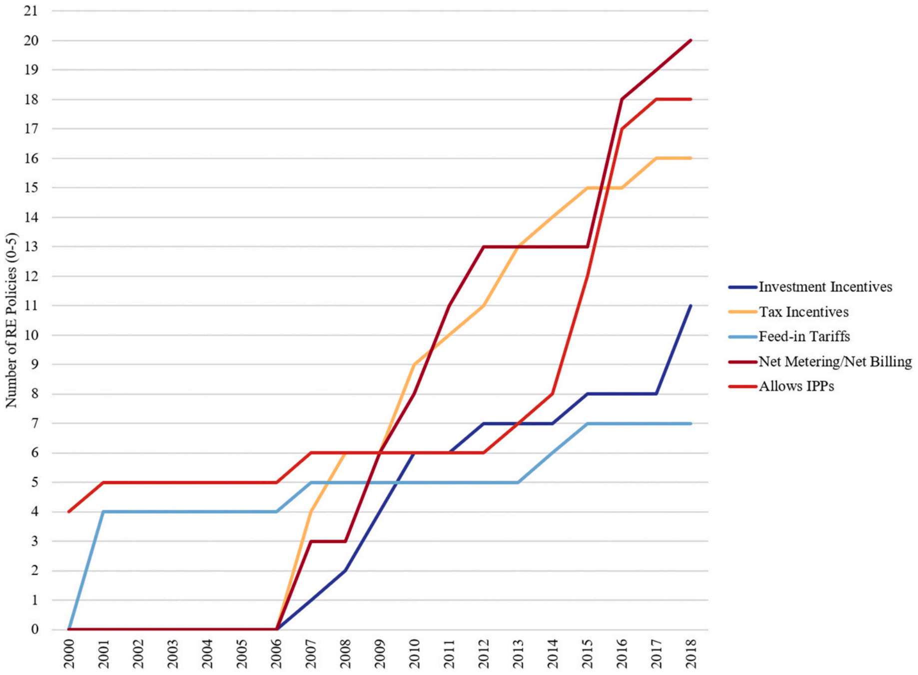

Fig. 3. Cumulative policy implementation by type.

Table 3
Timeline of RE policy enactment for islands in study.

Investment Incentives								DR	JAM	USVI BER	PR St.B		BAR			A&B			BON SAB St.E
Tax Incentives								DR GR GD MAR	BAH PR		BER T&C USVI	T&T	St. K	BAR JAM	AR	A&B		HA	
Feed-in Tariff		GD MAR St.B St.M						DR							USVI	CUR			
Net-Metering/ Net Billing								PR GR USVI		CAY St.V St.L	BAR BER	JAM CUR DR	A&B AR				BON DOM SAB St. E T&C	BAH	BVI
Allows IPPs	GD MAR St.B St.M	DR						DOM						ANG	BAR	A&B BAH BVI JAM	BON GR SAB St.E St.L	BER	
	'00	**'01**	**'02**	**'03**	**'04**	**'05**	**'06**	**'07**	**'08**	**'09**	**'10**	**'11**	**'12**	**'13**	**'14**	**'15**	**'16**	**'17**	**'18**

ANG = Anguilla, A&B = Antigua & Barbuda, AR = Aruba, BAH = The Bahamas, BAR = Barbados, BER = Bermuda, BON = Bonaire, BVI = British Virgin Islands, CAY = Cayman Islands, CUR = Curaçao, DOM = Dominica, DR = Dominican Republic, GR = Grenada, GD = Guadeloupe, HA = Haiti, JAM = Jamaica, MAR = Martinique, PR = Puerto Rico, SAB = Saba, St.B = St. Barthelemy, St.E = St. Eustatius, St.K = St. Kitts & Nevis, St.L = St. Lucia, St.M = St. Martin (French), St.V = St. Vincent & the Grenadines, T&T = Trinidad & Tobago, T&C = Turks & Caicos, USVI = US Virgin Islands.

combination of technical, social, and financial factors particular to island geographies, including inadequate technical capacity of institutions and workforce, fossil fuel subsidies, small market sizes and diseconomies of scale, lack of information and awareness of RE benefits, among others (Blechinger, 2015; Weisser, 2004; Ince et al., 2016). The technical challenge of integrating high shares of RE into island grids has been a particularly intractable issue given the need for sophisticated control strategies and energy storage technology to maintain grid stability (Gay and Shirley, 2018; Blechinger, 2015). A lack of technical confidence in managing the variability of RE on the part of the utility and/or regulator often translates into a reluctance to progress beyond low levels of RE penetration.

Access to external finance has also impeded the diffusion of renewable technology (Blechinger, 2015; Atteridge and Savvidou, 2019). IRENA has estimated that $16 billion in investment to SIDS would be needed to meet the targets identified in their NDCs. However, in a review of development aid for energy activities in SIDS, Atteridge and Savvidou (2019) found that the scale of assistance was small relative to overall financing needs. While project financing needs remain unmet, donors did allocate over $1.3 billion in development assistance to SIDS

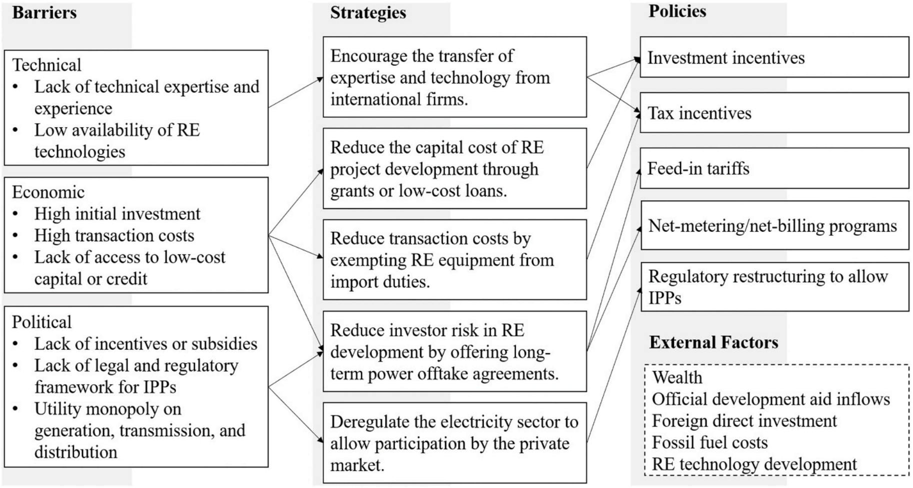

Fig. 4. Conceptual framework of analysis.

(inclusive of non-Caribbean SIDS) for energy policy reform and institutional technical assistance between 2002 and 2016 (Atteridge and Savvidou, 2019). This assistance likely played a strong role in sustaining the high rate of new policy implementation beyond the Kyoto Protocol era and throughout the 2010s.

Matching global trends, wind and solar PV account for the majority of RE growth in the Caribbean. Whereas globally wind has been the dominant technology, installed capacities of solar in the Caribbean surpassed wind in the mid-2000s. Solar growth in the region is likely to continue outpacing wind development given the low technical complexity, abundance of solar resource, and the recent focus on improving grid resiliency through grid asset decentralization. The dominance of solar technology over wind may also reflect logistical and technical challenges which decrease the economic feasibility of wind projects relative to solar farms. For example, Blechinger (2015) argues that in small Caribbean islands lower efficiency wind turbines are often used due to load profile and grid infrastructure limitations. Furthermore, ports and port infrastructure are often inadequate to receive and handle turbine components (Lantz et al., 2012). Finally, a recent analysis of development aid for energy in small island developing states by Atteridge and Savvidou (2019) highlights a preference among donors and recipient countries for solar PV but few large-scale investments in wind projects.

This global comparison throws into question the role of islands as frontrunners for a RE transition. Large industrialized countries have been able to transition faster on a large scale because they do not face the barriers of finance and scale which apply to islands. Still, island states still have the opportunity to catch up, as the total investment and capacities needed for RE transition are minor compared to the global figures. Given the limited technical and financial capacities of many island governments, it is especially critical that efforts moving forward focus on implementing the most effective policy instruments to accelerate the energy transition.

3.5. *Relevance of empirical results to RE policy implementation*

Numerous studies identify antiquated regulatory and legislative frameworks and a lack of financial incentives as an impediment to the development of RE in the Caribbean (Blechinger, 2015; Dornan and Shah, 2016; Weisser, 2004). It is therefore unsurprising that four of the five policies tested (investment incentives, tax incentives, feed-in tariffs, and net-metering/net-billing) were significantly correlated with growth in renewable capacity in at least one of the total RE or technology-specific regressions. For ease of interpretation, Figs. 6 and 7 provide a visual summary of our empirical findings for both regression specifications, where a blank space indicates an insignificant result and the color corresponds to the magnitude of the regression coefficient.

Feed-in tariffs and net-metering/net-billing programs were the strongest performers of all five policies and were positively and significantly correlated with growth in total non-hydro RE, solar (in the FE specification only), and wind capacity. This finding is supported by Zhao et al. (2013), Liu et al. (2019), and Dijkgraaf et al. (2018) who, through similar econometric techniques, demonstrated a positive effect of feed-in tariffs on RE development. Feed-in tariffs have been implemented worldwide and are widely recognized as price instruments which can quickly and efficiently encourage RE growth and especially solar PV. Net-metering/net-billing programs were as strongly correlated as feed-in tariffs with increases in installed capacities of RE. The effectiveness of both policies can be attributed to two main factors: 1) the minimization of financial risk to potential private RE developers and/or prosumers by offering a long-term guaranteed purchase agreement for energy at a rate that will ensure an acceptable return on investment (Jacobs et al., 2013) and 2) the establishment of a clearly-defined regulatory and legal regime within which actors can confidently operate alongside utility monopolies.

The strong correlation of net-metering/net-billing programs with wind capacity growth is puzzling, as small-scale wind generation is uncommon in the Caribbean. This finding may stem from a strong correlation (0.46) between tax incentives and net-metering/net-billing, resulting in an overestimation of the latter. It is also likely that the establishment of a net-metering or net-billing program indicates a certain political willingness to implement RE and/or an openness on the part of the monopoly utility to integrate renewable resources. This makes sense in the case of wind project development which, given the large scale necessary to maximize efficiency and achieve economies of scale, must often be done in close collaboration with the utility.

The differences between feed-in tariffs, net-metering, and net-billing are subtle and have become increasingly blurred as innovation in policy making produces hybrid policies which defy conventional classifications (Couture et al., 2015). This is especially true in the Caribbean, where the terms are used almost interchangeably. However, understanding the distinctions between these policies is important as each incentivizes a different model of RE generation. A feed-in tariff provides developers with a long-term purchase agreement which guarantees payment for electricity generated from renewable sources (Menanteau et al., 2003), and is primarily intended to incentivize large-scale development by IPPs. Net-billing is similar in that it provides a guaranteed payment for renewably generated electricity, but the key difference is that the generator is also a customer of the utility. Furthermore, net-metering/net-billing programs generally have capacity caps which

Table 4
Regression results.

Specification	Fixed Effects Model						Panel Corrected Standard Error					
Variables	RE 1	RE 2	Solar 1	Solar 2	Wind 1	Wind 2	RE 1	RE 2	Solar 1	Solar 2	Wind 1	Wind 2
InvestmentInc	0.4220 (0.2927)	–	−2.623*** (0.7064)	−2.324*** (0.4880)	−2.017 (1.536)	–	0.2982 (0.7524)	–	−1.436** (0.7148)	−1.206* (0.7404)	−0.1129 (0.9807)	–
TaxInc	−0.04587 (0.6938)	–	1.222 (1.048)	–	2.454*** (0.5332)	2.275*** (0.4440)	−0.7914 (0.5533)	–	−0.1446 (0.5808)	–	1.331** (0.5373)	1.207** (0.5259)
FiT	2.962*** (0.9443)	2.950** (0.7859)	3.254*** (0.8093)	3.277*** (0.7540)	2.410** (1.145)	2.306** (0.9101)	1.778** (0.7866)	1.306* (0.7840)	1.177 (0.8102)	–	1.350** (0.5461)	1.073 (0.7234)
NMNB	2.704*** (0.6778)	2.773*** (0.6685)	2.378*** (0.5163)	2.649*** (0.4659)	3.0178*** (0.6316)	2.734*** (0.5264)	1.377** (0.5566)	1.208** (0.5573)	1.276** (0.4939)	0.9599** (0.4886)	1.120** (0.5461)	0.6754 (0.5354)
IPP	−0.2941 (0.5121)	–	−0.4709 (0.4325)	–	0.7529 (0.5195)	–	0.4872 (0.5079)	–	−0.4792) (0.6202)	–	0.2503 (0.4986)	–
Income, ln	1.587*** (0.3923)	1.698*** (0.6273)	3.725** (0.4634)	3.728** (1.308)	2.648*** (0.6296)	2.210*** (0.4951)	0.5043 (1.016)	–	1.498 (1.0323)	–	−0.2658 (1.017)	–
ODA	2.179*** (0.6418)	2.179*** (0.6273)	2.449*** (0.4634)	2.350*** (0.4255)	−0.9404** (0.3940)	−0.9191** (0.4014)	1.935*** (0.3841)	1.920*** (0.3847)	2.115*** (0.4153)	2.085*** (0.4158)	−0.2801* (0.2139)	−0.3948 (0.2567)
FDI	0.04213*** (0.01800)	0.04200** (0.01643)	0.02922 (0.0193)	–	0.07056*** (0.01590)	0.0700*** (0.01617)	0.01594 (0.01735)	–	3.532e-2 (0.1724)	–	0.0254 (0.02177)	–
FuelCost, ln	3.825* (2.193)	3.853* (2.118)	5.600** (2.104)	5.109** (2.020)	−1.1223 (2.153)	–	−0.2216 (1.544)	–	0.9286 (1.535)	–	−0.5377 (0.7300)	–
PatentCount, ln	1.48e-5*** (8.91e-7)	1.45e-5*** (6.07e-7)	1.56e-5*** (1.58e-6)	1.65e-5*** (1.44e-6)	1.31e-6 (1.20e-6)	–	2.38e-5*** (2.22e-6)	2.43e-5*** (1.26e-6)	2.48e-5*** (1.52e-6)	2.7e-5*** (1.01e-6)	1.15e-5*** (1.73e-6)	1.21e-5*** (1.11e-6)
N^a	532	532	532	532	532	532	532	532	532	532	532	532
Island Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.567	0.566	0.652	0.647	0.399	0.394	0.632	0.598	0.697	0.659	0.586	0.530

Standard errors in parenthesis. * denotes significance at 10%, ** denotes significance at 5%, *** denotes significance at 1%. aN = 532 because the regression excludes Bonaire, Saba and St. Eustatius for which FDI and ODA data was unavailable. RE 1 provides the estimation results of the five policy dummies on total cumulative RE capacity inclusive of solar, wind, biomass and geothermal. RE 2 shows the same regression but with insignificant variables omitted as a robustness check. Solar 1 and Wind 1 show the estimation results of the policies which are applicable to that technology type on cumulative solar and wind capacity respectively. Solar 2 and Wind 2 are included as robustness checks and are identical to Solar 1 and Wind 1 but with insignificant variables omitted.

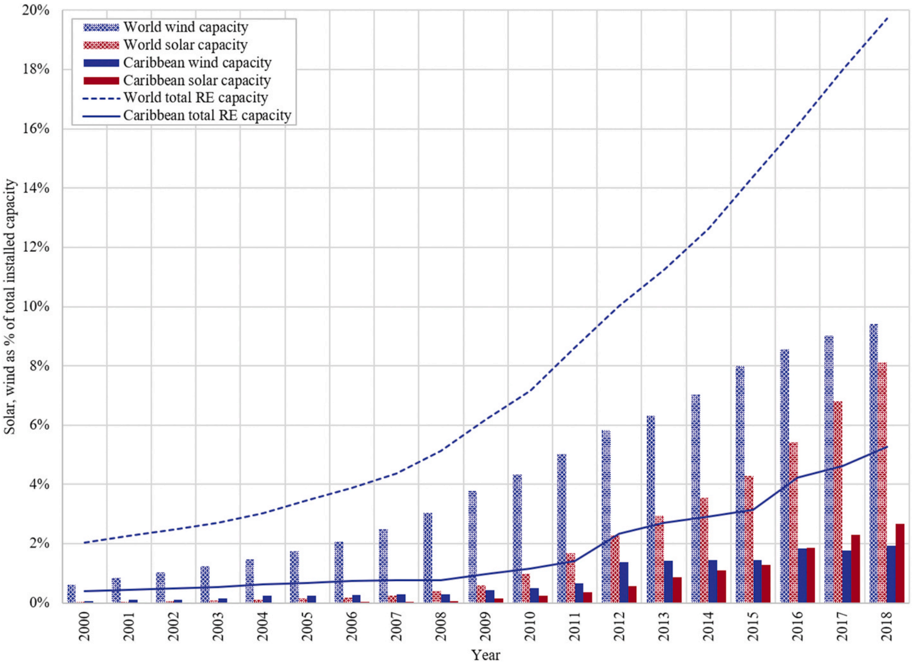

Fig. 5. Comparison of Caribbean and global RE growth rates.

Fig. 6. Visualization of policy regression results for FE specification

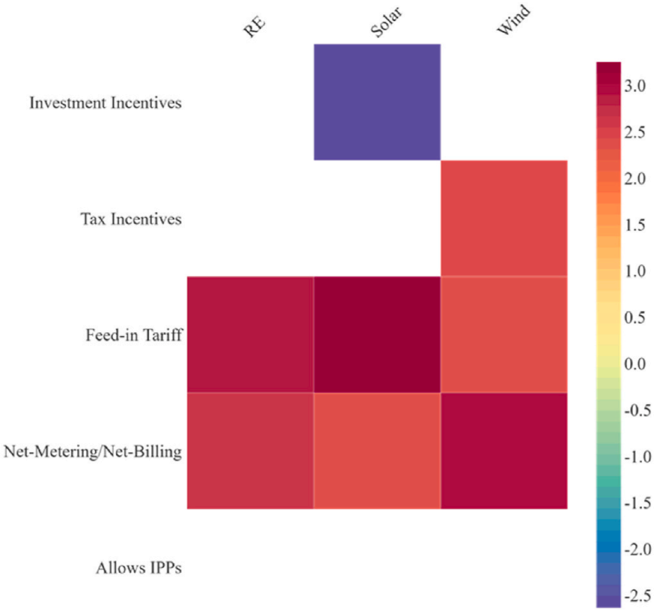

Fig. 7. Visualization of policy regression results for PCSE specification

limit eligibility to small-scale systems. Given this distinction, the strong correlation of net-metering/net-billing programs with increases in renewable capacity indicate that customer distributed energy systems have played as large a role as private developers in increasing RE penetration.

Our study revealed a negative correlation with PV implementation and investment incentives, and no correlation with total RE or wind. We note that the category of investment incentives is more heterogeneous than those of the other policy categories, encompassing rebate programs, technical assistance grants, and public funds which support RE in addition to energy efficiency measures. The impact of investment incentive policies on energy efficiency may confound their effects on RE development, leading to the unexpected negative correlation with solar development.

A utility monopoly on electricity generation is often cited as a key barrier to RE development in the Caribbean (Blechinger, 2015; Iyare and Moseley, 2012). However, the enactment of policies to revoke the utility monopoly and allow the entrance of IPPs into the electricity generation market was not correlated with total RE, solar, or wind capacity. This seems to imply that while this legislative reform is a necessary precursor to enable later policies, it is not sufficient to entice IPPs to develop projects. In many cases, legislation to allow IPPs does not outline a standardized interconnection procedure, leaving would-be investors to navigate an opaque, bureaucratic, and ultimately expensive interconnection process (Shirley and Kammen, 2013). Though important as a first step in electricity sector reform, regulatory restructuring is ultimately ineffective in isolation because of its inability to decrease investment risk.

Our analysis revealed significant positive correlations between development assistance and total RE and solar PV, but a negative correlation for wind development. These findings support Atteridge and Savvidou's (2019) work which highlights a strong preference for solar projects on the part of development financiers, and an unwillingness to make the large commitments required to fund expensive wind projects beyond feasibility stages. Fuel cost was significantly correlated with increases in total RE and solar capacity for the FE specification, but insignificant in the case of wind energy. This could suggest that high fuel costs (which are commonly passed directly to ratepayers through fuel adjustment charges) may be a strong motivation for consumers to invest in solar PV systems. As the utility does not absorb the cost fluctuations, there is little incentive for them to work with wind developers. Patent count was significant only for total RE and solar. The significance of patent count can be credited to innovation in solar technology which lowered manufacturing costs, improved efficiency, and overall made the technology less expensive and widely available (Benson and Magee, 2014).

Our analysis provides evidence that policy instruments support the development of RE on Caribbean islands, but also underscores the need for policies to be carefully designed to suit the specific RE type and island characteristics. Overall, our findings suggest that incentivizing IPPs through feed-in tariffs and supporting the uptake of decentralized PV systems through net-metering/net-billing are the most broadly effective policies.

3.6. Predictive analysis of net-metering/net-billing and feed-in tariffs policies

Translating our empirical findings to actual RE capacity growth, our empirical analysis suggests that the average marginal effect of a feed-in tariff and net-metering/net-billing policy is between 6-19 MW and 4–15 MW, respectively, as shown in Figs. 8–9. The bottom of these ranges represent the lower bound of the 95% confidence interval of the PCSE specification, and the top of the range represents the upper bound of the 95% confidence interval of the FE specification.

While this added capacity may be small in absolute terms, it can be large in relative terms given that the magnitude of current RE deployment in the islands is relatively small for all but the largest and most densely populated islands. IEA, 2018, St. Kitts & Nevis, for example, had an estimated 68.2 MW of total installed RE capacity, and no net-metering/net-billing policy or feed-in tariff in place. The implementation of a net-metering/net-billing policy could, thus, lead to a 9–28% growth in total RE capacity - a significant increase. Fig. 10 shows this graphically, assuming that in the no policy scenario RE capacity in St. Kitts & Nevis continues to grow at the same rate as during the 2000–2018 period and assuming an average of 9.5 MW as the marginal effect of implementing a net-metering/net-billing policy.

It is important to be cognizant that these estimates are averaged across the 31 islands included in the study. The impact of a policy in a specific island is highly dependent on a number of institutional, geographic, and economic factors. We also stress that these results are correlative only, and do not imply a causal relationship. Regardless, these findings, paired with our theoretical understanding of the barriers to RE growth in the islands and the emerging recognition of the role of decentralized energy systems in supporting climate resiliency, point towards net-metering/net-billing and feed-in tariff policies as particularly attractive for island policymakers.

3.7. Deep dive on RE policy in Jamaica

Jamaica has one of the longest histories of deploying renewables in the Caribbean and among the highest electricity rates in Latin America. IEA, 2018, commercial electricity prices increased 28%, from $213.79/MWh in 2016 to $273.20/MWh, as did industrial and residential rates. Heavy fuel oil's share of generation has decreased drastically since then (from 64.3% of annual generation IEA, 2018 to 27.6% in 2020) (JPS, 2020a). Despite this, and even with savings from the 2020 drop in fuel prices being passed along to consumers, rates averaged US $0.30/kWh at the end of 2020 (JPS, 2020b). Cost recovery continues to be a challenge for the utility and sole distributor, Jamaica Public Service Company (JPS), costing the company millions in losses annually.

Due to the constraints of heavy fuel dependance, since the early 1990's the Jamaican government has been exploring RE opportunities, and after rigorous feasibility study, the former Government-held Petroleum Corporation of Jamaica (PCJ), commissioned the 20.7 MW

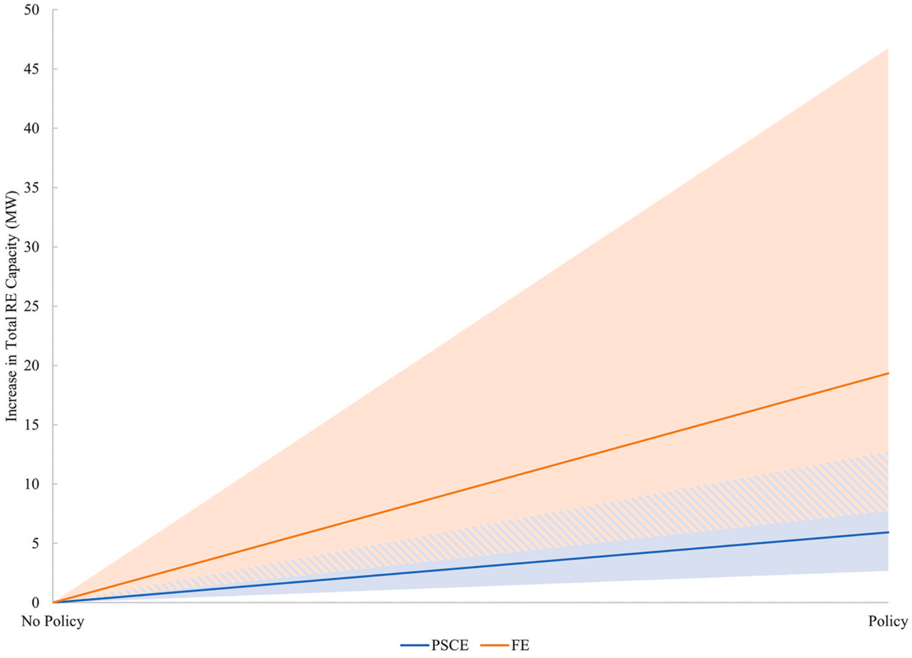

Fig. 8. Predicted marginal effect of feed-in tariff after two years on total RE capacity in MW for both model specifications with 95% confidence intervals.

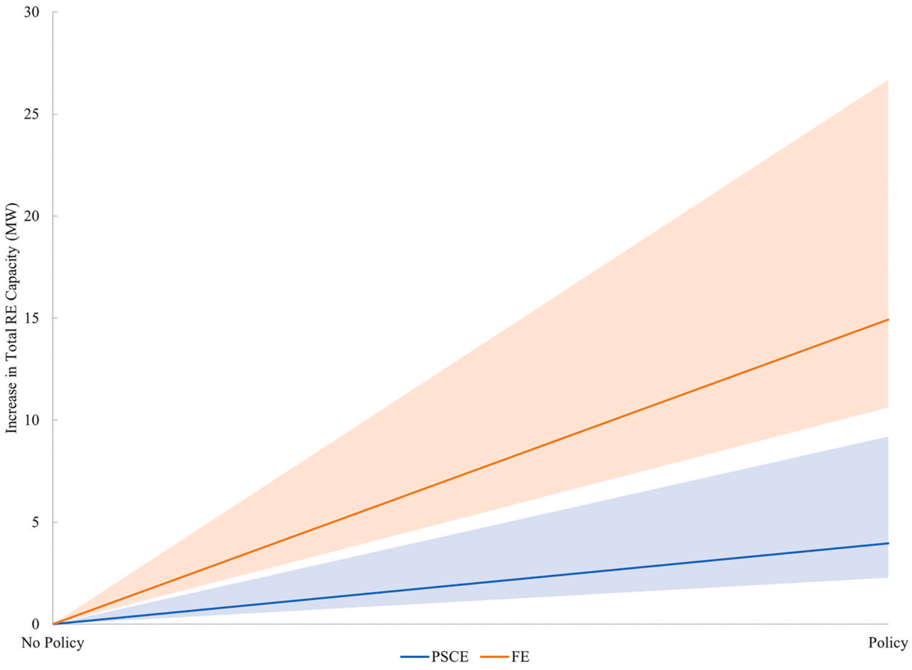

Fig. 9. Predicted marginal effect of net-metering/net-billing policies after two years on total RE capacity in MW for both model specifications with 95% confidence intervals.

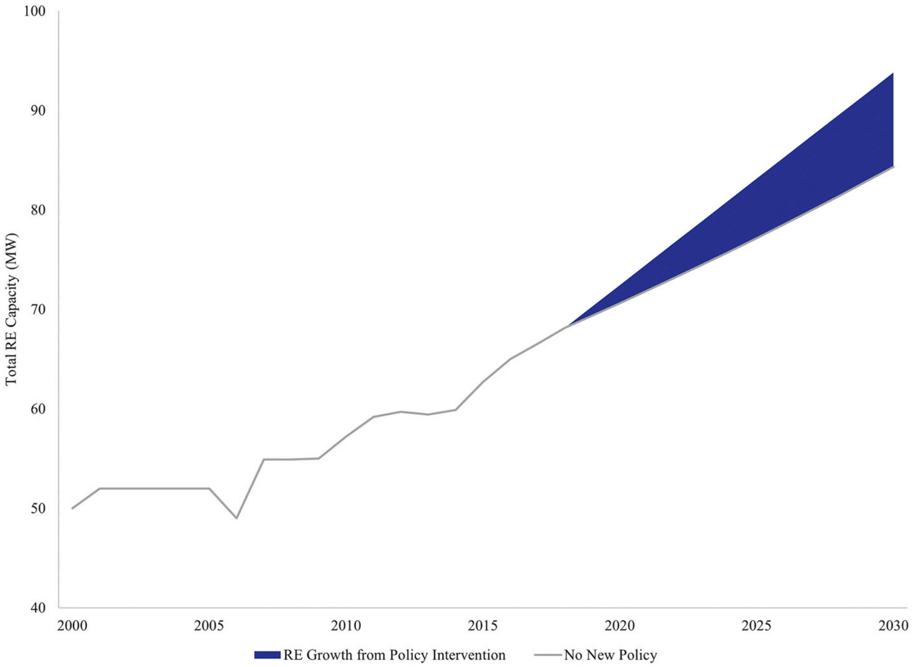

Fig. 10. Predicted increase in total RE capacity in St. Kitts & Nevis between 2020 and 2030 assuming the introduction of a net-metering/net-billing policy.

Wigton Windfarm in 2004, directly financed through a National Bank of Jamaica loan and Dutch grants. A further 18 MW was subsequently added by 2010. The success and learning from this experience led to the Office of Utilities Regulations (OUR) issuing a regulatory policy guideline for capacity expansion, classifying large, medium and small additions and stipulating that generation above 15 MW would be subject to competitive tender. Since then, there have been two major renewable energy capacity auctions launched by OUR.

In March 2008, OUR announced its first "build own operate" renewable energy auction, which was awarded to JPS for a 6.4 MW hydro plant and a 3 MW wind farm (OUR, 2008). The National Energy Policy was then established in 2009, and was seen as a model for other islands, laying out an aggressive goal of 20% renewables by 2030. To meet this target, another auction for 115 MW renewable energy capacity through 20-year power purchase agreements was announced between 2012 and 2015. By 2016 the four winners had been issued licenses – 60.3 MW and 57 MW of large-scale wind and solar respectively. The auctions directly drove investment in the sector for Jamaica, peaking at $183 million in investments in 2015 alone (ClimateScope, 2019).

Jamaica thus demonstrates a clear example of the electricity market design popular in Caribbean nations with higher RE penetration: a vertically integrated, single buyer electric utility with IPP participation, and long-term power purchase agreements largely granted through auction procedures (Viscidi and Yépez-García, 2020; Lopez Soto et al., 2019). While the latest studies show that 80% of the current renewable capacity in the broader Latin American and Caribbean region has been driven by public tenders and auctions (GWEC, 2020), Jamaica is the only Caribbean country to employ auction mechanisms to date. For auctions to be successful, there must be enough investor competition for the auction to be oversubscribed, thereby driving down the costs. OUR, for example, received a total of 19 bids interested in supplying 37 MW to the national grid, totaling nearly 500 MW. The smaller markets of the Eastern Caribbean may not have projects large enough to attract multiple investors, demonstrating the limitations of scale, project bankability and access to finance. As the Caribbean moves towards increased cooperation between utilities vis-à-vis the 2013 CARICOM Energy Policy, joint auctions may be an option for smaller islands. This requires future study.

Jamaica is also a strong case study of the important role distributed technologies can play in increasing capacity, if well incentivized. The OUR piloted net billing in 2012 through JPS. RE systems of up to 10 kW for residential installations and up to 100 kW for commercial installations were eligible. Consumers with their own generation facilities receive JPS's short-term variable avoided-cost rate plus 15% for electricity delivered to the national grid (averaging J$20.3/kilowatt-hour (kWh) or US$ 0.18/kWh over the pilot period) for five-year contract periods (Doris et al., 2015). Importantly, Jamaica collects no value added tax (VAT) for solar or wind components. The Development Bank of Jamaica (DBJ) also launched microcredit products for residential and small commercial customers for energy efficiency and renewable energy equipment (DBJ), further improving the incentives for RE owners.

The program was very successful and by 2015 over 300 applications were received. The program received roughly equal numbers of commercial and residential applicants, showing that net-metering policies are one way to engage non-commercial as well as commercial stakeholders. That said, commercial installations are naturally larger (averaging 24.6 kW) and contributed to almost 10 times as much installed capacity as residential installations (averaging 4.2 kW).

In a survey conducted after the initial pilot, participants in the net-billing program reported a reduction in the cost of their electric bills up to about 30%. That said, initial concerns included the constraints of the system size cap, the upfront deposit requirement which is cost-prohibitive to most of the population, interconnection fees, the long wait period for interconnection, and issues with the licensing and approval protocol. Importantly, however, customers with multiple systems reported an improvement in the application system over the pilot period (NREL, 2015).

The program was relaunched with improvements in 2016, and there are now almost 800 licenses for net billing – 70 since the beginning of 2019 alone, accounting for 5.8 MW of capacity (Jamaica Observer, 2019a). Net billing licenses almost exclusively favor rooftop solar, as the decreasing cost in solar panel costs and high retail electric rates result in attractive payback periods. While the DBJ has recently opened another $50 million line of credit for small businesses, financed by the IDB (IDB, 2020), expanded access to finance continues to be a need.

Today, renewables account for 8% of generation on island (over 350 GWh/year), which is far above the observed Caribbean average of 5.3% (ClimateScope, 2019). Jamaica thus demonstrates how an "all of the above approach" that carves out clear, specific mechanisms for large-scale generation and attractive incentives for distributed generation can collectively drive renewables deployment. Opening the market to IPP competition and encouraging access to commercial finance, even at the micro-level, were key to creating the enabling environment for policy interventions. It should be noted that since the 2016 capacity expansion, JPS has reported stability issues caused by significant variability in RE generation. A 24.5 MW hybrid energy storage system was commissioned by JPS in 2019, which has helped with stability and reliability issues attributed to this increased variable RE penetration (Jamaica Observer, 2019b). Thus, a comprehensive approach to system planning that focuses on reliability, stability, security, and power quality is important to support optimal grid management and so that end-users are not adversely affected.

4. Limitations and future work

A key constraint of the present work is that the regression specifications are limited in their ability to be causally interpreted in applied research (Imai and Kim, 2020). We instead suggest that findings be interpreted as correlative. A second limitation is the binary categorization of policy implementation, which measures simply whether or not a policy has been implemented with no indication of how aggressive a particular island's policy is in relation to its peers. Though we deem this appropriate for this study in which we seek to provide the first comprehensive analysis of the Caribbean policy environment, future research should focus on developing and testing metrics for policy aggressiveness similar to Jenner et al. (2013) and Yin and Powers (2010). Qualitative policy comparisons similar to Jacobs et al. (2013) would be helpful in providing additional granularity on best practices for RE policy design. A detailed comparison of net-metering and feed-in tariffs presents a particularly fruitful area for further research, as both policies were frequently implemented and seemingly effective but understudied in the academic literature. Similarly, further research to compare the tradeoffs between various RE market institutional structures would aid policymakers seeking to implement power sector reforms.

To ensure the robustness of our econometric analysis, we tested the five policies which were the most frequently implemented. However, there are a broad range of options available to policymakers including public tenders, research and development funding, institution creation, RE auctions, energy efficiency measures, solar hot water heating programs, transportation electrification and renewable portfolio standards which were not implemented with sufficient frequency over the study period to merit inclusion in our economic model. Our model also does not account for policies such as fossil fuel subsidies which could work against RE market expansion, such as we suggest is the case in Trinidad and Tobago. Though static heterogeneities from these policies are controlled for via the island-level fixed-effects, a limitation of this work's approach is that changes in these policies over the study period are not controlled for and are potentially confounding.

There are other factors in addition to policy which could provide additional insight on renewable deployment, such as ease of doing business and political ambition. However, these linkages were not able to be fully explored given the limited availability of data for non-sovereign islands. The effects of political economy may also be important given the close political affiliations of many of the islands with better-resourced nations. In fact, a preliminary analysis of political status revealed stronger RE performance for Dutch and French islands compared to their US and UK-affiliated counterparts. Though a full examination of the topic is outside the scope of the current work, future research regarding these connections would be fruitful.

The 2017, 2019 hurricane seasons wrought historical levels of loss of life, economic disruption and physical damage in the Caribbean. As the effects of climate change continue to grow increasingly apparent in the region, the dialogue surrounding energy governance has shifted towards discussions of climate change adaptation. Moving forward, RE, and especially decentralized RE, is likely to play a large role in efforts to bolster the resiliency of electric power grids but will require guidance through informed and well-crafted policy. We conclude by suggesting that, while the technical and engineering components of island grid resiliency have been well-studied, the policy to attract the necessary investment and ensure the affordability of upgrades for ratepayers merits further exploration.

Despite the limitations, our work has been able to significantly expand the knowledge on policy implementation and effectiveness for

RE deployment on Caribbean islands. The findings should guide local and international policymakers in their efforts to promote RE in the region. In addition, we have made our dataset publicly available to encourage more research on RE implementation and its respective barriers and solutions on Caribbean islands.

5. Conclusion and policy implications

We begin the conclusion and summary of our paper by reflecting on the main research questions: what policy instruments are most effective for renewable energy deployment on Caribbean islands? Our statistical analysis reveals that feed-in tariffs and net-metering/net-billing programs have the strongest positive correlation with the deployment of total installed capacity of RE in the 31 islands. While we caution against a causal interpretation, the results still demonstrate that these policies are correlated with remarkable increases in RE. For example, feed-in tariffs and net-metering/net-billing programs were correlated with average increases in the installed capacity of RE on the order of 6–19 MW and 4–15 MW, respectively. We did not find significant correlations for investment incentives, tax incentives or regulatory restructuring to allow IPPs. Looking at the specific RE technologies, we can state that solar PV is most effectively supported with net-metering/net-billing programs, while wind development responds favorably to tax incentives and feed-in tariffs. Tax incentives, which have been a popular policy measure over the study period, were only significantly correlated with wind development. In our discussion, we argue that this is because of the large scale of wind power projects compared to the more decentralized character of solar PV. In terms of control variables, we also observed a strong positive correlation between development assistance on total renewable capacity. While development assistance had a particularly strong correlation with solar it was negatively correlated with wind power, suggesting that solar receives preferential treatment to wind by international donors.

Addressing our main research question also answered many underlying questions: What types of RE policies have been most popular in the Caribbean? When did most islands begin implementing policies? How has the implementation of RE capacities evolved over time in the Caribbean relative to global figures? We found that regulatory restructuring to allow IPPs and feed-in tariffs were among the earliest policies to be implemented due to the French overseas territories. However, net-metering and net-billing policies were rapidly implemented after 2006, with 20 of the 31 islands having some form of the policy by 2018. Looking at RE deployment, solar PV has overtaken wind power in terms of installed capacity as the most commonly used RE technology on Caribbean islands. Despite favorable natural conditions, solar PV and wind accounted for 2.7% and 1.9% of the total installed capacities IEA, 2018 – amounting to about half of the global average. This underlines the need for effective policy instruments to accelerate the implementation of RE projects in the Caribbean.

We therefore recommend that policymakers in the Caribbean and on other SIDS deploy or strengthen the following policy instruments to encourage more rapid growth of RE capacity. For solar PV, net-metering/net-billing is a viable and effective solution to incentivize decentral implementation. As this instrument is limited to electricity consumers on the island, it should be complemented with feed-in tariffs for small to large-scale PV implementation by private investors and IPPs. For wind power development we recommend tax incentives in combination with feed-in tariffs. Overall, the influence of policy instruments on wind power implementation is less significant than for decentralized PV, indicating that the government, regulators, and or utilities may need to lead development on a project-by-project basis.

In the wake of shocks such as the 2017 hurricane season and the COVID-19 pandemic, the dialogue amongst decision-makers in the region is turning towards infrastructure resiliency. RE, especially in its small-scale, distributed form, can play an important role not just in reducing emissions and reducing fossil fuel dependency, but in bolstering energy system resiliency (IEA, 2020; Daw and Stout, 2019). While we have demonstrated that there are a range of policies which can be effective tools to encourage growth of RE, some, such as net-metering/net-billing programs, promote a model of RE development which can also address resiliency concerns. As islands progress towards a sustainable transition in their energy systems, we urge policymakers to choose policy interventions strategically with these resiliency considerations in mind.

Data availability

The datasets of RE policy implementation are available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Jessica Kersey: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Philipp Blechinger:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Rebekah Shirley:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2021.112340.

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