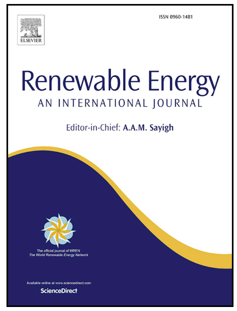

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The case for Islands' Energy Vulnerability: Electricity Supply Diversity in 44 Global Islands

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Highlights

- Islands attributes and demographics encapsulate their power sector fuel mix and therefore their diversity and intensity metrics
- The average islands energy and emissions intensity has been growing by 23.4% and 12.35% correspondingly.
- Diversity has improved by 21.3% (SWI) and 2% (HHI) since 2000.

Abstract

Energy supply security is a multifaceted challenge for all countries and especially for small island nations that might have limited adaptive capacity. Previous studies showed that islands experience energy scarcity and isolation from energy markets due to their remote location making energy supply security a challenging issue. We estimate energy supply diversity and concentration for 44 islands in order to provide an island specific benchmark approach for energy supply security. We use established metrics Shannon-Wiener index (SWI), Herfindahl-Hirschman index (HHI) with Energy Information Administration (EIA) fuel mix data. To confront the issues of supply security and sustainability we test energy diversity against energy and emissions intensity. The global character of the research along with the wide range of islands covered allows useful comparisons between countries and for a means of benchmarking against the indices while creating certain defined country clusters. Overall it is found that average island energy intensity increased by 23.4 % with a corresponding increase of 12.4% on their emissions intensity for the period 2000-2015. On the other hand, diversity has improved by 21.3% (SWI) and by 2% (HHI) since 2000. We argue that fossil-fuel lock-in for islands must break in order to UN Sustainable Development Goal 7 to be achieved particularly for vulnerable island nations.

Keywords

Energy security; global islands; diversity; security; carbon emissions, benchmarking

ABBREVATIONS

Island Name	ISO ALPHA-2 CODE	Island Name	ISO ALPHA-2 CODE
Aruba	AW	New Caledonia	NC
Bahamas	BS	Niue	NU
Bahrain	BH	Papua New Guinea	PG
Cayman Island	KY	Reunion	RE
Cook Islands	CK	Saint Helena	SH
Cyprus	CY	Saint Kitts	KN
Dominica	DM	Saint Lucia	LC
Dominica Rep	DO	Saint Pierre	PM
Falkland Islands	FK	Saint Vincent	VC
Faroe Islands	FO	Samoa	WS
Guadeloupe	GP	Sao Tome	ST
Haiti	HT	Seychelles	SC
Iceland	IS	Solomon Island	SB
Ireland	IE	Sri Lanka	LK
Jamaica	JM	Suriname	SR
Madagascar	MG	Taiwan	TW
Maldives	MV	Tonga	TO
Malta	MT	Trinidad and Tobago	TT
Martinique	MQ	Turks and Caicos	TC
Mauritius	MU	Vanuatu	VU
Montserrat	MS	Virgin Islands British	VG
Nauru	NR	Virgin Islands US	VI

1. Introduction

Energy is a key aspect of a country's economy and access to affordable energy is a prerequisite for growth and competitiveness [1] . Access to energy can be challenging and is considered as one of the main pillars of wellbeing and sustainable development of modern societies [2]. Economic activity requires mainstream commodities produced, delivered and used with energy while linked to the environmental and social development of a country [3,4].

Concerns about energy supply security along with climate change are shaping the global energy systems in ways that were never considered possible. Increased population in emerging economies has resulted in a drastic growth of global energy demand leading to disruptions of energy supply in not self-sufficient countries [5]. Risks associated with energy supply extend beyond resource availability to its transportation and transformation into secondary commodities and distribution through the appropriate infrastructure to the end-user [6]. The close link of energy supply and climate change challenges the existing governance and policy bodies due to the multidimensional nature of the aforementioned issues.

Climate change amplifies risks associated with disruption in supply and demand and combined with infrastructure vulnerability it can create long-term energy security stresses or short-term episodic shocks affecting various types of consumers, including increasingly demanding households [7–9] and industrial users [10]. Beyond the consequent macroeconomic policy effects of climate change, there is also a significant shift on companies' managerial and marketing orientation, mainly driven by consumers green awareness [11–13] and their interplay with energy utilities [14]. While at corporate level there is flexibility for energy hedging against risk the same cannot be applied in national energy portfolios and indeed those of smaller island nations [15,16] Prioritisation of energy security against climate change mitigation policies and vice versa can have a direct impact on a country's energy roadmap and hence on large scale investment decisions [17]. In this context, it is necessary to evaluate the resilience of existing energy systems as availability of energy resources and their accessibility, are considered essential parameters to the sustainability of a country's economy.

Although there is broad agreement of the themes covered by energy security, no widely adopted definition exists. While, resource availability has been the most crucial element of energy supply security in past decades [18] a pattern that has gradually given space to diversity [19,20] and more recently to sustainability parameters of security is identified. The concept itself is context dependent, multidimensional and has been integrated and developed through the years. The four main pillars are identified along the 4 A's namely 1) availability 2) accessibility 3) affordability and 4) acceptability. The specific dimensions are then incorporated into other dimensions including and not limited to infrastructure, governance and efficiency.

Most of those dimensions are interrelated and some are cause or effects of the interplay between them [21]. For example, low availability may be the leading cause of lack of affordability as scarcity can lead to higher price; equally, when affordability is low, accessibility might also be restricted to privileged users as it happens in developing countries with lack of universal access to energy. Technological advances, awareness of climate change effects and a turn to green sustainable practices changed the nature of the term of energy security to a multidimensional, dynamically evolving issue since core solutions of the past (e.g. abundant access to oil) do not fit with today's low carbon energy planning for the future. The existing literature on resilience establishes a quantitative or theoretical framework [22]. Energy security studies differ either on the regions examined or the methodology used over certain periods of time. The majority of those country-level specific studies focus either on Asian or European countries where the energy security issue is more profound. Furthermore, they look on certain primary energy fuels examining the supply side of energy security [23–27].

Grubb et al. (2006) [28]in order to represent an energy supply security metric, considered the diversity of fuel mix as used in the electricity sector and robustness, against interruption of other sources for the U.K electricity sector. Later, Chalvatzis and Rubel (2015) [24] accessed the Chinese electricity portfolio using a combination of Hirschman and Shannon concentration and diversity indices. Those studies along with the majority of other studies, do not consider any economic or political aspect that might have involved such as price volatility. Sovacool et al. (2011) [29], Kruyt et al. (2009) [30], proposed composite indicators concerning the availability, accessibility affordability and acceptability parameters of energy security applied on OECD Countries, using mainly indicators surrounding oil and fossil fuels.

While there is a body of literature examining energy security through various angles using different indices, there is also a lack of a clear benchmarking scale for different regions. That gap in benchmarking for resilience metrics has been first identified by Hickey et al (2010) [31] who mention the lack of a particular range that would indicate satisfactory or insufficient fuel diversity. Chalvatzis and Ioannidis (2017) [32] initiate a benchmark metric for EU countries based on SWI and HHI energy supply diversity of primary fuels and import dependence. The authors conclude that while benchmarking for energy security metrics offers significant value in evaluative comparisons it does need to be used within a pre-specified context. That is to say, that since energy security is not in itself a commonly agreed dimension, it is proxied against lesser or more complex metrics. As such their explanatory references for benchmarking require a sensible common background. The classification could be done based on resource endowment, joint up regulatory frameworks, geopolitical issues and other factors that could potentially shape the strategy followed by a group of compared countries. Therefore, a benchmarking heuristic for EU countries is useful for the EU context with its converging common energy and climate policy [33,34]despite the diverse endowment background [35]. In this manuscript, we revisit energy security benchmarking, by looking into the geographic context, rather than policy convergence. We argue that island nations have received very little attention in the energy security literature despite their importance as case studies; hence the focus of this manuscript is on benchmarking energy security for global islands.

2. The Case for Global Islands

Security, carbon neutrality and affordability are the parameters forming what is known as the energy trilemma; and nowhere is the energy trilemma more widely pronounced than in the confined space of remote and isolated islands [36,37]. Islands usually are locked into expensive fossil fuel imports, in isolated markets leading to low fuel mix diversity and high carbon and other emissions relatively to their economic growth [38] which make them perform worse than their inland counterparts [39]. In addition to that, their economy and lifelines are often dependent on tourism industry and connections with a mainland country. Geographical distance and geopolitical affairs with main distributing countries are crucial parameters for their accessibility to main energy sources.

Energy dependence is often extremely high because islands cannot take advantage of their renewable energy potential, especially solar and wind, because of poor grid infrastructure [37,40]. However, islands lend themselves to excellent testing case studies for innovative energy solutions which could set the example for larger scale, on-grid applications[41]. Their remoteness, relative small size and flexible governance makes them potentially adaptable to change and capable of significant shifts unlike large regions with monolithic energy governance [42].

Despite the existence of numerous studies concerning energy sustainability in national and regional levels the existing literature focusing on islands as case studies for energy security is very limited [43]. Zafirakis and Chalvatzis (2014) [40] examine the potential role of innovative energy storage technologies to facilitate energy security improvements for Greek islands which are electrically isolated from the Greek mainland grid [44]. In another study, Chuang and Ma (2013) [45] quantify energy supply security using diversity indices to assess Taiwan’s energy supply system. Gils and Simon (2017) [37] used a linear optimization approach to propose an ideal pathway for a 100% renewable energy system highlighting the required transition on storage systems and the required investment cost reduction needed for the scenario to be feasible. Within the islands energy supply security literature, we identify the following gaps which we address with this manuscript:

a. No study focuses on a group of autonomous islands with different attributes in order to identify patterns concerning their economic and physical characteristics which lead to diversity metric benchmarking.

b. No study focused on islands’ electricity sector supply security since the small number of studies carried out concern primary energy sources.

c. Energy supply security and climate change parameters are not treated jointly as the latter is more often part of the adaptation literature.

For this research, we evaluate 44 global autonomous islands in different continents with a range of attributes. In this regard, we perform a security evaluation of their electricity sector fuel portfolio and contrast the results with their energy and carbon intensity as a measure of environmental sustainability for energy security.

3. Methodology

3.1 Approach and data

Most often policymakers and the research literature treat energy security and climate change as two distinct policy goals [46]. At the same time, complex optimisation modelling is frequently employed to support decision makers to adopt appropriate sustainable energy paradigms [47,48]. On one hand climate change policies aim to transform the global energy trade by transitioning from reliance on fossil fuels to low carbon energy sources. Most studies find that climate stabilization policies will reduce energy imports by up to 75% by 2050 on average globally; however, this number varies on regional level, depending on whether the region is a net energy importer or exporter [49]. Nevertheless, renewable energy growth results in a larger share for indigenous energy and as a result imports reduction. Combining diversity and concentration indices to measure energy supply security along with emissions and energy intensity, we identify sustainable roadmaps of development for international islands [50].

Conceptually, it can be argued that dependence has given way to diversity as the dominant security paradigm and that the latter is indeed more fitting for an increasingly interconnected world [51–53] [51,52,54]. Regarding sustainability two intensity metrics are considered to evaluate both efficiency using energy intensity, and carbon footprint using emissions intensity[55,56]. The two most widely used indices, Shannon-Wiener[57–59] and Herfindahl-Hirschmann[28,60]are evaluated alongside intensity metrics for the power sector of 44 global islands.

For this research, data was sourced from EIA [50] which provides the widest available coverage of global islands but limits fuel type disaggregation to seven. Specifically, coal, gas and oil are counted in a single fuel option and the other options are: nuclear; hydroelectric; geothermal; wind; solar; biomass and waste. Our choice of using the EIA database than, for example, the more detailed data provided by IEA [61] is compensated by the significantly higher number of islands (44 in EIA ,versus 8 in IEA) and the more up to date data (2015 versus 2014) provided by EIA. Furthermore, since the scope of the research is to provide useful guidance on benchmarking, the actual disaggregation, for as long as it is consistent allows for useful comparisons which can be greatly benefitted by a large number of islands. Most importantly, bundling of fossil fuels in one fuel category is an issue of lesser importance for a study focused on islands, very few of which use coal, gas or any other fossil fuel than oil.

3.2 Intensity Metrics

Emissions intensity is an indicator of a country's carbon footprint and a body of literature has examined the factors affecting it such as total emissions, economic structure and efficiency [62,63]. Emissions intensity is defined as the ratio between the total emissions over GDP of a country. Therefore, it shows the emissions a country emits to produce a unit of wealth. In a similar way, we define energy intensity as the ratio of the total energy consumed divided by the GDP of a country. Therefore, energy intensity shows the amount of energy a country consumes to produce a unit of wealth. Hence:

$$Emissions\ Intensity = \frac{Total\ Emissions}{GDP}$$

for which

GDP= Gross Domestic Product PPP 2010

$$Energy\ Intensity = \frac{Energy\ Consumed}{GDP}$$

for which

GDP= Gross Domestic Product PPP 2010

3.3 Diversity Indices

3.3.1 Shannon–Wiener Index

It is considered one of the 17 equations that changed the world, developed by the engineer Claude Shannon at the era of post-World War 2 [64]. Its uses vary from statistical mechanics, information in cybernetics, entropy in thermodynamics, economics [65], ecology and genetics . Within energy studies it was introduced by Stirling (1994) [58] to evaluate the diversity of the UK electricity supply sector as a proxy of its energy supply security.

For n number of energy sources (options) available in the power sector fuel mix the Shannon–Wiener Index (SWI) is:

$$SWI = -\sum_{i=1}^{n} S_i \times ln(S_i)$$

Where:

n is the number of options

S_i is the proportional reliance on the i^{th} option.

ln is the natural logarithm used.

For the calculation of the SWI, each primary energy source available in the fuel mix represents one option. Each option is added as the percentile of the calculated number. For example, if an option accounts for 10% of the total energy mix then it will be treated as 0.10 in the index. The minimum value that the index can take is zero when the system relies on one option. Since the number of options n≥1, SWI cannot be negative. A system with two equally weighted options will have a diversity of 0.69 (2dp) and so on. A system can potentially take infinite options which give us an infinite SWI since $\ln(\infty) = \infty$. Although the index increases with the number of options the increase rate declines gradually. Grubb et al (2006) [28] in an attempt to provide a generic benchmarking for Shannon-Wiener index, indicated that a SWI value below 1 shows a less diverse system relying on 2 or 3 options, where energy supply is more vulnerable to possible destructions and a value above 2 indicates a system with multiple options, more secure to interruptions of particular supply components. The diversity can be used on the assumption that each different option is independent from each other and there is no interrelation between them.

3.3.2 Herfindahl–Hirschman Index

HHI index has a crucial role in competition economics where it is used by the US Federal Trade Commission in the assessment of likely competitive effects of horizontal mergers [66]. Moreover, it has statutory role for the approval of bank mergers as the post market HHI index should not exceed 18% and the index increase, or decrease should not cause a change greater than 2% [62]. The index measures concentration of the individual market share of the participants. The higher the HHI, the higher the concertation so the less diverse is the system examined. Again, its origin is located in ecology where is known as “Simpson Index”[24] .

For n number of energy sources (options) available in the energy fuel mix portfolio the Herfindahl-Hirschman Index (HHI) is:

HHI=$-\sum_{i=1}^{n} S_i^2$

Where:

n is the number of options

S_i is the proportion of option i expressed as a percentage.

The sum of the squares of the share of each fuel entering the power sector equals the HHI index of that particular electricity fuel mix portfolio. For example, an option contributing n% of the total fuel mix will be treated as n and in the index calculation it will become n^2. The minimum value HHI can take is approaching 0 when the system relies on infinite options. In economic terms that will mean perfect competition. A system with two equal options will have an index of 2,500 and so on. The index takes its maximum value when there is only one option available and this is 10,000. This connotes that the index ranges between 0≤HHI≤10,000. A suggestion from the US Department of Justice sets the benchmark of 1,500 for a competitive marketplace and 2,500 for a highly concentrated one [64]. Additionally, it illustrates that transactions that may disrupt HHI by more than 200 points in highly concentrated markets are more likely to increase market power. Similarly, with the SWI index, the assumption that each different option is independent from each other is necessary.

<u>3.4 Parallel Indices and Sustainability through different angles</u>

Although both diversity and concentration indices are widely used for estimating energy supply diversity most of the literature rules out one to be the "best" index to use to examine the energy supply security of a country. Stirling (1998) [65] favoured the SWI since he pointed out the disruption of the variety and balance with HHI. Cohen et al (2011) [67] discussed the greater sensitivity of SWI on the contribution of each of the options in the total energy mix instead of focusing on the total number of options. Le Coq and Paltseva (2009) favoured HHI for EU energy security on the basis that EU countries have less diverse energy portfolios and HHI is better suited to capture those risks [68]. Other researchers preferred to use both indices complimentary as they tend to behave differently with certain triggers [28,32].

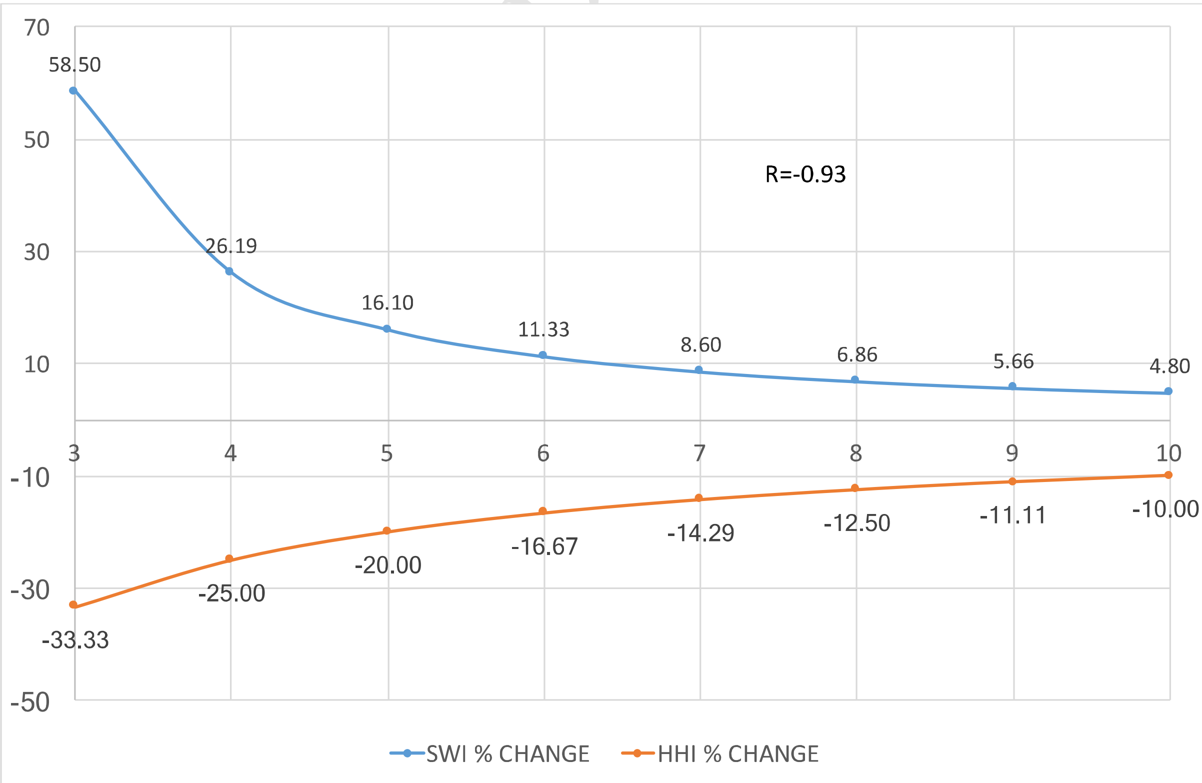

Figure 1: *SWI and HHI % differences as number of equally contributing options grows.*

When plotted against the % change for every higher integer number of equally contributing options SWI and HHI provide an approximate “mirroring” image (Figure 1). This reflects their inverse nature focusing on diversity and concentration respectively and also that they do not behave in exactly the same way. We can see that the absolute value of the differences is bigger for HHI with the exception of the first two cases which refer to low diversity mixes. Keeping the contribution of the options equal, we can conclude that that HHI is more sensitive on the number of options. There is high correlation between the rate of change for the two indices as the number of options increases.

4. Results

In visualizing diversity, the 44 islands are grouped in those with higher diversity (Figure 2), moderate diversity (Figure 4), and lower diversity (Figure 6) as measured by SWI. Using the same structure, we illustrate HHI Figures 3,5 and 7 indicating any group changes to identify sensitivity of the indices.

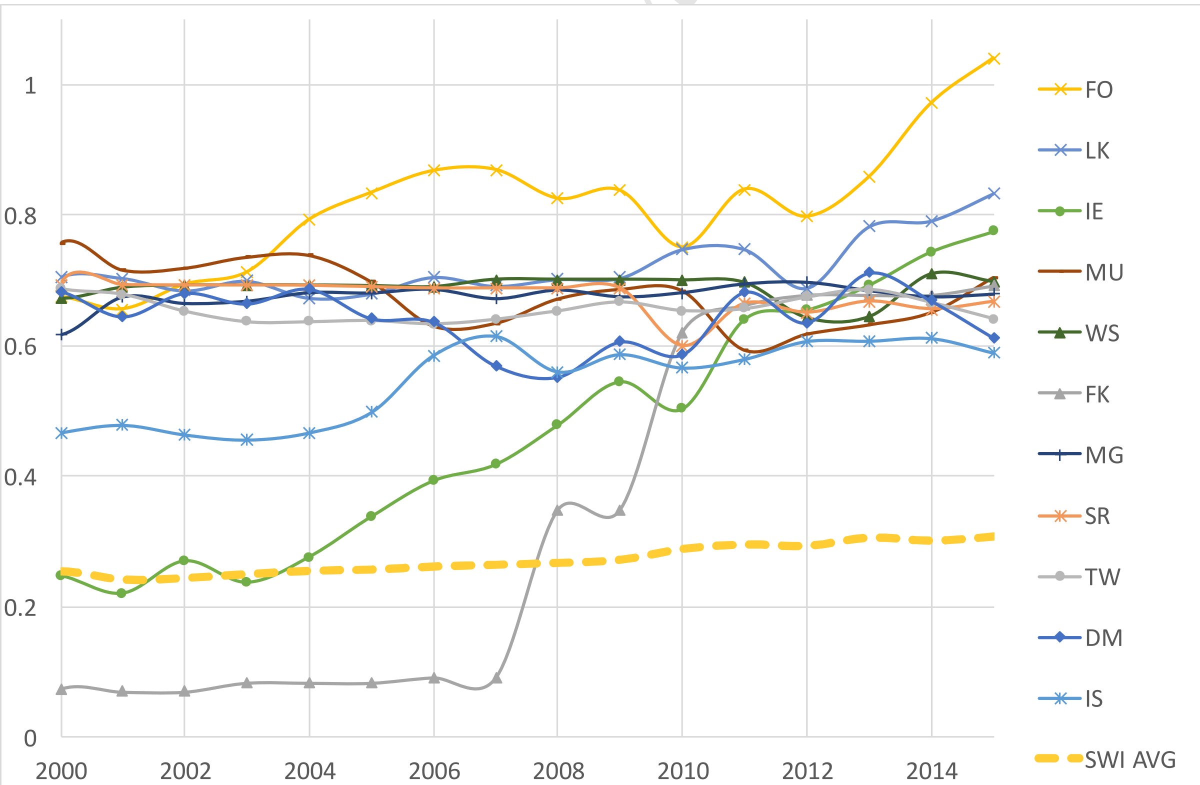

Figure 2: *Power sector diversity measured with SWI for islands of the higher diversity group between 2000-2015. Data Source: EIA.*

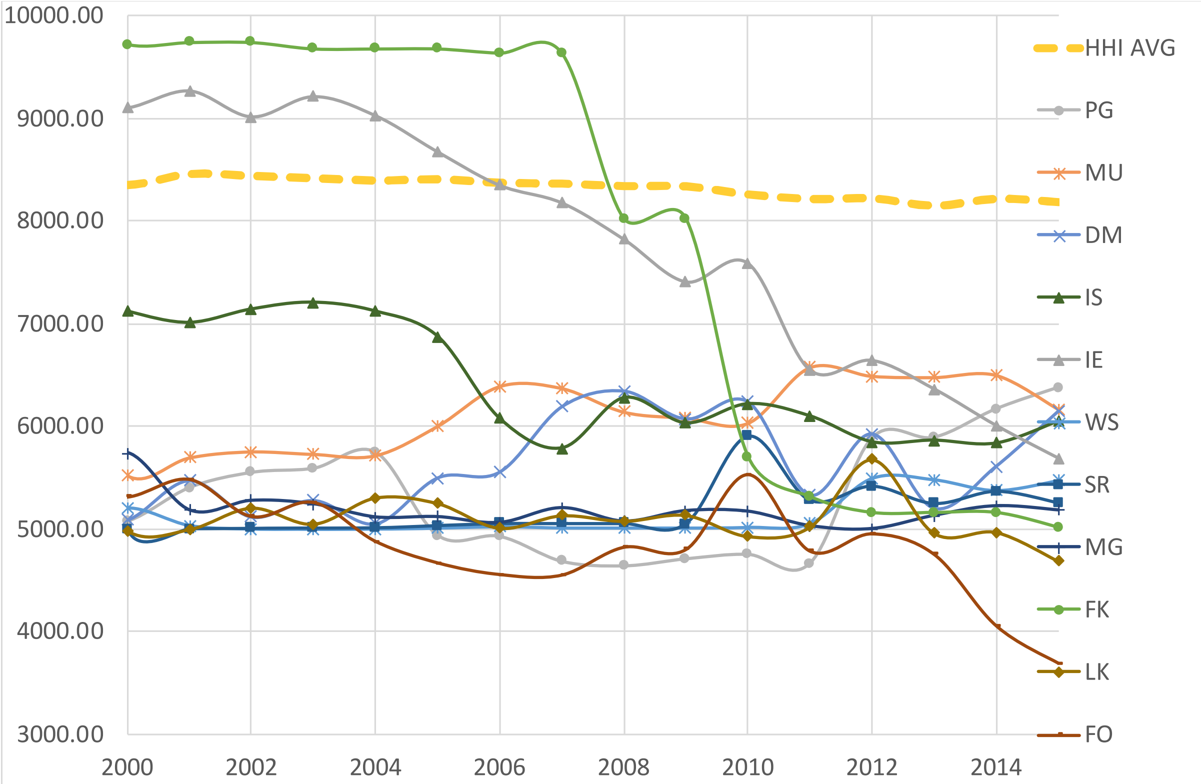

Figure 3: *Power sector concentration measured with HHI for islands of the lower concentration group between 2000-2015. Data Source: EIA.*

Both indices show Faroe Islands and Sri-Lanka as the islands with higher diversity and lower concentration in their electricity sector. Faroe Islands experience a subsequent improvement of its diversity of 54.1% compared with 2000 by adding wind energy as an option to its electricity fuel mix. Particularly, in 2015 wind energy holds 18.2% of the total electricity fuel mix reducing fossil fuels' share by 24.4% compared with 2000. The aim of the island to cover 100% of its electricity needs by renewables seems to be feasible especially with the introduction of tidal power in its energy mix [69].

Sri-Lanka is one of the fastest growing economies especially after the end of the civil war in 2009 [70]. The increase of 45.24% at the country's purchasing power parity was linked to an energy demand increase by 3.1 TWh. The demand was met by fossil fuels in the fuel mix and particularly the opening of Lakvijaya Coal Plant in 2011 which resulted in diversity improvement and carbon emissions deterioration. Although it is one of the most diverse islands, high reliance on hydro and fossil fuels often disrupts the supply security of the country as both sources are associated with a wide range of weather and geopolitical vulnerabilities [1]. Potential increase of wind and solar energy could provide the power sector with higher diversity and lower reliance on incumbent resources.

Iceland and Ireland are the two main European countries included in this group of islands. Iceland is a distinct case as its electricity supply in 2015 was renewable by 99.8%. In particular geothermal and hydropower comprise 100% of the renewable energy produced in Iceland. Reliance on seasonally variable hydroelectric power is gradually being replaced by geothermal energy improving both diversity and concentration indices by129.85% and 31% respectively. In a previous study, examining the primary supply diversity of Iceland, [71] it was found that the 250% increase on Iceland energy demand since 1990 was met by renewable energy. Additionally, imported fossil fuels are mainly used in transport and fishing industries where ambitious plans are in place to transform the transportation sector with wider use of electric vehicles [72] transforming Iceland to an almost zero emissions economy.

It is worth mentioning that the 3 most populous islands [73] are found to belong in the higher diversity group (Madagascar, Taiwan, Sri-Lanka with populations of 25,054,161; 23,508,428; 22,409,381 as estimated on 2017). Population impacts the power sector structure as it drives energy demand which subsequently opens more options for power supply including renewable energy.

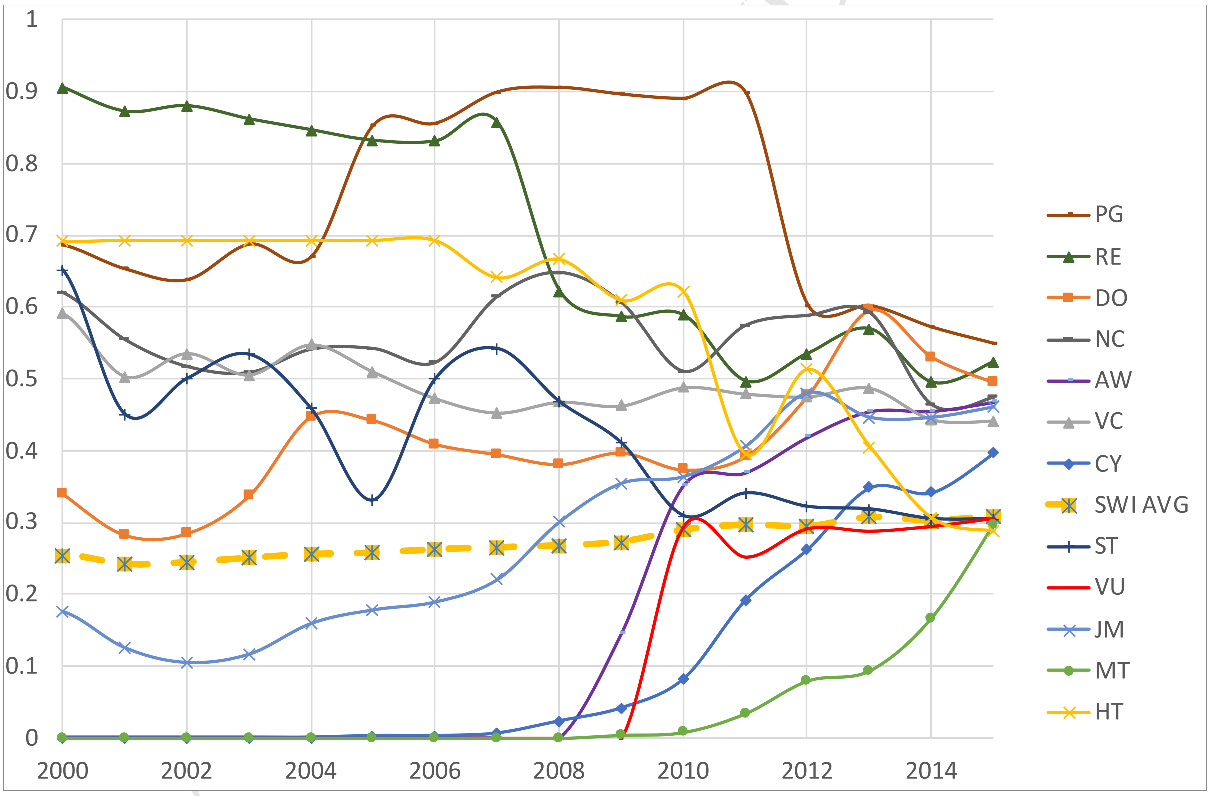

Figure 4: *Power sector diversity measured with SWI for islands of the moderate diversity group between 2000-2015. Data Source: EIA.*

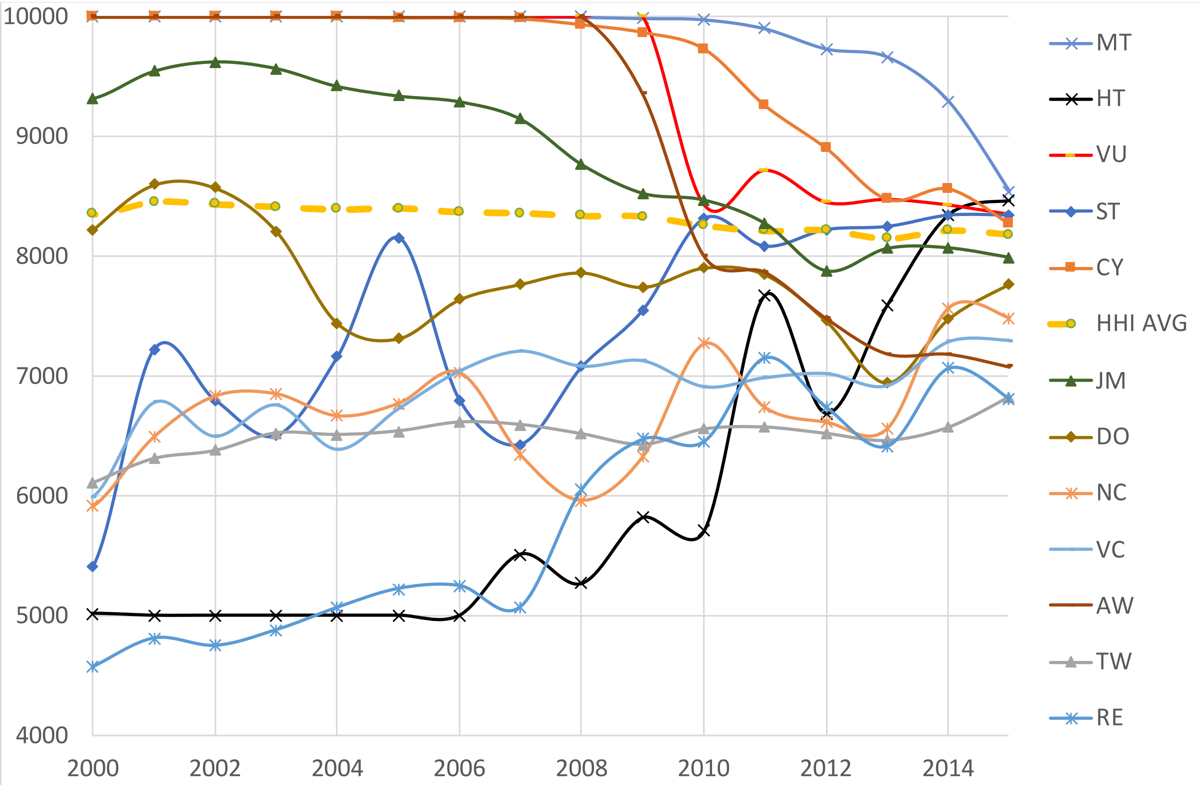

Figure 5: *Power sector concentration measured with HHI for islands of the moderate concentration group between 2000-2015. Data Source: EIA.*

In the moderate group, we can find mainly middle size islands including the European Union islands of Cyprus and Malta. Those islands along with Vanuatu and Aruba used to have 0 diversity until 2010 and 2008 respectively, relying exclusive on oil for power generation. In Vanuatu, and at larger scale in Aruba introduction of wind energy has boosted diversity. Malta and Cyprus are the EU's countries with the least diverse power sector as they rely excessively on imported oil. Recent solar energy growth in Malta improved the electricity diversity which still relies only on 2 options while Cyprus introduced 3 more options; wind, solar and biofuels, in its electricity fuel mix portfolio. Furthermore, some islands change groups depending on the index they are examined with (Table 1).

Table 1: Showing shifts between diversity and concentration groups for 2015. Source: EIA.

Country	SWI Group	HHI Group
Taiwan	High	Moderate
Papua New Guinea	Moderate	Low

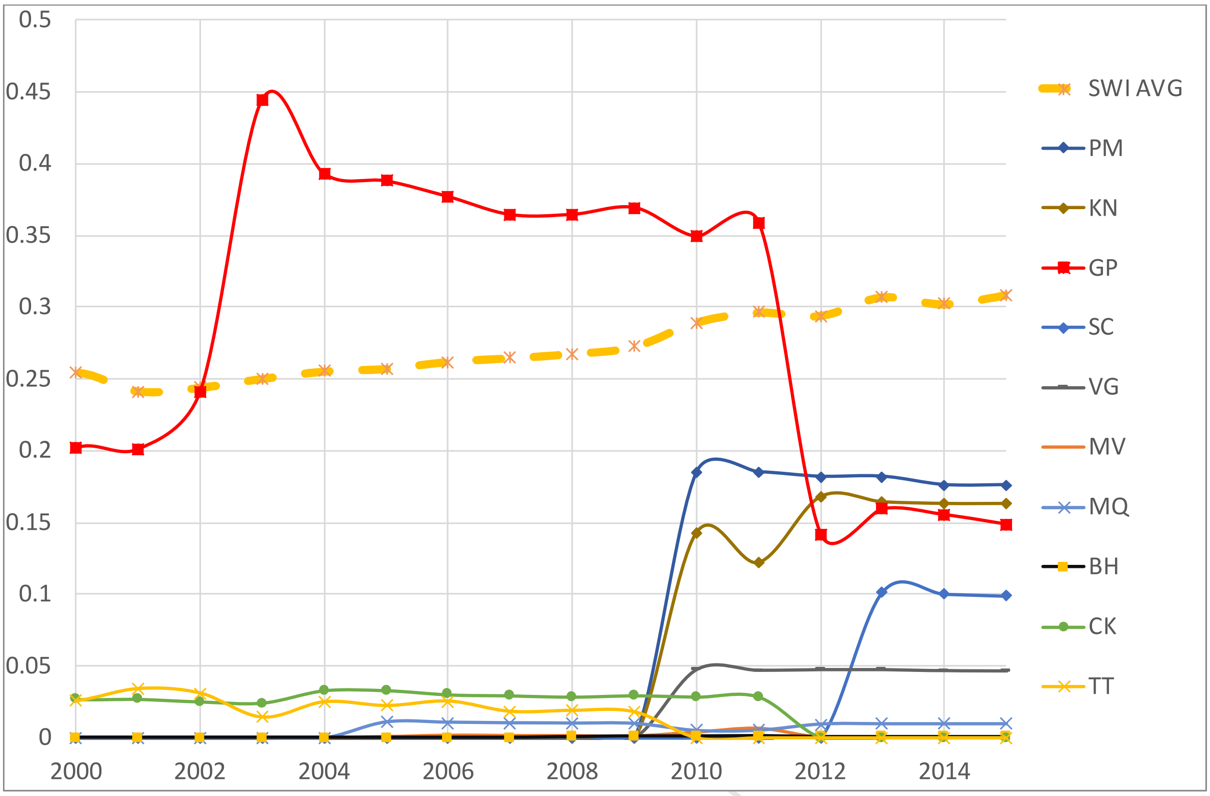

Figure 6: *Power sector diversity measured with SWI for islands of the lower diversity group between 2000-2015. Data Source: EIA.*

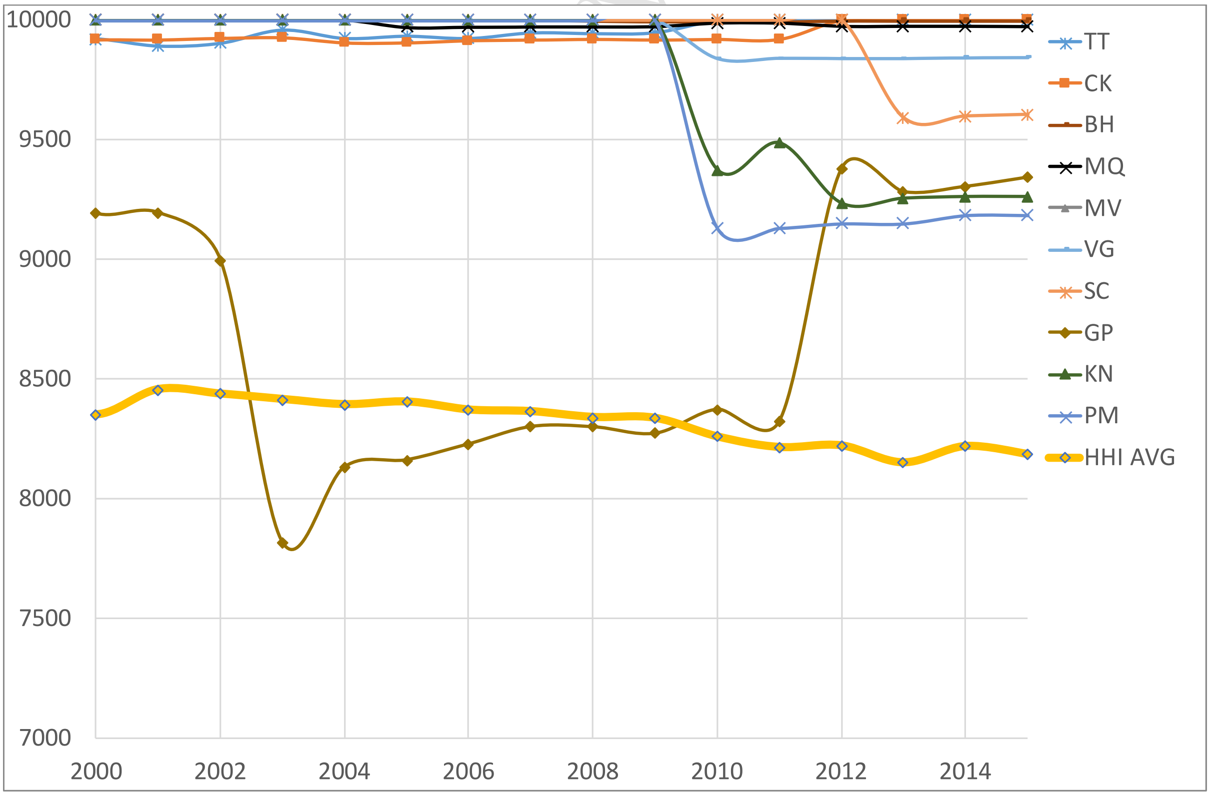

Figure 7: *Power sector concentration measured with HHI for islands of the higher concentration group between 2000-2015. Data Source: EIA.*

Cyprus and Malta managed to gradually improve their power sector diversity but several of the examined islands have zero diversity or 100% concentration. Specifically, Barbados, Cayman Islands, Montserrat, Nauru, Niue, Saint Helena Saint Lucia, Solomon Island, Tonga, Turks and Caicos and US Virgin Islands have zero power sector diversity as they rely only on oil. Moreover, the two fossil-fuel producing islands of Bahrain and Trinidad belong in the same group. Trinidad has zero diversity since 2009, when biomass ceased to exist as an electricity fuel mix option and Bahrain's use of wind power is as negligible as 0.0037%. As power production in Bahrain grows without any wind energy investment, the share of wind in power production has been in decline since 2008. The low diversity group contains the majority of the smallest islands globally including Nauru the smallest, by surface, inhabited island in the world at 8 square miles and population of 9,642 [74]. Any diversity appeared in their electricity generation is sourced mainly by wind or solar energy depending on the islands' natural endowment.

5. Discussion of the results

Complete reliance on any single energy source exposes energy supply to unsustainable risk [75] and our analysis indicates that several small islands are locked-in to unstainable power supply systems. Overall, however, there is a gradual but significant increase of 35.2% of total island diversity since 1990 (Figure 8). This improvement accelerates after 2002 alongside a concurrent increase in oil price between 2002 and 2014. Despite not distinguishing among fossil fuels throughout our analysis, due to data limitations, it is worth mentioning that almost all fossil fuel energy used on islands is imported oil. Only few islands produce fossil fuels; therefore, oil price hikes hurt most islands' economies severely.

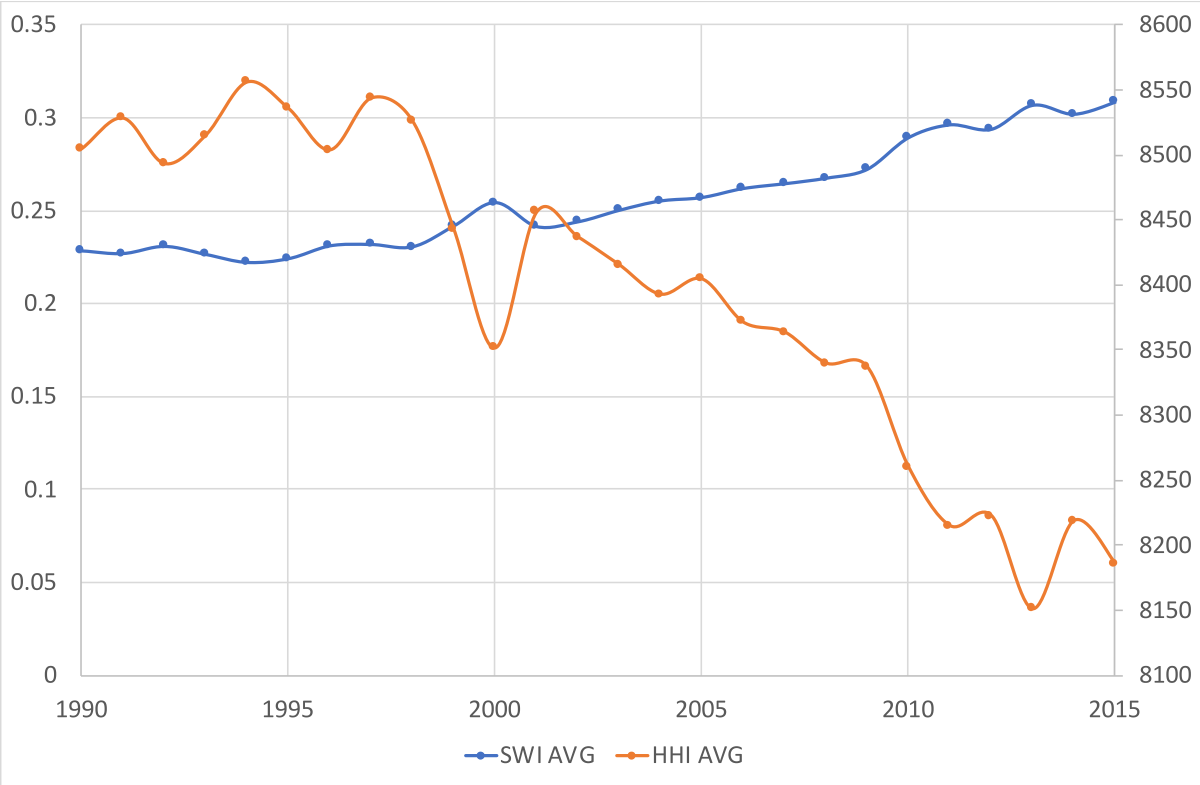

Figure 8: *Power sector average diversity and concentration measured with SWI and HHI between 2000-2015. Data Source: EIA.*

Given that fossil fuels are examined as one option and that nuclear energy is not widespread in the island nations of this study, only renewables offer a realistic alternative that can alter diversity. Renewable energy often contributes more than one new option in islands' fuel mix and its growth rate can be initially rapid. At the same time the indices used for measuring energy supply diversity and concentration are sensitive to the balance among the fuel options and to their total number; therefore, they tend to show a disproportionately large diversity increase even when an option with relatively negligible contribution is introduced to the fuel mix. Most of the islands examined in this manuscript have a relatively low number of options in their fuel mix.

Islands are usually small countries and their contribution to total global greenhouse emissions is negligible [76]], however, their energy and emissions intensity reveals how they are locked into fossil fuels. The synergy between climate change mitigation and energy supply security policies for a sustainable global energy system is imperative. In order to develop pathways to a sustainable, decarbonized energy future the potential trade-offs between those two issues require greater attention [77]. The energy strategy adopted by different countries is based on their own capabilities and priorities. For this study we examine emissions and energy intensities (Figure 9) and we project them along energy supply security for the latest year available (2015) to identify sustainable paradigms for energy security risk policies. The trajectory between the two-intensity metrics is increasing in contrast to global energy and emissions intensity. Islands average energy intensity increased by 23.4 % with a corresponding increase of 12.4% on their emissions intensity.

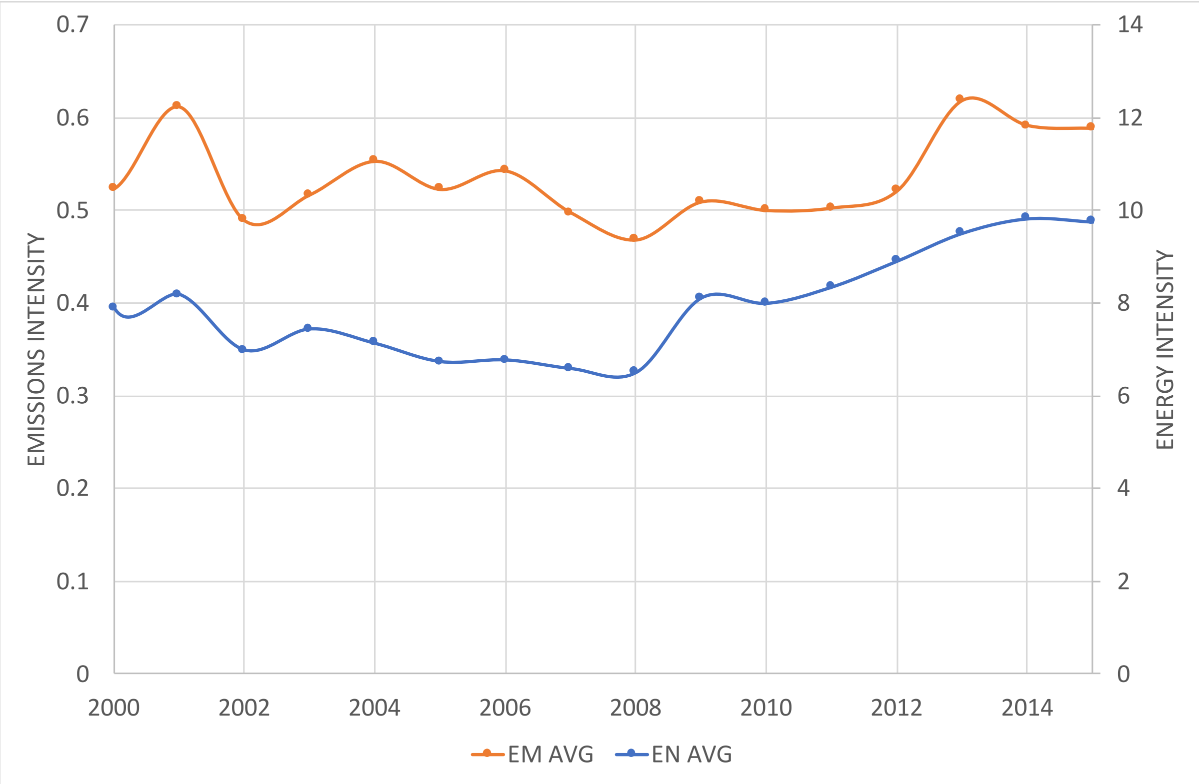

Figure 9: *Average emissions and energy intensities between 2000-2015 measured in MM tones CO_2/ Billion \$2010 GDP PPP and 1000 Btu/\$2010 GDP PPP. Data Source: EIA.*

While the average islands' energy and emissions intensity has been growing (Figure 9), every individual island presents a different case. Fourteen islands have decreased their energy and emissions intensity during 2000-2015, indicating a trajectory of decarbonisation and improved energy efficiency (Figure 10). For almost all the islands of this study energy and emissions intensity have been moving in the same direction, apart from Iceland, Saint Vincent and Samoa. Both Iceland and St Vincent experienced a significant increase of their energy intensity which was met with a rapid renewable energy increase leading to lower emissions intensity. In general, islands that reduced their energy intensity appear to reduce their emissions as a consequence of renewable energy sources introduction.

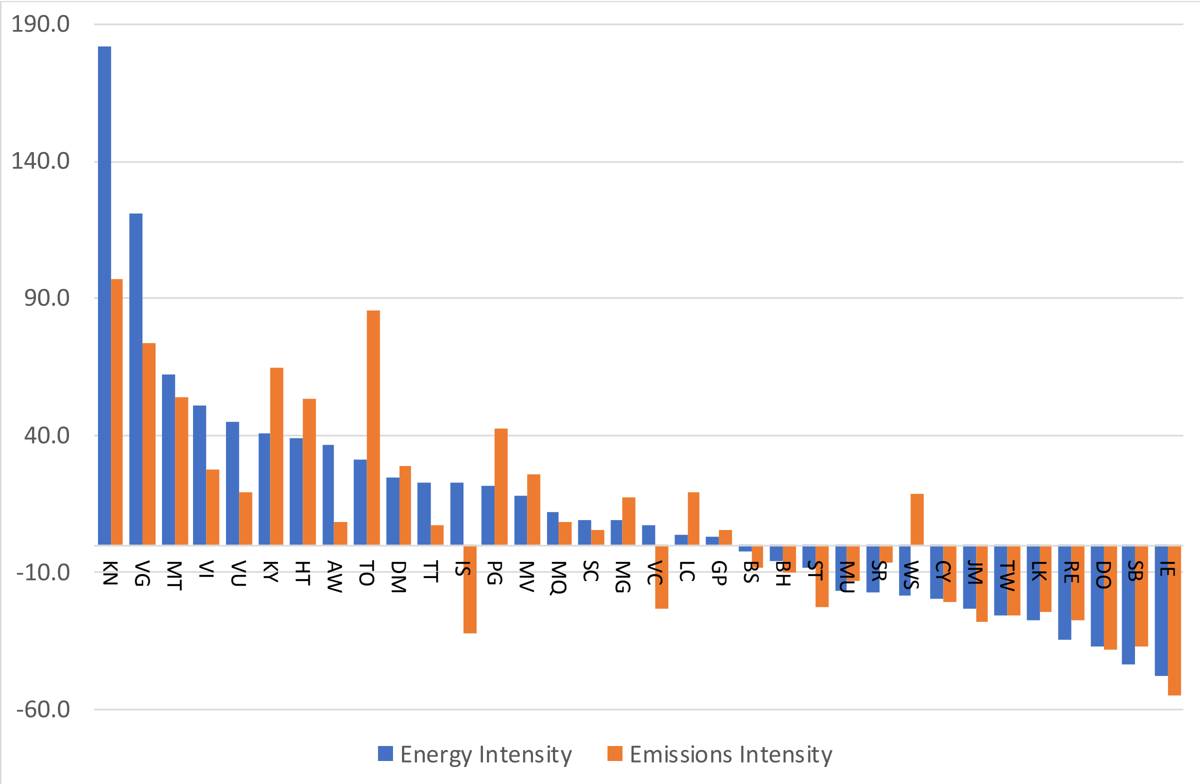

Figure 10: *Energy and Emissions Intensities % difference between 2000-2015. For British Virgin Islands 2004-2015. Data Source: EIA.*

In further consideration for the increasing contribution of renewable energy generally and in islands specifically, we examine the dual role of renewable energy in island energy systems. The duality consists of increasing diversity and reducing emissions and even energy intensity. Using 2015 (most recent data available) as a snapshot, we plot diversity (as measured by SWI for all options) against energy intensity (Figure 11) and emissions intensity (Figure 12) for all islands. The plots indicate that higher diversity is linked with lower energy and emissions intensity. Increased renewable energy directly contributes to fuel mix diversity in the studied islands and on average reduces emissions intensity since there is a substitution of fossil fuels with zero-emissions energy.

At the same time, increased diversity is linked to reduced energy intensity, which is less straight-forward. Considering that the main driver for increased diversity is increased use of renewable energy, it can be assumed that there is a link between increased use of renewable energy and lower energy intensity which is not an intuitive outcome; arguably there is no direct causality between increased renewable energy and reduced energy intensity. However, hypothesizing on this issue there are two other potentially explanatory factors; energy scarcity and the subsequently required energy awareness [78,79]. It can be argued that islands which invest in renewable energy are those which do not have abundant access to fossil fuels, either by being fossil fuel producers or within a major fossil fuel supply chain or transport route. As a result, they are faster to introduce renewables as a competitive energy source to support them in reducing their reliance on imported expensive fossil fuels. Furthermore, islands that experience energy scarcity might be forced to adopt deeper energy efficiency.

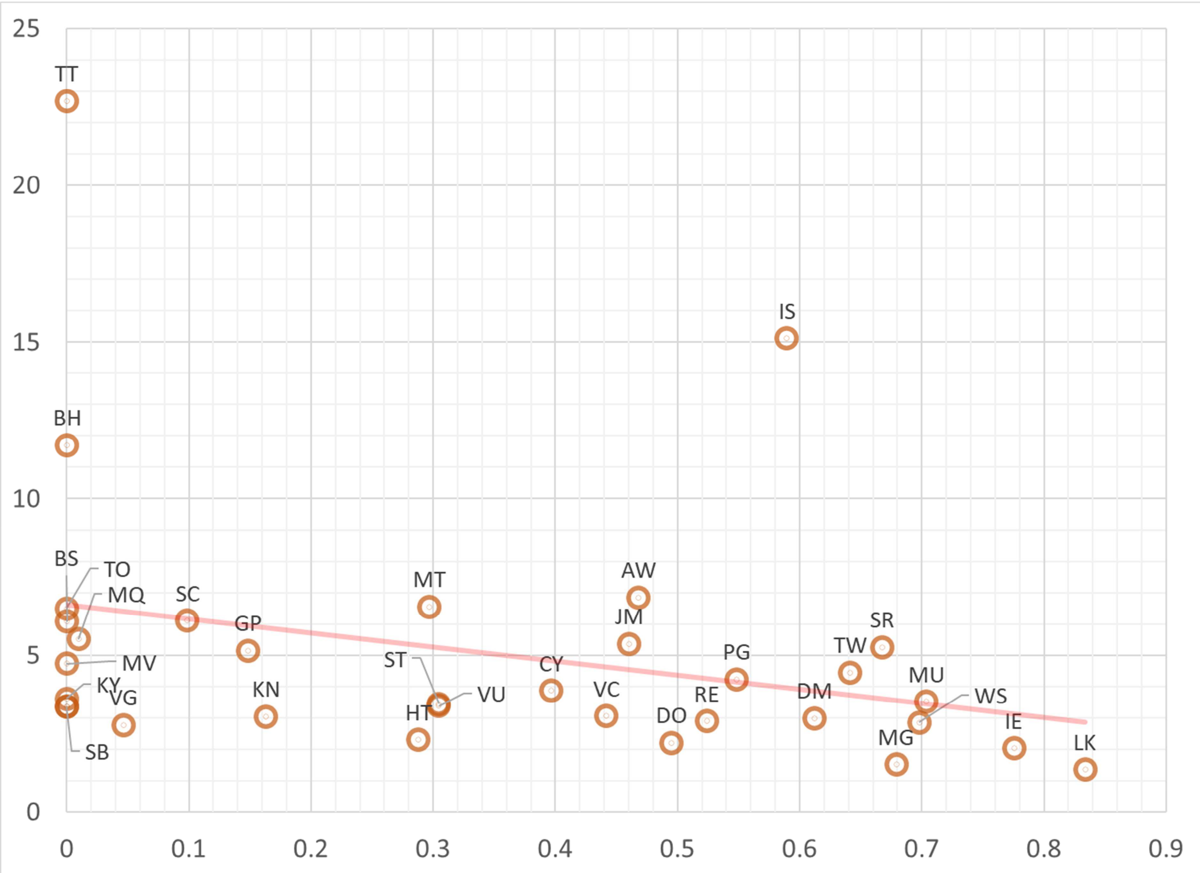

Figure 11: *SWI index (horizontal axis) against Energy Intensity (vertical axis) for 2015. Data Source: EIA.*

With most islands appearing to follow the higher diversity – lower energy trajectory, Trinidad & Tobago, Bahrain and Iceland are the clear outliers. Trinidad & Tobago and Bahrain are the islands with the highest energy and emissions intensity and zero diversity as they rely almost exclusively on natural gas and oil. Bahrain is a large oil producer in the Middle East and Trinidad & Tobago is the largest natural gas producer of the Caribbean. Bahrain subsidized oil prices encouraged over-consumption where Trinidad & Tobago's downstream petrochemical sector keeps both its emission and energy intensity at high levels. Iceland, is also an outlier but for diametrically different reasons, as it achieves almost zero emissions intensity with negligible use of fossil fuels. Its low emissions intensity is combined with high diversity making a paradigm for sustainable energy supply. The energy supply security and low emissions patterns of Iceland are more significant if we consider that hydro power and geothermal energy present lower variability and stochasticity in comparison to other renewables, such as wind or solar energy.

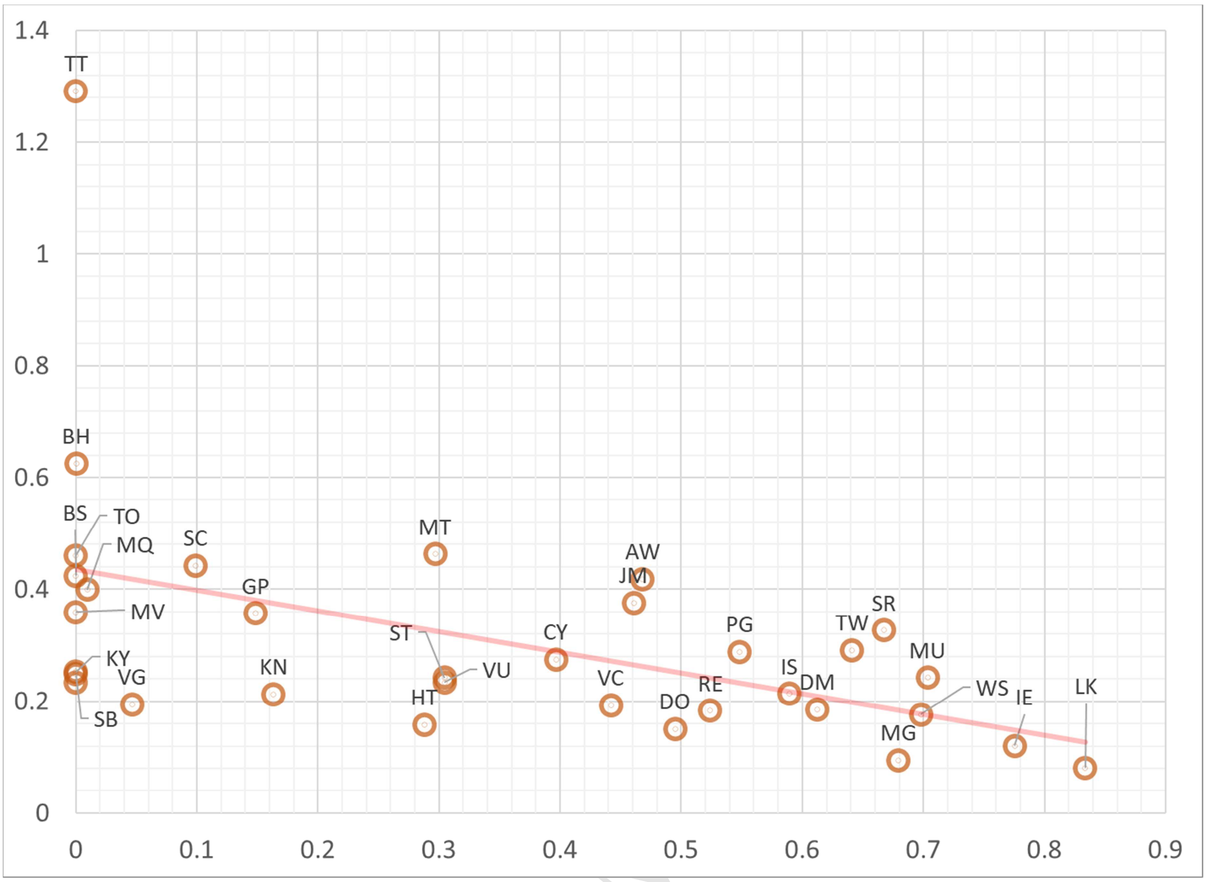

Figure 12: *SWI index (horizontal axis) against Emissions Intensity (vertical axis) for 2015. Data Source: EIA.*

6. Conclusion

Fuel mix diversity is a prerequisite for a sustainable energy future and can be considered as a strategic response to energy scarcity and uncertainty that challenges most countries. Although most island nations are the countries least responsible for climate change, paradoxically, they are the first to experience its consequences [80]. Their narrow resource import and export base, vulnerabilities to external economic shocks, and exposure to intense and frequent natural disasters facilitate the need for urgent transformations on the existing energy policy systems. Their remoteness, relative small size and flexible governance makes them potentially adaptable to change and capable of significant shifts unlike large regions with monolithic energy governance [42]. Indeed, islands lend themselves to excellent testing case studies for innovative energy solutions which could set the example for larger scale, on-grid applications. Acknowledging their role Small Island Developing States (SIDS) are mentioned in the UN Sustainable Development Goals, the recent UN framework to promote the sustainability agenda. SIDS are explicitly referred to in Goal 7 for Affordable and Clean Energy, and specifically in sub-Goal 7.B which requires sustainable energy services supported by infrastructure expansion and technology upgrade, for access to affordable, reliable, sustainable and modern energy for all by 2030. Moreover, Goal 13 refers to promotion of mechanisms for raising capacity for effective climate change related planning [81,82] of which, sustainable energy is a key enabler.

With this manuscript we provide for the first time a comprehensive evaluation of energy supply for 44 global islands and we set the agenda for the interlinkage between energy supply diversity and intensity of energy use and emissions. This is as much an energy issue as it is a development issue as energy is an undoubted contributor to economic development [83]. Within the UN Sustainable Development Goals and the UNFCCC Paris Agreement there is special care for SIDS as the first victims of climate change [84]. Our research confirms and further analyses the energy supply vulnerability assigned on SIDS and makes further links with their energy and emissions intensity as drivers for their environmental and economic sustainability agenda.

As with every piece of research, ours is not free of weaknesses. Firstly, the granularity of our data does not allow for a detailed break-down of fossil fuels, a trade-off we had to take in order to use the wide-coverage of the US Department for Energy database. Moreover, we argue that this choice has only limited impact on the overall results as most islands only use imported oil. Secondly, the technical focus of this manuscript did not allow for a thorough analysis in the context of the global sustainability agenda, of which the islands of the study are prime test case studies.

Further research should strengthen the connection of energy supply security and the global sustainability agenda, particularly with focus on the increased attention on UN Sustainable Development Goals, the forthcoming reviews of the Nationally Determined Contributions [85] under the Paris Agreement [86] and the forthcoming UN IPCC sixth assessment report in 2021 [87].

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