Essays on energy vulnerability and energy transition in Small Island Developing States

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To my family.
To Shaydes.

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Abstract

Anthropogenic climate change and its unequivocal impacts on all aspects of human existence are widely recognised, particularly in small island developing states (SIDS). Changes in the energy sector are essential to respond to climate change since it is the largest emitter of greenhouse gases (GHGs). However, the existing literature on the link between energy, economy, and environment regarding the challenges faced by these island territories is incomplete. This thesis fills this gap by looking at ways to build a sustainable energy future in SIDS. More specifically, we seek to understand the factors that make island energy systems vulnerable and determine the extent to which the energy transition process could play a role in mitigating their relative energy vulnerability while addressing climate change imperatives. The thesis is organised around three chapters, each of which constitutes a contribution to the literature. In the first chapter, we develop a composite index that identifies the critical dimensions of energy vulnerability for 36 SIDS. The environmental dimension, represented by the carbon content of primary energy, contributes most to the vulnerability of island energy systems. This finding calls for a gradual shift away from fossil fuels, on which SIDS are highly dependent. The following two chapters focus on the Republic of Mauritius (RoM). The second chapter examines the drivers of electricity consumption and the underlying temporal dynamics over the period 1978-2019. We show that energy conservation policies in the power sector do not necessarily impede economic growth in the RoM. The third chapter investigates the economic and technical feasibility of implementing energy and climate targets using a cost-optimisation approach over the period 2019-2050 with the TIMES model. We show that achieving the renewable energy penetration target is not compatible with the environmental commitments made by the RoM. Moreover, the transition to a low-carbon power system is mainly based on mature and already commercialised technologies.

Keywords: *climate change, SIDS, composite index, energy vulnerability, energy system modelling, energy transition, climate and energy policies*

Résumé

Le changement climatique anthropique et ses impacts sans équivoque sur tous les aspects de l'existence humaine font consensus, en particulier dans les petits États insulaires en développement (PEID). Le secteur énergétique constituant le principal émetteur de gaz à effet de serre (GES), ses évolutions revêtent une importance stratégique pour répondre au changement climatique. La littérature existante sur le lien entre l'énergie, l'économie et l'environnement au regard des défis auxquels sont confrontés ces petits territoires insulaires est incomplète. Cette thèse vise à combler cette lacune en se penchant sur les pistes permettant de construire un avenir énergétique durable dans les PEID. Plus spécifiquement, nous cherchons à comprendre les facteurs qui rendent les systèmes énergétiques insulaires vulnérables et déterminons dans quelle mesure le processus de transition énergétique pourrait jouer un rôle dans l'atténuation de leur vulnérabilité énergétique relative tout en répondant aux impératifs du changement climatique. La thèse s'organise autour de trois chapitres qui constituent chacun une contribution à la littérature. Dans le premier chapitre, nous construisons un indice composite de vulnérabilité énergétique qui identifie les dimensions critiques de la vulnérabilité énergétique pour 36 PEID. La dimension environnementale, représentée par l'intensité carbone de l'énergie primaire, contribue le plus à la vulnérabilité des systèmes énergétiques insulaires. Ce constat incite à l'abandon progressif des énergies fossiles dont les PEID dépendent largement. Les deux chapitres suivants se concentrent sur la République de Maurice (RdM). Le deuxième chapitre étudie les moteurs de la consommation d'électricité et la dynamique temporelle sous-jacente sur la période 1978-2019 dans ce pays. Nous montrons que les politiques d'économie d'énergie dans le secteur de l'électricité n'entravent pas nécessairement la croissance économique dans la RdM. Le troisième chapitre analyse la faisabilité économique et technique de la mise en œuvre des objectifs énergétiques et climatiques en utilisant une approche d'optimisation des coûts sur la période 2019-2050 avec le modèle TIMES. Nous montrons que l'atteinte de l'objectif de pénétration des énergies renouvelables n'est pas compatible avec les engagements environnementaux pris par la RdM. Par ailleurs, la transition vers un système électrique faiblement carboné se base essentiellement sur des technologies matures et déjà commercialisées.

Mots clés : *changement climatique, PEID, indice synthétique, vulnérabilité énergétique, modélisation du système énergétique, transition énergétique, politiques climatiques et énergétiques*

Acronyms and abbreviations

°C	degree celcius
ADEME	Agence de l'Environnement et de la Maîtrise de l'Energie
ADF	Augmented Dickey Fuller
AIMS	Atlantic, Indian Ocean, Mediterranean and South China Sea
AOSIS	Alliance of Small Island States
AR1	First Assessment Report
AR2	Second Assessment Report
AR5	Fifth Assessment Report
ARDL	autoregressive distributed lag
BAU	Business as usual
BESS	Battery energy storage system
BIC	Bayesian Information Criteria
BoD	Benefit of the Doubt
CAPEX	Capital expenditure
CCNUCC	Convention-Cadre des Nations Unies sur les Changements Climatiques
CDN	Contributions déterminées au niveau national
CEB	Central Electricity Board
CEMOI	Centre d'Economie et de Management de l'océan Indien
CGE	Computable general equilibrium
CI	Composite indicator
CH4	Methane
CO2	Carbon dioxide
COP	Conference of the parties
CPI	Climate Policy Initiative
CUSUM	Cumulative sum
CV	Critical value
DEA	Data envelopment analysis
DR	Discount rate
ECM	Error-correction model
ECT	Error-correction term
EDGAR	Emission Database for Global Atmospheric Research
EEA	European Environment Agency
EEMO	Energy Efficiency Management Office

EISD	Energy indicators for sustainable development
EnVI	Energy vulnerability index
ER	Energie renouvelable
ES	Energy security
EVI	Economic Vulnerability Index
FDI	Foreign direct investment
GDP	Gross domestic product
GES	Gaz à effet de serre
GETS	General-to-specific
GHG	Greenhouse gas
GIEC	Groupe d'experts intergouvernemental sur l'évolution du climat
GNI	Gross national income
Gt	Gigaton
GVA	Gross added value
GWh	Gigawatt hours
HDI	Human Development Index
HFO	Heavy fuel oil
IAEA	International Atomic Energy Agency
IC	Indice composite
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power producers
IRENA	International Renewable Energy Agency
JI	Joint implementation
JRC	Joint research centre
KPSS	Kwiatkowski–Phillips–Schmidt–Shin
Kt	Kiloton
ktoe	Kiloton of oil equivalent
LCOE	Levelized cost of electricity
LDC	least developed countries
LFG	landfill gas
LNG	liquefied natural gas
LTES	Long-term Energy Strategy
MARENA	Mauritius Renewable Energy Agency
MCS	Matrice de compatabilité sociale
MEGC	Modèle d'équilibre général calculable
MEPU	Ministry of Energy and Public Utilities
MESD	Ministry of Environment and Sustainable Development
MLBoD	Multi-layer benefit of the doubt

MLDEA	Multi-layer data envelopment analysis
Mt	Megaton
MW	Megawatt
MWALD	Modified WALD
N2O	Nitrous oxide
NDC	Nationally Determined Contribution
NPV	Net present value
OECD	Organisation for Economic Cooperation and Development
OPEX	Operational expenditure
OSeMOSYS	Open-Source Energy Modelling System
PC	Principal components
PCA	Principal component analysis
PEID	Petites économies insulaires en développement
PIB	Produit Intérieur Brut
PP	Phillips–Perron
PV	Photovoltaic
RdM	République de Maurice
RE	Renewable energy
RES	Reference Energy System
RoM	Republic of Mauritius
SAM	Social Accounting Matrix
SDG	Sustainable Development Goals
SDR	Social Discount Rate
SE4ALL	Sustainable Energy for all
SIC	Schwarz Information Criteria
SIDS	Small Island Developing States
SM	Statistics Mauritius
SR15	Special Report on Global Warming of 1.5 °C
SWI	Shannon-Wiener Index
TIMES	The Integrated MARKAL Efom System
TFC	Total final consumption
TJ	Terajoule
TPES	Total primary energy supply
UN	United Nations
UNCDP	United Nations Committee for Development Policy
UNCTAD	United Nations Conference on Trade and Development
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme

UNFCCC	United Nations Framework Convention on Climate Change
UN-OHRLLS	Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States
URA	Utility Regulatory Authority
VAR	Vector autoregressive
VECM	Vector error-correction model
WB	World Bank
WEF	World Energy Forum

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General introduction

> *"We did not come to fear the future. We came here to shape it."*
>
> *Barack Obama*

Climate change: a challenge for humanity

The need for climate action

Global warming is expected to reach 1.5°C between 2030 and 2050 if it continues at the current rate (Masson-Delmotte et al., 2018). However, the special report on 'Global Warming of 1.5°C' (SR15) published by the Intergovernmental Panel on Climate Change (IPCC) warns of the climate emergency and the risks associated with climate inaction, the latter representing a global risk to humanity.[1] This report sends a strong signal to the international community, highlighting that "*every half-degree matters, every year matters and every choice matters*".[2]

It is necessary to reduce the cumulative emissions of CO_2 and the future radiative forcing outside CO_2 (Figure 1) to limit global warming. Reduction efforts should be based on collective action to benefit all nations, especially vulnerable communities. However, individually, no country has a short-term interest in mitigating its emissions. Indeed, climate change is a non-exclusive and non-rival global public good (Buchholz & Sandler, 2021). Agents are therefore not encouraged to internalise the negative externalities linked to their activities. However, several studies have shown that delaying action would be more costly than tackling climate change, thus generating considerable economic damage (Stern et al., 2006; Bueno et al., 2008; Chevalier et al., 2008; Fortes et al., 2014; Sanderson & O'Neill, 2020).

Environmental awareness is not new. Since the first United Nations conference on the environment in 1972, the international debate on the challenges of climate change led to the setting up of the IPCC in 1988. Since its first assessment report (AR1) published

[1] In 2021, climate inaction ranks second in terms of probability of occurrence and impact (WEF, 2021).
[2] Petteri Taalas and Joyce Msuya, https://www.ipcc.ch/sr15/about/foreword/

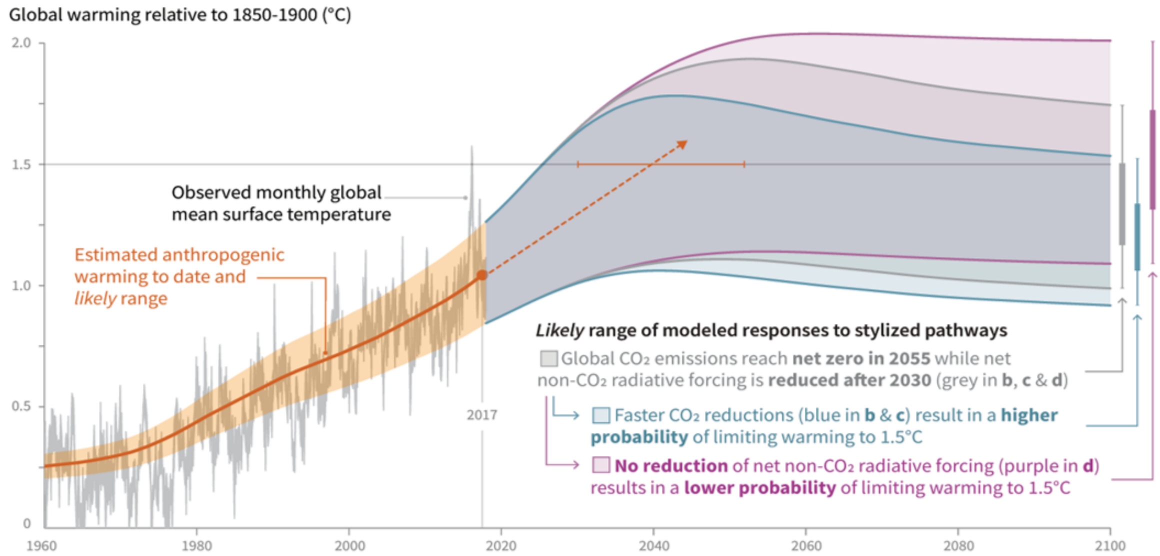

Figure 1: Global temperature change

Source: Masson-Delmotte et al. (2018)

in 1990, the IPCC has recognised and established the contribution of anthropogenic climate change to global warming. Indeed, the IPCC reports make it possible to assess the evolution of the temperature increase over time and the anthropogenic part. In addition, the different scenarios of future evolution according to the levels of emissions and concentrations of greenhouse gases (GHG) in the atmosphere are also assessed. These reports also warn of the dangers and impacts of the evolution of different temperature increase scenarios on the entire biosphere (land, ocean, meteorology). Moreover, the reductions needed to limit the rise in temperature to "*a level that would prevent dangerous anthropogenic interference with the climate system*" (Article 2 of the UNFCCC, p.9) are also considered. For example, in 2014, the IPCC estimated that a 40-50% reduction in emissions from 2010 levels was needed by 2030 to limit global warming to 1.5°C (Pachauri et al., 2014).[3]

Responses from the international community

The IPCC reports thus serve as scientific support for the various international negotiations. The United Nations Framework Convention on Climate Change (UNFCCC), which came into force in 1994, recognises the global dimension of climate-related risks. It calls for collective action through negotiations at the various Conferences of the Parties (COP).

Since the first COP in 1995 in Berlin, these climate negotiations have gone through

[3]A global warming limit of 2°C would require a 25% reduction in emissions for the same milestone year.

many twists and turns. The adoption of the Kyoto Protocol in 1997 (which came into force in 2005) is synonymous with a commitment by the international community to mitigate GHG emissions. Mitigation is defined as "*human actions to reduce greenhouse gas sources or enhance carbon sinks*" (Pachauri et al., 2014, p.125). It focuses on the causes of climate change. These early commitments involved industrialised countries grouped as Annex I countries[4] and accounted for at least 55% of global emissions. In the first commitment period from 2008 to 2012, Annex I countries had to reduce their emissions by at least 5.2% compared to 1990 levels. For example, market mechanisms were introduced to mitigate GHG emissions. These included domestic and international emissions trading, clean development mechanisms and joint implementation.[5]

The results of this first phase were mixed.[6] Moreover, during the second commitment period from 2013 to 2020, the absence of ratification by the United States, China, Japan and Russia compromised the protocol's success, despite more ambitious objectives (-18%).[7] In addition, the balance of power between developed and developing countries has changed, and commitments based on mitigation strategies have seen a competitor emerge in the negotiations: adaptation policies.

Adaptation refers to the "*process of adjusting to the current or expected climate and its consequences in order to mitigate its adverse effects and exploit its beneficial effects*" (Pachauri et al., 2014, p.118). Thus, adaptation strategies address the effects of climate change (Van Gameren et al., 2014). The insufficient reduction in global emissions and the associated prospects for further warming have changed developing countries' position, demanding access to funds to support adaptation policies. These tensions crystallised at the Copenhagen conference (COP15). As a result, a more integrated vision of responsibilities and so-called 'voluntary' actions were proposed in 2010 at COP16 in Cancún (Aykut Stefan & Dahan, 2011) to bring the international community together under a new agreement.

The adoption of the Paris Agreement in 2015 at COP21 and its entry into force the following year marks a new and essential turning point for the international community, with the ratification of the international treaty by all countries (196 in total), including major emitting countries such as China and the United States. These countries committed themselves to "*achieve a balance between anthropogenic emissions by sources*

[4]OECD countries and economies in transition are those listed in Annex I.

[5]These mechanisms have been the subject of numerous academic studies (Haites & Yamin, 2000; See, 2000; Timilsina & Shrestha, 2006; Diakoulaki et al., 2007; Ellis et al., 2007; Gilau et al., 2007; Schneider et al., 2008; Karakosta et al., 2009; Ciscar & Dowling, 2014).

[6]Although signatory countries achieved a 24% reduction during this period, this very positive result does not consider the absence of ratification of the protocol by the United States on the one hand and the fall of the Eastern bloc towards 1990 on the other. Thus, emissions would have fallen by only 4%, as shown by some studies (Den Elzen & De Moor, 2002), which is below the 5.2% objective.

[7]https://unfccc.int/

and removals by sinks of greenhouse gases" (Article 4 of the Paris Agreement).[8] In addition, the Paris Agreement requires signatory countries, including developing countries, to communicate and submit nationally determined contributions (NDCs) to mitigate GHG emissions.[9]

Mitigation and adaptation strategies are essential components of climate policies to meet these reduction targets (Tol, 2005; Hasson et al., 2010; van Vuuren et al., 2011; Heuson et al., 2014; Shrestha & Dhakal, 2019). However, the issues related to these strategies are different according to the territories. In this context, this thesis is particularly interested in the implications for adopting mitigation strategies for small island developing states (SIDS) and how these can also address adaptation needs in their case.

Adaptation as a short-term response: the concept of vulnerability

Adaptation strategies seek to manage the consequences of global warming, such as drought, rising sea levels or an increase in extreme weather events. In other words, adaptation is about reducing the vulnerability of natural and human systems to the effects of climate change. For a long time, adaptation to climate change remained a secondary topic, but it received increased attention at the beginning of the 21^{st} century through the UNFCCC (Hasson et al., 2010; de Murieta et al., 2014). Moreover, the IPCC has widely highlighted the heterogeneity of countries in terms of their vulnerability to climate change. Indeed, the IPCC reports show that developing countries and coastal and island territories are more vulnerable to rising sea levels and more frequent and intense extreme weather events.

The IPCC has contributed significantly to the use and definition of vulnerability. However, this definition has been refined throughout the reports. For example, in its Second Assessment Report (AR2), "vulnerability" was defined more generally as "*the extent to which climate change may cause damage or harm to a system in adapting to changing climatic conditions*" (Bolin et al., 1995, p.28). The Fifth Assessment Report defines vulnerability as the "*susceptibility or predisposition to adverse effects*" in the context of climate change (Pachauri et al., 2014).

Academically, the concept of vulnerability has been adapted and used for issues other than climate change, including natural disasters, hazards and economic issues

[8] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[9] Although not a legally binding document, Article 3 of the Paris Agreement requires NDCs to be reported every five years based on more ambitious and rigorous efforts than the previous ones, in line with the 'principle of progression'. The Agreement also put forward monetary funds to help countries adapt to climate change.

more generally. However, there is no widely accepted definition (Adger, 2006; Gallopín, 2006; Smit & Wandel, 2006; Füssel, 2007). A simple definition given by Dow (1992) and Turner et al. (2003) refers to "*the degree to which a system is susceptible to damage due to exposure to a hazard*" (Turner et al., 2003, p.8094). The absence of a common definition of vulnerability implies a considerable difference in assessment and measurement depending on the scientific field and underlying context.

Adaptation has now become **necessary** because whatever measures are implemented today, even the most drastic ones, inertia will cause temperatures to rise until around 2040. However, mitigation policies, which have historically dominated political and climate debates,[10] continue to represent strategies that are **critical** in lowering temperatures since "*[...] global warming is dominated by past and future CO_2 emissions*" (IPCC, 2021, p.16). While adaptation to the effects of global warming is necessary for the short-term, temperature regulation can only be achieved with long-term emission mitigation.

Mitigation as a long-term response: the role of energy systems

The energy supply sector is by far the largest emitter of GHG emissions. Indeed, global CO_2 emissions represented 33.5 billion tonnes in 2018 and increased by 1.6 times between 1990 and 2018 (IEA, 2018). However, the increase in global emissions is a direct consequence of the increase in energy supply and demand resulting from human activities (Quadrelli & Peterson, 2007). Therefore, a rise in temperature beyond 1.5°C will occur even if the reduction objectives announced in the national commitments are fully met (IEA, 2021).

Figure 2 illustrates the emission trajectories compatible with global warming limited to 1.5°C. A '*net-zero*' future requires the massive integration of clean technologies and a rapid shift away from fossil fuels. Furthermore, electrification will play an essential role in the ongoing energy transition, calling for greater flexibility in the power system through enabling environments such as storage technologies, sectoral coupling and demand-side management (IEA, 2021).

Energy and environmental issues are inevitably part of the much broader context of climate change (Boiteux et al., 2019; Chevalier et al., 2008). Kemmler & Spreng (2007) characterise energy as the ultimate commodity. On the one hand, energy is a strategic good that fuels modern societies. On the other hand, activities related to the production and consumption of energy contribute to anthropogenic climate change (Ansuategi, 2014) through the release of harmful gases into the atmosphere. The energy system is therefore of strategic importance in the mitigation of climate change (Rogelj

[10] A greater share of climate finance flows is directed to mitigation activities (CPI, 2019).

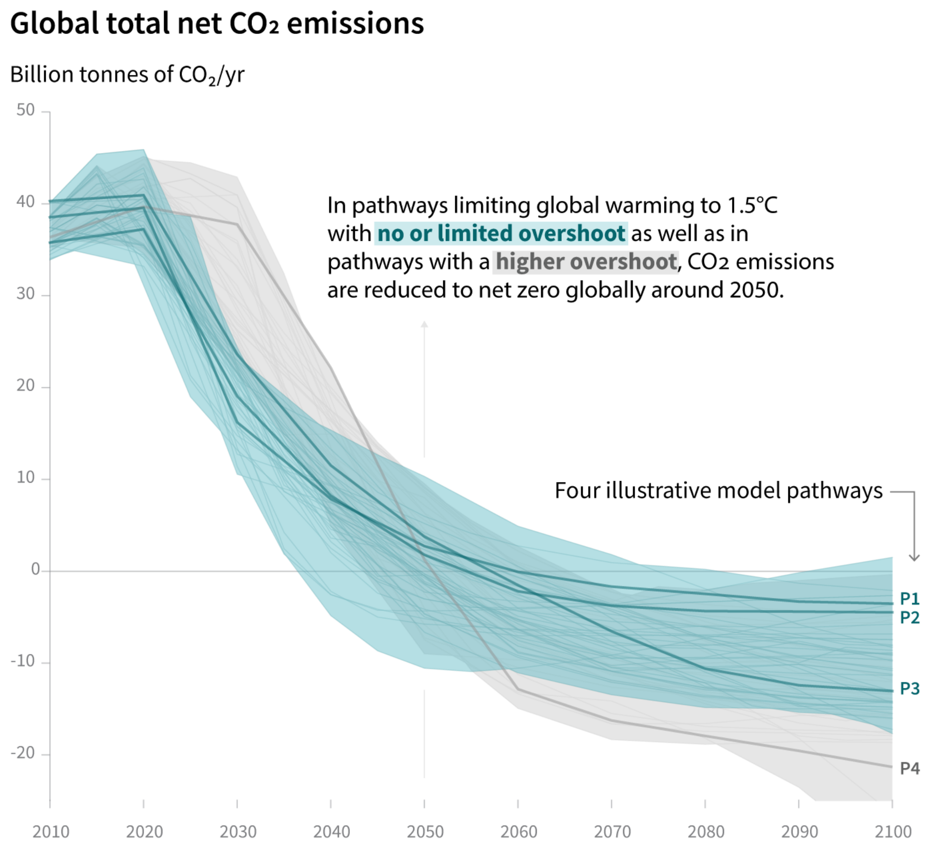

Figure 2: Emission trajectories compatible with a global warming limited to 1.5 °C

Note: P1 to P4 represent four examples of modelled trajectories under different mitigation strategies to reduce global net anthropogenic CO_2 emissions.
Source: Adapted from Masson-Delmotte et al. (2018)

et al., 2018).

The global energy system needs to undergo profound transformations. Response options for mitigation in the energy sector include the integration of renewable energy, the shift to low-carbon technologies, improved energy efficiency, CO_2 phase-out options and improved transmission and distribution networks. Moreover, implementing policy instruments[11] to incentivise and accompany mitigation efforts raises essential questions: what are the technologically feasible options and their underlying economic consequences?

This thesis addresses these issues by modelling energy systems. In this way, the medium- and long-term energy-economy and energy-environment interactions that lead to improved energy management are studied. In particular, it considers the capital, operating and maintenance costs of new technological options and the prices needed to

[11] These include, for example, economic instruments (taxes, tradable allowances and subsidies for renewables), regulatory approaches (efficiency/environmental standards), awareness-raising campaigns or even voluntary actions (Pachauri et al., 2014).

guide the energy transition.

The case of small island developing economies

Heterogeneous and vulnerable territories

The IPCC gives small island developing states (SIDS) special treatment due to their high vulnerability to climate change. The impacts foreseen in the different scenarios considered for island territories include sea-level rise, damage caused by extreme events, environmental degradation, coral bleaching and an increase in global surface temperature.

The Alliance of Small Island States (AOSIS),[12] established in 1990, has represented the interests of small island and low-lying coastal developing states in international negotiations on climate change, sustainable development and ocean conservation. Since their formal recognition as a distinct group of countries by the United Nations in 1992, SIDS, grouped within AOSIS, have placed climate change alongside other specific issues on the international agenda. Furthermore, the coalition played a crucial role in shaping the outcome of the Paris Agreement by insisting on the need to ensure that global emissions trajectories are compatible with keeping the temperature increase well below 1.5°C.

In addition to the physical impacts induced by climate, SIDS also suffer from several vulnerabilities[13] as illustrated in Table 1. The concept of vulnerability is particularly relevant to the study of the group of SIDS, especially to characterise their fragility (Briguglio, 1995; Guillaumont, 2009; Feindouno et al., 2020).

Table 1: Climate and non-climate vulnerabilities in SIDS

	Physical	Socio-economic	Socio-ecological
Non-climate vulnerabilities	Seismic risks Landslide risks Tsunami risks	Urbanization Pollution	Habitat loss and degradation Invasive species Overexploitation Human encroachment Diseases
Climate-induced vulnerabilities	Sea-level rise Tropical and extra-tropical cyclones Increasing air and sea surface temperatures Changing rainfall patterns		

Source: Nurse et al. (2014), adapted by the author.

However, despite having received much attention in the literature, there is no uni-

[12]AOSIS currently comprises 39 SIDS members, https://www.aosis.org/about/member-states/.
[13]These vulnerabilities are top priorities, such as poverty, education and health.

versal definition of a small island developing state. This is mainly due to the heterogeneity of the countries that make up this group despite their common characteristics. Indeed, the official list of 58 SIDS[14] recognised by the United Nations[15] also includes territories not sharing similar characteristics with most SIDS *sensu stricto* (Table 2). For example, we note that their population varies between 11,000 (Nauru) and 11,402,000 (Haiti) inhabitants, while their surface area varies between 21 (Nauru) and 462,840 km^2 (Papua New Guinea).[16] Disparities in human development compound this. In 2019, Singapore had a Human Development Index (HDI) of 0.938, while Guinea-Bissau was among the least developed countries with an HDI of 0.48.[17] However, we note that most of these small territories have a balance of trade deficit with imports significantly higher than exports.

The economic literature has contributed to the recognition of the structural handicaps of SIDS (Briguglio, 1995; Guillaumont, 2009).[18] Smallness, insularity, increased dependence on strategic imports or openness to international trade are inherent characteristics of SIDS (Briguglio et al., 2009; Briguglio, 2014; Bates et al., 2014; Angeon & Bates, 2015). Guillaumont (2009) introduces the concept of structural economic vulnerability, which includes only those factors that are independent of a country's policies (Guillaumont, 2009; Guillaumont et al., 2020). It is commonly accepted that these territories, although heterogeneous, are more or less vulnerable, hence the importance of special and differentiated treatment.

Paradoxically, the contribution of these territories to global greenhouse gas emissions is negligible. In 2018, SIDS contributed 0.7% of global CO_2 emissions.[19] This can be explained by their relatively low level of development and their small size. However, these territories will have to increase their production and experience strong demographic growth. To set the example, the SIDS have submitted their NDCs, which consider their respective adaptive capacity in the fight against climate change. Overall, the energy and power sectors have been the primary focus of mitigation measures. The ultimate challenge for these territories will be to balance the various policy objectives while

[14]These are located in three distinct geographical regions: the Caribbean, Pacific and Atlantic, Indian Ocean, Mediterranean and the South China Sea.

[15]The United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States (UN-OHRLLS), https://www.un.org/ohrlls/content/list-sids.

[16]http://data.un.org/

[17]http://hdr.undp.org/

[18]The use of the concept of vulnerability favours equal access to financing that encompasses the sole criterion of the level of income and gives greater legitimacy and credibility to the allocation of development aid, notably by offering special and differentiated treatment to SIDS and least developed countries (LDCs) affected by various vulnerabilities. Thus, vulnerability should influence access to and conditions of financing (WB, 2017, p.2).

[19]Calculated by the author on 48 SIDS using the European Commission's EDGAR emissions database (Crippa et al., 2019).

Table 2: Descriptive statistics on key indicators for SIDS

SIDS	CODE	POP	AREA	GDPPC	AGR	IND	SERV	EXP	IMP	EVI	HDI
Antigua and Barbuda	ATG	98	442	16727	2	23.8	74.2	37	568	32.28	0.778
Bahamas	BHS	393	13940	32218.1	1	14.8	84.2	494	4087	28.15	0.814
Bahrain	BHR	1702	771	24133.5	0.3	43.7	56	14355	18680	28.35	0.852
Barbados	BRB	287	431	17745.9	1.5	14.9	83.6	462	1618	16.47	0.814
Belize	BLZ	398	22966	4884.7	11	13.7	75.3	245	986	40.39	0.716
Cabo Verde	CPV	556	4033	3635.4	6.2	22.6	71.3	76	941	38.16	0.665
Comoros	COM*	870	2235	1400.5	31.5	12.4	56.1	49	201	39.71	0.554
Cuba	CUB	11327	109884	8821.8	3.8	25.2	71	828	7498	27.52	0.783
Dominica	DMA	75	750	7691.3	13.8	19.7	60.7	18	304	34.65	0.756
Dominican Republic	DOM	10848	48671	7650.1	6	30.3	56.2	11117	20599	21.53	0.742
Fiji	FJI	896	18272	6267	35.7	13.3	51	1137	2650	38.77	0.743
Grenada	GRD	112	345	10485.9	6.3	16.2	88.9	32	470	34.1	0.779
Guinea-Bissau	GNB*	1968	36125	778.4	49.9	13.3	38.1	3731	188	40.45	0.48
Guyana	GUY	787	214969	4900.8	14.7	38.4	64.4	1405	3467	45.56	0.682
Haiti	HTI*	11402	27750	834.9	18.6	31.7	32.6	746	3118	33.38	0.51
Jamaica	JAM	2961	10990	5354.3	7.7	23.5	65.7	1586	6339	28.85	0.734
Kiribati	KIR*	119	726	1627.4	24	15.6	70.5	10	554	66.08	0.63
Maldives	MDV	540	300	10330.6	6.5	15	52.8	163	2883	44.06	0.74
Marshall Islands	MHL	53	181	3666.9	15.7	12.1	68.7	34	71	59.94	0.704
Mauritius	MUS	1272	1969	11222	3.2	20.1	77.3	1876	5601	22.26	0.804
Micronesia	FSM	115	702	3296.4	28	6.5	76.5	1	8	51.02	0.62
Nauru	NRU	11	21	11875.9	2.4	37.5	42.3	NA	NA	37.37	NA
Palau	PLW	22	459	15859.4	3.5	8.8	81.6	8	169	47.88	0.826
Papua New Guinea	PNG	8947	462840	2681.4	19.5	30.5	53.5	11798	3130	30.93	0.555
St Kitts and Nevis	KNA	57	261	19275.4	1.2	27.7	87.3	63	338	35.32	0.779
St Lucia	LCA	184	539	10566	1.8	11.6	88.7	55	598	32.44	0.759
St Vincent and the Grenadines	VCT	111	389	7361.3	8.6	17.8	78	37	335	28.22	0.738
Samoa	WSM	198	2842	4249.6	9.4	14.6	51.2	32	390	28.07	0.715
Sao Tomé and Principe	STP*	219	964	1948.1	11.3	15.4	46.1	14	165	29.91	0.625
Seychelles	SYC	98	457	16377.9	2.4	13.4	53.2	824	1438	40.18	0.796
Singapore	SGP	5850	719	67720.9	0	26.1	80.1	390332	358975	25.52	0.938
Solomon Islands	SLB*	687	28896	1946.9	25.4	15.2	51.5	611	348	45.82	0.567
Suriname	SUR	587	163820	6003.7	12.3	34.5	51.8	1461	1711	44.16	0.738
Timor-Leste	TLS*	1318	14919	2035.5	10	49.6	47.9	154	536	40.14	0.606
Tonga	TON	106	747	4885.8	22	21	57.8	15	311	43	0.725
Trinidada and Tobago	TTO	1400	5127	17130.3	1.1	42.8	54	12336	1951	27.55	0.797
Tuvalu	TUV*	12	26	4000.6	21.9	12.5	69.9	0	12	56.98	NA
Vanuatu	VUT*	307	12189	3037.2	22.8	11.2	63	51	289	39.14	0.609

Note: Countries marked with an asterisk (*) are also least developed countries (LDCs). Data is from the United Nations database for 2020 unless otherwise indicated. *POP* designates the population in thousand, *AREA* designates the surface area in km^2, *GDPPC* designates the GDP per capita measured in current dollars. *AGR*, *IND* and *SERV* represent respectively the share (%) of the agricultural, industrial and tertiary (services) sectors in the gross value added. *EXP* and *IMP* respectively designate exports and imports measured in millions of current dollars. *EVI* represents the economic and environmental vulnerability index calculated by the United Nations Development Committee for 2020. *HDI* is the Human Development Index calculated by the United Nations for the year 2019.
Source: Compiled by the author.

addressing the negative impacts of climate change. Hence the need to develop diagnostic tools that enable the development of public policies specifically designed for SIDS. In this case, why should these small territories engage in the energy transition?

Energy transition, a "win-win" strategy for SIDS?

The response to climate change involves a diverse set of adaptation and mitigation actions at the national level. This raises questions about the capacity of SIDS to cope with the effects of climate change. Indeed, the costs of adaptation are higher in small islands due to the indivisibility of utilities and other services (Nurse et al., 2014), underlining the critical need for climate finance (Robinson & Dornan, 2017).

This leads to the following fundamental question around which this thesis is structured: **How can small island developing states reduce their energy vulnerability by addressing climate change mitigation imperatives?** The relevance of this question for policymakers is justified in the context of climate change, including energy-economy-environment interactions. This thesis contributes to the discussion on the situation of SIDS and proposes avenues for policy development. Therefore, this thesis investigates the energy-economy-environment nexus in the context of SIDS through the lens of energy vulnerability and energy transition and their interactions with climate change. We argue that energy transition is a win-win strategy for these small territories. From an environmental point of view, it would help reduce GHG emissions, an objective compatible with the commitments of the Paris Agreement. From an economic point of view, it would improve the performance of island energy systems, which are heavily dependent on strategic imports such as fossil fuels, which often result in high energy import bills.

Climate change is undoubtedly one of the main drivers of the energy transition. In addition, mitigation measures to reduce the effects of climate change are being developed to meet the requirements of the Paris Agreement. Restructuring and transforming energy systems to meet ambitious energy and climate goals relies on improved supply-side efficiency. It also requires a review of consumption patterns to reduce the pressure on the productive system. Although the energy transition is not a one-size-fits-all solution, studying future energy production mix trajectories is necessary to identify potential cost-effective energy systems. The rapidly falling costs of critical renewable technologies offer a tremendous opportunity for SIDS to trigger the profound transformation of their respective energy systems while pursuing multiple energy objectives. This leads us to question the type of transition expected in SIDS, given their specificities.

Small island developing states are the focus of this thesis. While the literature on island territories has focused extensively on climate change (Nurse & Moore, 2005;

Briguglio et al., 2007; Kelman & West, 2009; Campbell & Barnett, 2010; Betzold, 2015; Robinson, 2017; Kelman, 2018; Mycoo, 2018; Robinson, 2018), natural hazards (Pelling & Uitto, 2001; Méheux et al., 2007; Julca & Paddison, 2010; Kelman et al., 2011; Baarsch & Kelman, 2016; Sjöstedt & Povitkina, 2017) or economic vulnerability (Briguglio, 1995; Encontre, 1999; Adrianto & Matsuda, 2004; Guillaumont, 2010; McGillivray et al., 2010), the literature focusing on energy issues, particularly in terms of vulnerability and the energy transition, is relatively incomplete. Moreover, islands in the Atlantic, Indian Ocean, Mediterranean, and South China Sea (AIMS) are even less studied than their Pacific and Caribbean counterparts. The most frequently used argument is the unavailability of data, thus limiting the transposition of some studies to these territories. Therefore, this thesis is of global interest as small island developing states are among the first victims of climate change. In this sense, the significant contribution of this thesis is the enrichment of knowledge on these territories.

Overview of research work

This thesis is structured around three chapters based on four original papers. These chapters address the challenges for island energy systems to respond to climate change and ensure a sustainable energy future. Chapter 1 assesses the energy vulnerability of a group of SIDS.[20] The objective is to develop a reliable and robust measure of this phenomenon to quantify the degree of exposure of island energy systems to different shocks. The discussion focuses on ways to mitigate this vulnerability.

Chapters 2[21] and 3[22] focus on the energy transition challenges in the Republic of Mauritius (RoM). The RoM is an interesting case study considering the relative competitiveness of its diversified and outward-looking economy.[23] Furthermore, the energy transition of the RoM could serve as a benchmark for other SIDS (AOSIS members or those in the western Indian Ocean) with similar characteristics in terms of energy performance and development stage. In addition, the close collaboration with the network operator enabled access to data that are usually difficult to obtain for other island territories. Moreover, this thesis benefited from a Campus France Mauritius scholarship to study sustainable development issues in the RoM.

In Chapter 2, we address the issue of electricity consumption as a critical variable

[20] Chapter 1 was co-authored with Sabine Garabedian and Stéphane Blancard. See Genave et al. (2020) published in *Ecological Economics* on 18 January 2020. The subsection on sensitivity analysis is based on a working paper written by the author, entitled "*Impacts of normalising benefit-of-the-doubt composite indicators.*"

[21] Chapter 2 was submitted to the journal *Energy Studies Review* on 26 February 2021.

[22] Chapter 3 was co-authored with Sandrine Selosse and submitted to the journal *Energy Policy* on 9 July 2021.

[23] https://www.edbmauritius.org

in the long-term planning of any power system. In addition, the temporal dynamics of electricity demand and its main drivers are studied and discussed. Finally, chapter 3 focuses on the supply side of the energy transition. In addition, we explore the future trajectories of two island power systems in the RoM - Mauritius and Rodrigues. We specifically address the transformations that both systems might face based on economic, environmental, technical and political constraints.

Energy vulnerability in SIDS

Given the crucial role of energy systems in addressing climate change, we first identified the strengths and weaknesses of these systems. Most SIDS rely heavily on imported fossil fuels for their primary energy requirements, exposing their economies to volatile oil markets and disruption risks in the supply chain. Chapter 1 seeks to answer the following questions: **What does energy vulnerability entail for island energy systems? What are the contributing factors? How can it be measured?**

We propose a conceptual framework for studying and measuring structural energy vulnerability to answer these questions. The concept of structural vulnerability is borrowed from the literature on structural economic vulnerability (Guillaumont, 2006, 2009, 2010). This literature highlights the concepts of 'shocks' and 'exposure' to identify the intrinsic determinants of exposure and its transmission channels (Goavec, 2016). In this thesis, we apply the concept of structural vulnerability to the energy system. In other words, this vulnerability is independent of the public policies that aim to reduce it. We define energy vulnerability as "*the degree of sensitivity of energy systems to external shocks and internal dysfunctions related to energy production, transmission and distribution*". How do we measure this phenomenon?

The indicators frequently used to carry out this measurement are grouped into dashboards or aggregated into composite indicators (CIs). Dashboards provide an overview, while CIs are used to synthesise information on a given phenomenon (Nardo et al., 2008). Thus, several indicators are mathematically aggregated to generate a single value. However, the latter is strongly criticised given the subjectivity inherent in choosing the weighting scheme for the different dimensions characterising the phenomenon. Moreover, the lack of consensus within the scientific community makes this stage of index construction particularly delicate, risking compromising the index's effectiveness in communicating the relevant information needed for rapid decision-making —nevertheless, CIs act as essential tools that can account for the specificities of SIDS.

To address some of these criticisms, we apply a data-driven approach to the construction of our index. First, 21 energy indicators for sustainable development were selected from those proposed by the International Atomic Energy Agency (IAEA) and existing literature. We then performed a principal component analysis (PCA) to reduce the number of variables that characterise energy vulnerability to eight. Several sources are used to collect the data: the United Nations Statistical Division, the World Bank and the Emissions Database for Global Atmospheric Research (EDGAR) of the Joint Research Centre of European Commission.

The final step is to aggregate the sub-indicators into a composite index of energy vulnerability. We opt for the 'Benefit of Doubt' (BoD) approach, derived from the Data Envelopment Analysis (DEA) method applied to composite indices. This approach is particularly interesting for the construction of indices due to its invariance to the units of measurement (Melyn & Moesen, 1991; Zhou et al., 2010; Savić & Martić, 2017). In other words, it allows efficiency scores to be calculated based on endogenous weights that are flexible enough to adapt to various units of measurement. To highlight the hierarchical structure of the energy vulnerability concept, we adopt a multi-layer model called *Multi-layer Benefit of the Doubt* (MLBoD). The latter is calculated for 36 UN member SIDS for the year 2015.

Few studies have focused on island territories to study energy vulnerability (Ioannidis et al., 2019; Gatto & Busato, 2020). Therefore, we contribute to the literature on SIDS by concentrating on the most significant number of island territories for which data were available. Furthermore, the proposal of a new definition of energy vulnerability allows us to understand the phenomenon better. The originality of this definition lies in the distinction between the two components 'shocks' and 'exposure' characterising energy vulnerability. The latter is then represented by the economic, environmental and social dimensions.

From a methodological point of view, the contribution of this study lies in the construction of a composite index capable of reflecting this phenomenon. It deals with two types of indicators (desirable and undesirable) without prior data transformation. In addition to identifying the factors contributing most to vulnerability, the ranking obtained allows the most vulnerable countries to request international assistance to make their energy systems less vulnerable.

The results indicate that most SIDS require significant efforts to reduce GHG emissions (environmental dimension). In addition, the indicators that constitute the economic dimension also require special attention. Indeed, most island energy mixes are relatively concentrated. Consequently, a profound transformation of island energy systems seems necessary to reduce their vulnerability.

Electricity consumption dynamics: the main drivers

Electricity demand is the driving force of the power system. It influences the optimal decisions on the sizing and location of power plants and the choice of generation technologies that supply electricity. Electricity supply and demand must be constantly matched. Understanding the dynamics of electricity consumption is crucial as electricity grid management becomes more complex in the energy transition context. Indeed, the future evolution of demand will condition future investments, hence the importance of understanding the factors that can influence electricity demand. Chapter 2 seeks to answer the following questions: **What are the main determinants of electricity consumption in Mauritius? What is the nature of their relationship?**

To answer these questions, we take the Republic of Mauritius (RoM) as a case study to analyse the main drivers of electricity consumption. The literature on electricity demand dynamics generally focuses on critical factors such as economic growth and productivity, technological innovation or energy prices. Empirical studies on advanced and emerging economies are substantial in the literature (Kraft & Kraft, 1978; De Vita et al., 2006; Halicioglu, 2007; Adom et al., 2012; Adom, 2017; Al-Bajjali & Shamayleh, 2018). However, there is no consensus regarding the nature and magnitude of the relationship between these variables. This may be due to different models and techniques or the period chosen to study these dynamics. The choice of the country may also impact the results given the different economic conditions and stages of development.

Several studies use econometrics and more or less advanced regression techniques such as vector autoregression models (VAR) and vector error correction models (VECM). The autoregressive distributed lag model (ARDL), belonging to the family of dynamic models developed by Pesaran et al. (1995) and Pesaran et al. (2001), can also be used. The ARDL model is particularly suitable for small sample sizes with few observations and a mixture of stationary and non-stationary variables. Moreover, the short- and long-term time effects of the explanatory variables on the dependent variable can be captured (Acaravci & Ozturk, 2010; Zachariadis, 2010). For these reasons, we have chosen the ARDL approach to highlight the relationship between our variables.

We study the temporal dynamics between electricity consumption, income per capita, average electricity price and exports per capita in Mauritius over the period 1978-2019. The data used come from *Statistics Mauritius* and the World Bank's World Development Indicators database. Our contribution is mainly empirical. This study sheds new light on the specific case of Mauritius and attempts to fill a gap in the literature on electricity consumption in SIDS.

We demonstrate the existence of a long-run equilibrium between electricity consumption, real GDP per capita, electricity prices and exports per capita. Electricity consumption is inelastic to price and income in the short and long run. Moreover, the Toda-Yamamoto causality test confirms the neutrality hypothesis between electricity consumption and GDP per capita and exports per capita. Therefore, implementing energy-saving measures targeting the electricity sector does not hinder economic growth and does not harm the gains from exports. These results provide insights into public policy. Our study calls for a re-examination of previous perspectives on energy policy in Mauritius. As part of an energy transition process, the Mauritian government can focus on energy efficiency measures without severe consequences for the Mauritian economy. Policymakers should encourage consumers to change their consumption habits and increase energy efficiency.

System integration of renewable energy and mitigation of GHG emissions

The transition to a low-carbon future requires rethinking technological and institutional systems while correcting inequalities and environmental problems. Chapter 3 focuses on the transition of the power systems of two islands in the Republic of Mauritius (RoM). It seeks to answer the following questions: **Which policy objective is most likely to shape a secure and sustainable energy future for the two island power systems in the Republic of Mauritius? Which critical energy technologies will most likely help the RoM achieve the transition to clean energy? What investment choices will shape the energy future of Mauritius and Rodrigues**?

Several analytical tools exist to model energy systems.[24] The choice of a particular model depends on several parameters such as the problem statement, the desired spatial and temporal resolution or the data to enter the model. These tools are generally categorised into three main groups: top-down models, bottom-up models and hybrid models (Grubb et al., 1993; Zagamé, 2008; Herbst et al., 2012; Fortes et al., 2013; Al Irsyad et al., 2017; Boiteux et al., 2019).

Top-down models are based on macroeconomic principles and use the underlying economic theory to model the interdependencies and interactions between markets as a function of prices (Böhringer, 1998). These models are used to evaluate the macroeconomic impacts of energy taxes or changes in energy systems (Jacobsen, 1998). Bottom-up models are appreciated for the technological richness that they can represent. These are used to explore future trajectories of energy supply and demand given a set of economic, environmental, technical and political constraints (Brouwer et al., 2018). This makes them relevant for energy planning and the analysis of long-term energy sector restructuring (Jacobsen, 1998). Finally, hybrid models, also called integrated models, are

[24] Ringkjøb et al. (2018) reviews a total of 75 modelling tools for energy and power system analysis.

those that combine both top-down and bottom-up approaches.[25] This family of models describes the economy from a detailed description of technologies as in the bottom-up models and from aggregated market data, with the primary objective of modelling energy-economy interactions (Rivers & Jaccard, 2005; Hourcade et al., 2006; Böhringer & Rutherford, 2009).

Given our objectives and time scale, we adopt a forward-looking approach based on the TIMES (Integrated MARKAL-EFOM System) model generator. The latter belongs to the bottom-up family of models and provides a rich base of technologies. It allows the representation of energy dynamics over a multi-period horizon. In addition, TIMES can inform the type of transition possible and its speed. We develop a RoM-TIMES model whose objective is to minimise the total discounted cost of the systems under consideration. The RoM, like many other SIDS, made a legally binding commitment to the Paris Agreement in 2015 - to reduce its CO_2 emissions by 30% by 2030. The year 2030 is considered a milestone year, marking the irreversibility of the effects of global warming if the reduction efforts made prove insufficient. Furthermore, it has set a renewable energy (RE) penetration target of 35% by 2025.

To this end, we study the technical feasibility and economic viability of implementing the renewable energy penetration targets while meeting the environmental commitments of the Republic of Mauritius (RoM) over the period 2019-2050. Documents published by the Ministry of Energy and Utilities (MEPU) are used to develop the different scenarios to be studied (MEPU, 2009, 2015; MESD, 2017; MEPU, 2019). In addition, data on resource potential and generation technologies are retrieved from Statistics Mauritius (SM) and the grid operator on both islands, the Central Electricity Board. They are used to calibrate the base year's model and develop the reference energy system.

Our main contribution revolves around the territorialisation of the prospective study. There are local disparities in the supply and demand of electricity and the density of the grid. Therefore, a more localised approach is necessary to carry out such an analysis and develop recommendations that suit the realities of each territory. Unlike existing studies based on aggregated data, we consider the specificities of each power system.

According to the hypotheses retained in the model, a transition based on the RE penetration target of 35% by 2025 and 40% by 2030 is not compatible with the Nationally Determined Contributions (NDC) in the RoM. On the contrary, a cap on emissions is more likely to achieve both energy and climate objectives by 2030. Sufficient and timely investments will condition the achievement of this dual objective to support the integration of low-carbon or even neutral technologies. In Rodrigues, the contribution of biomass to the production of electricity underlines the importance of implementing

[25] See for example Böhringer (1998), Kumbaroğlu & Madlener (2003), McFarland et al. (2004), Remme & Blesl (2006), and Bauer et al. (2008).

an appropriate framework for the sustainable development of this sector. In addition to this transition, there are socioeconomic aspects to be considered for providing reliable, safe and affordable electricity.

Introduction générale

> *"Construire l'avenir c'est construire le présent."*
>
> *(Saint-Exupéry, 1948, p.759)*

Le changement climatique : un défi pour l'humanité

La nécessité de l'action climatique

Le réchauffement de la planète devrait atteindre 1,5 °C entre 2030 et 2050 s'il se poursuit au rythme actuel (Masson-Delmotte et al., 2018). Or, le rapport spécial sur 'le réchauffement planétaire de 1,5 °C' (SR15) publié par le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) alerte sur l'urgence climatique et les risques liés à l'inaction climatique, ce dernier représentant un risque global pour l'humanité.[26] Ce rapport envoie un signal fort à la communauté internationale en soulignant que "*chaque demi-degré compte, chaque année compte et chaque choix compte*".[27]

Afin de limiter le réchauffement climatique, il est nécessaire de réduire les émissions cumulées de CO_2 et le forçage radiatif futur hors CO_2 (Figure 1). Cette réduction devra s'appuyer sur une mobilisation collective qui profitera à toutes les nations, en particulier aux communautés les plus vulnérables. Cependant, individuellement, aucun pays n'a, à court terme, un intérêt à contraindre ses émissions. En effet, le changement climatique est un bien collectif mondial non exclusif et non rival (Buchholz & Sandler, 2021). Les agents ne sont donc pas incités à internaliser les externalités négatives liées à leurs activités. Or, plusieurs études ont montré que retarder les actions serait plus coûteux que de s'attaquer au changement climatique, engendrant ainsi des préjudices économiques considérables (Stern et al., 2006; Bueno et al., 2008; Chevalier et al., 2008; Fortes et al., 2014; Sanderson & O'Neill, 2020).

La prise de conscience environnementale n'est pas nouvelle. Depuis la première

[26] En 2021, l'inaction climatique se classe au deuxième rang en termes de probabilité d'occurrence et d'impact (WEF, 2021).

[27] Petteri Taalas et Joyce Msuya, https://www.ipcc.ch/sr15/about/foreword/

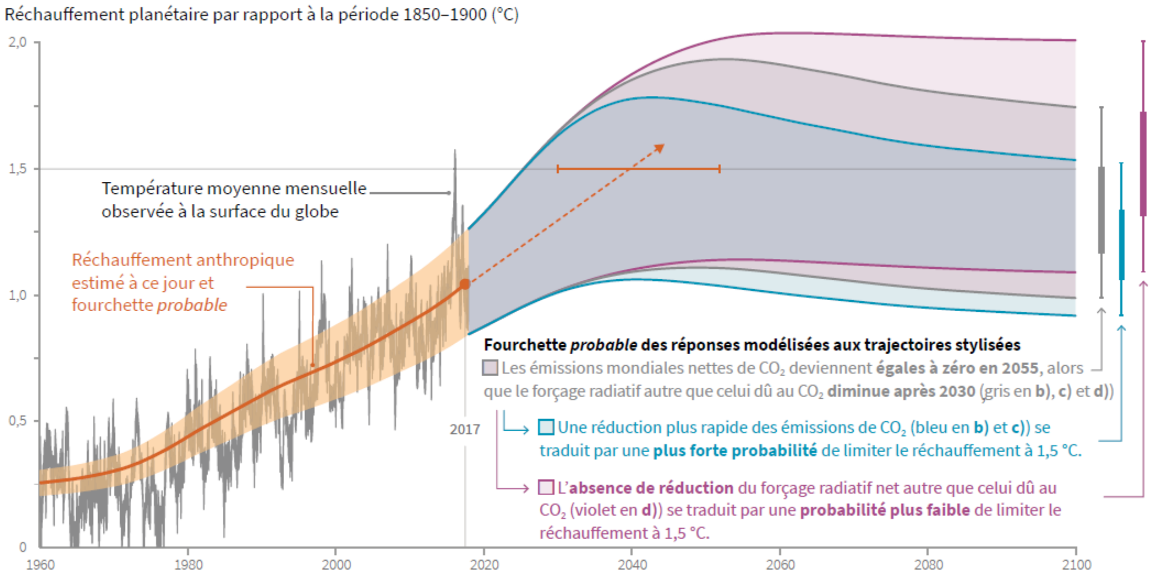

Figure 1: Variation de la température mondiale

Source : Masson-Delmotte et al. (2018)

conférence des Nations Unies sur l'environnement en 1972, le débat international sur les enjeux du changement climatique a débouché sur la mise en place du GIEC en 1988. Depuis son premier rapport d'évaluation (AR1) publié en 1990, le GIEC reconnaît et établit la contribution du changement climatique d'origine anthropique au réchauffement de la planète. En effet, les rapports du GIEC permettent d'évaluer l'évolution de la hausse des températures dans le temps ainsi que la part qui est d'origine anthropique. Par ailleurs, les différents scénarii d'évolution future en fonction des niveaux d'émissions et de concentrations de gaz à effet de serre (GES) dans l'atmosphère sont également évalués.

Ces rapports alertent également sur les dangers et les impacts de l'évolution des différents scénarii de hausse des températures sur l'ensemble de la biosphère (terre, océan, météorologie, etc.) et les réductions nécessaires pour limiter la hausse des températures "*à un niveau qui empêche toute perturbation anthropique dangereuse du système climatique*" (article 2 de la CCNUCC, p.9). En 2014, le GIEC estimait qu'une baisse des émissions de 40 à 50 % par rapport aux niveaux de 2010 est nécessaire à l'horizon 2030 pour limiter le réchauffement planétaire à 1,5 °C (Pachauri et al., 2014).[28]

Les réponses de la communauté internationale

Les rapports du GIEC servent ainsi de support scientifique aux différentes négociations internationales. La Convention-cadre des Nations unies sur les changements climatiques

[28] Un réchauffement planétaire limité à 2 °C nécessiterait une réduction de 25 % des émissions pour la même année charnière.

(CCNUCC), entrée en vigueur en 1994, reconnaît la dimension mondiale des risques liés au climat. Elle lance alors l'appel à une action collective impulsée par des négociations qui se tiendront lors des différentes Conférences des Parties (COP).

Depuis la première COP en 1995 à Berlin, ces négociations sur le climat ont connu de multiples péripéties. L'adoption du Protocole de Kyoto en 1997 (qui entra en vigueur en 2005) est synonyme d'engagement de la communauté internationale ayant pour objectif l'atténuation des émissions de GES. L'atténuation est définie comme des "*interventions humaines visant à réduire les sources de gaz à effet de serre ou à augmenter les puits de carbone*" (Pachauri et al., 2014, p.125). Elle se concentre sur les causes du changement climatique. Ces premiers engagements concernaient les pays industrialisés rassemblés comme pays de l'Annexe I[29] qui devaient représenter au moins 55 % des émissions mondiales. Durant la première période d'engagement allant de 2008 à 2012, les pays signataires de l'Annexe I devaient réduire leurs émissions d'au moins 5,2 % par rapport aux niveaux de 1990. Des mécanismes de marché ont par exemple été introduits pour atténuer les émissions de GES. Il s'agissait notamment des marchés de permis d'émissions nationaux et internationaux, des mécanismes de développement propre et de la mise en oeuvre conjointe.[30]

Le bilan de cette première phase sera mitigé.[31] Durant la seconde période d'engagement allant de 2013 à 2020, l'absence de ratification des Etats-Unis, de la Chine, du Japon ou encore de la Russie ont réellement compromis la réussite du protocole malgré des objectifs relevés (-18 %).[32] De plus, les rapports de force entre pays développés et pays en développement se sont modifiés et les engagements basés sur des stratégies d'atténuation ont vu apparaître un concurrent au niveau des négociations : les politiques d'adaptation.

L'adaptation fait référence aux "*démarches d'ajustement au climat actuel ou attendu, ainsi qu'à ses conséquences, de manière à en atténuer les effets préjudiciables et à en exploiter les effets bénéfiques*" (Pachauri et al., 2014, p.118). Ainsi, les stratégies d'adaptation s'attaquent aux effets du changement climatique (Van Gameren et al., 2014). L'insuffisante réduction des émissions mondiales et les perspectives de réchauffement qu'elles induisent a modifié la position des pays en développement qui revendiquent l'accès à des fonds pour soutenir les politiques d'adaptation. Ces tensions

[29] Les pays de l'OCDE et les économies en transition sont ceux visés à l'Annexe I.

[30] Ces dispositifs ont notamment fait l'objet de nombreuses études universitaires (Haites & Yamin, 2000; See, 2000; Timilsina & Shrestha, 2006; Diakoulaki et al., 2007; Ellis et al., 2007; Gilau et al., 2007; Schneider et al., 2008; Karakosta et al., 2009; Ciscar & Dowling, 2014).

[31] Bien que la réduction affichée par les pays signataires durant cette période soit de 24 %, ce résultat d'apparence très positif ne tient pas compte de l'absence de ratification du protocole des Etats-Unis d'une part et la chute du bloc de l'est vers 1990 d'autre part. Ainsi, les émissions n'auraient réellement baissé que de 4 % comme le montre certaines études (Den Elzen & De Moor, 2002), ce qui est en deça de l'objectif des 5,2 %.

[32] https://unfccc.int/

se sont cristallisées lors de la conférence de Copenhague (COP15). Une vision plus intégrée des responsabilités et des actions dites 'volontaires' a été proposée en 2010 lors de la COP16 à Cancún (Aykut Stefan & Dahan, 2011) avec pour objectif le rassemblement de la communauté internationale sous un nouvel accord.

L'adoption de l'Accord de Paris en 2015 lors de la COP21 et son entrée en vigueur l'année suivante marque un nouveau tournant important pour la communauté internationale, avec la ratification du traité international par l'ensemble des pays (196 au total) incluant de grands pays émetteurs comme la Chine et les États-Unis. Ces pays se sont engagés "*à atteindre un équilibre entre les émissions anthropiques par les sources et les absorptions par les puits de gaz à effet de serre*" (article 4 de l'Accord de Paris).[33] En outre, l'Accord de Paris requiert des pays signataires, y compris les pays en développement, de communiquer et de soumettre des contributions déterminées au niveau national (CDN) afin d'atténuer les émissions de GES.[34]

Les stratégies d'atténuation et d'adaptation sont des composantes essentielles des politiques climatiques pour répondre à ces objectifs de réduction (Tol, 2005; Hasson et al., 2010; van Vuuren et al., 2011; Heuson et al., 2014; Shrestha & Dhakal, 2019). Or, les enjeux relatifs à ces stratégies sont différents selon les territoires. Dans ce contexte, cette thèse s'intéresse tout particulièrement aux implications quant à l'adoption des stratégies d'atténuation pour les petites économies insulaires en développement (PEID) et comment celles-ci peuvent également répondre dans leur cas à des besoins d'adaptation.

L'adaptation comme réponse de court terme : la notion de vulnérabilité

Les stratégies d'adaptation consistent à gérer les conséquences du réchauffement climatique telles que la sécheresse, ou encore l'élévation du niveau des mers ou encore la multiplication des phénomènes climatiques extrêmes. Dit autrement, l'adaptation consiste à réduire la vulnérabilité des systèmes naturels et humain aux effets du changement climatique.

Longtemps restée un sujet secondaire, l'adaptation au changement climatique a fait l'objet d'une attention accrue au début du 21^{e} siècle par le biais de la CCNUCC (Hasson et al., 2010; de Murieta et al., 2014). En outre, l'hétérogénéité des pays quant à leur vulnérabilité face au changement climatique a largement été mise en avant par le GIEC.

[33] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[34] Bien qu'il ne s'agisse pas d'un document juridiquement contraignant, l'article 3 de l'Accord de Paris exige que les CDN fassent l'objet d'un rapport tous les cinq ans sur la base d'efforts plus ambitieux et plus rigoureux que les précédents, conformément au 'principe de progression'. Cet Accord a également mis en avant des fonds financiers pour aider les pays à s'adapter au changement climatique.

En effet, les rapports du GIEC font état d'une plus grande vulnérabilité des pays en développement et des territoires côtiers et insulaires face à l'élévation du niveau des mers et aux évènements climatiques extrêmes qui sont plus fréquents et plus intenses.

Le GIEC a largement contribué à l'utilisation et à la définition du concept de vulnérabilité. Or, cette définition s'est affinée au cours des rapports. Dans son deuxième rapport d'évaluation (AR2), la vulnérabilité a été définie plus généralement comme "*la mesure dans laquelle le changement climatique peut causer des dommages ou nuire à un système pour s'adapter aux nouvelles conditions climatiques*" (Bolin et al., 1995, p.28). Le cinquième rapport d'évaluation définit la vulnérabilité comme la "*propension ou prédisposition à subir des effets néfastes*" dans le contexte du changement climatique (Bolin et al., 1995; Watson et al., 1996, 2001).

Sur le plan académique, le concept de vulnérabilité a été adapté et utilisé pour d'autres problématiques que le changement climatique, notamment les catastrophes naturelles, les risques et de manière plus générale les problèmes économiques. Cependant, il n'existe aucune définition largement acceptée (Adger, 2006; Gallopín, 2006; Smit & Wandel, 2006; Füssel, 2007). Une définition simple donnée par Dow (1992) et Turner et al. (2003) se réfère au "*degré auquel un système est susceptible de subir des dommages en raison de l'exposition à un danger*" (Turner et al., 2003, p.8094). L'absence de définition commune implique une évaluation et une mesure de la vulnérabilité qui diffèrent considérablement selon le domaine scientifique et le contexte.

L'adaptation est aujourd'hui devenue **nécessaire** puisque quelles que soient les mesures mises en œuvre aujourd'hui, même les plus drastiques, l'inertie engendrera une hausse des températures jusqu'en 2040 environ. Cependant, les politiques d'atténuation, qui ont historiquement dominé les débats politiques et climatiques,[35] continuent de représenter des stratégies **indispensables** dans la baisse des températures puisque "*[...] le réchauffement global est dominé par les émissions passées et futures de CO_2*" (IPCC, 2021, p.16). Si l'adaptation aux effets du réchauffement climatique est nécessaire à court terme, la régulation des températures ne pourra s'effectuer qu'avec une atténuation des émissions à long terme.

L'atténuation comme réponse à long terme : le rôle des systèmes énergétiques

Le secteur de l'approvisionnement en énergie est de loin le principal émetteur d'émissions de GES. En effet, les émissions mondiales de CO_2 représentaient 33,5 milliards de tonnes en 2018 et ont été multipliées par 1,6 entre 1990 et 2018 (IEA, 2018). Or, la hausse des

[35] Une part plus importante des flux de financement du climat est dirigée vers les activités d'atténuation (CPI, 2019).

émissions mondiales est une conséquence directe de l'augmentation de l'offre et de la demande d'énergie résultant des activités humaines (Quadrelli & Peterson, 2007). Une hausse des températures au-delà de 1,5 °C se produira même si les objectifs de réduction annoncés dans les engagements nationaux sont pleinement respectés (IEA, 2021).

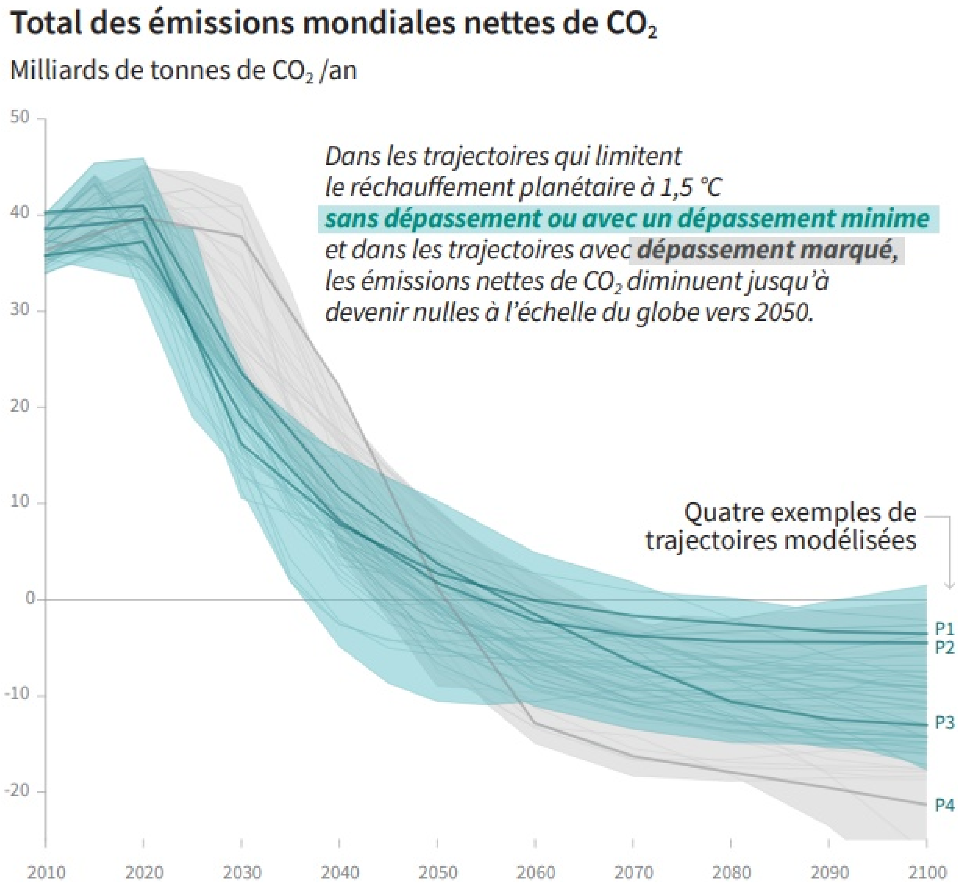

Figure 2: Trajectoires des émissions compatibles avec un réchauffement planétaire limité à 1,5 °C

Note : P1 à P4 représentent quatre exemples de trajectoires modélisées selon différentes stratégies d'atténuation en vue de réduire les émissions nettes mondiales de CO_2 d'origine anthropique.
Source : Adapté de Masson-Delmotte et al. (2018)

La Figure 2 illustre les trajectoires d'émissions compatibles avec un réchauffement planétaire limité à 1,5 °C. Un avenir '*net zéro*' nécessite l'intégration massive de technologies propres et un abandon rapide des combustibles fossiles. Par ailleurs, l'électrification jouera un rôle important dans la transition énergétique en cours, appelant à une plus grande flexibilité du système électrique grâce à des environnements favorables tels que les technologies de stockage, le couplage sectoriel et la maîtrise de la demande (IEA, 2021).

Les questions liées à l'énergie et à l'environnement s'inscrivent inévitablement dans le contexte beaucoup plus large du changement climatique (Boiteux et al., 2019; Chevalier et al., 2008). Kemmler & Spreng (2007) caractérisent l'énergie comme le bien ultime. D'une part, l'énergie est un bien stratégique qui alimente les sociétés modernes. D'autre part, les activités liées à la production et à la consommation d'énergie contribuent au changement climatique anthropique (Ansuategi, 2014) par la libération de gaz nocifs dans l'atmosphère. Le système énergétique revêt donc une importance stratégique dans l'atténuation du changement climatique (Rogelj et al., 2018).

Le système énergétique mondial doit subir de profondes transformations. Les options de réponse pour l'atténuation dans le secteur de l'énergie comprennent l'intégration des énergies renouvelables, le passage à des technologies à faible émission de carbone, l'amélioration de l'efficacité énergétique, les options d'élimination du CO_2 et l'amélioration des réseaux de transmission et de distribution. En outre, la mise en œuvre d'instruments politiques pour inciter et accompagner les efforts d'atténuation[36] soulève des questions importantes : quels sont les options technologiquement possibles et quelles sont les conséquences économiques de ces pistes ?

Cette thèse s'intéressera à ces questions en modélisant les systèmes énergétiques. Elle étudie ainsi sur le moyen et le long terme les interactions énergie-économie et énergie-environnement qui permettent d'améliorer la gestion de l'énergie. Elle tient notamment compte des dépenses d'investissement, d'exploitation et de maintenance des nouvelles options technologiques, ainsi que des prix nécessaires pour guider la transition énergétique.

Le cas des petites économies insulaires en développement

Des territoires hétérogènes et vulnérables

Les petites économies insulaires en développement (PEID) bénéficient d'un traitement spécifique par le GIEC de par leur forte vulnérabilité face au changement climatique. Les impacts prévus dans les différents scénarii envisagés pour les territoires insulaires comprennent l'élévation du niveau de la mer, les dommages causés par les événements extrêmes, la dégradation de l'environnement, le blanchiment des coraux ou encore l'augmentation de la température à la surface du globe.

L'Alliance des petits États insulaires (AOSIS),[37] créée en 1990, a représenté les intérêts des petits États insulaires et des États côtiers en développement de faible altitude

[36] Ils comprennent, par exemple, des instruments économiques (taxes, quotas négociables et subventions pour les énergies renouvelables), des approches réglementaires (normes d'efficacité/environnementales), des campagnes de sensibilisation ou encore des actions volontaires (Pachauri et al., 2014).

[37] L'AOSIS comprend actuellement 39 PEID membres, https://www.aosis.org/about/member-states/.

dans les négociations internationales sur le changement climatique, le développement durable et la conservation des océans. Depuis leur reconnaissance officielle en tant que groupe distinct de pays par les Nations unies en 1992, les PEID, regroupés au sein de l'AOSIS, ont inscrit le changement climatique à côté d'autres questions qui leur sont spécifiques sur l'agenda international. Par ailleurs, la coalition a joué un rôle essentiel dans l'élaboration des résultats de l'Accord de Paris en insistant sur la nécessité de garantir des trajectoires d'émissions mondiales avec le maintien de l'augmentation de la température bien en dessous de 1,5 °C.

Outre les impacts physiques induits par le climat, les PEID souffrent également de plusieurs vulnérabilités[38] comme l'illustre le Tableau 1. Le concept de vulnérabilité est particulièrement pertinent pour étudier le groupe des petits États insulaires en développement, en particulier pour caractériser leur fragilité (Briguglio, 1995; Guillaumont, 2009; Feindouno et al., 2020).

Table 1: Vulnérabilités climatiques et non climatiques dans les PEID

Vulnérabilités non climatiques	Physique	Socioéconomique	Socio-écologique
	Risques sismiques Risques de glissement de terrain Risques de tsunami	Urbanisation Pollution	Perte et dégradation de l'habitat Espèces envahissantes Surexploitation Pollution Empiètement humain Maladies
Vulnérabilités climatiques	Élévation du niveau de la mer Cyclones tropicaux et extra-tropicaux Augmentation des températures de l'air et de la surface de la mer Modification du régime des précipitations		

Source : Nurse et al. (2014), adapté par l'auteure.

Cependant, bien qu'ayant fait l'objet d'une attention particulière dans la littérature, il n'existe pas de définition universelle de ce qu'est une petite économie insulaire en développement. Cela est principalement dû à l'hétérogénéité des pays formant ce groupe en dépit de leurs caractéristiques communes. En effet, la liste officielle de 58 PEID[39] reconnue par les Nations unies[40] recense également des territoires présentant peu ou prou des caractéristiques incombant aux PEID *stricto sensu* (Tableau 2). Nous retenons par exemple que leur population varie entre 11,000 (Nauru) et 11,402,000 (Haïti) habitants tandis que leur superficie varie entre 21 (Nauru) et 462,840 km^2 (Papouasie-Nouvelle-Guinée).[41] À cela s'ajoute des disparités en termes de développement humain. En 2019,

[38]Ces vulnérabilités constituent des priorités absolues et concernent notamment la pauvreté, l'éducation ou encore la santé.

[39]Ces derniers sont situés dans trois régions géographiques distinctes : les Caraïbes, le Pacifique et l'Atlantique, l'océan Indien, la Méditerranée et la Mer du Sud de Chine.

[40]Le Bureau du Haut Représentant pour les pays les moins avancés, les pays en développement sans littoral et les petits États insulaires en développement des Nations unies (UN-OHRLLS), https://www.un.org/ohrlls/content/list-sids.

[41]http://data.un.org/

Singapour affichait un indice de développement humain (IDH) de 0,938 alors que la Guinée-Bissau figurait parmi les pays moins développés avec un IDH de 0,48.[42] Cependant, nous notons que la plupart de ces petits territoires affichent un déficit de la balance commerciale avec des importations nettement supérieures aux exportations.

La littérature économique a notamment contribué à la reconnaissance des handicaps structurels dont sont frappés les PEID (Briguglio, 1995; Guillaumont, 2009).[43] La petitesse, l'insularité, la dépendance accrue aux importations stratégiques ou encore l'ouverture au commerce international sont des caractéristiques inhérentes aux PIED (Briguglio et al., 2009; Briguglio, 2014; Bates et al., 2014; Angeon & Bates, 2015). Guillaumont (2009) introduit le concept de vulnérabilité économique structurelle qui comprend uniquement les facteurs indépendants des politiques d'un pays (Guillaumont, 2009; Guillaumont et al., 2020). Il est communément admis que ces territoires, bien qu'hétérogènes, sont plus ou moins vulnérables, d'où l'importance d'un traitement spécial et différencié.

Paradoxalement, la contribution de ces territoires aux émissions globales de gaz à effet de serre est négligeable. En 2018, les PEID ont contribué à 0,7 % des émissions mondiales de CO_2.[44] Ceci s'explique notamment par leur relative faible niveau de développement et leur petite taille. Cependant, ces territoires seront amenés à croître leur production et connaîtront une forte croissance démographique. Pour montrer la voie, les PEID ont notamment soumis leur CDN qui tiennent compte de leur capacité d'adaptation respective dans la lutte contre le changement climatique. Dans l'ensemble, les secteurs de l'énergie et de l'électricité ont été les premiers visés par les mesures d'atténuation. Le défi ultime pour ces territoires sera de trouver un équilibre entre les divers objectifs politiques tout en s'attaquant aux impacts négatifs du changement climatique. D'où la nécessité de développer des outils de diagnostic qui permettent d'élaborer des politiques publiques spécifiquement conçues pour les PEID. Dans ce cas, quel est l'intérêt pour ces petits territoires de s'engager dans la transition énergétique ?

[42] http://hdr.undp.org/

[43] L'utilisation du concept de vulnérabilité favorise l'égalité d'accès aux financements qui englobent le seul critère du niveau de revenu et donne une plus grande légitimité et crédibilité à l'allocation de l'aide au développement, notamment en offrant un traitement spécial et différencié aux PEID et aux pays les moins avancés (PMA) affectés par diverses vulnérabilités. Ainsi, "*la vulnérabilité devrait influencer l'accès et les conditions de financement*" (WB, 2017, p.2).

[44] Calculé par l'auteure sur 48 PEID en utilisant la base de données EDGAR sur les émissions de la Commission Européenne (Crippa et al., 2019).

Table 2: Statistiques descriptives des indicateurs clés pour les PEID

PEID	CODE	POP	AREA	GDPPC	AGR	IND	SERV	EXP	IMP	EVI	HDI
Antigua-et-Barbuda	ATG	98	442	16727	2	23,8	74,2	37	568	32,28	0,778
Bahamas	BHS	393	13940	32218,1	1	14,8	84,2	494	4087	28,15	0,814
Bahrein	BHR	1702	771	24133,5	0,3	43,7	56	14355	18680	28,35	0,852
Barbade	BRB	287	431	17745,9	1,5	14,9	83,6	462	1618	16,47	0,814
Belize	BLZ	398	22966	4884,7	11	13,7	75,3	245	986	40,39	0,716
Cap-Vert	CPV	556	4033	3635,4	6,2	22,6	71,3	76	941	38,16	0,665
Comores	COM*	870	2235	1400,5	31,5	12,4	56,1	49	201	39,71	0,554
Cuba	CUB	11327	109884	8821,8	3,8	25,2	71	828	7498	27,52	0,783
Dominique	DMA	75	750	7691,3	13,8	19,7	60,7	18	304	34,65	0,756
République Dominicaine	DOM	10848	48671	7650,1	6	30,3	56,2	11117	20599	21,53	0,742
Fidji	FJI	896	18272	6267	35,7	13,3	51	1137	2650	38,77	0,743
Grenada	GRD	112	345	10485,9	6,3	16,2	88,9	32	470	34,1	0,779
Guinée-Bissau	GNB*	1968	36125	778,4	49,9	13,3	38,1	3731	188	40,45	0,48
Guyana	GUY	787	214969	4900,8	14,7	38,4	64,4	1405	3467	45,56	0,682
Haiti	HTI*	11402	27750	834,9	18,6	31,7	32,6	746	3118	33,38	0,51
Jamaique	JAM	2961	10990	5354,3	7,7	23,5	65,7	1586	6339	28,85	0,734
Kiribati	KIR*	119	726	1627,4	24	15,6	70,5	10	554	66,08	0,63
Les Maldives	MDV	540	300	10330,6	6,5	15	52,8	163	2883	44,06	0,74
Marshall (îles)	MHL	53	181	3666,9	15,7	12,1	68,7	34	71	59,94	0,704
Maurice	MUS	1272	1969	11222	3,2	20,1	77,3	1876	5601	22,26	0,804
Micronésie	FSM	115	702	3296,4	28	6,5	76,5	1	8	51,02	0,62
Nauru	NRU	11	21	11875,9	2,4	37,5	42,3	NA	NA	37,37	NA
Palau	PLW	22	459	15859,4	3,5	8,8	81,6	8	169	47,88	0,826
Papouasie-Nouvelle-Guinée	PNG	8947	462840	2681,4	19,5	30,5	53,5	11798	3130	30,93	0,555
Saint-Kitts-et-Nevis	KNA	57	261	19275,4	1,2	27,7	87,3	63	338	35,32	0,779
Sainte-Lucie	LCA	184	539	10566	1,8	11,6	88,7	55	598	32,44	0,759
Saint-Vincent-et-Grenadines	VCT	111	389	7361,3	8,6	17,8	78	37	335	28,22	0,738
Samoa	WSM	198	2842	4249,6	9,4	14,6	51,2	32	390	28,07	0,715
Sao-Tomé-et-Principe	STP*	219	964	1948,1	11,3	15,4	46,1	14	165	29,91	0,625
Seychelles	SYC	98	457	16377,9	2,4	13,4	53,2	824	1438	40,18	0,796
Singapour	SGP	5850	719	67720,9	0	26,1	80,1	390332	358975	25,52	0,938
Iles Salomon	SLB*	687	28896	1946,9	25,4	15,2	51,5	611	348	45,82	0,567
Suriname	SUR	587	163820	6003,7	12,3	34,5	51,8	1461	1711	44,16	0,738
Timor-Leste	TLS*	1318	14919	2035,5	10	49,6	47,9	154	536	40,14	0,606
Tonga	TON	106	747	4885,8	22	21	57,8	15	311	43	0,725
Trinité-et-Tobago	TTO	1400	5127	17130,3	1,1	42,8	54	12336	1951	27,55	0,797
Tuvalu	TUV*	12	26	4000,6	21,9	12,5	69,9	0	12	56,98	NA
Vanuatu	VUT*	307	12189	3037,2	22,8	11,2	63	51	289	39,14	0,609

Note : Les pays suivis d'un astérisque (*) sont également des pays moins avancés (PMA). Les données

proviennent de la base de données des Nations Unies pour l'année 2020 sauf indication contraire. *POP* désigne la population, *AREA* désigne la surface en km^2, *GDPPC* désigne le PIB par habitant mesuré en dollars courants. *AGR*, *IND* et *SERV* représentent respectivement la part (%) des secteurs agricole, industriel et tertiaire (services) à la valeur ajoutée brute. *EXP* et *IMP* désignent respectivement les exportations et importations mesurées en millions de dollars courants. *EVI* représente l'indice de vulnérabilité économique et environnementale calculé par le Comité des Nations unies pour le développement pour 2020. *HDI* représente l'indice de développement humain calculé par les Nations Unies pour l'année 2019. Source : compilé par l'auteure.

La transition énergétique, une stratégie “gagnant-gagnant” pour ces territoires ?

La réponse au changement climatique implique un ensemble diversifié d’actions d’adaptation et d’atténuation au niveau national. Cela soulève des questions relatives à la capacité des États insulaires en développement à faire face aux effets du changement climatique. En effet, les coûts d’adaptation sont plus élevés dans les petites îles en raison de l’indivisibilité des services publics et des services entre autres (Nurse et al., 2014), soulignant le besoin impérieux de financement climatique (Robinson & Dornan, 2017).

Ceci nous amène à la question fondamentale suivante autour de laquelle cette thèse est structurée : **comment les petites économies insulaires en développement en répondant aux impératifs d’atténuation du changement climatique peuvent réduire leur vulnérabilité énergétique ?** La pertinence de cette question pour les décideurs publics trouve sa justification dans un contexte de changement climatique, notamment les interactions énergie-économie-environnement. Cette thèse contribue à la discussion sur la situation des PEID et propose des pistes pour l’élaboration de politiques publiques. Par conséquent, cette thèse étudie le lien économie-énergie-environnement dans le contexte des PEID à travers le prisme de la vulnérabilité énergétique et de la transition énergétique ainsi que leurs interactions avec le changement climatique. Nous soutenons que la transition énergétique est une stratégie gagnant-gagnant pour ces petits territoires. D’un point de vue environnemental, elle permettrait notamment de réduire les émissions de GES, un objectif compatible avec les engagements de l’Accord de Paris. D’un point de vue économique, elle améliorerait les performances des systèmes énergétiques insulaires, fortement dépendants d’importations stratégiques telles que les combustibles fossiles, qui se traduisent souvent par des factures d’importation d’énergie élevées.

Le changement climatique est indéniablement l’un des principaux déclencheurs de la transition énergétique. En outre, les mesures d’atténuation pour réduire les effets du changement climatique sont élaborées pour répondre aux exigences de l’Accord de Paris. La restructuration et la transformation des systèmes énergétiques en vue d’atteindre des objectifs ambitieux en matière d’énergie et de climat reposent sur une meilleure efficacité de l’offre. Elle nécessite également de revoir les modes de consommation afin de réduire la pression exercée sur le système productif. Bien que la transition énergétique ne soit pas une solution unique, il est nécessaire d’étudier les futures trajectoires de mix de production de l’énergie pour identifier les systèmes énergétiques rentables potentiels. La baisse rapide des coûts des technologies renouvelables essentielles offre une formidable opportunité de déclencher la transformation profonde de leurs systèmes énergétiques respectifs tout en poursuivant des objectifs multiples en matière d’énergie. Par ailleurs, à quel type de transition peut-on s’attendre dans les PEID compte tenu de leurs spécificités

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Les petites économies insulaires en développement constituent l'objet d'étude de la thèse. Si la littérature sur les territoires insulaires s'est beaucoup intéressée au changement climatique (Nurse & Moore, 2005; Briguglio et al., 2007; Kelman & West, 2009; Campbell & Barnett, 2010; Betzold, 2015; Robinson, 2017; Kelman, 2018; Mycoo, 2018; Robinson, 2018), risques naturels (Pelling & Uitto, 2001; Méheux et al., 2007; Julca & Paddison, 2010; Kelman et al., 2011; Baarsch & Kelman, 2016; Sjöstedt & Povitkina, 2017) ou encore la vulnérabilité économique (Briguglio, 1995; Encontre, 1999; Adrianto & Matsuda, 2004; Guillaumont, 2010; McGillivray et al., 2010), celle qui s'intéresse aux enjeux énergétiques, notamment sous le prisme de la vulnérabilité et la transition énergétique, est relativement pauvre. Par ailleurs, les territoires de l'Afrique, l'océan Indien, Méditerranée et mer de Chine méridionale (AIMS) sont encore moins étudiés que leurs homologues situés dans le Pacifique et dans les Caraïbes. L'argument le plus fréquemment utilisé est celui de l'indisponibilité des données, limitant ainsi la transposition de certaines études à ces territoires. Cette thèse a donc un intérêt global dans la mesure où les petites économies insulaires en développement sont parmi les premières victimes du changement climatique. En ce sens, l'apport majeur de cette thèse est l'enrichissement de la connaissance sur ces territoires.

Vue d'ensemble des travaux de recherche

Cette thèse est structurée autour de trois chapitres basés sur quatre articles originaux. Ces chapitres aborderont les enjeux pour les systèmes énergétiques insulaires à répondre au changement climatique dans le but d'assurer un futur énergétique durable. Le chapitre 1 évalue la vulnérabilité énergétique d'un groupe de PEID.[45] L'objectif est de développer une mesure fiable et robuste de ce phénomène afin de quantifier le degré d'exposition des systèmes énergétiques insulaires à différents chocs. La discussion porte notamment sur les pistes d'atténuation de cette vulnérabilité.

Les chapitres 2[46] et 3[47] s'intéressent aux enjeux de la transition énergétique dans la République de Maurice (RdM). Cette dernière constitue un cas d'étude intéressant compte tenu de la relative compétitivité de son économie diversifiée et tournée vers l'extérieur.[48] Par ailleurs, la transition énergétique de la RdM pourrait servir de référentiel aux autres PEID membres de l'AOSIS ou encore ceux du bassin ouest de l'océan Indien

[45] Chapitre 1 a été coécrit avec Sabine Garabedian et Stéphane Blancard. Voir Genave et al. (2020) publié dans *Ecological Economics* le 18 janvier 2020. La sous-section sur l'analyse de sensibilité est basée sur un document de travail rédigé par l'auteur, intitulé "*Impacts of normalizing benefit-of-the-doubt composite indicators*".

[46] Le chapitre 2 a été soumis à la revue *Energy Studies Review* le 26 février 2021.

[47] Le chapitre 3 a été coécrit avec Sandrine Selosse et soumis au journal *Energy Policy* le 9 juillet 2021.

[48] https://www.edbmauritius.org

ayant des caractéristiques similaires en termes de performance énergétique et de niveau de développement. De plus, l'étroite collaboration avec l'opérateur de réseau nous a permis d'avoir un accès privilégié à certaines données qui sont difficilement accessibles pour d'autres territoires insulaires. Cette thèse a notamment bénéficié d'une bourse Campus France Maurice afin d'y étudier les problématiques relatives au développement durable dans la RdM.

Nous abordons dans le chapitre 2 la problématique de la consommation d'électricité qui représente une variable clé dans la planification à long terme de tout système électrique. En outre, la dynamique temporelle de la demande et ses principaux déterminants sont étudiés et discutés. Le chapitre 3, quant à lui, s'attèle à étudier l'aspect "offre" de la transition énergétique. En outre, nous explorons les trajectoires futures de deux systèmes électriques insulaires dans la RdM – Maurice et Rodrigues. Plus précisément, nous abordons les transformations auxquelles ces derniers pourraient être confrontés compte tenu des contraintes économiques, environnementales, techniques et politiques.

La vulnérabilité énergétique dans les PEID

Compte tenu de l'importance des systèmes énergétiques dans la lutte contre le changement climatique, il nous semblait nécessaire dans un premier temps de diagnostiquer les forces et faiblesses de ces derniers. La plupart des PEID dépendent fortement des combustibles fossiles importés pour leurs besoins énergétiques primaires. Par conséquent, ces derniers sont exposés à la volatilité des cours du pétrole et aux risques de rupture dans la chaîne d'approvisionnement. Le chapitre 1 cherche à répondre aux questions suivantes : **Que signifie la vulnérabilité énergétique pour les systèmes énergétiques insulaires ? Quels sont les facteurs qui y contribuent ? Comment mesurer ce phénomène ?**

Pour répondre à ces questions, nous proposons un cadre conceptuel pour étudier et mesurer la vulnérabilité énergétique structurelle. Le caractère structurel est emprunté de la littérature sur la vulnérabilité économique structurelle (Guillaumont, 2006, 2009, 2010). Cette littérature met en exergue les concepts de 'chocs' et d''exposition' avec pour objectif l'identification des déterminants intrinsèques de l'exposition et ses canaux de transmission (Goavec, 2016). Dans cette thèse, nous appliquons le concept de vulnérabilité structurelle au système énergétique. En d'autres termes, cette vulnérabilité est indépendante des politiques publiques qui permettent de la réduire. Nous définissons la vulnérabilité énergétique comme *le degré de sensibilité des systèmes énergétiques aux chocs externes et dysfonctionnements internes liés à la production, au transport et à la distribution de l'énergie*. Se pose alors la question de la mesure de ce phénomène.

Les indicateurs fréquemment utilisés pour effectuer cette mesure sont regroupés dans des tableaux de bord ou agrégés en indicateurs composites (IC). Les tableaux de bord fournissent une vue d'ensemble tandis que les IC servent à synthétiser l'information relative à un phénomène donné (Nardo et al., 2008). Ainsi, plusieurs indicateurs sont agrégés mathématiquement pour générer une valeur unique. Ces derniers sont fortement critiqués compte tenu de la subjectivité inhérente au choix du système de pondération des différentes dimensions caractérisant le phénomène. L'absence d'un consensus au sein de la communauté scientifique rend cette étape de construction de l'indice particulièrement délicate, risquant de compromettre l'efficacité de ce dernier à communiquer les informations pertinentes et nécessaires à une prise de décision rapide. Néanmoins, les IC sont plus que jamais nécessaires, notamment pour rendre compte des spécificités des PEID.

Pour palier certaines critiques évoquées, nous appliquons une approche orientée par les données pour la construction de notre indice. Un ensemble de 21 indicateurs énergétiques pour le développement durable ont été sélectionnés parmi ceux proposés par l'Agence internationale de l'énergie atomique (IAEA). Nous avons ensuite effectué une analyse en composantes principales afin de réduire à huit le nombre de variables pour caractériser la vulnérabilité énergétique. Plusieurs sources sont utilisées pour collecter les données : la division statistique des Nations unies, la Banque mondiale et la base de données sur les émissions du Conseil commun de recherche de l'Europe.

La dernière étape consiste à agréger les sous-indicateurs en un indice synthétique de vulnérabilité énergétique. Nous optons pour l'approche 'bénéfice du doute' (BoD) qui découle de la méthode d'analyse par enveloppement des données (DEA) appliquée aux indices synthétiques. Cette approche est particulièrement intéressante pour la construction des indices en raison de son invariance aux unités de mesure (Melyn & Moesen, 1991; Zhou et al., 2010; Savić & Martić, 2017). Elle permet de calculer les scores d'efficacité sur la base de pondérations endogènes et suffisamment flexibles pour s'adapter à diverses unités de mesure. Afin de faire ressortir la structure hiérarchique du concept de vulnérabilité énergétique, nous adoptons un modèle multicouches appelé *Multi-layer Benefit of the Doubt* (MLBoD). Ce dernier est calculé pour 36 PEID membres des Nations unies pour l'année 2015.

Peu d'études se sont intéressées aux territoires insulaires pour étudier la vulnérabilité énergétique (Ioannidis et al., 2019; Gatto & Busato, 2020). À ce titre, nous contribuons à la littérature sur les PEID en nous intéressant au plus grand nombre de territoires insulaires pour lesquels des données étaient disponibles. Par ailleurs, la proposition d'une nouvelle définition de la vulnérabilité énergétique nous permet de mieux appréhender le phénomène. L'originalité de cette définition tient à la distinction entre les deux composantes 'chocs' et 'exposition' caractérisant la vulnérabilité énergétique. Ces dernières sont ensuite caractérisées par les dimensions économique, environnementale et sociale.

D'un point de vue méthodologique, l'apport de cette étude réside dans la construction d'un indice synthétique capable de refléter ce phénomène. Il traite notamment de deux types d'indicateurs (désirables et indésirables) sans pour autant procéder à une transformation préalable des données. Au-delà de l'identification des facteurs contribuant le plus à la vulnérabilité, le classement obtenu permet aux pays les plus vulnérables de demander une aide internationale pour rendre leurs systèmes énergétiques moins vulnérables.

Les résultats indiquent que la plupart des PEID nécessitent des efforts importants de réduction des émissions de GES (dimension environnementale). Par ailleurs, les indicateurs qui constituent la dimension économique doivent également faire l'objet d'une attention particulière. En effet, la plupart des mix énergétiques insulaires sont relativement peu diversifiés. Par conséquent, une transformation profonde des systèmes énergétiques insulaires paraît nécessaire pour réduire leur vulnérabilité.

Dynamique de la consommation d'électricité : les principaux déterminants

La demande d'électricité est le moteur du système électrique. Elle influence les décisions optimales relatives au dimensionnement et l'emplacement des centrales électriques ainsi qu'au choix des technologies de production qui fournissent l'électricité. L'adéquation entre l'offre et la demande d'électricité doit être constamment assurée. Il est crucial de comprendre la dynamique de cette consommation à l'heure où la gestion du réseau électrique devient plus complexe dans le cadre de la transition énergétique. En effet, l'évolution future de la demande conditionnera les investissements futurs, d'où l'importance de comprendre les facteurs pouvant influencer la demande d'électricité. Le chapitre 2 cherche à répondre aux questions suivantes : **Quels sont les principaux déterminants de la consommation d'électricité à Maurice ? Quelle est la nature de leur relation ?**

Pour répondre à ces questions, nous prenons la République de Maurice (RdM) comme cas d'étude pour analyser les principaux moteurs de la consommation d'électricité. La littérature sur la dynamique de la demande d'électricité s'intéresse généralement aux facteurs clés tels que la croissance économique et la productivité, l'innovation technologique ou encore les prix de l'énergie. Les études empiriques sur les économies avancées et émergentes sont substantielles dans la littérature (Kraft & Kraft, 1978; De Vita et al., 2006; Halicioglu, 2007; Adom et al., 2012; Adom, 2017; Al-Bajjali & Shamayleh, 2018). Or, il n'existe pas de consensus lorsqu'il s'agit de la nature et l'ampleur de la relation entre ces variables. Cela peut notamment s'expliquer par l'utilisation de différents modèles et techniques ou encore la période choisie pour étudier cette dynamique. Le choix du ou des pays peut également avoir des conséquences sur les résultats compte tenu des conditions économiques et stades de développement différents.

Plusieurs études font appel à l'économétrie et à des techniques de régression plus ou moins avancées tels que les modèles vectoriels autorégressifs (VAR) et les modèles vectoriels à correction d'erreurs (VECM). Le modèle autorégressif à retards échelonnés (ARDL), appartenant à la famille des modèles dynamiques développés par Pesaran et al. (1995) et Pesaran et al. (2001), peut également être utilisé. Le modèle ARDL est particulièrement adapté aux échantillons de petite taille avec peu d'observations et un mélange de variables stationnaires et non stationnaires. Par ailleurs, il permet de capturer les effets temporels à court et long terme des variables explicatives sur la variable dépendante (Acaravci & Ozturk, 2010; Zachariadis, 2010). Pour ces raisons, nous avons choisi l'approche ARDL pour mettre en lumière la relation entre nos variables.

Nous étudions la dynamique temporelle entre la consommation d'électricité, le revenu par habitant, le prix moyen de l'électricité et les exportations par habitant à Maurice sur la période 1978-2019. Les données utilisées proviennent de *Statistics Mauritius* et de la base de données des Indicateurs de Développement Mondial de la Banque Mondiale. Notre contribution est principalement empirique. Cette étude apporte un éclairage nouveau sur le cas spécifique de l'île Maurice et tente de combler un vide dans la littérature sur la consommation d'électricité dans les PEID.

Nous démontrons l'existence d'un équilibre de long terme entre la consommation d'électricité, le PIB réel par habitant, le prix de l'électricité et les exportations par habitant comme principaux déterminants. La consommation d'électricité est inélastique au prix et au revenu à court et à long terme. De plus, le test de causalité de Toda-Yamamoto confirme l'hypothèse de neutralité entre la consommation d'électricité et le PIB par habitant et les exportations par tête. Par conséquent, la mise en œuvre de mesures d'économie d'énergie ciblant le secteur électrique n'entrave pas la croissance économique et ne nuit pas aux gains issus des exportations. Ce résultat est d'autant plus éclairant pour les politiques publiques. Notre étude appelle à un réexamen des perspectives précédentes sur les politiques énergétiques à mettre en œuvre à Maurice. Dans le cadre d'un processus de transition énergétique, le gouvernement mauricien peut miser sur des mesures d'efficacité énergétique sans conséquences graves pour l'économie mauricienne. Les décideurs publics doivent inciter les consommateurs à modifier leurs habitudes de consommation et tendre vers la sobriété énergétique.

Intégration des énergies renouvelables et atténuation des émissions de gaz à effet de serre

La transition vers un futur bas carbone nécessite de repenser les systèmes technologiques et institutionnels tout en corrigeant les inégalités et les problèmes environnementaux. Le chapitre 3 s'intéresse à la transition des systèmes électriques de deux îles dans la République de Maurice. Il cherche à répondre aux questions suivantes : **Quel objectif politique est le plus à même de façonner un avenir énergétique sûr et durable pour les deux systèmes électriques insulaires de la République de Maurice ? Quelles technologies énergétiques critiques sont les plus susceptibles d'aider la RdM à réaliser la transition vers une énergie propre ? Quels choix d'investissement façonneront le futur énergétique de l'île Maurice et de l'île Rodrigues ?**

Plusieurs outils analytiques existent pour modéliser les systèmes énergétiques.[49] Le choix d'un modèle en particulier dépend de plusieurs paramètres tels que la problématique en question, la résolution spatio-temporelle souhaitée ou encore des données à renseigner dans le modèle (Ringkjøb et al., 2018). Ces outils sont généralement classés en trois grandes familles : les modèles descendants (« top-down »), les modèles ascendants (« bottom-up ») et les modèles hybrides (Grubb et al., 1993; Zagamé, 2008; Herbst et al., 2012; Fortes et al., 2013; Al Irsyad et al., 2017; Boiteux et al., 2019).

Les modèles descendants sont basés sur des principes macroéconomiques et utilisent la théorie économique sous-jacente pour modéliser les interdépendances et les interactions entre les marchés en fonction des prix (Böhringer, 1998). Ces modèles sont notamment utilisés pour évaluer les impacts macroéconomiques des taxes sur l'énergie ou encore des changements dans les systèmes énergétiques (Jacobsen, 1998). Les modèles ascendants quant à eux sont appréciées pour la richesse technologique qu'il est possible de représenter. Ces derniers sont utilisés pour explorer les trajectoires futures de l'offre et la demande d'énergie compte tenu d'un ensemble de contraintes économiques, environnementales, techniques et politiques (Brouwer et al., 2018). Ce qui les rend pertinents pour la planification de l'énergie et l'analyse de la restructuration du secteur énergétique à long terme (Jacobsen, 1998). Enfin, les modèles hybrides, également appelés modèles intégrés, sont ceux qui combinent à la fois les approches descendantes et ascendantes.[50] Cette famille de modèles décrit l'économie à partir d'une description détaillée des technologies comme dans les modèles ascendants et de données de marché agrégées, avec pour objectif premier de modéliser les interactions énergie-économie (Rivers & Jaccard, 2005; Hourcade et al., 2006; Böhringer & Rutherford, 2009).

[49] Ringkjøb et al. (2018) passe en revue un total de 75 outils de modélisation pour l'analyse des systèmes énergétiques et électriques.

[50] Voir par exemple Böhringer (1998), Kumbaroğlu & Madlener (2003), McFarland et al. (2004), Remme & Blesl (2006), et Bauer et al. (2008).

Compte tenu de nos objectifs et de notre échelle de temps, nous adoptons une approche prospective basée sur le générateur de modèles TIMES (The Integrated MARKAL-EFOM System). Ce dernier appartient à la famille de modèles « bottom-up » et fournit une base riche de technologies. Il permet de représenter la dynamique énergétique sur un horizon de plusieurs périodes. De plus, TIMES peut informer sur le type de transition possible et la vitesse à laquelle elle peut être réalisée. Nous développons un modèle RoM-TIMES dont l'objectif est de minimiser le coût total actualisé des systèmes considérés. La RdM, comme de nombreux autres PEID, a pris un engagement juridiquement contraignant envers l'Accord de Paris en 2015 - celui de réduire ses émissions de CO_2 de 30% d'ici à 2030. L'année 2030 est considérée comme une année charnière, marquant l'irréversibilité des effets du réchauffement climatique si les efforts de réduction réalisés s'avèrent insuffisants. Par ailleurs, elle a fixé un objectif de pénétration des énergies renouvelables (ER) de 35% d'ici à 2025.

À cette fin, nous étudions la faisabilité technique et la viabilité économique de la mise en œuvre des objectifs de pénétration des énergies renouvelables tout en respectant les engagements environnementaux de la République de Maurice (RdM) sur la période 2019-2050. Les documents publiés par le Ministère de l'Énergie et des services publics (MEPU) sont utilisés pour développer les différents scénarios à étudier (MEPU, 2009, 2015; MESD, 2017; MEPU, 2019). Les données sur le potentiel des ressources et les technologies de production sont récupérées auprès de Statistics Mauritius (SM) et de l'opérateur du réseau sur les deux îles, le Central Electricity Board. Elles sont utilisées pour calibrer le modèle pour l'année de référence et développer le système énergétique de référence.

Notre principale contribution s'articule autour de la territorialisation de l'étude prospective. Il existe des disparités locales au niveau l'offre et de la demande d'électricité ainsi que la densité du réseau. Une approche plus localisée est donc nécessaire pour mener une telle analyse et élaborer des recommandations adaptées aux réalités de chaque territoire. Contrairement aux études existantes réalisées sur des données agrégées, nous considérons les spécificités de chaque système électrique.

Selon les hypothèses retenues dans le modèle, une transition basée sur l'objectif de pénétration des EnR de 35% à l'horizon 2025 et de 40 % d'ici à 2030 n'est pas compatible avec la contribution déterminée au niveau national dans la RdM. Au contraire, un plafonnement des émissions est plus susceptible d'atteindre simultanément les objectifs énergétiques et climatiques à l'horizon 2030. L'atteinte de ce double objectif sera conditionnée par des investissements suffisants et opportuns pour soutenir l'intégration de technologies bas carbone voir neutres. À Rodrigues, la contribution de la biomasse à la production d'électricité souligne l'importance de la mise en œuvre d'un cadre adapté pour le développement soutenable de cette filière. A cette transition s'ajoute des considérations socioéconomiques pour la fourniture d'une électricité fiable, sûre et abordable.

Chapter 1

Energy vulnerability in small island developing states

1.1 Introduction

All countries are facing the challenge of ensuring an uninterrupted supply of energy to secure energy services for their populations (Sovacool, 2013). Moreover, energy plays a vital role in economic growth and development,[1] as it is a significant input for economic and social activities (Toman & Jemelkova, 2003). Conversely, the combustion of fossil fuels is mainly responsible for the deterioration of the atmosphere because of the accumulation of carbon dioxide (CO_2) and other harmful gases (Kemmler & Spreng, 2007). Therefore, governments worldwide are prioritising this strategic good (Patlitzianas et al., 2008; Böhringer & Bortolamedi, 2015); this calls for sound management and planning.

Energy challenges are even more significant in small island developing states (SIDS), which are already dealing with several structural handicaps, including small size, remoteness, and a narrow production base. These handicaps hinder their economic growth and prosperity (Briguglio, 1995; Adrianto & Matsuda, 2004; Garabedian & Hoarau, 2011; Blancard & Hoarau, 2013). Most SIDS are not endowed with fossil energy resources. Their reliance on imported fossil fuels is one of their most significant challenges. This situation exacerbates their exposure to external disturbances such as energy price volatility and disruption risks in their energy supply chains, thereby jeopardising their sustainable energy future. Understanding the consequences of such disruptive events is an essential part of the energy planning and management required to design adequate strategies and tailored solutions for critical energy challenges.

Energy vulnerability concerns are not new.[2] This is confirmed by the substantial

[1] Defining energy access: 2020 methodology, IEA, Paris, https://www.iea.org/articles/defining-energy-access-2020-methodology

[2] In this chapter, we view energy vulnerability from a systemic perspective. We do not consider fuel poverty or household energy vulnerability. For interested readers, see Bouzarovski et al. (2014), Legendre

literature dedicated to the study of this phenomenon, along with other concepts such as 'energy security' (ES). ES studies had expanded from their classical beginnings following the oil crises in the 1970s, when the primary concern was the reliable supply of cheap oil under the threat of embargoes and price manipulation by oil producing countries. ES-related issues now encompass energy sector challenges and include increasingly diverse issues such as equitable access to modern energy and climate change mitigation (Goldthau, 2012).

There are many definitions of ES in the literature, given its multidimensional and multidisciplinary nature. Any security concept must answer three questions: security for whom?, security for which values?, and security from what threats? (Cherp & Jewell, 2014). The International Energy Agency (IEA) defines ES as "*the uninterrupted availability of energy sources at an affordable price*".[3] Blum & Legey (2012) define ES as "*the ability of an economy to provide sufficient, affordable and environmentally sustainable energy services in a way that maintains a maximum welfare state, even when problems would force it to do otherwise*" (Blum & Legey, 2012, p.1982). Recurring energy security dimensions include accessibility (i.e., access to energy and to clean fuels and technologies), affordability (i.e., the supply of energy services at affordable prices), acceptability and availability (i.e., ensuring that energy is physically available in adequate amounts; APERC, 2007). Chester (2010) uses availability, affordability, sustainability and appropriateness. Brown et al. (2014) studied 22 OECD countries and identified ten energy security indicators derived from four main dimensions, namely availability, affordability, energy and economic efficiency, and environmental management. Cherp & Jewell (2011) offer three perspectives on energy security based on the evolution of the concept: sovereignty in terms of military and geopolitical strategies, robustness in the face of the vulnerability of complex energy systems, and resilience[4] following the liberalisation of energy systems. Energy security also refers to the "*low vulnerability of vital energy systems*" (Cherp & Jewell, 2014, p.418; Guivarch & Monjon, 2017, p.530).

We adopt the definition of Guivarch & Monjon (2017) and Cherp & Jewell (2014) to distinguish energy security from energy vulnerability. Cherp & Jewell (2014) argue that this definition is more suitable to investigate the vulnerabilities of (vital) energy systems. Vulnerability comprises key elements of risks and exposure, which enables the identification, measurement and management of threats faced by energy systems. Moreover, we emphasise the concept of vulnerability which is particularly relevant for small island developing economies. The concept of energy vulnerability thus reflects the sensitivity of island energy systems to exogenous shocks. Consequently, it enables the diagnosis of

& Ricci (2015), Bouzarovski (2018), Desvallées et al. (2020), and Charlier et al. (2021).

[3] https://www.iea.org/topics/energy-security

[4] For interested readers, see O'Brien & Hope (2010) and Molyneaux et al. (2016) for a discussion on resilience in energy systems.

the energy situation in these territories and identification of those dimensions hindering the proper functioning of energy systems.

Several methods can be used to assess energy vulnerability and security.[5] However, most studies focus on energy (in)security (Jansen et al., 2004; Scheepers et al., 2007; Sovacool & Mukherjee, 2011).[6] Among the commonly used approaches, composite indices have become increasingly popular due to their simplicity, transparency, and (above all) their ability to capture the complexity and multidimensionality of phenomena such as energy security.

Studies on macroeconomic energy vulnerability is relatively scarce. We have identified several conceptual and methodological shortcomings in the existing literature. On a conceptual level, no suitable framework for capturing the energy vulnerability of energy systems has been proposed. Studies consider only specific aspects of energy vulnerability. For example, Gupta (2008) assessed the oil vulnerability of several oil-importing countries. On the methodological level, several studies have transformed indicators using popular normalisation techniques before their aggregation process (Gupta, 2008; Gnansounou, 2008). These studies have not considered the nested structure of composite indices with multiple dimensions. Finally, in terms of global coverage, most studies have focused on industrialised nations or emerging economies (Gnansounou, 2008; d'Artigues & Vignolo, 2012; Sovacool, 2013), leaving out developing countries, particularly island territories. However, two studies focusing on islands are worth mentioning: Ioannidis et al. (2019) and Gatto & Busato (2020).

Ioannidis et al. (2019) covered a sample of 44 islands and focused on one aspect of vulnerability: the diversity of electricity supply. The authors combine Shanon-Wiener diversity and Herfindahl-Hirschmann concentration indices to propose sustainable development roadmaps for these territories. Energy and carbon intensity indicators are also used for this purpose. The results suggest that the electricity mix of island territories such as Barbados, Saint Lucia, Solomon Islands or Tonga is 100% concentrated due to their exclusive dependence on oil for electricity production. Although insightful, the study failed to capture the global scope of this phenomenon for island energy systems.

Gatto & Busato (2020) propose a global measure of vulnerability through the construction of a composite index. The authors define energy vulnerability as "*the degree to which an energy system or entity is more likely to get exposed to adverse events or change, and risks to fall into traps in economic, social, environmental and governance terms*" (Gatto & Busato, 2020, p.2). The resulting composite index is based on the economic, social

[5] See Månsson et al. (2014) for a review of the commonly used methodologies for assessing energy security

[6] See Valdés (2018) for a review focused on energy security indicators.

and environmental dimensions. Governance is the fourth dimension. The energy vulnerability index proposed by Gatto & Busato (2020) is computed as the weighted sum of seven pillars falling under the four dimensions indicated above. The authors conclude that producer countries are the least vulnerable due to their low exposure to supply chain disruption risks. Furthermore, countries characterised as 'green' are less vulnerable due to their relatively good performance in terms of electricity consumption from renewable sources.

This study makes several contributions to the literature. The first one is conceptual. No proper research framework has yet been established for the study of macroeconomic vulnerability. Moreover, no consensus has been reached about widely accepted definition of the concept. Energy vulnerability is a significant challenge that negatively affects countries' economic, environmental, and social prospects worldwide, including SIDS. Providing a suitable framework for studying this phenomenon is an essential first step toward mitigating energy vulnerability. We propose a definition broad enough to allow for the identification of various factors that contribute to energy vulnerability directly or indirectly based on the structural economic vulnerability literature, which makes use of shock and exposure components (see Guillaumont, 2009, 2010). This ad hoc structure fits well with energy vulnerability studies, since the objective is to emphasise those factors over which SIDS have no control and are therefore independent of current political orientations. Energy vulnerability is thus defined as the "*degree of sensitivity of an energy system to external threats or internal dysfunctions related to the technology available for the production, transmission and distribution of energy*". The exposure component captures the extent to which these territories are sensitive to potential adverse events. The shock component accounts for the transformations these territories may undergo following a specific shock. We then select a pool of indicators - categorised as economic, environmental, and social - that are interlinked to form a multilayered hierarchical structure for our composite index of energy vulnerability.

The second contribution is methodological. The indicators that reflect these two sub-indices (exposure and shock) entering the composite index construction are selected through a Principal Component Analysis (PCA). After this identification step, we select the weighting system and aggregation method to construct a composite index. In our study, we implement the Färe et al. (2019) model combined with the Multi-Layer Benefit-of-the-Doubt (MLBoD) proposed by Shen et al. (2013). On the one hand, the approach of Färe et al. (2019) deals with desirable and reverse indicators (i.e., indicators with positive and negative impacts, respectively, on the composite index). On the other hand, the MLBoD model reflects the hierarchical structure of the composite index, taking into account the contribution of sub-indices and the various dimensions to energy vulnerability. To the best of our knowledge, ours is the first study on energy vulnerability to combine these approaches.

Finally, we compute a composite index of energy vulnerability for 36 SIDS that are members of the United Nations. We argue that prior research has failed to give sufficient consideration to SIDS when attempting to construct composite indexes for capturing energy vulnerability. We aim to fill this gap and foster a better understanding of the critical energy challenges faced by these territories. Existing studies on energy vulnerability and security do not incorporate the specificities of SIDS. We seek to address the lack of a synthetic index for capturing energy vulnerability that considers the underlying economic, environmental, and social dimensions of energy vulnerability (IAEA, 2005).

The remainder of this chapter is organised as follows. Section 1.2 provides insights into the relationship between island energy systems and vulnerability. Section 1.3 describes how the energy vulnerability index (EnVI) is constructed. The selection of dimensions and underlying indicators, along index-construction steps are also detailed in this section. The results are presented and discussed in Section 1.4. Finally, Section 1.5 concludes and provides suggestions for future research.

1.2 Heterogeneous island energy systems and vulnerability

Encontre (2004) identifies several listings of SIDS, ranging in number from 29 to 48.[7] The UN recognises 58 SIDS,[8] of which 38 are UN members. We opted to consider only the UN-member SIDS to investigate the relative energy performance levels among island energy systems.[9] SIDS are already afflicted by structural handicaps associated with their small size, remoteness, narrow domestic markets, and high dependence on external trade (Briguglio, 1995; Adrianto & Matsuda, 2004; Guillaumont, 2009, 2010). SIDS face several energy challenges at the economic, environmental, and social levels.

The economic challenges include a heavy reliance on imported fossil fuels (coal, petroleum products, and natural gas), mainly for electricity generation and fuel for the transport sector (Blechinger et al., 2016; Atteridge & Savvidou, 2019). Indeed, 31 out of the 36 SIDS are considered net energy importers (see Table A.1 in 3.5) based upon

[7]These comprise a pragmatic list of 29 SIDS of the United Nations Conference on Trade and Development (UNCTAD), a political list of 39 SIDS that form the Alliance of Small Island States, an institutional list of 46 SIDS according to the United Nations, and an economic list of 48 SIDS according to the United Nations Secretariat.

[8]United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries, and Small Island Developing States (UN-OHRLLS; http://unohrlls.org/about-sids/, accessed on 07/10/2019).

[9]Thirty-six SIDS were selected instead, since data were not available for the Marshall Islands and Nauru.

their respective energy balances.[10] There is a wide heterogeneity among the net energy importers. Of the 31 SIDS, 24 had energy dependency rates above 80% in 2015. On the other hand, two SIDS had the lowest dependency rates (less than 30%) in the same year, mainly due to conventional energy sources, such as fuel wood, biomass, and waste.[11] The paradox is that a majority of small island states have substantial indigenous renewable sources like solar and wind energy that are still untapped (Blechinger et al., 2016); this is mainly due to their poor energy infrastructures and the high initial upfront costs of greener technology alternatives (Gils & Simon, 2017).

Reliance upon external sources of energy exacerbates SIDS' exposure to external threats on international energy markets, such as energy price fluctuations (mainly those of petroleum products), which could disrupt their domestic economies (Hamilton, 1983). Moreover, higher energy prices place burdens on their national budgets, thus affecting their balance of payments (Hamilton, 2003; Henriques & Sadorsky, 2011). Furthermore, the concentration of fossil fuel reserves in a few producing countries can be linked to energy security concerns for net importing countries, including SIDS. Political instability in these producing regions can also lead to energy access issues, resulting in disruption risks in their primary energy supply chains (Ioannidis et al., 2019).

Highly concentrated energy mixes could be detrimental to the proper functioning of their economies. A significant proportion of the islands' primary energy supplies is sourced from fossil fuels. Energy mix concentration can also arise when a few indigenous sources of energy dominate the domestic mix. Some least developed SIDS make substantial use of biofuels and waste, which account for over 70% of their primary energy supply.[12] On the other hand, SIDS endowed with natural fossil resources are also exposed to supply disruption risks that could negatively affect the production, transmission and distribution of energy. A well-diversified energy mix is thus seen as a bulwark against external shocks (Percebois, 2007; Gupta, 2008; Gnansounou, 2008; d'Artigues & Vignolo, 2012).

The social challenges faced by SIDS include the accessibility and affordability of energy use. The gap between advanced and developing economies translates into the use of modern energy services for several uses versus the use of traditional fuels such as charcoal and fuelwood for cooking, heating, and lighting (IAEA, 2005; Vera & Langlois, 2007). In 2015, several SIDS were struggling to provide universal access to electricity to their respective populations. This is a severe problem encountered by less-developed

[10] From The 2015 Energy Balances published by the United Nations Statistics Division, (https://unstats.un.org/unsd/energystats/pubs/balance/, accessed on 15/10/2019).

[11] These include SIDS such as Guinea-Bissau and Haiti (from the Sustainable Energy For All (SE4ALL) database of The World Bank (https://datacatalog.worldbank.org/dataset/sustainable-energy-all, accessed on 15/10/2019).

[12] Data retrieved from The 2015 Energy Balances published by the United Nations Statistics Division (https://unstats.un.org/unsd/energystats/pubs/balance/, accessed on 11/11/2019).

SIDS with the lowest access rates, ranging from 15% to 84% for access to electricity and from 1.5% to 18% for access to clean technologies in 2015.[13] This problem also affects the provision of modern and clean technologies for lighting and cooking, leading to health-related concerns in these territories owing to the indoor air pollution caused by the combustion of traditional fuels.

Emissions of greenhouse gases linked to the production, transmission, and distribution of energy have long-term impacts on the environment. Environmental degradation due to the production and consumption of energy is hampering sustainable development in SIDS (Vera & Langlois, 2007). Environmental concerns have gained increasing attention worldwide, with influential publications like the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC) warning against the disruptive impacts of climate change and global warming on economies, societies, and the environment as a whole (Pachauri et al., 2014). Though their contributions to global warming are insignificant (Heger et al., 2008; Julca & Paddison, 2010), SIDS have pledged to abate their CO_2 emissions through Nationally Determined Contributions (NDCs) following the Paris Agreement.[14] On average, carbon emissions have risen 94% between 1970 and 2015 to reach 3.85 tons per capita.[15]

Despite sharing common characteristics and facing similar energy challenges, SIDS form a heterogeneous group. As such, assessing their energy vulnerability levels is essential. The following section describes the method used to measure these levels.

1.3 Methodology

We assess energy vulnerability in SIDS based on several energy indicators. We adopt a data-driven approach consisting of several steps to compute a composite index of energy vulnerability from the design of a conceptual framework to the aggregation of individual indicator values into a unique composite index score. These steps are represented in Figure 1.1. Finally, we demonstrate via an empirical example how divergent computation approaches may impact the results.

[13] World Development Indicators, The World Bank, http://datatopics.worldbank.org/world-development-indicators/, (accessed on 14/11/2019).

[14] NDC registry (https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx, accessed on 15/11/2019).

[15] Emission Database for Global Atmospheric Research (EDGAR) informs researchers and decision-makers on the evolution of the emission inventories over time for countries worldwide (https://edgar.jrc.ec.europa.eu/, accessed on 14/11/2019).

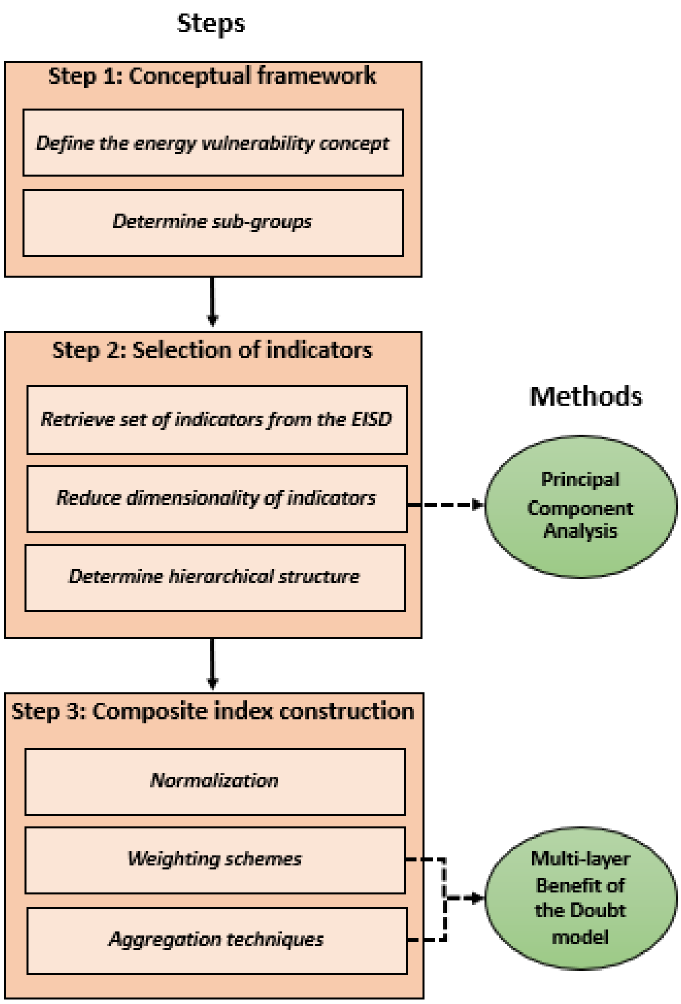


Figure 1.1: Steps for composite index construction

Note: The above figure illustrates the modelling steps adopted in this study to develop the energy vulnerability index. First, a conceptual framework is developed in step 1 to understand and define the energy vulnerability concept. Based on the proposed definition, the shock and exposure components are identified. Indicators are selected at step 2. We retrieve a set of variables that best capture the phenomenon we want to measure. We then reduce the dimensionality of our data set using the principal component analysis. The hierarchical structure is also determined at this stage. The final step involves the computation of the energy vulnerability index. The Multi-layer benefit of the doubt approach is used to weigh and aggregate the sub-indicators into a unique index value. We skip normalization since the MLBoD model is unit invariant.
Source: the authors.

1.3.1 Data set description

1.3.1.1 Data

An energy vulnerability index for 2015 was computed for 36 SIDS. These territories are grouped into three main regions: AIMS, the Caribbean, and the Pacific. Initially, we intended to use the complete list of SIDS UN members,[16] but not enough data were available for the Marshall Islands and Nauru. The list of countries studied can be found in Table A.1 of Appendix A. Data were retrieved from the United Nations Statistics Division and The World Bank. Data on CO_2 emissions were extracted from the Emission Database for Global Atmospheric Research[17] (EDGAR; Olivier et al., 2016). All indicator data sources are reported in Tables B.1 and B.2 of Appendix B.

1.3.1.2 Selection of indicators

The first step is to identify a proper framework for energy vulnerability (Nardo et al., 2008; Luzzati & Gucciardi, 2015). Based on the definition given earlier, energy vulnerability is seen as a threat to SIDS' sustainable energy future if nothing is done to mitigate it. The next step is to select indicators that best capture energy vulnerability through a multivariate analysis. Potential indicators were identified using the energy indicators for sustainable development (EISD)[18] proposed by the International Atomic Energy Agency along with other international organisations (IAEA, 2005) and the literature on energy security and vulnerability (Gnansounou, 2008; Gupta, 2008; Iddrisu & Bhattacharyya, 2015; Narula & Reddy, 2016; Genave, 2019).

There is no best practice for indicator selection. Principal component analysis (PCA) is typically used to compute a covariance matrix to reduce redundancy in the dataset. The linear combination of all indicators gives the principal components (PC). Table 1.1 shows the eigenvalues of the principal components for the initial set of 21 variables (see Table B.1 in Appendix B). The first PC accounts for the most significant variance (31.5%). Based on the common practice of the Kaiser rule criterion (Kaiser, 1960), only those dimensions (i.e. principal components) with eigenvalues greater than one are kept. This is the case for the first seven dimensions, as shown in Table 1.1. Altogether, they explain 89% of the total variance in the dataset.

[16]We opted for the list of SIDS of the United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries, and Small Island Developing States (UN-OHRLLS). This list recognises a total of 58 SIDS, of which 38 are UN members. (http://unohrlls.org/about-sids/, accessed on 07/10/2019)

[17]Emission Database for Global Atmospheric Research (EDGAR) informs researchers and decision makers on the evolution of the emission inventories over time for countries worldwide (edgar.jrc.ec.europa.eu).

[18]The EISD publication is a joint effort of the International Atomic Energy Agency in collaboration with the United Nations Department of Economic and Social Affairs (UNDESA), the International Energy Agency (IEA), Eurostat, and the European Environment Agency (EEA).

Table 1.1: Eigenvalues and variance explained

Dimensions	Eigenvalue	Variance (%)	Cumumative variance (%)
Dim.1	6.6	31.5	31.5
Dim.2	4.4	21.1	52.5
Dim.3	2.3	10.8	63.3
Dim.4	1.6	7.6	70.9
Dim.5	1.5	7.2	78.1
Dim.6	1.3	6.4	84.5
Dim.7	1.0	4.7	89.2
Dim.8	0.6	2.9	92.1
Dim.9	0.5	2.2	94.3
Dim.10	0.4	2.0	96.3
Dim.11	0.3	1.3	97.6
Dim.12	0.2	1.0	98.5
Dim.13	0.1	0.6	99.1
Dim.14	0.1	0.3	99.4
Dim.15	0.0	0.2	99.7
Dim.16	0.0	0.2	99.8
Dim.17	0.0	0.1	99.9
Dim.18	0.0	0.1	100.0
Dim.19	0.0	0.0	100.0
Dim.20	0.0	0.0	100.0
Dim.21	0.0	0.0	100.0

Source: the authors.

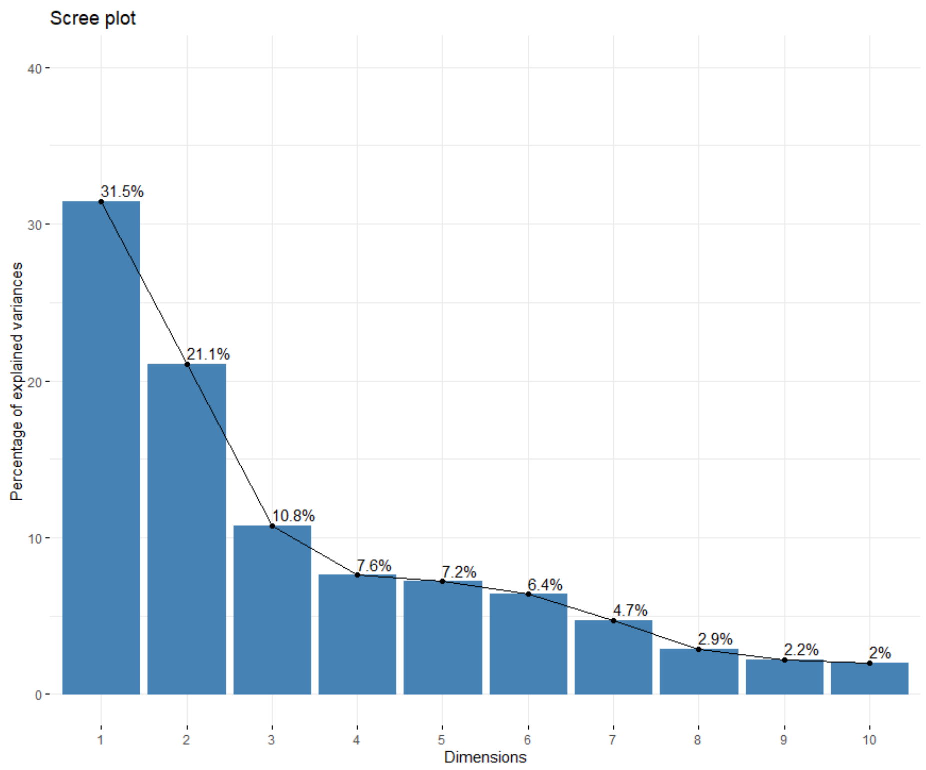


Figure 1.2: Scree plot analysis

Note: The break occurs after the third PC.
Source: the authors.

Another way to select the number of PCs to retain is through a scree plot analysis (Cattell, 1966). Figure 1.2 plots the components on the X-axis and the corresponding eigenvalues on the Y-axis. We decide to keep the first three principal components (before the 'elbow-like' break occurs), which altogether explain more than 60% of the variance in the dataset. The initial set of 21 variables is reduced to a final set of eight indicators which covers several dimensions, such as availability, accessibility, and environmental sustainability. The Pearson correlation coefficients of the final eight indicators are illustrated in the correlogram[19] in Figure 1.3. They are displayed according to the direction of the relationship (positive or negative) between the variables. For instance, ECO1 and ECO16 are negatively correlated (-0.765). The rationale for each selected indicator used in the construction of our composite index is provided in Table 1.2.

[19]The correlogram is a graphical representation of a correlation matrix.

	ECO10	ECO16	ECO13	ENV3	SOC1	ECO14	ECO1	ECO5
ECO10	1	0.23	-0.15	-0.07	-0.05	-0.28	0	0.29
ECO16		1	-0.33	0.07	-0.43	0.06	-0.76	-0.08
ECO13			1	0.05	0.33	-0.01	0.13	-0.35
ENV3				1	0.4	-0.34	-0.15	-0.39
SOC1					1	-0.36	0.28	-0.36
ECO14						1	-0.14	-0.03
ECO1							1	0.52
ECO5								1

Figure 1.3: Correlogram of the final eight indicators

Source: the authors.

Table 1.2: Description of indicators

Dimension	Indicator	Rationale
Economic	Primary energy supply per capita (ECO1)	Primary energy supply per capita indicates the level of energy physically available for consumption (IAEA, 2005).
	Final energy intensity per unit of GDP (ECO5)	Energy use per unit of GDP is a "marker of aggregate energy intensity" for an economy (IAEA, 2005, p.18). It indicates how much energy is employed to produce one unit of output (GDP). Energy intensity in small islands and other developing countries is usually lower compared to advanced economies. The primary reason is the underlying economic structure of most SIDS. The higher the value of ECO5, the lower the economy's efficiency to produce one extra unit of output. Island energy systems thus tend to be more vulnerable due to increased pressure on the system. Monitoring energy intensity over time offers a good indication of whether countries have been successful in energy transition (i.e. using less energy to achieve the same level of GDP).
	Energy intensity in the transport sector (ECO10)	Non-diversity in transport fuels render countries more vulnerable Gupta (2008). Emissions from the transport sector accounted for over 20% of total global CO_2 emissions in 2016 with more than 90% of global energy transportation based on fossil fuels (IEA, 2018).
	Energy import dependency (ECO13)	Energy import dependency is a critical issue for SIDS and other island territories since most of them rely heavily on imported fossil energy for their primary energy supply (Raghoo et al., 2018). Therefore, disruptions in primary energy supply could negatively affect economic activities, and have disastrous impacts on long-run economic growth (Bhattacharyya, 2011), thereby increasing their exposure to external shocks. Moreover, the higher the dependency ratio, the higher the energy vulnerability as island nations are more sensitive to shocks (Percebois, 2007).
	Energy mix diversity (ECO14)	Most primary energy mixes of islands are characterised by heavy use of fossil fuels. Diversifying the local energy mix is seen as a critical strategy for anticipating significant disruptions in the primary energy supply. Two methods are extensively used in the literature to investigate the diversity (or concentration) of energy mixes: The Shannon-Wiener (SW) diversity index and the Herfindahl-Hirschman (HH) concentration index. Several studies use this metric (or a modified version) to assess fuel diversity (Jansen et al., 2004; APERC, 2007). In this study, we opt for the SW diversity index. Islands that rely solely on a single energy source have an SW index equivalent to zero. A more diversified energy mix helps to reduce systematic risks linked to international energy markets (Månsson et al., 2014).
	Overall system conversion efficiency (ECO16)	An efficient system conversion captures the ability of the energy supply system to meet the present and future needs of a society reliably and efficiently and using clean sources. The higher the conversion efficiency, the less energy lost during conversion, and the less energy-vulnerable the country will be since less energy will be required to satisfy the same level of useful energy (i.e., total final consumption requirement; Iddrisu & Bhattacharyya, 2015
Environmental	Carbon content of primary energy (ENV3)	Carbon dioxide (CO_2) released from the combustion of fossil fuels contributes to global warming and climate change, calling for the phasing out of carbon-based fuels. A high score in this dimension indicates that a country is vulnerable from an energy viewpoint since countries heavily reliant on fossil fuels are more vulnerable to future energy and climate policies like carbon taxes and carbon caps.
Social	Access to electricity (SOC1)	Access to electricity in SIDS varies greatly (Wolf et al., 2016; Surroop & Raghoo, 2017; Raghoo et al., 2018). Indeed, islands like Comoros and Guinea-Bissau still struggle to provide universal access to their population. Adequate access to electricity represents a considerable challenge that local authorities have yet to overcome, as highlighted by the UN's sustainable development goal (SDG) 7 (Nations, 2015). The higher the proportion of people having access to electricity, the lower the energy vulnerability.

Source: the authors.

Figure 1.4 presents a four-layer hierarchical structure for the energy vulnerability concept. The first layer is composed of the eight indicators. The second layer contains four dimensions (two under the exposure sub-index and two under the shock sub-index). In contrast, the third layer is composed of two subcomponents (exposure sub-index and shock sub-index). The fourth and final layer (EnVI) is obtained by aggregating the two subcomponents. Please note that the composite index should be interpreted as an index of non-vulnerability since MLBoD computes efficiency scores (i.e., the higher, the better). Raw data on the eight selected indicators and a box plot analysis for the identification of outliers are provided in Table C.1 and Figure C.1 of Appendix C respectively.

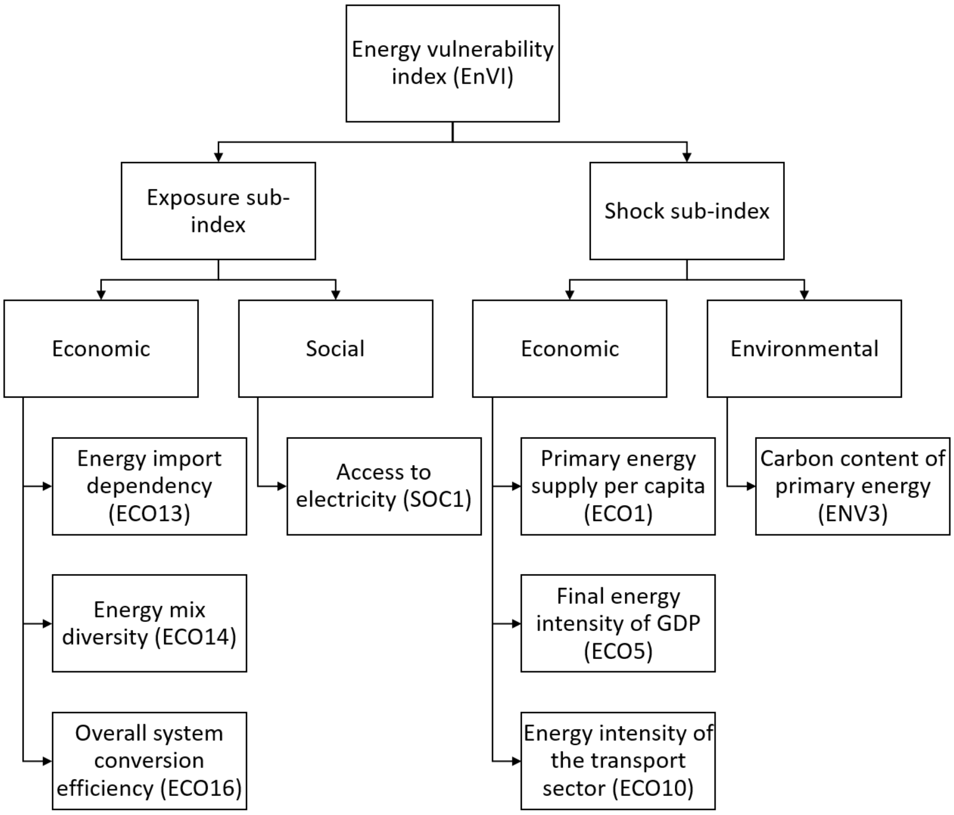


Figure 1.4: Hierarchical structure of the composite index of energy vulnerability (EnVI)
Source: the authors.

The next step is to assign weights to all indicators and aggregate them.

1.3.2 Composite indicator construction

We now proceed to the next step: summarising the information provided by the energy vulnerability indicators into a unique value. Energy vulnerability is thus expressed as the weighted average of all the vulnerability dimensions for a selected country in terms of each indicator. Our challenge is to determine the meaningful weights required to construct the composite index. Weighting methods are broadly categorised into statistical models (e.g., principal components or regression analysis) and based on public/expert opinion (e.g., budget allocation process or conjoint analysis). The former category includes the 'Benefit-of-the-Doubt' (BoD) model, which is rooted in the data envelopment analysis (DEA) proposed by Charnes et al. (1978).

In essence, DEA is a tool for evaluating the performance of a set of units that use inputs to produce outputs. It requires constructing a production frontier representing the maximum achievable outputs from inputs and measuring the distance between each unit and the efficient frontier. This frontier is built from practical observation of the best-performer group. The inefficient units are below the frontier. In a traditional DEA model, the efficiency of a unit is defined as the maximum of the ratio of the weighted sum of outputs to the weighted sum of inputs. This definition requires that the set of weights that maximises this ratio be found using mathematical programming for each unit. For example, suppose the ratio value is maximal, and no other unit obtains a better value with the same set of weights. In that case, the evaluated unit is deemed efficient and is located on the frontier.

The DEA and related models present numerous advantages. They are based solely on data and thus avoid the subjectivity associated with techniques relying on expert judgement or public opinion polls. This is particularly useful when dealing with composite indices generally characterised by uncertainty and a lack of consensus regarding appropriate weighting schemes. The DEA selects weights that maximise the composite index for each country under investigation (Zhou et al., 2007). Each country is allowed to use the set of weights that places it in the best possible position. Therefore, the countries are less likely to contest their assigned weights (Cherchye et al., 2007).

Two remarks should be made about the DEA methodology. First, a country's score reflects its energy vulnerability relative to the rest of the sample. Therefore, a country with a score equal to unity may be vulnerable in absolute terms. We can imagine other vulnerability measures based on samples that integrate other countries or groups less vulnerable in absolute terms to take this element into account. The actual position of the countries under investigation can thus be analysed on a different scale.

Second, despite its numerous advantages, the DEA methodology is deterministic, causing its scores to be sensitive to a data noise problem (e.g., the presence of outliers). Therefore, additional analysis may be necessary to solve this problem and avoid compromising the robustness of the results.[20] We use a simple and effective subsampling approach inspired by Kneip et al. (2008).[21] As presented intuitively by Valdmanis et al.

[20] A non-technical but comprehensive overview concerning noise, uncertainty, and measurement issues in the DEA can be found in Dyson & Shale (2010).

[21] For more on possible theoretical and methodological approaches, please see Cazals et al. (2002) and Simar & Wilson (2011).

(2017) and Leleu et al. (2018), the technique is implemented as follows. First, numerous subsamples of a predetermined size are selected from the initial sample of observed decision-making units (countries in this case). Second, the estimated CI is computed for each sample, and the final estimate is the average across the sub-samples. Since the estimated frontier is based on a random selection of countries that varies over the sub-samples, a country is not always compared with potential outliers. Thus, the final result can be interpreted as a robust measure of CI. Once the distribution of CI scores is obtained for each entity, we derive a confidence interval (see Table E.1 of Appendix E) for our composite indicator by eliminating $\alpha/2$ of the value at each tail of the distribution (we consider a significance level α of 5%).

1.3.2.1 The Benefit-of-the-Doubt (BoD) model

Of the available composite indicators, the multiplicative form of the output-oriented basic DEA model with multiple outputs (i.e., indicators) and a single dummy input equal to unity was used to determine the weighting scheme and to allow aggregation (See Cherchye et al., 2007; Van Puyenbroeck & Rogge, 2017). This DEA model has also been called the 'Benefit-of-the-Doubt' method and was proposed by Melyn & Moesen (1991).[22]

Let J be the number of countries evaluated in terms of R indicators. The respective index sets of countries and indicators are defined as $j = 1, \ldots, J$, $r = 1, \ldots, R$. For a country o, the basic BoD model can be formulated as follows:

$$
\begin{aligned}
& CI_o = max \sum_{r=1}^{R} \hat{u}_r y_{ro} \\
& \text{s.t.} \\
& \sum_{r=1}^{R} \hat{u}_r y_{rj} \leq 1, \quad j = 1, \ldots, J \\
& \hat{u}_r \geq 0, \quad r = 1, \ldots, R
\end{aligned}
\tag{1.1}
$$

Where CI_o is the value of composite indicator of the evaluated entity o; $\hat{u}_r$ is the weight assigned to indicator r for evaluated entity o; y_{rj} is the value of indicator r of entity j.

The BoD model (1.1) illustrates the underlying 'benefit-of-the-doubt' concept clearly.[23] In the absence of information on the actual weights, the model seeks the best

[22] See Rogge (2012) for a useful discussion on the BoD model.
[23] See Appendix D for a simple example of a BoD model and its comparison with other weighting and aggregation techniques.

set of weights for each, which are used to aggregate the indicators into a composite index. The first restriction guarantees that no country can obtain a score larger than unity under these weights. The second constraint is introduced so that none of the weights will take a zero value.[24] The value on this composite index is therefore bounded in the interval [0,1]. Countries that achieve a score equal to unity are considered the least energy-vulnerable of the sample; if the score is lower than unity, the country is considered the most energy-vulnerable.

The conventional BoD model (1.1) assumes that the sub-indicators are measured on scales, for which higher values indicate better composite indicators. Thus, they can be used only if all the indicators are expressed in the same direction. Therefore, it proves to be inappropriate in cases where increases in some sub-indicator values entering the CI construction are considered fortunate (hereafter 'desirable indicators'). In contrast, increases in some others are considered unfortunate (hereafter 'reverse indicators'). Several approaches have been proposed to deal with this problem, such as data transformation techniques (e.g., normalisation, rescaling or ranging normalisation, translation, multiplicative inverse).[25] The values of indicators for which value increases are not desirable are transformed to allow their treatment as desirable indicators. As pointed out by Färe et al. (2019), this can be problematic since the BoD model is not translation-invariant in the indicators. Moreover, the values of the composite indicators may be affected differently depending on the data transformation approach used (Liu & Sharp, 1999; Liu et al., 2010).

The alternative approaches consider these reverse indicators as undesirable outputs (e.g. Zanella et al., 2015b,a). Insofar as they are inspired by the traditional framework of Chung et al. (1997), the weak disposability of undesirable outputs is also assumed. Thus, the undesirable outputs can be reduced only by simultaneously decreasing the values of the desirable outputs. Moreover, as pointed out by Färe et al. (2019), the assumption of null-jointness associated with these types of approaches (i.e., that desirable outputs cannot be produced without producing some undesirable outputs) is challenging to justify in the context of the BoD model. Therefore, Färe et al. (2019) propose an approach that uses a modified BoD model and a single version of the constant return to scale DEA model. Unlike undesirable indicators, reverse indicators are not necessarily accompanied by desirable indicators, and a reduction in reverse indicator values does not automatically imply a reduction in desirable indicator values.

Let J be the number of countries evaluated in terms of R indicators, partitioned into p desirable and $(R-p)$ reverse indicators. The respective index sets of countries,

[24]Without more restriction on weights, the composite index represents the lower bound on vulnerability given the optimal set of weights assigned to each country.

[25]See Scheel (2001) and Liu et al. (2010) for lists of data transformation techniques.

desirable and reverse indicators are defined as $j = 1,\dots,J$, $r = 1,\dots,p,\dots,\ R$. For a country o, the conventional BoD model (1.1) considering both desirable and reverse indicators can be formulated as follows, based on Färe et al. (2019):

$$
\begin{aligned}
& CI_o = max \sum_{r=1}^{p} \hat{u}_r y_{ro} - \sum_{r=p+1}^{R} \hat{u}_r y_{ro} \\
& \text{s.t.} \\
& \sum_{r=1}^{p} \hat{u}_r y_{rj} - \sum_{r=p+1}^{R} \hat{u}_r y_{rj} \leq 1, \quad j = 1,\dots,J \\
& \hat{u}_r \geq 0, \quad r = 1,\dots,p,\dots,R
\end{aligned}
\tag{1.2}
$$

Where CI_o is the value of the composite indicator of evaluated entity o; $\hat{u}_r$ is the weight assigned to indicator r for evaluated entity o; y_{rj} is the value of indicator r of entity j.

The main difference between (1.2) and (1.1) is that we seek to maximise the weighted sum of both the desirable and reverse indicators, with the latter being subtracted from the former. Therefore, model (1.2) allows us to gain in generality.

1.3.2.2 The Multi-Layer Benefit-of-the-Doubt (MLBoD) model

The DEA literature offers several proposals for composite indicator construction (See Cherchye et al., 2007; Zhou et al., 2007, or, more recently Rogge, 2018). Most of them do not explicitly discuss several composite indicators' hierarchical structure and thus do not propose a suitable model. One exception is the MLBoD proposed by Shen et al. (2013) based on the multi-level data envelopment analysis model initially proposed by Meng et al. (2008) and linearised in the same year by Kao (2008). Shen et al. (2013) state that the MLBoD model has more discriminating power than standard BoD-like models. Its most important feature is its architecture, which suits studies involving multidimensional phenomena where hierarchical structures need to be explicit. Given the hierarchical structure of the energy vulnerability composite index in our study, we propose a modified MLBoD model with desirable and reverse indicators.

Let us consider additional information about the hierarchical structure of the composite index. Let J be the number of countries evaluated in terms of R indicators partitioned in p desirable and $(R-p)$ reverse indicators with a K-layered hierarchy. The respective index sets of countries, desirable and reverse indicators, and layers are defined as $j = 1,\dots,J$, $r = 1,\dots,p,\dots,\ R$ and $k = 1,\dots,\ K$. Let $f_k = 1,\dots,\ R^{(k)}$ be the fth category in the kth layer, where $R^{(k)}$ is the number of categories in the kth layer. $R^{(1)} = R$, i.e. the number of categories in the first layer is equal to the number of indicators. $y_{f_k j}$ represents the value for country j on the indicators of the fth category in the kth layer. For a country o, the modified MLBoD model can be formulated as follows:

$$\begin{aligned}
& CI_o = max \sum_{f_1=1}^{p} \hat{u}_{f_1} y_{f_1 o} - \sum_{f_1=p+1}^{R} \hat{u}_{f_1} y_{f_1 o} \\
& \text{s.t.} \\
& \sum_{f_1=1}^{p} \hat{u}_{f_1} y_{f_1 j} - \sum_{f_1=p+1}^{R} \hat{u}_{f_1} y_{f_1 j} \leq 1, \quad j = 1, \ldots, J \\
& \hat{u}_{f_1} \geq 0, \quad f_1 = 1, \ldots, p, \ldots, R
\end{aligned} \tag{1.3}$$

Where $\hat{u}_{f_1}$ is the set of optimal weights assigned to the indicators of the fth category in the first layer for country o obtained by solving the model; $y_{f_1 j}$ and $y_{f_1 o}$ are the values for country j and, o respectively, on the indicators of the fth category in the first layer; $R^{(k)}$ is the number of categories in the kth layer.

At this stage, for the evaluated country o, model (1.3) estimates the weights $\hat{u}$ that maximise the weighted sum of both the desirable and reverse indicators, with the latter being subtracted from the former, of the categories in the first layer. Since $R^{(1)} = R$, model (1.3) is similar to the BoD model (1.2): The hierarchical structure of the composite index is not yet considered. Doing that requires specifying the importance of the weights in each category of each layer and limiting their flexibility. Fortunately, model (1.3) is sufficiently general to allow consideration of additional restrictions on the weights.[26] Following Shen et al. (2013), we consider upper and lower limits corresponding to the internal weights associated with the indicators of the fth category in the kth layer, which sum to unity within a particular category.[27]

Formally, we have $\frac{\sum_{f_1 \in A^k_{f_k}} \hat{u}_{f_1}}{\sum_{f_1 \in A^{(k+1)}_{f_{k+1}}} \hat{u}_{f_1}}$ where $A^k_{f_k}$ is the set of indicators of the fth category in the kth layer. By adding this restriction on weights to model (1.3), the model is now written as follows:

[26] There are several ways to integrate restrictions on sub-indicator shares. For a presentation of these approaches or an examination of the role the restriction in DEA can play, please see Cherchye et al. (2007), or Pedraja-Chaparro et al. (1997) respectively.

[27] By imposing this restriction, we avoid having all the weight carry over to a single indicator of each layer. This allows us to moderate the score value obtained for each country if there were no constraints.

$$
\begin{aligned}
&CI_o = max \sum_{f_1=1}^{p} \hat{u}_{f_1} y_{f_1 o} - \sum_{f_1=p+1}^{R} \hat{u}_{f_1} y_{f_1 o} \\
&\text{s.t.} \\
&\sum_{f_1=1}^{p} \hat{u}_{f_1} y_{f_1 j} - \sum_{f_1=p+1}^{R} \hat{u}_{f_1} y_{f_1 j} \leq 1, \quad j = 1, \ldots, J \\
&L \leq \frac{\sum_{f_1 \in A^k_{f_k}} \hat{u}_{f_1}}{\sum_{f_1 \in A^{(k+1)}_{f_{k+1}}} \hat{u}_{f_1}} \leq U, \quad f_k = 1, \ldots, R^{(k)}; \quad k = 1, \ldots, K-1 \\
&\hat{u}_{f_1} \geq 0, \quad f_1 = 1, \ldots, p, \ldots, R
\end{aligned}
\tag{1.4}
$$

Where L and U represent the lower and upper limits imposed on the corresponding internal weights. The goal is to aggregate the indicator values within a particular category of a particular layer via the weighted-sum approach, in which the sum of the internal weights equals one.

1.3.3 Sensitivity analysis

Composite indices (CI) are valuable tools that aggregate multidimensional phenomena to benchmark best practices and design policy recommendations. However, summarising information often involves selecting and aggregating desirable (reverse) indicators that have a positive (negative) impact on the final index score, hence the importance of designing an appropriate framework beforehand. In this section, we highlight the importance of studying the way reverse indicators are treated before aggregation.[28] More specifically, we show that the treatment of reverse indicators is an important aspect that should not be overlooked when developing a composite index, given that different techniques may generate nuanced results.

Normalisation in this section refers to either the **transformation** of reverse indicators into desirable ones or the **rescaling** of reverse indicators. We seek to address the practical research problem of whether reverse indicators should be treated before aggregating them into a meaningful composite index. This section reappraises the extent to which the treatment of reverse indicators impacts the relative performance of countries and what it entails for CI-based policy assessment. Regarding the treatment of reverse indicators, direct and indirect approaches can be used (Scheel, 2001; Zanella et al., 2015b; Halkos & Petrou, 2019).

[28] This subsection is based on a working paper entitled "*The impacts of normalizing reverse indicators in Benefit-of-the-doubt composite indexes*".

1.3.3.1 Direct approach

Direct approaches do not require data manipulation: they treat reverse indicators in their original form by using explicit model specifications (Cherchye et al., 2015).[29] Thus, model (1.4) is based on a direct approach, since reverse indicators keep their original form.

1.3.3.2 Indirect approach

Indirect approaches transform reverse indicators into desirable ones before computing the entity's overall performance (Halkos & Petrou, 2019), primarily through normalisation techniques.[30] Shen et al. (2013) applied the 'distance from the leader' technique to transform reverse indicators and compute a Road Safety Performance Index. Zhou et al. (2007) took the reciprocal of reverse indicators to compute a Sustainable Security Index. Several research paradigms covering various fields, including the well-known Human Development Index (UNDP, 1990; Despotis, 2005) used the min-max procedure[31] to re-scale and transform desirable and reverse indicators, respectively. This latter technique is one of the most commonly used normalisation techniques for energy security composite indices (Ang et al., 2015), with normalised values set in the [0,1] interval. Under the indirect approach, reverse indicators are transformed into desirable indicators ($y_{f_1 o}$) through normalisation as follows:

$$y_{f_1 o} = \frac{\text{max value of the sample} - \text{actual value of the country}}{\text{max value of the sample} - \text{min value of the sample}}$$

The min-max normalisation procedure is based on the sample maxima and minima. Indicator values lie in the $[0, 1]$ interval. As a result, the indirect approach takes the form of a standard BoD model as in model (1.1) but now includes an additional constraint on internal weights to reflect the hierarchical structure of the composite index. The CI score represents the weighted sum of all (desirable) indicators as follows:

[29] Examples of direct approaches include the Public Health Index (Färe et al., 2019) and the performance assessment of Brazilian hydropower plants based on a directional distance function model (Zanella et al., 2015b).

[30] Normalisation is primarily carried out to remove scale differences between indicators. The most popular techniques include ranking, distance from the leader, distance from the mean, or z-score standardisation (Freudenberg, 2003; Nardo et al., 2008).

[31] Other models, can assess the impact of transforming reverse indicators without the need to have values between 0 and 1. In contrast, the min-max procedure simultaneously transforms and re-scales reverse indicators.

$$
\begin{aligned}
& CI_o = max \sum_{f_1=1}^{R} \hat{u}_{f_1} y_{f_1 o} \\
& \text{s.t.} \\
& \sum_{f_1=1}^{R} \hat{u}_{f_1} y_{f_1 j} \leq 1, \quad j = 1, \dots, J \\
& L \ \leq \ \frac{\sum_{f_1 \in A^k_{f_k}} \hat{u}_{f_1}}{\sum_{f_1 \in A^{(k+1)}_{f_{k+1}}} \hat{u}_{f_1}} \leq U, \quad f_k = 1, \dots,\ R^{(k)}; \quad k = 1, \dots, K-1 \\
& \hat{u}_{f_1} \ \geq 0, \quad f_1 = 1, \dots, R
\end{aligned}
\tag{1.5}
$$

1.3.3.3 Hybrid approach

The hybrid approach serves as the reference model for comparison: it combines the direct and indirect approaches. The model specification is based on model (1.4). The main difference is that both desirable and reverse indicators require data manipulation. In essence, desirable indicators are simply rescaled. To account for the negative impact of reverse indicators on the overall composite index value, reverse indicators are transformed as follows:

$$
y_{f_1 o} = \frac{\text{actual value of the country} - \text{min value of the sample}}{\text{max value of the sample} - \text{min value of the sample}}
$$

Thus, the hybrid approach helps to distinguish between the impacts of rescaling reverse indicators compared to the direct approach, i.e., model (1.4) and the impacts of data transformation compared to the indirect approach, i.e., model (1.5).

1.4 Results and discussion

This section presents and discusses the results of the empirical analysis derived from model (1.4).

1.4.1 Index score and country ranking

The eight indicators, comprising three desirable and five reserve indicators, were combined into a unique value. For each SIDS, the best possible indicator weights must be selected under a set of constraints. Five hundred replications were performed to derive robust MLBoD scores and rankings. The MLBoD results reflect relative vulnerability, since the performance of a country is benchmarked on other countries' performance values in the dataset. For example, Table 1.3 shows that Cape Verde scored the optimal score (1) while Papua-New-Guinea had the worst energy performance (0.2929). Thus, the SIDS' performance on each indicator constitutes the starting point for identifying their relative strengths and weaknesses.

Figure 1.5 reports the final MLBoD values for the SIDS. Countries are ranked from most vulnerable to least vulnerable. Cape Verde acts as a benchmark that underperforming countries can use to learn the best energy practices. The results should be interpreted carefully. An optimal score (1) in the MLBoD represents a lower bound on vulnerability given the optimal set of weights assigned to each country. Cape Verde is the leader in this sample: The island is the least energy-vulnerable SIDS of the group. However, we cannot confirm that it is invulnerable in absolute terms, as we measured relative energy vulnerability based on the performance of all the territories in the sample. Moreover, all the SIDS would obtain an optimal score of one if Cape Verde's performance for each indicator was assigned; thus, no other SIDS is allowed to have a score greater than one under the best set of weights.

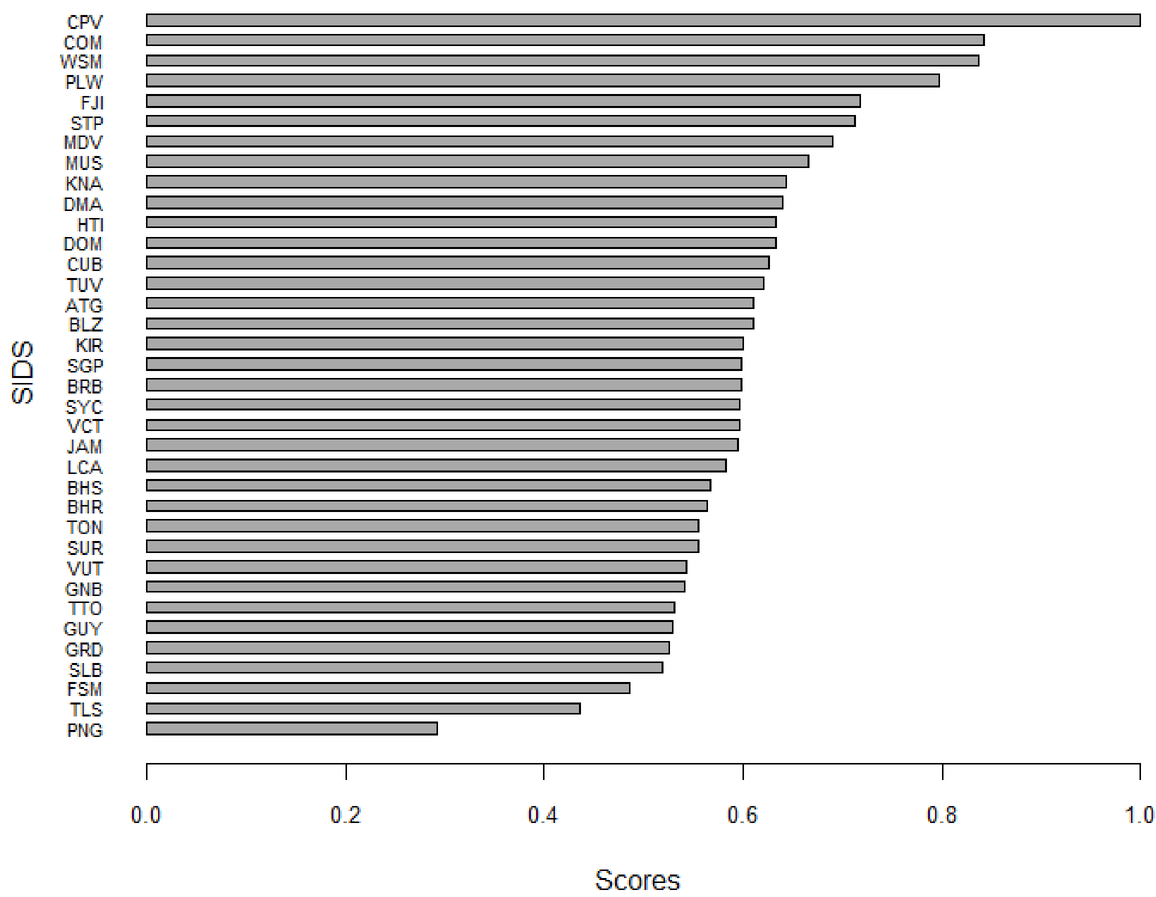


Figure 1.5: Country ranking from most (0.2929) to least vulnerable (1)

Source: the authors.

Table 1.3: MLBoD scores and (weighted) performance for each indicator

SIDS	MLBoD Score	Rank	Desirable			Reverse				
			ECO14	ECO16	SOC1	ECO1	ECO5	ECO10	ECO13	ENV3
CPV	1.0000	1	0.002	0.343	1.829	0.275	0.018	0.173	0.003	0.706
COM	0.8427	2	0.003	0.525	1.307	0.113	0.017	0.071	0.003	0.789
WSM	0.8377	3	0.002	0.173	1.647	0.181	0.018	0.136	0.002	0.648
PLW	0.7979	4	0.000	0.189	1.550	0.379	0.028	0.205	0.003	0.326
FJI	0.7183	5	0.002	0.120	1.466	0.138	0.015	0.116	0.003	0.599
STP	0.7119	6	0.005	0.681	0.888	0.129	0.020	0.103	0.004	0.606
MDV	0.6899	7	0.000	0.525	0.999	0.135	0.007	0.103	0.004	0.586
MUS	0.6661	8	0.003	0.099	1.375	0.142	0.006	0.076	0.003	0.586
KNA	0.6433	9	0.000	0.091	1.311	0.148	0.004	0.049	0.003	0.555
DMA	0.6401	10	0.001	0.092	1.312	0.114	0.005	0.053	0.002	0.590
HTI	0.6328	11	0.004	0.890	0.608	0.171	0.051	0.117	0.002	0.529
DOM	0.6322	12	0.003	0.121	1.254	0.091	0.003	0.043	0.002	0.606
CUB	0.6256	13	0.002	0.086	1.273	0.120	0.008	0.012	0.002	0.595
TUV	0.6217	14	0.001	0.100	1.254	0.047	0.005	0.070	0.002	0.608
ATG	0.6099	15	0.000	0.101	1.231	0.156	0.007	0.095	0.003	0.461
BLZ	0.6097	16	0.005	0.540	0.783	0.115	0.008	0.080	0.002	0.513
KIR	0.6000	17	0.001	0.428	0.901	0.040	0.008	0.084	0.004	0.594
SGP	0.5987	18	0.002	0.058	1.282	0.222	0.002	0.006	0.013	0.500
BRB	0.5986	19	0.001	0.125	1.181	0.123	0.004	0.031	0.003	0.547
SYC	0.5973	20	0.000	0.125	1.186	0.132	0.003	0.027	0.005	0.547
VCT	0.5959	21	0.001	0.139	1.157	0.075	0.003	0.043	0.002	0.579
JAM	0.5947	22	0.001	0.138	1.156	0.084	0.005	0.061	0.002	0.549
LCA	0.5822	23	0.000	0.104	1.164	0.075	0.003	0.028	0.002	0.579
BHS	0.5680	24	0.000	0.232	1.008	0.122	0.003	0.017	0.003	0.527
BHR	0.5638	25	0.001	0.049	1.177	0.294	0.004	0.029	0.002	0.335
TON	0.5553	26	0.000	0.247	0.963	0.033	0.003	0.052	0.002	0.565
SUR	0.5545	27	0.003	0.505	0.703	0.102	0.004	0.066	0.003	0.481
VUT	0.5435	28	0.004	0.639	0.550	0.054	0.010	0.063	0.003	0.519
GNB	0.5409	29	0.004	1.300	0.263	0.143	0.072	0.135	0.002	0.673
TTO	0.5304	30	0.001	0.030	1.121	0.310	0.010	0.015	0.001	0.285
GUY	0.5289	31	0.002	0.484	0.668	0.082	0.007	0.061	0.003	0.474
GRD	0.5252	32	0.001	0.212	0.932	0.058	0.002	0.029	0.002	0.529
SLB	0.5181	33	0.004	0.620	0.509	0.045	0.011	0.017	0.002	0.539
FSM	0.4866	34	0.000	0.461	0.604	0.050	0.009	0.112	0.003	0.405
TLS	0.4356	35	0.002	0.403	0.550	0.024	0.001	0.051	0.003	0.440
PNG	0.2929	36	0.006	0.456	0.179	0.042	0.005	0.042	0.002	0.257

Note: For instance, CPV's MLBoD score is obtained as follows: $[(0.002+0.343+1.829)-(0.275+0.018+0.173+0.003+0.706)]$.
Source: the authors.

The weights, determined endogenously based on each country's relative performance, provide insights for public policymaking. For the lagging countries with less favourable MLBoD scores, the composite index acts as an incentive to improve their performance instead of a punishment. MLBoD provides useful benchmarks for lower-ranking countries based upon a linear combination of the observed best performances. Country scores and rankings are meaningful as indicators of relative performance. However, more insights can be gained when the composite indices are broken down and individual dimensions are analysed.

The MLBoD guarantees that realistic and acceptable weights are assigned to each indicator by restricting the weight flexibility in each category on each layer (Shen et al., 2013; Babaee et al., 2015). Each dimension and sub-index are represented and taken into account during the aggregation step. This holds for every SIDS in the dataset. The relative contribution of each indicator (%) is based upon the weight assigned to that indicator. The contributions for each country vary between 35% and 65%, with 30% of flexibility. This range constitutes the lower and upper bounds for the contribution of each indicator. Relative contributions are calculated so that the dimensions with low values are those in which the SIDS must direct the most significant effort. This is discussed in more detail in the following section.

1.4.2 The dimensions' contribution to energy vulnerability

We consider the relative contribution[32] of the dimensions to compute the energy vulnerability index. We thus make full use of the hierarchical structure of the index to target the areas in which the SIDS must make additional efforts to mitigate their relative vulnerability, since the weighting scheme will enhance the dimensions in which each country is most efficient.

The contributions of the exposure and shock sub-indices are 65% and 35%, respectively, for all SIDS (see Table F.1 in Appendix F). This means that SIDS are all more vulnerable on the shock component. Going down the hierarchical structure (layer 3), we observe disparities in the contributions of each dimension. Figure 1.6 maps the SIDS according to the relative contributions of the economic and environmental dimensions for shock (vertical axis) and of the economic and social dimensions for exposure (horizontal axis). Examining the contributions of each dimension allows us to form groups of SIDS and gain useful insights into where the SIDS are weak in specific dimensions.

[32]The contribution (%) is based on the set of weights determined by the model during the optimisation process. For example, the contribution of dimension D1 is given by the ratio of the weight of D1 (i.e. the sum of the weights of ECO13, ECO14 and ECO16) and the sum of the respective weights of D1 and D2. Note that D1 and D2 constitute the exposure sub-index. For instance, the contribution of D1 for ATG (35%) under model (1.4) is obtained as follows: $\left[\frac{0.00692}{(0.00692+0.0126)} \times 100\right]$.

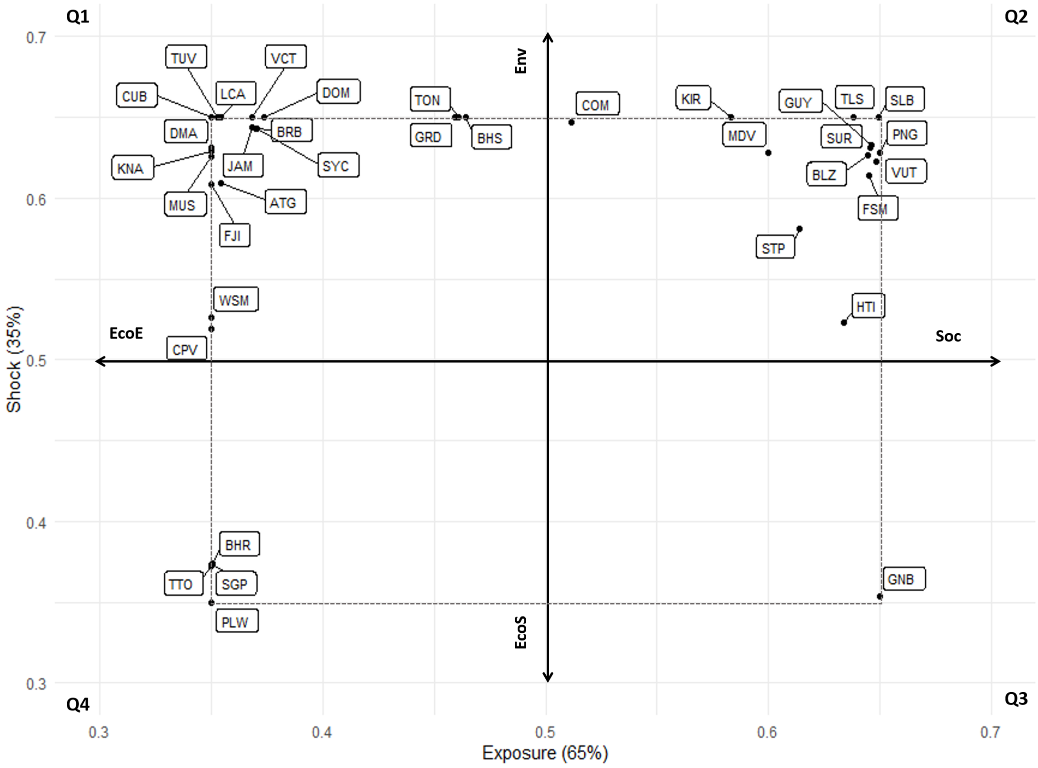


Figure 1.6: Relative contribution of various dimensions to energy vulnerability for each SIDS

Note: SIDS are mapped according to their relative contribution to the economic dimensions of the exposure (EcoE) and shock (EcoS) sub-indices on the horizontal and vertical axes, respectively. Mapping EcoE and EcoS means that the relative contribution of the social and environmental dimensions of the exposure and shock sub-indices can therefore be deduced. For example, Cape Verde's (CPV) EcoE contributed 35% (therefore Soc contributed 65%) and EcoS contributed 52% (therefore Env contributed 48%). We can thus conclude that CPV performed poorly on the economic dimension of the exposure sub-index (EcoE) and, to a lesser extent, on the environmental dimension of the shock sub-index.
Source: the authors.

The SIDS in Q1 must focus on environmental aspects (ENV3) since they are located closer to the extremes of Q1, except for Samoa (WSM) and Cape Verde (CPV), which are closer to the horizontal axis. These two SIDS have similar contributions, with their economic and social dimensions in the shock exposure sub-index contributing almost equally to energy vulnerability. Their main weaknesses are their relative performance levels for the economic dimension of the exposure sub-index.

The SIDS in Q2 also perform poorly on the environmental dimension, although the SIDS closer to the far right also need to improve their performance on the social dimension (SOC1); these include Guyana (GUY), Vanuatu (VUT), Micronesia (FSM), Suriname (SUR), and Belize (BLZ). Comoros (COM), also located in Q2, is closer to the vertical axis; the island is ranked second based on the MLBoD score. Although the relative contributions of both dimensions in the exposure sub-index are almost equal for SIDS in Q2, the contribution of the economic dimension in the shock sub-index is higher than the contribution of the environmental dimension, suggesting the need for additional effort on that dimension.

Guinea-Bissau (GNB) is the only SIDS located in Q3. Its position indicates that additional effort needs to be made to improve the social dimension in the exposure sub-index and the economic dimension in the shock sub-index. Guinea-Bissau is amongst the least electrified of the SIDS, with only 15% of the population having access to electricity in 2015.

The last quadrant (Q4) comprises four SIDS: Bahrain, Palau, Singapore, and Trinidad and Tobago. The economic dimensions in both the exposure and shock sub-indices contribute more to their relative energy vulnerability. These SIDS (especially Bahrain and Trinidad and Tobago) have relatively high primary energy supply per capita. Therefore, this group should focus on improving energy efficiency to reduce their overall energy consumption (ECO1 and ECO5).

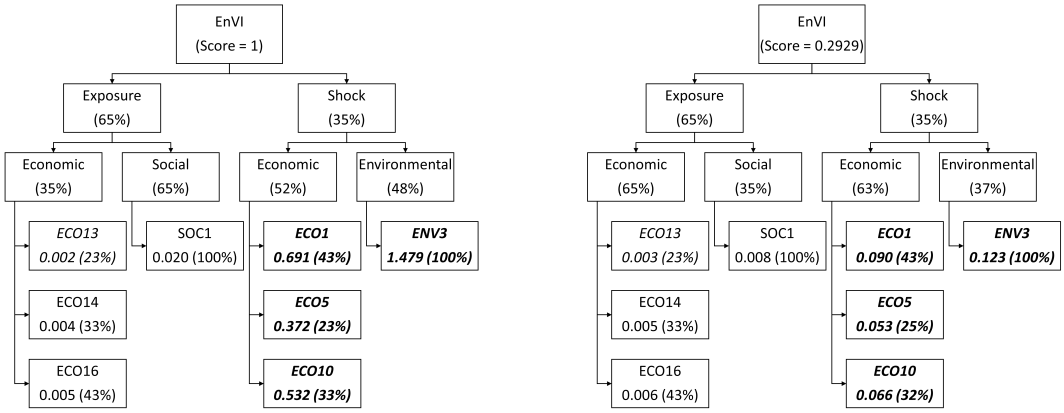
The shock sub-index contributes more to energy vulnerability (35%) than does the exposure sub-index (65%) for all SIDS. However, the exposure component is no less critical. The more exposed a country is, the more likely it is to be affected by exogenous shocks. Therefore, priority areas regarding the contribution of each dimension to overall energy vulnerability can be identified more easily. On a strictly individual level, most SIDS need to focus on the environmental dimension. Indeed, 31 out of the 36 displayed a lower environmental dimension (Q4) contribution than the economic dimension (Q3) on the shock sub-index. On the other hand, most of the SIDS (22) displayed a lower contribution of the economic dimension (Q1) than of the social dimension (Q2) in the exposure sub-index.

We present the case of two SIDS, Cape Verde (leader) and Papua-New-Guinea (laggard), in the following section.

1.4.3 Leader and laggard

Cape Verde is selected as the reference country based on this particular sample and set of indicators. It provides interesting insights into the energy vulnerability mitigation efforts countries need to make based on the energy performances of the leader. Though Cape Verde does not have a 100% secure energy system (i.e., zero vulnerability), it serves as the reference country by which underperforming countries can benchmark the best energy practices. As a leader, Cape Verde illustrates the progress required by those countries considered more vulnerable (those with scores lower than one) through its performance on each indicator in each dimension. Underperforming SIDS can thus work toward Cape Verde's performance level, which can be grasped in terms of a measurable and achievable target for each indicator.

Figure 1.7 provides valuable insights regarding the indicator weights and contributions (%) in each category of each layer of the hierarchy for each country (i.e., the leader and the laggard). More weight is allocated to those dimensions considered 'reverse' since the weighted average of the reverse dimensions (in bold and italics) is subtracted from the weighted average of the 'desirable dimensions', thus punishing relatively poor performance in those dimensions.



(a) Cape Verde (CPV)　　(b) Papua-New-Guinea (PNG)

Figure 1.7: Assigned indicator weights (and shares)

Source: the authors.

Weighting schemes are specific for each country and demonstrate where there is scope for improvement through public policies. Although Papua-New-Guinea has the most vulnerable energy system, the gap between Papua-New-Guinea and Cape Verde is not intractable. Therefore, understanding the performance of Cape Verde on each indicator is a first step toward improving Papua-New-Guinea's overall performance. Cape Verde had a relatively good performance on each indicator, except for its energy dependency (ECO13).

Papua-New-Guinea needs to make a substantial effort in several dimensions. Regarding the social dimension (SOC1), it achieved only 23% of electrification in 2015. This was the second-worst performance in the sample after Guinea-Bissau. The island still struggles to provide its population with universal access to electricity. Energy vulnerability concerns also relate to the environmental dimension (ENV3). Papua-New-Guinea's primary energy mix had a relatively high carbon content (2,084 tons CO_2 per toe against 0.477 tons CO_2 per toe for Cape Verde), primarily due to the presence of petroleum products. This is confirmed by the contribution of Papua-New-Guinea's dimension to its overall MLBoD score. The social dimension (SOC1) contributed 35%, while the environmental dimension (ENV3) contributed 37%. The lower contribution indicates that there is room for improvement in those targeted dimensions.

By contrast, the laggard performed well on the economic dimension (ECO13), indicating that the island is less dependent on imports of fossil fuels (0.526 toe) than is the leader (1.324 toe). Moreover, Papua-New-Guinea had the most diversified primary energy mix of the sample. However, its outstanding performance on only one dimension was insufficient to propel the island into a higher rank. Overall, if we benchmark Cape Verde's performance, Papua-New-Guinea could improve the energy intensity of its economy (ECO5), focusing on the transport sector (ECO10). Moreover, given its relatively inefficient conversion system, using more efficient technologies could allow it to not only ensure efficient conversion of primary energy into useful final energy but also make its economy less energy-intensive.

We also discuss some critical elements that the SIDS should consider and act upon to mitigate their energy vulnerability. To outline the main implications of designing a composite index of energy vulnerability - first, the hierarchical (or nested) structure of our composite index helps to improve our understanding of the factors that exacerbate energy vulnerability in these territories; second, our composite index can serve as a decision-making tool and thus has policy relevance for both analysis and public communication. Finally, benchmarking implies identifying the most efficient unit (i.e., the least vulnerable) as an improvement target for underperforming SIDS.

The structural transformation of the islands' energy systems is necessary for energy vulnerability mitigation. This can be done in several ways, depending on which factors are contributing the most to the relative vulnerability of each SIDS. Exposure to exogenous shocks can be detrimental to the proper functioning of small economies, particularly in terms of economic growth and poverty reduction, with which the SIDS are struggling. Designing a composite index is therefore critical for helping policymakers identify priority areas.

Tackling energy vulnerability requires striking the right balance between being exposed to and being impacted by shocks to lower the global impact of the two combined. Diversifying domestic energy (ECO14) mixes is often seen as a bulwark against exogenous shocks. In addition, a well-diversified energy mix might help dampen the impact of fluctuating energy prices on international markets, especially petroleum products. Diversification strategies may also lower the risk of disruption in the SIDS' energy supply chains, considering a few countries' concentration of fossil reserves.

Technical and technological challenges also deserve attention. Some SIDS experienced heavy losses while converting primary energy into useful final energy (ECO16). The use of more efficient production technologies could enhance the conversion of primary energy into final energy, thus limiting losses overall. Relatively poor SIDS were still struggling to provide universal access to electricity (SOC1) to their population in 2015. International aid and regional cooperation are necessary for supporting SIDS in their transition to more resilient energy systems. This can be done through investment, technological transfers, and technical assistance.

1.4.4 Impacts of normalizing reverse indicators

Table G.1 in Appendix G shows country scores and rankings across the three approaches. Cape Verde remained insensitive to data manipulation across all methods, with an optimal score of one. CI scores ranged between 0.293 and 1 under the direct approach, 0.360 and 1 under the hybrid approach, and 0.761 and 1 under the indirect approach. Comoros (COM) was also identified as a group leader when reverse indicators were rescaled, i.e., direct to hybrid. On the other hand, SIDS were closer to the group leader on average (with a higher CI mean of 0.917) under the indirect approach when reverse indicators were converted into desirable ones, i.e. hybrid to indirect approach. Moreover, Mauritius (MUS) and Samoa (WSM) also scored the maximum value of one. Considering the range of CI scores, one is under the impression that SIDS appear poorly energy vulnerable based on the indirect approach, since the worst performer was Micronesia (FSM) with a score of 0.761.

Overall, SIDS were more sensitive to the rescaling of indicators (direct to hybrid) than the transformation of reverse indicators into desirable ones (hybrid to indirect). This was especially the case for Haiti (HTI) and the Solomon Islands (SLB). The average absolute shift[33] in the country rankings for all SIDS was 4.25 places when indicators are rescaled. SIDS including the Fiji (FJI), Micronesia (FSM), and Samoa (WSM) did not report any change when indicators were rescaled. The rescaling of indicator values highly impacted the ranks of Haiti (HTI) and the Solomon Islands (SLB), which registered the most significant changes (-19 and +12 places, respectively). The transformation of reverse indicators into desirable ones (hybrid to indirect) did not fundamentally change the respective rankings of SIDS. The average absolute shift in the country rankings for all SIDS was 3.28 places. Five SIDS did not report any changes in their rankings: Belize (BLZ), Dominica (DMA), the Dominican Republic (DOM), Fiji (FJI) and Palau (PLW). The most impacted SIDS were St Vincent and the Grenadines (-9), followed by Haiti (HTI) and Vanuatu (VUT), which gained eight places.

We further investigated the impacts of treating reverse indicators on the relative contribution of dimensions to energy vulnerability (see Table G.2 in Appendix G). D1 and D2 denote the economic and social dimensions under the exposure sub-index, and D3 and D4 denote the economic and environmental dimensions under the shock sub-index. Most SIDS did not report significant changes following the rescaling of indica-

[33]The average absolute shift in country ranking ($\overline{R_s}$) "captures the relative shift in the position of the entire system of countries (M) in a single number" (Nardo et al., 2008, p.118). It is computed as follows: $\overline{R_s} = \frac{1}{M}\sum_{c=1}^{M}|Rank_{ref}(CI_c) - Rank(CI_c)|$ where $Rank_{ref}$ refers to the rank given to the country under the hybrid approach.

tors. The five most impacted SIDS were Micronesia (30 points), Maldives (25 points), Kiribati (23 points), Singapore (25 points) and Timor-Leste (22 points). On the other hand, the transformation of reverse indicators into desirable ones further exacerbated the environmental dimension D4. Moreover, most SIDS experienced shifts relative to the contribution of a dimension in favour of another. For instance, Cuba (CUB) reported a shift from D1 to D2. The transformation of reverse indicators in this case led to a lower contribution of the D2 dimension, implying that Cuba should focus on the social dimension instead of the economic dimension. The results highlight the importance of comparing different models and techniques to achieve a reliable and valid interpretation, since the trade-offs between dimensions are impacted.

SIDS with scarce resources are less likely to simultaneously address all the factors contributing to energy vulnerability, since they call for the design of competing policy packages. Hence, the need to prioritise some dimensions to mitigate energy vulnerability becomes increasingly hazardous. For example, a shift from the social dimension to the economic dimension following the rescaling of reverse indicators would favour the implementation of energy efficiency and energy conservation policies at the expense of providing universal access to affordable and reliable electricity. Likewise, a shift from the environmental dimension to the economic dimension under the shock sub-index would prioritise diversification strategies that do not necessarily align with emissions reduction targets.

1.4.5 Impacts of improving energy performance

The results presented in the previous sub-sections suggest that a profound transformation of the energy system represents a way for SIDS to mitigate their relative energy vulnerability. This leads us to question the role of the energy transition in mitigating energy vulnerability. We evaluate the sensitivity of the overall performance of a small island state, Mauritius, to a change in the values of the sub-indicators. For this purpose, wa vary the value of each indicator from 10 to 80%. Table 1.4 shows the results obtained. We did not include SOC1 since access to electricity in Mauritius is close to 100% on the island.

In general, we observe that the score and ranking of Mauritius in relation to other countries vary significantly following an improvement in the sub-indicator of the carbon intensity of primary energy (ENV3). Thus, an improvement of 80% in ENV3 propels Mauritius to first place (1st) with Cape Verde. Considerable efforts are needed, i.e. an improvement of 40-50%, for Mauritius to gain three places in the ranking under the ECO1 and ECO16 indicators, respectively. Mauritius' position does not change as a result of a change in the value of the other sub-indicators (ECO5, ECO10, ECO13, and ECO14). In this sense, the energy transition represents a way for these small territories to mitigate

Table 1.4: Impacts on the score and rank of Mauritius

Improvement	ECO1		ECO5		ECO10		ECO13		ECO14		ECO16		ENV3	
(%)	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
10	0.664	8	0.657	8	0.660	8	0.662	8	0.660	8	0.663	8	0.668	8
20	0.669	8	0.656	8	0.659	8	0.659	8	0.659	8	0.671	8	0.702	6
30	0.672	8	0.652	8	0.664	8	0.664	8	0.662	8	0.670	8	0.721	5
40	0.675	8	0.656	8	0.663	8	0.660	8	0.654	8	0.702	5	0.754	5
50	0.679	7	0.656	8	0.669	8	0.655	8	0.660	8	0.706	5	0.798	4
60	0.689	7	0.657	8	0.671	8	0.658	8	0.654	8	0.734	5	0.840	3
70	0.695	5	0.657	8	0.673	8	0.663	8	0.663	8	0.754	5	0.888	2
80	0.714	5	0.656	8	0.681	8	0.654	8	0.659	8	0.762	5	1.000	1

Source: the authors.

their relative energy vulnerability.

The preliminary results of the sensitivity analysis demonstrate the role that such a transition could play in reducing energy vulnerability. It also offers the possibility to measure the degree of improvement of the overall energy performance of Mauritius. This translates, for example, into a more diversified energy mix, less dependence on imported fossil fuels or a decrease in CO_2 emissions, thus reducing the carbon intensity of primary energy needs. Particular attention should be paid to the environmental aspect, which, as demonstrated earlier, has a significant impact on the degree of vulnerability of Mauritius and other developing island territories.

1.5 Conclusion

This study proposed a composite index with which to assess energy vulnerability in SIDS using an MLBoD approach. Our contribution to research is thus twofold: conceptually, we propose a design for a composite index with a hierarchical structure; in methodological terms, we elaborate an MLBoD approach that considers desirable and reverse indicators. Specifically, we investigate the driving forces behind island energy systems' vulnerability through the nested, hierarchical structure of the composite index.

Uncertainties persist concerning increases in energy demand, fuel availability, prices, and technology changes and the environmental impacts of energy consumption are all factors that reinforce energy vulnerability concerns. In addition, there are apparent socioeconomic disparities amongst SIDS. Therefore, understanding the challenges island energy systems face is essential for energy planning and management and constitutes a first step toward mitigating energy vulnerability. Addressing energy challenges in SIDS is thus critical for overcoming the significant difficulties encountered in these territories.

We show that the composite index of energy vulnerability can be a valuable tool for SIDS in energy performance evaluation, benchmarking, and decision-making. We then provide a classification that highlights differences in SIDS' energy practice patterns. The main finding of this analysis is that most SIDS require significant effort at the environmental level. The economic dimension should also be addressed, with a general trend indicating that the SIDS' energy mixes are poorly diversified. Moreover, their heavy dependence on fossil fuels is detrimental to their energy systems due to their increased exposure to exogenous shocks. Many SIDS also need to implement energy efficiency measures to optimise their primary energy into secondary energy. Minimising losses in energy production, transmission, and distribution chains could help the SIDS reduce the amount of energy their socioeconomic activities consume.

The sample of SIDS investigated by this study might not be large enough to conclude that small island states are highly vulnerable from an energy viewpoint. Future research could investigate the relative vulnerability of other countries to overcome coverage concerns, while also exploring whether SIDS are more vulnerable than advanced or emerging economies. Moreover, the composite index of energy vulnerability is not a standalone tool for vulnerability mitigation. Given the many ad hoc features in the computation of a composite index, outcomes are bound to be different. We provided new insights into the nature and magnitude of changes in country performance based on how reverse indicators are treated. These aspects should not be overlooked when constructing composite indexes, especially in the presence of reverse indicators. The misinterpretation and mishandling of inaccurate information could, indeed, negatively impact the design of policy recommendations.

When constructing a meaningful composite index, there is no single best method to account for reverse indicators. Specific methodological and technical issues should be acknowledged when constructing a meaningful composite index. The assessment of the likely impacts of data transformation and rescaling on CI outcomes appears necessary to gauge the robustness and validity of composite indexes, especially in the presence of reverse indicators. Designing energy policies calls for striking the right balance between energy, socioeconomic, and environmental systems. We encourage the use of a composite index combined with other indicators of growth, development, and progress in order to obtain a more global and comprehensive overview of the specificities of SIDS.

Chapter 2

Estimating electricity consumption in Mauritius: an ARDL bounds test approach to cointegration

2.1 Introduction

Energy is a strategic resource for socio-economic activities and is widely recognised as an inherent feature of modern economies (Blum & Legey, 2012). Its strategic character lies in the plurality of its interrelations with other systems/components (Vera & Langlois, 2007). From an economic point of view, the considerations are mainly related to energy prices and taxes (Kaufmann, 1994; Speck, 1999; Baranzini et al., 2000; Chiu et al., 2015), or the competitiveness of the sectors driving growth (Bureau et al., 2013). Political and diplomatic considerations refer to energy security and independence or relations with suppliers (Bielecki, 2002; Pascual, 2015; Radovanović et al., 2017). Energy is also a social issue, dealing with inequalities, fuel poverty in households, affordability and accessibility issues (Winkler et al., 2011; Reddy, 2015). Finally, more than ever, environmental concerns related to the production and consumption of energy are added to these considerations (Richmond & Kaufmann, 2006; Ang, 2007; Soytas et al., 2007; Apergis & Payne, 2009a, 2010b). These examples, although not exhaustive, demonstrate the importance of developing adequate energy policies.

This chapter focuses on the demand side of the energy transition, and more specifically, on electricity consumption. World electricity consumption per capita grew by 120% between 1990 and 2018. It was the fastest growing energy source over the period (+4% on average per year) and represented 19.3% of total final consumption in 2018.[1] It was the second largest source of total final consumption after oil. As electrification gradually spreads beyond the power system to the whole economy, understanding what

[1] International Energy Agency, https://www.iea.org/fuels-and-technologies/electricity (accessed on 08/12/2020)

drives electricity demand becomes vital. Moreover, investigating the nature and magnitude of the relationship between electricity consumption and other economic variables is paramount for designing and successfully implementing energy and climate policies (Narayan & Singh, 2007).

Literature on the long-run equilibrium relationship between electricity consumption and other economic variables in industrialised and developing countries is substantial. Despite the abundance of empirical evidence, few studies have focused on SIDS[2] (Mishra et al., 2009; Wang et al., 2018; Sultan, 2012; Raghoo & Surroop, 2020; Antonakakis et al., 2017; Shahbaz et al., 2014; Sultan, 2012). Existing studies that include SIDS mostly adopt a multi-country analysis based on panel data. Wang et al. (2018) investigated the impact of urbanisation and economic growth on energy consumption and CO_2 emissions in 170 countries, including a total of 30 SIDS. Antonakakis et al. (2017) also carried out a similar study for a panel of 106 countries, including seven SIDS, categorised into four income groups (low income, lower middle income, upper middle income and high income). Shahbaz et al. (2014) studied the relationship between trade openness and energy consumption for a panel of 91 high, middle- and low-income countries, including four SIDS. Although insightful, these studies failed to address island-specific driving forces of electricity consumption.

On the other hand, Katircioglu (2013) and Narayan & Singh (2007) focused on a single SIDS in their respective studies. Katircioglu (2013) examined the interactions between energy and imports in Singapore for the period 1960-2011. The author found short- and long-run unidirectional causality running from energy to imports. The results suggest that any reduction in energy consumption based on conservation policies[3] would lower the trade volume and consequently reduce trade benefits (Sadorsky, 2011). Narayan & Singh (2007) examined the relationship between electricity consumption and GDP in Fiji. The authors found unidirectional long-run causality running from electricity consumption to GDP. As a result, conservation policies targeting reductions in electricity consumption will adversely impact Fiji's economic growth.

Sultan (2012) and Raghoo & Surroop (2020) are the only two known studies that focus on Mauritius. Sultan (2012) examined the electricity-GDP nexus for Mauritius over 1970-2009 using the ARDL bounds testing approach based on a neoclassical production function to assess the impact of energy and non-energy variables on economic growth. The author found that electricity and exports Granger-caused economic growth in the long-term. Raghoo & Surroop (2020) recently estimated price and income elasticities for petroleum products in Mauritius based on an energy demand function for oil and gas.

[2] Smyth & Narayan (2015) and Payne (2010a) stated that most studies focus on developed and industrialized countries.

[3] Energy conservation policies refer to measures undertaken to reduce energy consumption through energy efficiency or sobriety.

The authors found that gasoline was price and income inelastic in the short-run, while fuel oil was elastic in the long run. None of the studies on Mauritius explicitly estimate electricity consumption.

Considering the challenges faced by island power systems, future research should focus on single-country studies involving SIDS. This study fills the literature gap on electricity consumption in SIDS through a case study on Mauritius by answering the following questions:

1. What are the main drivers of electricity consumption in Mauritius?
2. What is the nature of the relationship between electricity consumption and other key economic variables?
3. Given that Mauritius wishes to embark on an energy transition process, what are the implications for public policy?

This study quantifies how aggregate electricity consumption per capita responds to changes in key economic variables. Our main contribution is, thus, empirical. Our estimated short- and long-run elasticities are valuable for quantitative assessments of policy interventions on energy prices, income, and exports. For this purpose, we apply the ARDL bounds test approach to cointegration developed by Pesaran et al. (1995) and Pesaran et al. (2001), a widely used framework to estimate energy demand relationships for time series data (Bentzen & Engsted, 2001). The ARDL bounds test approach to cointegration[4] appears to be relatively popular among researchers, often including an error correction model (ECM) representation of the underlying ARDL model. It has certain advantages over traditional methods of testing for cointegration like the Johansen cointegration test and the two-step Engle-Granger procedure: (i) it is statistically a more robust approach to determine the cointegration relation in small samples, (ii) it does not require that series are integrated of the same order, i.e. I (0) or I (1) (Ghatak & Siddiki, 2001; Zachariadis, 2010; Acaravci & Ozturk, 2010), and (iii) both short-run and long-run dynamics among variables can be estimated simultaneously while providing unbiased long-run estimates even in the presence of some endogenous variables (Narayan, 2005; Adom et al., 2012).

This chapter is structured as follows. Section 2.2 briefly reviews existing literature on the matter. Section 2.3 briefly presents the economic structure of Mauritius and electricity consumption. Section 2.4 describes the methods used to determine the relationship between electricity consumption and other economic variables. Section 2.5 discusses the empirical results. Section 2.6 concludes and considers the policy implications regarding the re-examination of prior perspectives on energy policies to implement

[4]For interested readers, see Hendry & Juselius (2000) and Hendry & Juselius (2001) for an explanation on cointegration.

in Mauritius.

2.2 Relevant literature

Since Kraft & Kraft (1978) pioneered work on the relationship between energy consumption and economic growth in the United States, research on the topic has flourished, albeit no consensus regarding the nature, the magnitude and the direction of relationships among energy and non-energy variables.[5] This outcome is not surprising as studies differ in geography, scale, period and estimation techniques. We focus on electricity consumption in this chapter. Several studies examine the link among (aggregate or sectoral) electricity consumption, economic growth (proxied by real GDP), and electricity price (Narayan, 2005; Adom, 2017). Other frequently used regressors include population (Zaman et al., 2012; Al-Bajjali & Shamayleh, 2018), trade, urbanization (Halicioglu, 2007; Adom et al., 2012), foreign direct investment (FDI) and temperature (De Vita et al., 2006; Zachariadis, 2010; Blázquez et al., 2013).

2.2.1 Energy consumption and economic growth

Energy is vital for economic growth and development, especially for energy-dependent countries like SIDS. Exploring the energy-growth nexus is crucial for the implementation of sound energy and climate policies (Narayan & Singh, 2007). Virtually all studies investigate the relationship between energy consumption and economic growth, proxied by either gross domestic product (GDP) or gross national income (GNI). We find in the literature the following hypotheses that help explain the energy-growth nexus (Apergis & Tang, 2013):

- Growth hypothesis
  Energy consumption is required to achieve economic growth (Squalli, 2007). Thus, "*an increase in energy consumption causes an increase in real gross domestic product (GDP)*" (Payne, 2010b, p.54). Unidirectional causality running from energy consumption to GDP means that the country is energy dependent. Negative shocks to energy, including, price fluctuations or energy conservation policies will adversely impact GDP. Empirical studies finding evidence of the energy-led growth hypothesis include Stern (1993), Mishra et al. (2009), Apergis & Payne (2010a), Apergis & Payne (2010c), and Apergis & Payne (2009b).

[5]Interested readers can refer to the following literature on energy consumption and economic growth: Stern (1993), Cheng & Lai (1997), Stern (2000), Hondroyiannis et al. (2002), Altinay & Karagol (2004), Oh & Lee (2004), Paul & Bhattacharya (2004), Zamani (2007), Lise & Van Montfort (2007), Belloumi (2009), Bartleet & Gounder (2010), Tsani (2010), Wang et al. (2011), Zhang (2011).

- Conservation hypothesis
  The conservation hypothesis supports unidirectional causality running from economic growth to energy consumption. Thus, energy consumption increases with higher levels of economic growth. In this case, energy conservation policies do not hinder economic growth (Omri, 2014).

- Feedback hypothesis
  The feedback hypothesis implies the existence of bidirectional causality between energy consumption and economic growth. In other words, both variables influence each other. In this case, "*higher energy consumption levels do not generate any harmful effects on economic growth*" (Apergis & Tang, 2013, p.25).

- Neutrality hypothesis
  Under the neutrality hypothesis, there is no causal relationship between energy and GDP. Thus, the implementation of energy conservation policies will not be detrimental to the country's economic growth since energy costs are negligible (Apergis & Tang, 2013; Belloumi, 2009). Policy measures targeting economic growth will not impact energy consumption either. Studies that support the neutrality hypothesis include Paul & Bhattacharya (2004), Belloumi (2009), Payne (2009) and Ozcan & Ozturk (2019).

2.2.2 Energy consumption and energy price

Several studies use energy prices as a critical determinant (Kamerschen & Porter, 2004; Amusa et al., 2009; Valizadeh et al., 2018; Squalli, 2007). Kamerschen & Porter (2004) used disaggregate sectoral electricity demand and found that residential customers in the United States were more price-sensitive than customers in the industrial sector. Using the ARDL bounds test to cointegration approach, Amusa et al. (2009) found that electricity prices did not have significant effects on electricity demand and recommended that future electricity prices based on pricing policies should be cost-reflective in South Africa. Valizadeh et al. (2018) used a bivariate model to examine the relationship between energy consumption efficiency and energy prices in the petrochemical industry in Iran. The authors found that energy prices had a significant and positive effect on energy consumption. The literature on price elasticities of energy demand provides diverging empirical results regarding estimates. Diverging results can be explained by the sample period, the country studied, the data used, or the type of model used. A meta-analysis of existing studies carried out by Labandeira et al. (2017) reported that average price elasticities of energy demand was -0.21 in the short-term and -0.61 in the long-term, indicating that energy demand was inelastic both in the short and long run.

2.2.3 Energy consumption and trade

There is substantial empirical evidence on the relationship between trade and energy consumption in the literature (Narayan & Smyth, 2009; Sadorsky, 2011, 2012; Aïssa et al., 2014; Nasreen & Anwar, 2014; Shahbaz et al., 2014; Jebli & Youssef, 2015; Kahouli, 2017; Zeren & Akkuş, 2020; Rahman, 2021). Investigating such a relationship is vital for the design of energy and trade policies and economic measures. An increase in economic activity through increased exports leads to an increase in energy consumption. On the other hand, energy is an essential production factor. Thus changes in energy consumption levels will likely affect the exports industry. Causality running from energy consumption to trade (exports and imports) implies that energy conservation policies "*will offset trade liberalisation policies designed to promote economic growth*" (Sadorsky, 2012, p.476). Shahbaz et al. (2014) found bidirectional causality between energy consumption and trade openness. Narayan & Smyth (2009) included exports to proxy trade openness in their study. The results support the neutrality hypothesis between energy consumption and exports. Sadorsky (2011) investigates the relationship between energy consumption and trade openness for a panel of eight countries in the Middle East. The author found causality running from exports to energy consumption and bidirectional causality between imports and energy consumption.

2.2.4 Other variables

Several determinants and control variables are found in the literature involving multivariate models:

- Urbanization
  Several researchers used urbanisation in their studies (Mishra et al., 2009; Solarin & Shahbaz, 2013). Urbanisation is relevant since it involves structural changes economy-wide and thus impacts energy consumption. It is commonly defined as the share of the total population living in urban areas. There might exist a unidirectional or bidirectional (usually positive) relationship between urbanisation and energy consumption. Mishra et al. (2009) found causality running from urbanisation to energy consumption in the short-run for small island states in the Pacific. Solarin & Shahbaz (2013) examined the relationship between economic growth, urbanisation and electricity consumption in Angola. The authors found bidirectional causality between electricity consumption and urbanization.

- Temperature
  The climate of a region can be broadly assessed by studying recorded annual temperatures. Assessing changes in temperature over time helps to understand

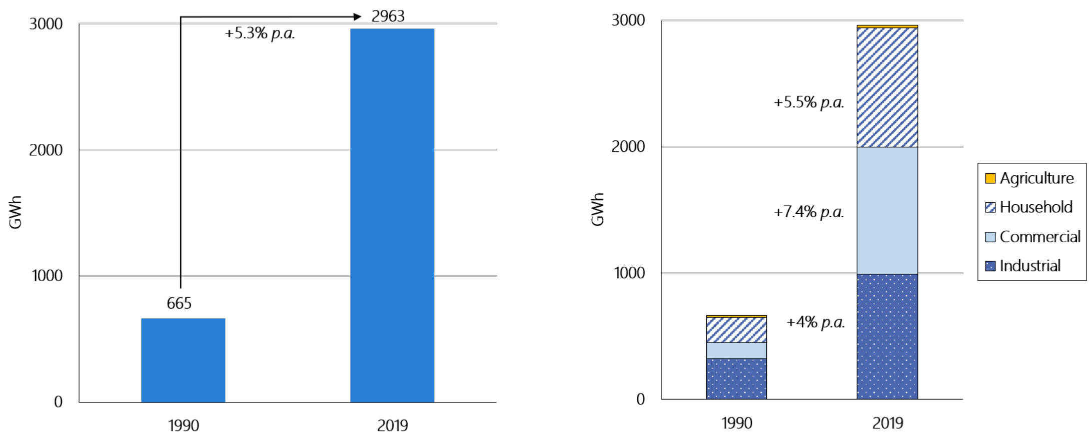
the general need for cooling or heating, thus influencing energy demand. Narayan (2005) and De Vita et al. (2006) both used temperature as an independent variable in their studies. Narayan (2005) focused on the impacts of income, price, air quality and temperature on household electricity demand in Australia. They found that temperature (measured in total degree-days) had a significant effect in the long run when both electricity and natural gas prices were included in the model. De Vita et al. (2006) found that national energy consumption in Namibia was sensitive to mean minimum temperature and decreases when the temperature increases. Most SIDS enjoy tropical climates. Thus, investigating the impacts of mean maximum temperature on electricity consumption would be relevant to capture demand for cooling.

- Foreign direct investment (FDI)
  Niles and Lloyd (2013) pledged for the assessment of the impacts of international aid on the energy sector in small island nations as this "*relates to the deployment of technologies and the formulation of policies*" [p.521]. The acquisition of both conventional and renewable technologies often depends on financial aid received from donor agencies and international organisations. According to Atteridge & Savvidou (2019), Mauritius was one of the top four recipient countries between 2002 and 2016, along with other SIDS, including the Dominican Republic, Haiti and Cape Verde. The authors also recommend that future studies assess the impacts of aid on island energy systems regarding, for instance, potential energy transition pathways. Foreign direct investment (FDI) is often used in the literature to measure financial development (Mudakkar et al., 2013; Zhao et al., 2020). Sadorsky (2010) found evidence of a positive relationship running from FDI to energy consumption in a panel of 22 emerging countries. Dube et al. (2009) showed a feedback effect between FDI and energy consumption in South Africa. These results are confirmed by Tang (2009) in the case of Malaysia in the short run. A similar finding by Zaman et al. (2012) showed that FDI Granger caused electricity consumption.

2.3 Macroeconomic background and electricity consumption in Mauritius

Mauritius is a sovereign island state located in the Southwest Indian Ocean Region. The island's population stood at 1.27 million in 2019, 40.8% of which lived in urban areas. The average annual growth rate of the population of 0.1% has remained stable over the years (SM, 2020d). Since its independence in 1968, Mauritius has transitioned from a low-income, agriculture-dependent economy (particularly on sugar production) to an open and diversified upper-middle-income economy characterised by growth in the industrial, financial and tourism sectors (UNEP, 2014). As a result, Mauritius has achieved steady growth rates above 3% over the past few years. In 2019, the three sectors contributing to gross value added (GVA) were wholesale and retail trade, manufacturing and financial and insurance activities, representing almost 40% of total contribution to GVA (SM, 2020c).

The island's inability to meet demand requirements in the 1960s[6] paved the way for early market liberalisation, with independent power producers (IPPs) jointly generating electricity to power the economy. Electricity consumption has been on the rise due to an ever-increasing demand for end-users and pressure to fulfil growth imperatives on the island. Total electricity consumption amounted to 2,963 GWh in 2019, compared to 665 GWh in 1990, representing an average annual increase of 3.9% over the period (SM, 2019). The share of electricity consumption in total final energy consumption was 25% in 2019. Electricity consumption by sector is presented in Figure 2.1.



(a) Aggregate electricity consumption (GWh) (b) Sectoral electricity consumption (GWh)

Figure 2.1: Evolution of aggregate and sectoral electricity consumption in Mauritius between 1990 and 2019

Source: the author.

Electricity demand in the residential sector usually depends on household income, on the price of electricity and other factors such as household size and weather conditions (Blázquez et al., 2013). Therefore, an increase in household income generates electricity consumption as households move up the energy ladder and acquire new electronic equipment. Figure 2.1 depicts this increase since 1990, suggesting a relatively close relationship with GDP per capita, as both have more than doubled over the period.

[6]Riviere (2015) depicted the history of electricity in Mauritius over the period 1880-2015.

According to the Household Budget Survey released in 2017, electricity represented 80% of households' total energy expenditure.

The commercial sector comprises several industries, including finance and insurance activities, wholesale and retail trade, and tourism. It is essentially service-oriented, with an increasing electricity demand for lighting, air conditioning, and refrigeration, for instance. The average annual growth rate in the commercial sector was 7% over the period, highlighting the link between favourable economic conditions and electricity consumption in the sector.

In Figure 2.1, the industrial (manufacturing) sector was the biggest electricity consumer in 1990 and has dominated total electricity sales since then. Increased electricity demand in the industrial sector can be explained by the economic expansion the island has been experiencing over the last decades. As a result, electricity is the primary energy source for the manufacturing and commercial sectors at 41.9% and 77.72% of total final energy consumption, respectively, highlighting its relative importance for industrial and commercial outputs.

Considering the energy efficiency target of 10% set by the local government (MEPU, 2009) by 2025, substantial effort must be made in terms of demand-side management to drive down consumption and use energy more efficiently. Understanding what factors can potentially impact aggregate electricity consumption in Mauritius remains an important question still unanswered today.

2.4 Methodology

2.4.1 Data

This study uses annual time series secondary data of aggregate electricity consumption per capita, real GDP per capita, real electricity price and real exports of goods and services per capita covering the period 1978-2019 (see Table A.1 of Appendix A for raw data and plots of time series). Descriptive statistics are presented in the following Table 2.1.

Table 2.1: Descriptive statistics in natural logarithm

Variables	Notation	Mean	Std. Dev.	Min	Max	Data sources
Electricity consumption per capita	$tecpc$	6.8668	0.7550	5.6333	7.7061	Statistics Mauritius
Real GDP per capita	$gdppc$	8.5361	0.4783	7.7512	9.3010	World Development Indicators (The World Bank)
Real electricity price	ep	1.2777	0.2814	0.5136	1.6988	Statistics Mauritius
Real exports of goods and services per capita	$exppc$	7.83397	0.51481	6.862	8.41338	World Development Indicators (The World Bank)

Source: the author.

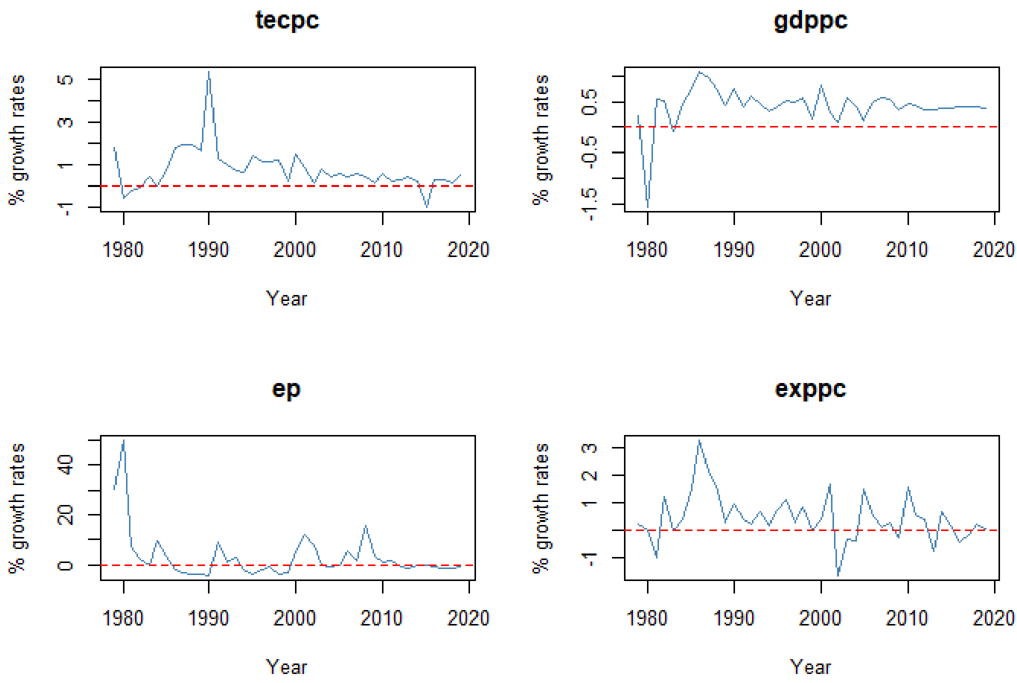


Figure 2.2: Growth rates (%) of series

Source: the author.

Figure 2.2 depicts the percentage growth rates from the four selected series. Understanding the likely events affecting the drivers of electricity consumption is a good starting point to uncover the potential links among the series. An increase in real GDP per capita should drive electricity consumption upwards. Through the structural transition from agriculture to economic diversification, including tourism, business outsourcing and financial services, macroeconomic reforms have sustained positive growth rates over the period.

Much like income, the export industry has benefited from macroeconomic reforms through preferential trade agreements between the 1970s and 1990s, leading to solid growth in exports of goods and services. However, the European Union's decision to lower sugar prices as from 2006 combined with the phasing out of the 'Multi-fiber Agreement' led to a decrease in exports. An increase in electricity tariffs, on the other hand, is supposed to drive electricity consumption downwards according to standard demand theory. However, the Central Electricity Board's (CEB) electricity rates have not increased significantly over the last decade. Moreover, electricity tariffs are currently cross-subsidised in Mauritius to relieve struggling customers and are thus not cost-reflective.

2.4.2 Empirical setting

Short-run dynamics and long-run relationships can be estimated using three popular autoregressive formulations (Rao, 2007): (1) the general-to-specific (GETS) approach based on Hendry et al. (1984), and Hendry (1987); (2) the Vector Error Correction Model (VECM) developed by Johansen (1988) which has gained in popularity across scholars and treats all variables of interest as endogenous; and (3) the Vector Autoregressive (VAR) models which also treat all variables as endogenous was initially developed for forecasting purposes. Other techniques with autoregressive formulations include the Engle-Granger two-step procedure (Engle & Granger, 1987), the Fully Modified Ordinary Least Squares (Phillips & Hansen, 1990) and the ARDL (autoregressive distributed lag) bounds test developed by Pesaran et al. (1995) and Pesaran et al. (2001). The ARDL bounds test approach is a variant of the GETS model.

To investigate the relationship between electricity consumption and other economic variables, we apply the following function[7]:

$$tecpc_t = \alpha_0 + \beta gdppc_t + \gamma ep_t + \lambda exppc_t + \varepsilon_t \tag{2.1}$$

Where $tecpc$ is the log of aggregate electricity consumption measured in kWh per capita; $gdppc$ is the log of real gross domestic product per capita in 2010 US \$ ep is the log of real average electricity price in 2010 US \$ $exppc$ is the log of real merchandise exports of goods and services per capita in 2010 US \$ α_0 is a constant and ε is the error term.

An ARDL model is estimated to capture the effects of real GDP per capita, real electricity price, and real exports per capita on electricity consumption. The log-linear ARDL model[8] based on Equation (2.1) is specified as follows:

$$tecpc_t = \alpha_0 + \sum_{i=1}^{p} \varphi_i tecpc_{t-i} + \sum_{j=0}^{q_1} \beta_j gdppc_{t-j} + \sum_{j=0}^{q_2} \gamma_j ep_{t-j} + \sum_{j=0}^{q_3} \lambda_j exppc_{t-j} + \varepsilon_t \tag{2.2}$$

Where p and q are the optimal lags of tecpc and the regressors, respectively. β_0, γ_0, and λ_0 represent the estimated parameters that translate the instantaneous effect of the respective explanatory variables on $tecpc$.

[7] See Appendix B for examples of model specifications in selected studies.

[8] $tecpc_t$ is explained by its own lagged (past) values and the contemporaneous and lagged values of $gdppc$, ep and $exppc$.

2.4.3 Methods

Investigating the presence of a long-run equilibrium relationship between energy consumption and other vital economic variables involves carrying out several preliminary tests, including the unit root test and the cointegration test. Economic variables are often affected by exogenous shocks, including legislative, technological and structural changes in the economy (Hendry & Juselius, 2000), leading to the variables being non-stationary. These variables are termed unit-root processes, which are "*a type of stochastic non-stationarity induced by the persistent cumulation of past effects*" (Hendry & Juselius, 2000, p.3) and therefore have non-constant means and variances over time. Once the variables are characterised, cointegration tests are carried out to investigate long-run equilibria between the variables of interest. The concept of cointegration was introduced by Granger (1981). Non-stationary variables are cointegrated when a linear combination of the latter is stationary. Thus, cointegrated variables are less likely to result in spurious or nonsense regressions.

Figure 2.3 illustrates the modelling strategy adopted to estimate electricity consumption in Mauritius. The first step is to determine the nature of our series by conducting unit root tests. Three outcomes are possible: (a) the series are all stationary (I(0)), in which case a vector autoregressive (VAR) model can be estimated in levels; (b) the series are all integrated of order 1 (i.e. variables need to be differentiated once to become stationary), in which case a cointegration test should be performed to avoid spurious regressions; (c) the series is a mix of stationary and non-stationary variables, in which case the ARDL bounds tests developed by Pesaran et al. (2001) should be performed. We opt for the ARDL bounds test approach to cointegration that is suitable for small samples (i.e. between 30 and 80 observations).[9] Unit root tests and the ARDL bounds test constitute the preliminary tests.

Suppose we reject the null hypothesis of no cointegration. In that case, we can then proceed to estimate the error-correction form of the autoregressive distributed lag model (ARDL-ECM). The latter identifies the short-run dynamics and the long-run equilibrium relationship among our variables. Finally, we conduct a causality test to study the direction of causality (in the Granger sense). We opt for the Toda-Yamamoto test, which is assumed to be superior to the traditional Granger test. We then proceed to estimate a VAR model augmented by the order of integration of the series. The modelling steps are explained in more detail in the following subsections.

[9] Narayan (2005) provides critical values for small samples.

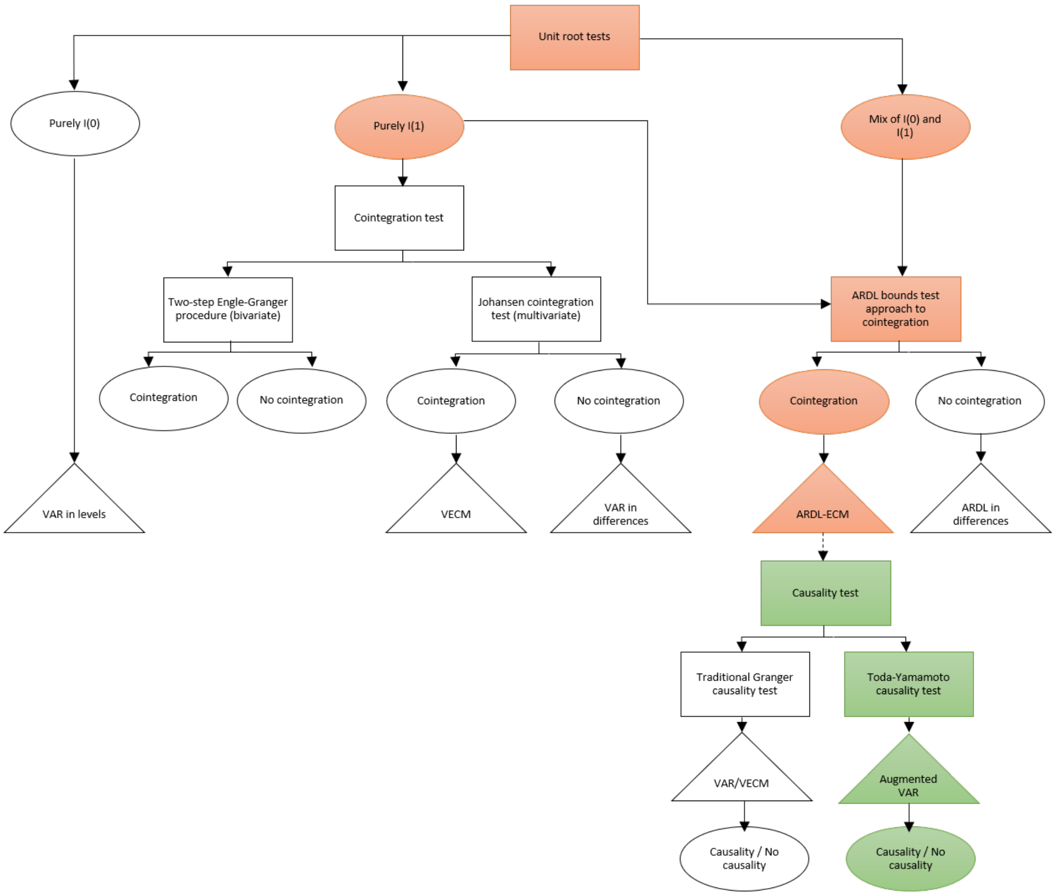


Figure 2.3: Schematic representation of modelling choices

Source: the author.

2.4.3.1 Unit root tests

Investigating the nature of time series data is essential to avoid spurious regression outcomes (Pao & Tsai, 2011). Hence, we test for the stationarity of data series using the Augmented Dickey-Fuller (ADF) test (Dickey & Fuller, 1979, 1981) and the Phillips-Perron (PP) test (Phillips & Perron, 1988). The ADF test proposes a parametric correction of the autocorrelation of the residuals. The PP test proposes a non-parametric method for controlling serial correlation of order greater than 1. It should be noted that the ADF and PP tests admit the same null hypothesis of non-stationarity. In addition, the Kwiatkowski, Phillips, Schmidt, and Shin (Kwiatkowski et al., 1992) test is carried out to cross-check the results. The KPSS test differs from the previous tests in that it admits stationarity around a deterministic trend or a constant as the null hypothesis.

2.4.3.2 ARDL bounds test approach to cointegration

To detect the presence of a long-run equilibrium relationship among the series, we apply the ARDL bounds test approach to cointegration of Pesaran et al. (2001) and use the critical values provided by Narayan (2005) which are suitable for small samples. We reparametrize Equation (2.2) into an error correction model (ECM), which enables the analysis of both short- and long-run dynamics.[10]

$$\begin{aligned}\Delta tecpc_t = \alpha_0 + \sum_{i=1}^{p-1}\varphi_i \Delta tecpc_{t-i} + \sum_{j=1}^{q_1-1}\beta_j \Delta gdppc_{t-j} + \sum_{j=1}^{q_2-1}\gamma_j \Delta ep_{t-j} \\ + \sum_{j=1}^{q_3-1}\lambda_j \Delta exppc_{t-j} + \delta_1 tecpc_{t-1} + \delta_2 gdppc_{t-1} + \delta_3 ep_{t-1} + \delta_4 exppc_{t-1} + \varepsilon_t\end{aligned} \tag{2.3}$$

Where Δ and ε_t are the first difference operator and the white noise error term, respectively. Coefficients of the lagged variables φ_i, β_j, γ_j and λ_j represent the short-run elasticities, while $\delta_1 - \delta_4$ represent the long-run elasticities.

The bounds test procedure is based on the F-statistic for cointegration analysis (Pesaran et al., 2001). Based on Equation (2.3), we test the null hypothesis of no cointegration, i.e. $H_0 : \delta_1 = \delta_2 = \delta_3 = \delta_4 = 0$ against the alternative hypothesis $H_1 : \delta_1 \neq \delta_2 \neq \delta_3 \neq \delta_4 \neq 0$. Pesaran et al. (2001) provide two sets of critical values acting as lower and upper bounds that cover all possible classifications of the regressors into purely I (0), purely I (1) or mutually cointegrated variables. If the F-statistic is lower than the lower bound, the null hypothesis cannot be rejected. If the F-statistic is greater than the upper bound, the null hypothesis is rejected. If the F-statistic lies in the interval, the test is said to be inconclusive (Acaravci & Ozturk, 2010).

The rejection of the null hypothesis of no cointegration confirms the existence of a long-term relationship in the model. Equation (2.3) can be rewritten to derive the lagged error correction term (ECT_{t-1}):

$$\begin{aligned}\Delta tecpc_t = \alpha_0 + \sum_{i=1}^{p-1}\varphi_i \Delta tecpc_{t-i} + \sum_{j=1}^{q_1-1}\beta_j \Delta gdppc_{t-j} + \sum_{j=1}^{q_2-1} \\ \gamma_j \Delta ep_{t-j} + \sum_{j=1}^{q_3-1}\lambda_j \Delta exppc_{t-j} + \psi_{tecpc} ECT_{t-1} + \epsilon_t\end{aligned} \tag{2.4}$$

Where ECT_{t-1} represents the deviation of $\Delta tecpc_t$ from its long-run equilibrium. ψ represents the adjustment parameter that restores equilibrium following a disturbance in the long-run equilibrium relationship. For $\Delta tecpc_t$ to error-correct, ψ should be negative and statistically significant (Wang et al., 2011). ϵ_t is assumed to be a serially

[10]We provide in Appendix C a simple example of how an ARDL (1,1) model can be reparameterised into an ECM.

uncorrelated error term. Equation 2.4 is a partial model[11] that requires the weak exogeneity assumption of regressors to hold for optimal inference and dynamic analysis (Engle et al., 1983), where "*the hypothesis of weak exogeneity for the long-run parameters is formulated as a parametric restriction on the adjustment coefficients*" (Johansen, 1992, p.9).

2.4.3.3 Toda-Yamamoto causality test

Cointegration does not provide information on the direction of causality between variables of interest (Hendry & Juselius, 2001).[12] Granger-causality exists when non-stationary series are cointegrated (Shahbaz et al., 2013). Testing for Granger causality using F-statistics when time series are non-stationary can lead to spurious causality, leading to misleading results (He & Maekawa, 2001). The Granger non-causality test proposed by Toda & Yamamoto (1995) uses a modified Wald (MWALD) test. It is said to be superior to standard Granger-causality tests (Ziramba, 2009; Appiah, 2018) since it "*results in better control of the Type I error probability with often little loss in power*" (Clarke & Mirza, 2006, p.207).

This procedure involves the determination of the maximal order of integration of all the variables (denoted d_{max}) and the optimal lag length (denoted k) for the augmented vector autoregressive (VAR) in the model (Sankaran et al., 2019). A standard MWALD test is conducted on the first k lags in the following augmented VAR ($k + d_{max}$):

$$\begin{bmatrix} tecpc_t \\ gdppc_t \\ ep_t \\ exppc_t \end{bmatrix} = \begin{bmatrix} \eta_0 \\ \theta_0 \\ \omega_0 \\ \pi_0 \end{bmatrix} + \sum_{i=0}^{k} \begin{bmatrix} \eta_{1i} & \eta_{2i} & \eta_{3i} & \eta_{4i} \\ \theta_{1i} & \theta_{2i} & \theta_{3i} & \theta_{4i} \\ \omega_{1i} & \omega_{2i} & \omega_{3i} & \omega_{4i} \\ \pi_{1i} & \pi_{2i} & \pi_{3i} & \pi_{4i} \end{bmatrix} \begin{bmatrix} tecpc_{t-i} \\ gdppc_{t-i} \\ ep_{t-i} \\ exppc_{t-i} \end{bmatrix}$$
$$+ \sum_{j=1}^{d_{max}} \begin{bmatrix} \kappa_{1j} & \kappa_{2j} & \kappa_{3j} & \kappa_{4j} \\ \zeta_{1j} & \zeta_{2j} & \zeta_{3j} & \zeta_{4j} \\ \tau_{1j} & \tau_{2j} & \tau_{3j} & \tau_{4j} \\ \phi_{1j} & \phi_{2j} & \phi_{3j} & \phi_{4j} \end{bmatrix} \begin{bmatrix} tecpc_{t-j} \\ gdppc_{t-j} \\ ep_{t-j} \\ exppc_{t-j} \end{bmatrix} + \begin{bmatrix} \epsilon_{1t} \\ \epsilon_{2t} \\ \epsilon_{3t} \\ \epsilon_{4t} \end{bmatrix} \tag{2.5}$$

For instance, in the above Equation 2.5, $gdppc_t$ does not cause $tecpc_t$ if $\sum_{i=0}^{k} \eta_{2i} = 0$ and $tecpc_t$ does not cause $gdppc_t$ if $\sum_{i=0}^{k} \theta_{1i} = 0$.

[11] Where marginal models do not contain information on the cointegrating vectors and the coefficient of the adjustment parameter.

[12] Although the literature on the energy-growth nexus (and other variables) is substantial, results tend to be inconclusive. No clear patterns regarding the direction of causality can be derived (Mehrara, 2007; Waheed et al., 2019)

2.5 Results and discussion

2.5.1 Unit root tests

The results for unit root tests are presented in Table 2.2 below. Under the ADF and PP tests, all variables appear to have unit roots at level except for the exports series ($exppc$), whose null hypothesis of unit root is rejected at the 5% significance level under the ADF test. Due to the low power of the previous unit root tests (Pfaff, 2008), we cross-checked our results with the KPSS test, which provides similar results. However, GDP per capita ($gdppc$) and exports ($exppc$) appear to be stationary, i.e. I (0), when a trend and a constant are included but are non-stationary when only a constant is included. Moreover, the null hypothesis of unit root processes under both ADF and PP tests is rejected at the 1% significance level when the series are taken in first differences. Therefore, we conclude that variables are I (1).

Table 2.2: Unit root tests

Variables	ADF			PP		KPSS	
	T&C	C	N	T&C	C	T&C	C
Level							
$tecpc$	−0.644	−2.770	-	−0.146	−1.579	0.445	2.079***
$gdppc$	−3.132	-	-	−3.517	0.439	0.107	2.159***
ep	−1.999	−1.044	0.721	−3.04	−2.704	0.137	1.201***
$exppc$	−2.249	−2.453	-	−0.662	−1.978	0.461	2.024***
First difference							
$tecpc$	−4.235***	-	-	−4.320**	-	-	-
$gdppc$	−4.939***	-	-	−5.439***	-	-	-
ep	−3.419	−3.417	−3.407***	−3.980**	-	-	-
$exppc$	−4.920***	-	-	−5.430***	-	-	-
CVs							
5%	−3.50	−2.93	−1.95	−3.586	−2.974	0.146	0.463
1%	−4.15	−3.58	−2.62	−4.338	−3.695	0.216	0.739

***, ** denote statistical significance at 1% and 5% level

Source: the author.

2.5.2 Bounds test approach to cointegration

The ARDL bounds test approach to cointegration is preferable when the sample size is small. The optimal lag length for the ARDL model is based on the Bayesian information criterion (BIC).[13] The latter suggests estimating the ARDL (1,0,0,0) model, which is tested against serial correlation, heteroscedasticity, functional form misspecification, normality and parameter stability. The results of diagnostic tests for the underlying model are reported in Appendix D.

The following Table 2.3 reports the results of the bounds test approach to cointegration. Since we have a sample size of 42 observations, exact critical values are computed and correspond to those found in Narayan (2005). The results indicate the existence of a unique cointegrating equation when electricity consumption is the dependent variable. Furthermore, the estimated F-statistic of 12.3 is above the upper critical bound at 1% significance level, thus rejecting the null hypothesis of no cointegration. We, therefore, consider $gdppc$, ep, and $exppc$ as long-run forcing variables of electricity consumption in Mauritius over the period 1978-2019.

Table 2.3: ARDL bounds test results

Equation	ARDL model	F-statistic	CVs at 5%		CVs at 1%	
			I (0)	I (1)	I (0)	I (1)
$F_{tecpc}(tecpc \mid gdppc, ep, exppc)$	$(1,0,0,0)$	12.3***	3.592	4.788	5.044	6.625
$F_{gdppc}(gdppc \mid tecpc, ep, exppc)$	$(3,1,0,0)$	3.827	3.582	4.806	5.037	6.695
$F_{ep}(ep \mid tecpc, gdppc, exppc)$	$(1,0,1,0)$	2.289	3.572	4.830	5.047	6.607
$F_{exppc}(exppc \mid tecpc, gdppc, ep)$	$(1,0,1,0)$	1.688	3.587	4.825	5.111	6.530

*** denotes statistical significance at 1% level

Source: the author.

A fundamental interest, in this case, is to know whether permanent changes in real GDP per capita, real exports per capita and real electricity prices affect the long-run path of electricity consumption. The existence of a dynamically stable relationship (cointegration), in this case, implies that electricity consumption can drift away from its long-run path in the short-run but will eventually be pulled back to its long-run trajectory by the error-correction mechanism.

2.5.3 Long- and short-run estimates

We proceed to estimate the short- and long-run estimates for Equation (2.4). The corresponding results are provided in Table 2.4.

In the short run, electricity consumption is inelastic to changes in GDP, its price and exports of goods and services. An increase in the price of electricity does not significantly change the demand for the commodity in the short run. A 1% rise in electricity price leads

[13] According to Adom (2017), the value of the F-statistic can prove to be sensitive to the number of lags for each variable.

Table 2.4: Error correction model

Dependent variable: *tecpc*	
	Coefficients (std. err)
Short-run coefficients	
(Intercept)	**−4.687** (0.845)***
$gdppc$	0.072 (0.088)
ep	**−0.148** (0.051)**
$exppc$	**0.272** (0.058)***
ECT_{t-1}	**−0.235** (0.047)***
Long-run coefficients	
(Intercept)	**−19.903** (2.699)***
$gdppc$	**0.307** (0.346)***
ep	**−0.628** (0.230)***
$exppc$	**1.154** (0.247)***
R^2	0.577
Adj. R^2	0.531
Std. Error	0.0417
Num. obs.	41

***, ** denote statistical significance at 1% and 5% level

Source: the author.

to a decrease of 0.15% in electricity consumption, indicating a relatively slow adjustment to price increases in the short run. Short-run income elasticity (GDP) was positive but not significant. Short-run price elasticity is negative and statistically significant, which is coherent with economic theory. Exports of goods and services have a positive and statistically significant impact on electricity consumption, which rises by 0.27% following an increase of 1% in exports.

The coefficient of the error correction term (ECT) is negative and significant (-0.235) at the 1% significance level. The short-run deviations of electricity consumption from its long-run equilibrium are corrected by almost 24% in the previous year. The relatively low value of the ECT coefficient can be explained by high transaction costs or a longer time required for adjustments. Sultan (2012) found a negative and statistically significant adjustment parameter of -0.05, indicating an even slower adjustment process for electricity consumption over the period 1960-2009.

The long-run price elasticity of electricity consumption was -0.628, meaning that a 1% change in electricity prices leads to a decrease of 0.63% in electricity consumption. Thus, electricity consumption is more elastic in the long run than in the short run.

Overall, increases in electricity prices will likely drive electricity conservation behaviours from end-users. However, given the inelastic nature of the electricity price effect, upward adjustments in electricity price will unlikely discourage electricity consumption in Mauritius. This is because prices are heavily subsidised and are not cost-reflective, according to the local network operator. Raghoo & Surroop (2020) found similar results for the demand for gasoline in Mauritius, explaining that own price inelasticity mainly resulted from the absence of substitutes.

In the long run, a 1% change in GDP will likely increase electricity consumption by 0.31%. Narayan (2005) found a similar positive income elasticity of 0.323 for Australia over the period 1969-2000. Electricity consumption in other studies was either elastic (Amusa et al., 2009; Adom et al., 2012; Adom, 2017) or inelastic (De Vita et al., 2006; Halicioglu, 2007; Zaman et al., 2012) to changes in income in the short-run following a 1% change in real GDP, depending on the country under investigation and the underlying economic structure.

Exports of goods and services are positively related to electricity consumption in the long run, with a potential 1.15% increase in electricity consumption following a 1% rise in exports. Overall, the signs of estimated parameters are in line with theoretical expectations. The significant positive impact of GDP and exports will likely outweigh the adverse effects of electricity price on consumption over the period considered. Therefore, policy measures other than tariff shocks to effectively drive electricity consumption downwards should be considered in Mauritius.

Diagnostic tests are carried out to ensure the goodness of fit of the ARDL model (Sari et al., 2008; Ibrahiem, 2015) and that residuals carry the expected desired properties. The following diagnostic tests were carried out: (1) Ramsey RESET test to identify potential misspecification in the model using the square of fitted values; (2) ADF test to ensure that residuals are white noise; (3) Breusch-Godfrey Lagrange Multiplier test for serial autocorrelation in residuals; (4) Breusch-Pagan-Godfrey test was applied to detect heteroscedasticity in the model based on the regression of squared residuals on squared fitted values; (5) Shapiro-Wilk normality test to ensure that residuals are normally distributed. The model diagnostic tests are provided in the following Table 2.5. All model assumptions are validated except the normality assumption.

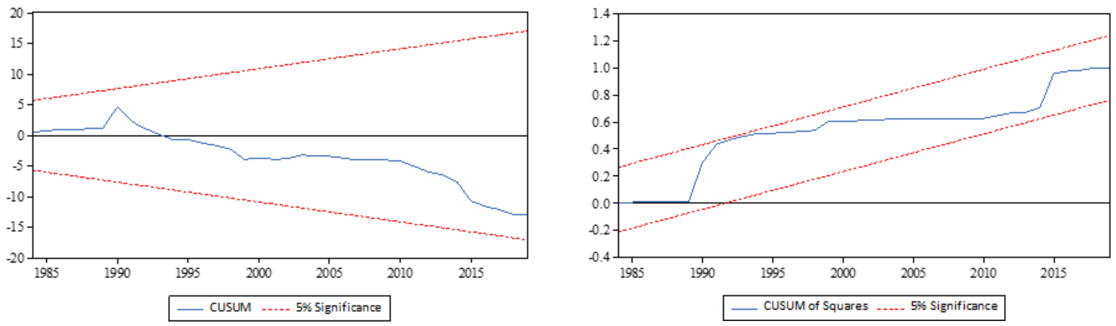
We then apply the cumulative sum (CUSUM) test of Brown et al. (1975) to investigate the global stability of the cointegration relationship over time. A relationship is stable if and only if the curves characterising the CUSUM and the CUSUM of squares remain within the critical band, i.e. at the 5% rejection threshold. The CUSUM plots in Figure 2.4 confirm the constancy of the regression relationships and the stability of parameters over the study period.

Table 2.5: Tests for model validation

Diagnostic tests	
Specification (Ramsey RESET test)	2.463 [0.100]
Unit root test (ADF test)	−4.369 [9.7*e*-05]***
Serial correlation (Breusch-Godfrey LM test)	0.037 [0.848]
Heteroscedasticity (Breusch-Pagan)	4.976 [0.289]
Normality (Shapiro Wilk test)	0.809 [8.5*e*-06]***
Stability (Recursive CUSUM test)	0.744 [0.194]

*** denotes rejection of the null hypothesis at 1% significance level

Source: the author.



(a) Recursive CUSUM test

(b) Recursive CUSUM of squares test

Figure 2.4: Stability plots for the estimated model

Source: the author.

We also conduct stochastic simulations to investigate the response path of electricity consumption, given a change in the shock variables over time. Figure 2.5 plots the cumulative response from shock variables to electricity consumption ($tecpc$) up to 30 periods ahead. See Appendix F for simulation plots of the cumulative response from the other variables.

In line with the long-run estimates, we find that innovations from real GDP per capita ($gdppc$) and real exports ($exppc$) positively impact electricity consumption. In contrast, innovations from real average electricity prices (ep) have negative impacts. As a result, beyond the initial equilibrium behaviour up to period 10, a one standard deviation shock to real GDP per capita causes positive increases in electricity consumption for 20 periods, after which the effect seems to stabilise. Similarly, a one standard deviation shock to real exports positively impacts electricity consumption upon impact and continues to do so over time. On the other hand, the middle graph shows that the shock to electricity price negatively affects electricity consumption over time.

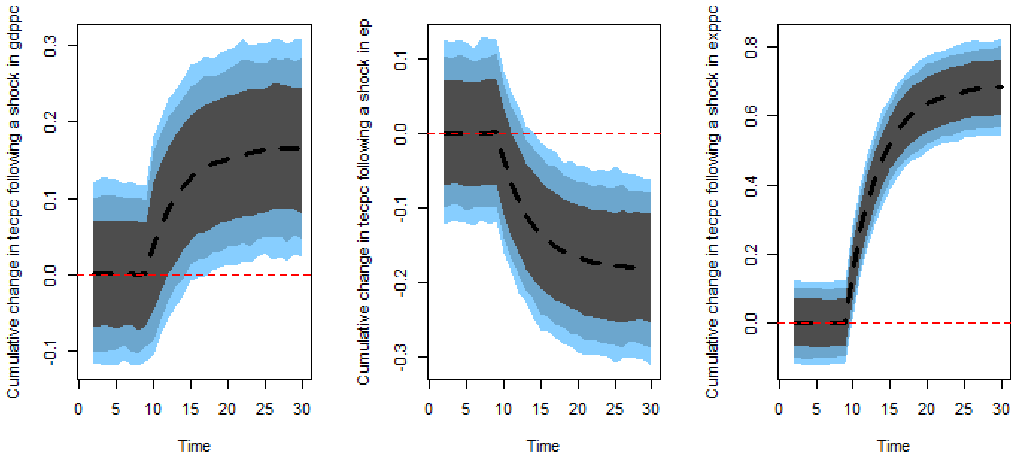


Figure 2.5: Cumulative response from shock variables to electricity consumption

Source: the author.

2.5.4 Causality analysis

Given cointegration among the series, we employed the Toda-Yamamoto causality test to determine the direction of causality. The maximal order of integration is one ($d_{max} = 1$) based on the unit root tests in subsection 2.5.1. The optimal lag length (k) for the augmented VAR ($k + d_{max}$) estimation is chosen based on BIC ($k = 1$). The empirical results for the augmented VAR (2) model are presented in Table 2.6.[14]

Table 2.6: Results of the VAR (2) causality analysis

Dependent variable	*tecpc*	*gdppc*	*ep*	*exppc*
tecpc		0.00023 (0.99)	0.68 (0.41)	0.91 (0.34)
gdppc	0.74 (0.039)		0.078 (0.78)	1.6 (0.15)
ep	5.4 (0.021***)	1.4 (0.23)		2.1 (0.15)
exppc	0.36 (0.55)	2.8 (0.093)	26.3 (2.9e-07***)	

Note: *** and ** denote 1% and 5% significance levels, respectively; p-values are in ().

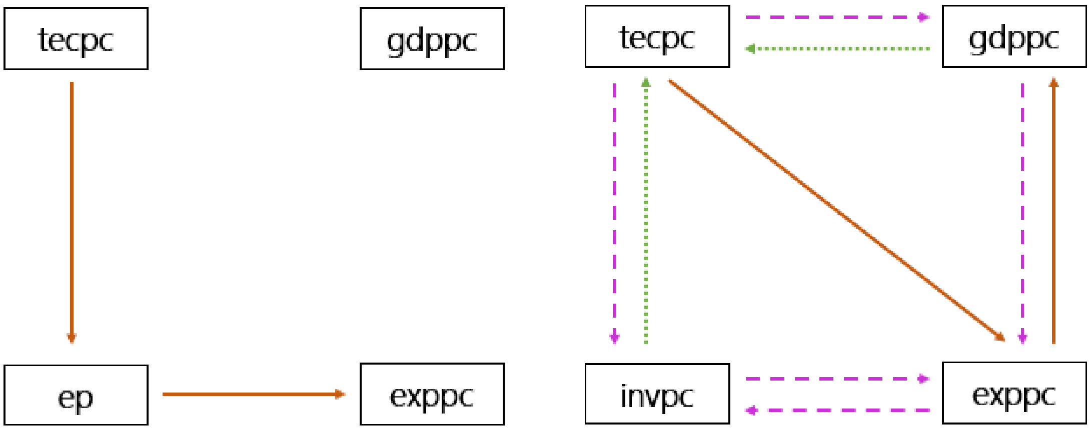
Source: the author.

There is a unidirectional causality running from electricity consumption to electricity price. The fact that electricity price does not Granger-cause electricity consumption suggests that a tariff shock would not necessarily affect electricity consumption, given the cross-subsidisation of electricity tariffs for low-usage groups in Mauritius. We also found unidirectional causality running from electricity prices to exports, with a significant causal effect. A tariff shock would financially burden export-oriented enterprises should electricity prices go up. This situation could hinder their competitiveness in international markets since Mauritius is a small, open economy with an outward-oriented

[14]Diagnostic tests for the augmented vector autoregressive (VAR) model are presented in Appendix E.

strategy.

The results support the neutrality hypothesis between electricity consumption and economic growth, meaning that electricity consumption does not Granger-cause economic growth and vice-versa over the period considered. Regardless of these results, one should be cautious when failing to find a causal relationship between the two because of potentially more nuanced relationships between specific energy types and economic growth (Smyth & Narayan, 2015). The neutrality hypothesis also holds for electricity consumption and exports. Any reductions in electricity consumption through energy conservation policies and demand-side management do not seem to offset trade liberalisation policies. Although electricity consumption remains a crucial input to fuel economic activity, Mauritius is not dependent on electricity consumption for economic growth. Although the population enjoys 100% access to electricity, total electrification has yet to spread across the island energy system - households still use liquified petroleum gas for cooking, and the transport energy mix heavily relies on fossil fuels.



(a) Current study (b) Sultan (2012)

Figure 2.6: Direction of Granger-causality

Source: the author.

Sultan (2012), on the other hand, found multiple short- and long-run causal relationships. Figures 2.6a and 2.6b illustrate the findings in the current study and Sultan (2012) respectively. Differences in the period and the methodology can partially explain the conflicting results. Consequently, Sultan (2012) warned against the negative impact of energy conservation policies on exports and GDP since he found bidirectional causality between the two variables. On the contrary, we found no causal effect in the sense of Granger in this study, suggesting that Mauritius can move forward with electricity conservation policies through already announced targets, including carbon emissions reductions, energy efficiency and demand-side management.

2.6 Conclusion

The lack of understanding of the nature and magnitude of the relationship between electricity consumption and other economic variables in Mauritius motivated this study. This study applied the ARDL bounds test approach to cointegration with an error correction model (ECM) representation over 1978-2019. As a result, we found a unique and stable cointegrating relationship among the variables. Furthermore, the adequacy of the model was checked against several assumptions on the model residuals and global constancy of the parameters.

The results indicate that GDP per capita, electricity price and exports of goods and services per capita significantly explain aggregate electricity consumption in Mauritius in the long run. Electricity price is the only factor that drives electricity demand downwards. However, the positive effect of GDP per capita and exports that outweighed the negative impact of electricity prices on electricity consumption can explain the continuous increase in electricity consumption. Electricity consumption was price and income inelastic, both in the short- and long run. In the short run, demand is inelastic due to the inability of consumers to quickly react to price changes and adjust their respective consumption patterns. With virtually no other substitutes on the island, electricity is difficult to store or replace, even in the long run. Electricity represents 25% of total energy consumption in Mauritius. The electrification process has yet to spread across the whole economy.

The Toda-Yamamoto causality test was applied to investigate the direction of causality among variables. This study supports the neutrality hypothesis between aggregate electricity consumption and economic growth. Furthermore, there was no Granger-causal relationship between electricity consumption and exports. Mauritius is slowly transitioning to a low carbon economy. Based on the findings in this study, we conclude that electricity conservation policies and demand-side management actions appear timely and necessary to lessen the pressure on the domestic power sector without adversely affecting economic growth and trade in the long run.

Further research is required to disentangle the complex relationship between electricity consumption and economic growth. As stated previously, the absence of Granger-causality between the series might hide more nuanced results than those presented in this study. Nevertheless, the econometric analysis of electricity consumption is essential for analysts, the Government and utility companies in Mauritius as the findings may provide answers as to the likely future pathways of electricity consumption. Furthermore, the empirical evidence of a dynamically stable cointegrating relationship presented in this study will be used to forecast electricity consumption in the long run and enhance energy transition scenarios for Mauritius.

Chapter 3

Sustainable energy and climate mitigation pathways in the Republic of Mauritius: a cost-optimisation approach

3.1 Introduction

Climate change represents a significant challenge for small island developing states (SIDS). The energy sector, which accounts for two-thirds of global GHG emissions, has a central role in mitigating emissions.[1] The issue is even more pressing for SIDS, heavily reliant on fossil fuel imports for their primary energy requirements (Surroop et al., 2018). Moreover, high energy costs and limited capacity are additional concerns (Weisser, 2004c; Lucas et al., 2017), reinforcing the need to engage in the clean energy transition (Weisser, 2004b; Timilsina & Shah, 2016; Wolf et al., 2016; Praene et al., 2018).

Despite facing numerous challenges associated with their respective energy systems, SIDS have shown strong political commitment by setting rather ambitious energy and climate targets (Atteridge et al., 2020). Recent observations have pointed to encouraging upward trends in renewable energy uptake in island energy systems, ultimately establishing the momentum for a climate-safe future.[2] Numerous SIDS are on their way to transitioning towards a low-carbon power system. These territories share similar characteristics with other island developing states that make it possible to scale up renewable energy (RE) penetration into their respective power generation mixes. Renewables accounted for 14% of the total primary energy supply of SIDS in the AIMS,[3] 6% in the Caribbean, and 30% in the Pacific in 2017. Bioenergy was the primary source of renewable energy in all three regions.[4]

[1] https://www.irena.org/climatechange
[2] https://islands.irena.org/RE-Progress/Progress-Data, (accessed 16/03/2021)
[3] AIMS stands for the Atlantic, Indian Ocean, Mediterranean and the South China Sea.
[4] SIDS lighthouses, https://islands.irena.org/RE-Progress/Regional-Profiles, (accessed 03/03/2021)

This study aims to provide technical and economic insights into the conditions for achieving renewable energy and GHG emissions reduction targets by 2050 for two islands in the Republic of Mauritius. This study serves as a decision-making tool for policymakers who will have to make choices in the framework of their energy policy. In addition, it aims to assess the technical and organisational implications of sustainable and low-carbon trajectories. This study examines the impacts of announced renewable energy targets and Nationally Determined Contributions (NDC) pledges (under the Paris Agreement) for two island power systems in the Republic of Mauritius. The primary goal is to develop new energy sector pathways towards achieving RE penetration and emissions reduction targets by 2050. We provide a detailed analysis of the challenges and opportunities ahead for Mauritius and Rodrigues Island and the changes that would be required over the next 30 years, including policy milestones set by the government of Mauritius.

Exploring future trajectories is paramount to shed additional light on the investments required, suitable policy instruments and cost-effective strategies to ensure a sustainable, low carbon power mix. Additionally, considering the challenges island energy systems face, investigating the future evolution of the power system is necessary to find more sustainable alternatives to current energy practices. For instance, the reduction of fossil energy dependency and the associated exposure to potential upward price variations or the challenge that insularity and smallness pose for the deployment of specific renewable technologies. All these concerns require adequate policy frameworks to be designed and implemented. This study focuses on two small islands in the Republic of Mauritius (RoM) – mainland Mauritius and Rodrigues Island – that have established energy and climate targets regarding GHG emissions reduction, energy efficiency, and penetration of higher shares of renewables. The share of fossil fuels in the energy mix in 2019 was over 80% in mainland Mauritius and almost 95% in Rodrigues Island (SM, 2020a).

In the Republic of Mauritius, the energy sector is the single most significant contributor to GHG emissions, accounting for 72% of total emissions in 2019 (SM, 2020b). The RoM, like most SIDS, has substantial untapped domestic RE potential. The island aims to reach 35% of RE penetration by 2025 mainly through bagasse, wind and solar energy as announced in the country's Long-term Energy Strategy (MEPU, 2009) and 40% by 2030 by introducing new RE technologies,[5] namely wave energy and offshore wind power as announced in the RE Roadmap 2030 (MEPU, 2019). Besides, an emissions reduction target of 30% by 2030 was ratified in 2016 following the Paris Agreement (MEPU, 2015) to transition to a low carbon energy system gradually.[6]

[5] https://www.edbmauritius.org/renewable-energy

[6] The RoM has yet to update its Nationally Determined Contributions (NDC).

Given the government's stated objectives, we investigate the sustainable and low emission pathways for the two islands in the RoM. We thus shed light on the challenges local authorities may face in pursuing energy transition goals. As such, we explore: (1) the future trajectory of both islands' power systems without targeted incentives from and for stakeholders, (2) CO_2 emissions trajectories considering the RoM's commitment to the Paris Agreement, and (3) the technical feasibility and economic viability of a 35% renewable mix by 2025 as a first step to achieving a sustainable and low carbon energy future. The prospective modelling exercise carried out in this study is extended to 2050 with the primary goal of exposing the challenges and opportunities ahead in terms of power system transition, investment requirements and the role of technologies in the power sector in Mauritius and Rodrigues. We seek to answer the following research questions:

1. Which policy target is most likely capable of shaping a secure and sustainable energy future for the two island power systems in the RoM?
2. Which critical energy technologies are most likely to help the RoM achieve the clean energy transition?
3. How will the system integrate renewables to decarbonise the power systems while meeting growing electricity demand?
4. What investment choices will shape the energy future of Mauritius and Rodrigues Island?

We investigate the future power mix trajectories in the RoM with a bottom-up, cost-optimisation model, which provides insights into possible future energy mix trajectories under a set of economic, technical, and political constraints (Brouwer et al., 2018). Higher shares of RE penetration into the energy mix are seen as a viable and sustainable option as far as the decarbonisation of current energy systems is concerned. Numerous countries, including SIDS, have substantial potential for domestic RE sources such as local biomass, solar, wind, and hydropower. Several studies have been conducted to account for larger RE shares into island energy systems (Blechinger et al., 2016; Neves et al., 2014; Erdinc et al., 2015; Després et al., 2015; Kuang et al., 2016).[7]

This chapter makes several contributions. Firstly, we provide further insights into the long-term evolution of the power sector for both Mauritius and Rodrigues Island. We can capture power sector specificities regarding supply, demand, and network density by modelling the two island power systems separately. Secondly, we extend the discussion

[7]Most studies tend to focus on European islands such as the Canary Islands (Gils & Simon, 2017; Cabrera et al., 2018; Meschede et al., 2018), Cyprus (Taliotis et al., 2017), Greek islands (Kougias et al., 2019) and Italian islands (Andaloro et al., 2012). Drouineau (2011) and Drouineau et al. (2014) assessed the grid stability and reliability of power supply on Reunion Island following higher shares of wind and solar energy

beyond the policy milestones to 2050. For this purpose, we adopt a normative approach for 2019-2030 based on established policy targets and an exploratory target beyond 2030 to 2050. Thirdly, our work considers an alternative CO_2 emissions reduction based approach to drive the evolution of the power mixes. Consequently, our results highlight the need for supplementary efforts and more ambitious plans from policymakers to achieve a sustainable energy transition in the RoM.

This chapter is organised as follows. Section 3.2 describes the current energy landscape in the RoM and briefly reviews the literature on studies in the Republic of Mauritius. Section 3.3 describes the cost-optimisation approach used to explore alternative future pathways and outlines the critical assumptions used in the model. The main findings are presented and discussed in section 3.4. Finally, section 3.5 concludes and proposes the way forward.

3.2 The energy landscape in the Republic of Mauritius

The Republic of Mauritius[8] is a small island developing state located East of Madagascar in the Indian Ocean. Together, the islands form the Republic of Mauritius covering 2,040 km^2. The total population stood at 1.27 million inhabitants in 2019 and is projected to decrease to 1.08 million by 2050 (SM, 2020d). In 2019, the three main sectors contributing to gross value added (GVA) in the RoM were wholesale and retail trade, manufacturing and financial and insurance activities, representing almost 40% of the total contribution to GVA (SM, 2020c).

Rodrigues Island is located 560 km to the North-East of mainland Mauritius. The island's economy is primarily based on tourism, agriculture and fishing. It is highly dependent on merchandise imports from mainland Mauritius, including heavy fuel oil (HFO) and diesel oil used for electricity generation and transportation. The industrial sector is poorly developed, and the main customer base for electricity consumption is the residential sector. Moreover, the island's total land area of 108 km^2 generates competition for land use, which limits RE deployment potential, including solar and wind farms.

3.2.1 Power system portfolio

We focus on the power sector in this study. In the 1990s, Mauritius electricity generation was essentially sourced from heavy fuel oil and diesel, as illustrated by Figure

[8]The term Republic of Mauritius (RoM) includes both mainland Mauritius and Rodrigues Island. Any references to Mauritius only concern the mainland.

3.1. The contribution of heavy fuel oil (diesel/fuel oil) to electricity generation has remained relatively constant over the years, while the share of coal has gradually increased. The liberalisation of the electricity market to include independent power producers of co-fired coal/bagasse power plants could explain the increased market share of coal. Hydropower has also remained constant, and its potential to produce electricity is weather-dependent.

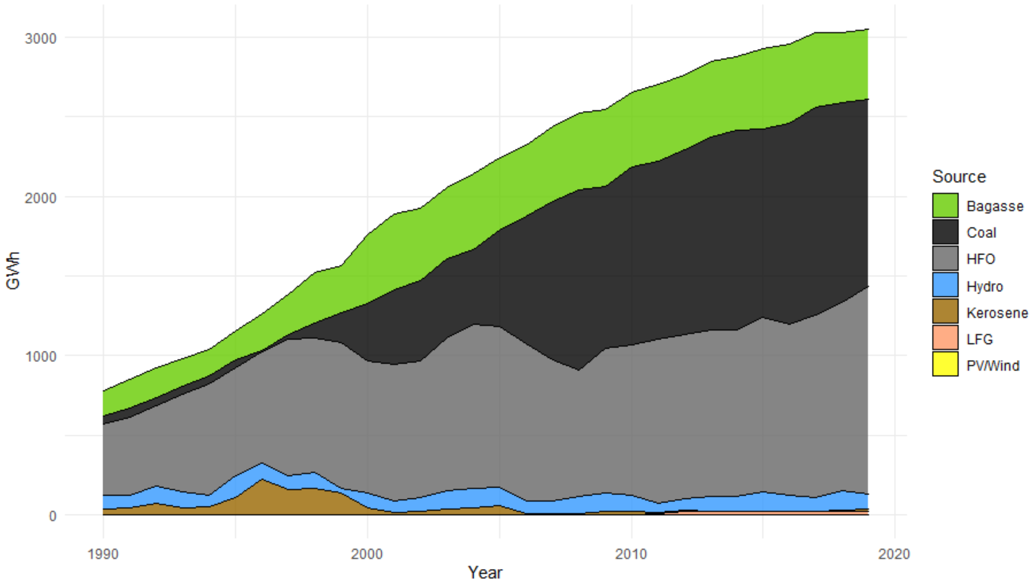
On the other hand, the power generation portfolio of Rodrigues Island is almost exclusively based on HFO. However, the relatively recent contribution of wind and solar PV to electricity generation has tentatively favoured diversity. The island has limited resources, but its significant solar radiation and favourable wind speed make it well located to develop a resource base sourced from renewable energy.

Electricity consumption roughly represents 25% of total energy consumption in the RoM. Upward trends in electricity consumption can be attributed to higher living standards, increased income, and favourable economic conditions that boost demand from the commercial and industrial sectors. As a result, total electricity consumption amounted to 2,841 GWh in 2017, compared to 665 GWh in 1990, representing a 4.3-fold increase over the period (SM, 2018a).

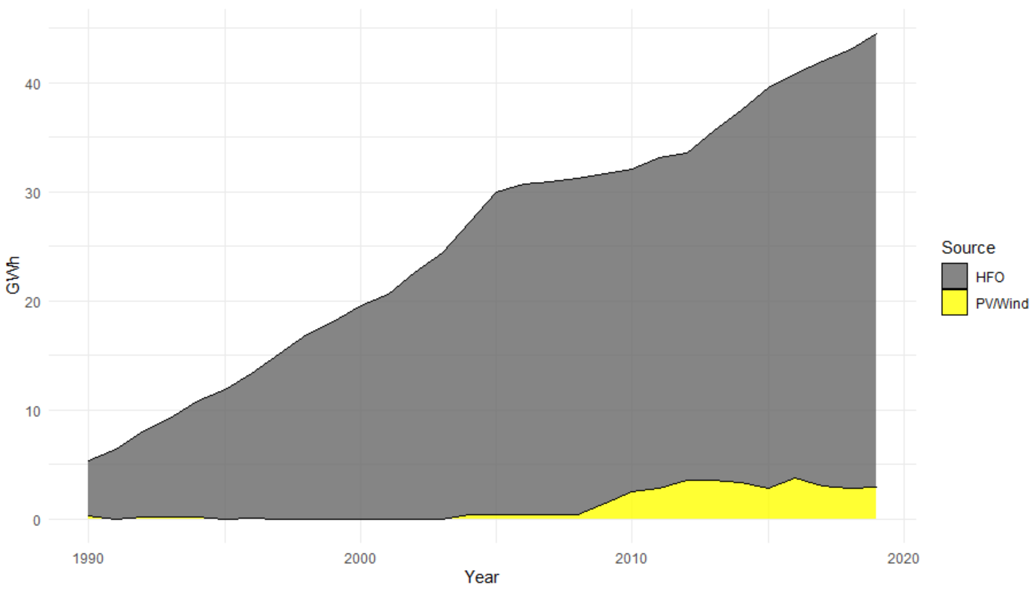
3.2.2 CO_2 emissions

Fuel combustion activities in the RoM, including the power sector, transport sector, and others, accounted for 4.2 Mt CO_2 in 2017 (SM, 2018b), as illustrated in Figure 3.2. The power sector (energy industries - ELC) reported a total of 2.52 Mt CO_2 emissions (60%) that same year, representing a 2.4-fold increase from emissions levels in 2000. The upward trend in emissions was mainly driven by carbon-intensive fuel combustion, primarily from coal followed by oil products. Fuel combustion activities for electricity generation contributed 60.4% to total gross CO_2 emissions in 2017, indicating the power sector's potential to play a central role in mitigating CO_2 emissions. Per capita total CO_2 emissions from the power sector have grown on average by 4.3% per annum since 2000 and stood at 2 tonnes in 2017. Targeting the electricity sector to reduce emissions appears relevant considering the adaptation challenges the RoM is currently facing.

The RoM's first submitted Nationally Determined Contributions (NDC) in 2015 regarding its commitment to the Paris Agreement sets a 30% emissions reduction target by 2030 relative to 2000 emissions levels. The RoM has estimated that 1.5 billion dollars would be required for mitigation actions (MEPU, 2015). The energy sector has been identified as one of the key sectors to address climate change. A restructuring of the current power system is necessary to face tomorrow's energy and climate challenges while guaranteeing reliable and affordable energy services. Low-carbon technologies,



(a) Mauritius



(b) Rodrigues

Figure 3.1: Electricity generation (GWh) over the period 1990-2017

Source: the authors.

especially domestic renewables, play a significant role in mitigating climate change. No carbon tax *per se* is currently in place in Mauritius, but duties are levied on imported fossil fuels. The policy instruments to be implemented will determine the relative speed at which this target will be met.

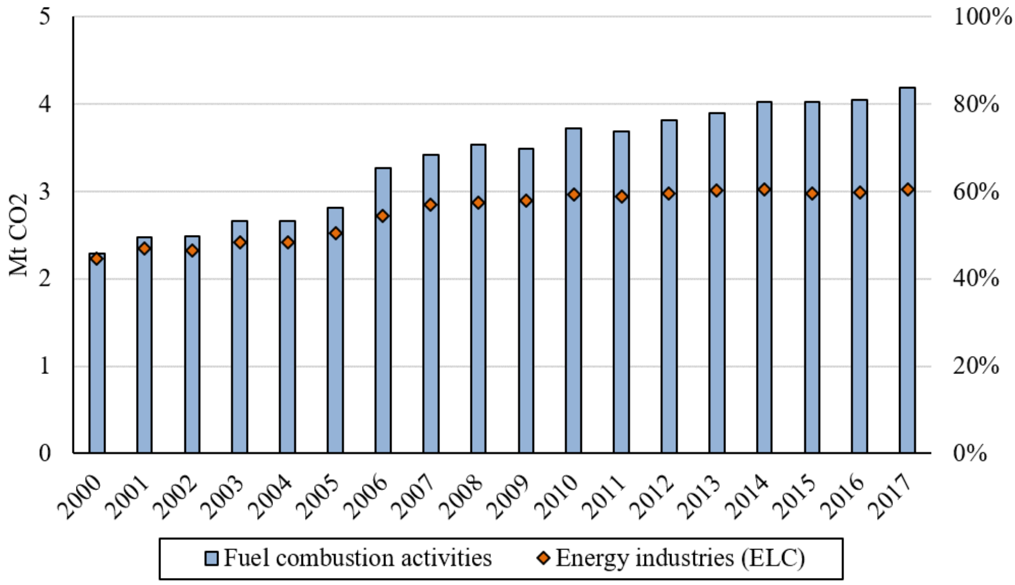


Figure 3.2: Past trends in CO_2 emissions in the RoM

Source: the authors.

3.2.3 Policy targets

The Ministry of Energy and Public Utilities (MEPU) is responsible for formulating energy policies and strategies in the RoM. Together with other parastatal bodies and divisions, the MEPU aspires to "*[. . .] promote sustainable development as part of Mauritius Island's sustainable vision*" (MEPU, 2009, p.1). Figure 3.3 depicts the central bodies governing the energy sector in the RoM.

The energy and climate policy targets and milestones years are illustrated in Figure 3.4. The RoM has set a 35% RE penetration target to be achieved by 2025, according to the Long-term Energy Strategy of the island state (MEPU, 2009). This objective has been reinforced by the RE Roadmap 2030, which sets out varying RE penetration targets by 2030. While Mauritius and Rodrigues extensively rely on foreign non-renewable energy for electricity generation, the Mauritius power generation mix is more diversified than Rodrigues. The latter possesses limited domestic RE sources but is well-endowed with solar and wind energy, although land use is likely to impact the location and size of future solar and wind farms.

Although no official reports or studies have investigated the island's potential for electricity generation, local biomass can also be exploited. Rodrigues Island has similar characteristics to El Hierro Island: small size, limited domestic RE sources, and significant solar and wind energy endowments. These technologies are considered mature enough to penetrate the power mix, coupled with decreasing investment costs. In this environment, policy instruments play a vital role in accelerating the energy transition.

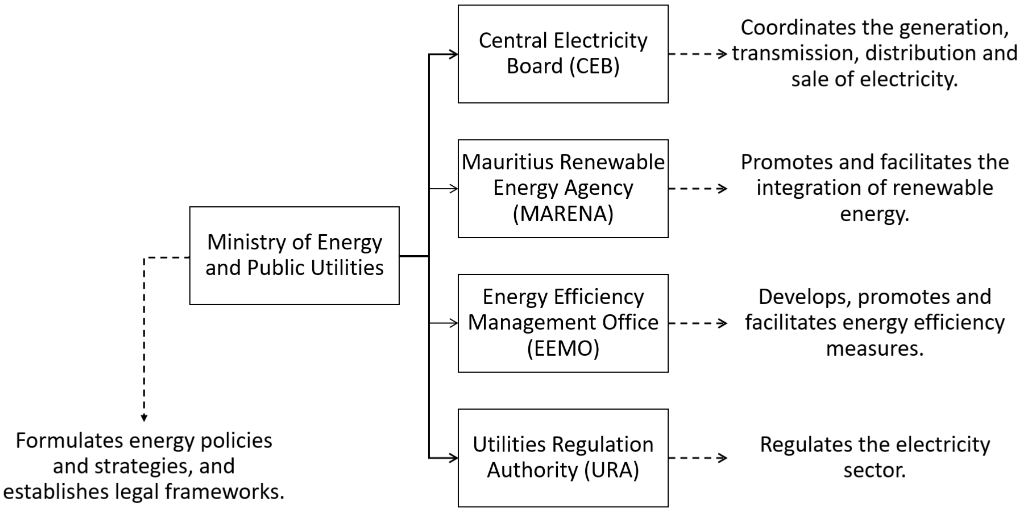


Figure 3.3: Governing bodies of the energy sector in the Republic of Mauritius

Source: the authors.

There is no carbon tax per se currently in Mauritius, but duties are levied on imported fossil fuels.

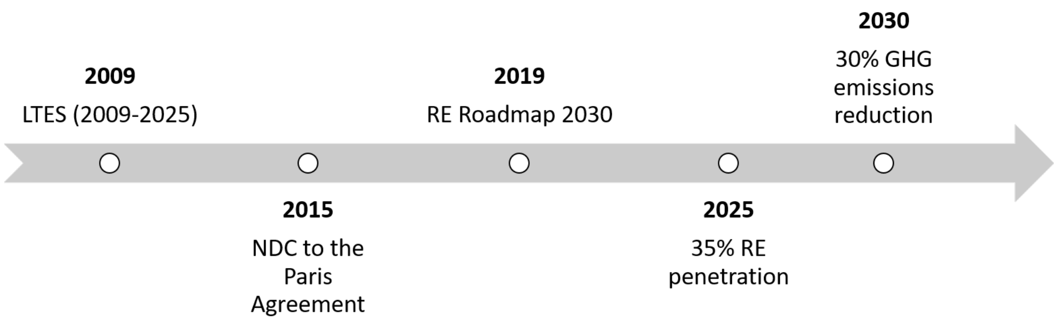


Figure 3.4: Policy milestones in the RoM

Source: the authors.

Setting RE targets is one thing; clearly defining priority policy areas is another. For example, if energy independence and energy security are the main concerns, less mature technologies such as ocean energy and offshore wind will be deployed. Moreover, maintaining diversity in the power generation portfolio is another critical concern for Mauritius and Rodrigues. In addition, the islands have different political orientations: while Mauritius is seeking 35% RE penetration by 2025, Rodrigues Island has pledged, although not officially to date, to achieve energy autonomy by 2030. However, an energy strategy has yet to be designed for the island, making this study particularly relevant to attain this goal.

An interesting discussion relative to both policy targets – sustainable energy and climate mitigation – investigates whether they are complementary or 'conflicting' targets. Different political targets call for different policy instruments. For example, would a 35% RE penetration rate in 2030 have the same impact as a 30% reduction in emissions by 2030? On the other hand, could the RE penetration target be more suitable to curb CO_2 emissions significantly? Besides technical and economic considerations, other essential aspects covering political, social and environmental issues. These include energy sovereignty, diversification of the power generation mix, carbon intensity, and affordable and reliable energy supply.

3.2.4 Relevant literature

Few studies have explored energy transition pathways for the RoM. Weisser (2004a) modelled four electricity supply scenarios for Rodrigues Island between 2001 and 2015 using the discounted cash flow approach to compare electricity generation costs over the modelling horizon. Four electricity supply scenarios with varying degrees of fossil and RE sources were analysed. The author recommended the combination of demand-side management with RE penetration to ensure long-run sustainable power generation. Shea & Ramgolam (2019) investigated Mauritius power system through a levelized cost of electricity (LCOE) analysis. The authors found that a technology's capacity factor had the most impact on its underlying LCOE. Solar power and bagasse had the greatest potential to meet RE targets in Mauritius. In contrast, the potential of hydropower and geothermal energy was deemed unfeasible.

Timmons et al. (2019) also used Mauritius as a case study to investigate a 100% RE penetration into the island's power mix over the horizon spanning from 2016 to 2040 with the OSeMOSYS model.[9] The authors found that the least-cost RE generation portfolio comprises roughly equal shares of biomass and variable RE sources such as solar PV and wind. Timmons et al. (2019) also pointed out the importance of storage technologies in enabling the uptake of RE technologies.

Edoo & King (2020) identified the technical challenges relative to achieving the RE target set by the government of Mauritius as outlined in its Long-term Energy Strategy (MEPU, 2009). The authors employed the EnergyPLAN[10] software to design four scenarios for 2025 and specifically addressed curtailment requirements regarding the integration of large RE shares. Edoo & King (2020) concluded that solar PV could play a significant role in achieving the 35% RE penetration target by 2025, provided conventional fuels are operated at high ramping rates. The Ministry of Energy and Public

[9]The Open Source Energy Modelling System (OSeMOSYS) is a cost-optimisation tool for long-run integrated assessment and energy planning (Howells et al., 2011).

[10]EnergyPLAN simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors (https://www.energyplan.eu/, accessed 23/04/2021)

Utilities released an Energy Roadmap in 2019 that primarily focused on RE integration into the power mix in 2025 and 2030. The report concludes that a 40% RE penetration is viable and feasible provided that wave energy is commercialised and the cost of offshore wind further decreases over time (MEPU, 2019).

Three main observations emerge from these studies. Firstly, islands are studied either as a single region, i.e. the Republic of Mauritius, or as a single island, but not together. Apart from Weisser (2004a), none of the studies distinguishes mainland Mauritius from Rodrigues Island. Although they are part of the RoM, both islands have distinct RE targets and disparate domestic energy potential to replace fossil fuels. Secondly, the integration of larger shares of RE and the underlying costs seem to be the primary concerns. As such, none of these studies specifically consider GHG emissions. The previously mentioned studies mainly focused on techno-economic indicators such as LCOE, marginal cost, and grid stability, which are essential factors when considering higher RE shares penetration. However, they all seem to overlook CO_2 emissions and thus fail to shed light on the environmental policies that can be put in place to abate emissions. Although integrating higher shares of renewables into the power mix would lead to a decline in emissions levels, climate policies *per se* have been neglected. Thirdly, these studies only present findings for milestone years without further information on the pathways to achieve the desired power system in a given year. The analyses proposed in these studies are limited to presenting results for specific years without revealing the trajectories and the efforts required to achieve them. The energy transition is a long-term process. Hence, they fail to replicate the long-term process nature of the energy transition. In this case, it is essential to understand the pace of technology deployment or how the model performs at intermediate periods to reach medium to long-term targets.

Our contribution to the existing literature unfolds into a clearer picture of the challenges that the RoM has yet to overcome, and particularly its efforts to abate CO_2 emissions. Hence, we aim to provide a clear sense of the direction the power sector would follow up to 2050 based on existing policy frameworks and current policy ambitions. We thus adopt a normative approach over 2019-2030 to model specific policy targets and an exploratory approach to 2050 and discuss the implications of energy use, technology uptake and emissions. We provide insights for mainland Mauritius and Rodrigues Island compared to existing studies on transition pathways for the Republic of Mauritius. In our model, we consider the specificities of each power system, which cannot be captured using aggregated data. For example, local disparities are related to both the demand and supply side and local network density.

Moreover, we carry out a more recent analysis of Rodrigues' future power system since Weisser (2004a). Consequently, the analysis and recommendations provided in this study are relevant to each power system's response, thus requiring a more localised approach that cannot be apprehended on a global scale. This chapter shows that the RoM can achieve the announced targets provided an appropriate set of incentives is designed to cater to the restructuring of the current power system.

3.3 Methodology

This study investigates the future energy pathways for the power systems of mainland Mauritius and the outer island of Rodrigues. We modelled the two islands separately to account for their specific power system structures. Inputs for both models were retrieved from Statistics Mauritius,[11] and specific data about new RE investment projects were collected from the Central Electricity Board.[12] The model was calibrated for the reference year 2019 based on data collected in that year. We adopted a cost-optimisation approach to investigate energy transition pathways for the RoM.

3.3.1 The TIMES model generator

The Integrated MARKAL-EFOM System (TIMES) model is a bottom-up optimisation model that highlights the evolution of an energy system, given the potential technological substitutions and potential future adjustments to meet energy demand and end-user services.[13] TIMES offers flexible time frames that consider the evolution from one year to another. Moreover, the modelling of technologies allows for the representation of energy flows and environmental flows (useful for CO_2 constraints).

The objective is to minimise the total discounted cost of the power system while meeting energy demand and responding to environmental and technical constraints. The model matches supply with demand to achieve equilibrium. This equilibrium is qualified as a 'partial equilibrium', being achieved only in the energy sector. The TIMES model generator thus uses optimisation techniques based on linear programming to compute the power system's least-cost path (Loulou et al., 2016). In addition, it works with perfect knowledge of the future and thus adopts a planning posture. Regional discounted costs are then aggregated into a single total cost, which constitutes the objective function to be minimised by the model in its equilibrium computation:

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} * ANNCOST(r, y) \tag{3.1}$$

[11] http://statsmauritius.govmu.org/

[12] https://ceb.mu/

[13] The TIMES model generator was developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA). It is extensively used to explore long-term energy scenarios and has multiple global, regional, national, and local applications. Interested readers can refer to the IEA-ETSAP website for more information: https://iea-etsap.org

where NPV is the net present value of the total system cost; $d_{r,y}$ is the discount rate; $REFYR$ is the reference year for discounting; $YEARS$ is the set of years for which there are costs, and R is the set of regions in the area of study. $ANNCOST(r, y)$ is the total annual cost in region r and year y. It includes capital costs (investment and dismantling), annual cost payments (fixed and variable), and lump-sum revenue (salvage value).

The TIMES model developed for the Republic of Mauritius, *RoM-TIMES*, is a multi-regional model with two internal regions.[14] Figure 3.5 illustrates the exogenous inputs and the expected outputs of the RoM-TIMES power system. The energy balance of the RoM (see Table A.1 of Appendix A) is used to build the reference energy system (RES) of both islands. The RES represents the relationships between the different commodities and technologies in a network diagram (see Figures B.1 and B.2 of Appendix B). We modelled the two power systems separately to highlight their differences and capture each system's specificities. For instance, unlike Mauritius, Rodrigues has limited domestic resources, including solar, wind and fuelwood. Furthermore, a unique low-voltage transmission network exists on the island, indicating a need for enhanced network security compared to mainland Mauritius.

The technologies considered in the RoM-TIMES model are disaggregated in the finest way possible, with each generating unit modelled to provide a faithful representation of the power systems of Mauritius and Rodrigues. It comprises 33 commodities and 115 technologies (see Tables B.1 and B.2 of Appendix B).[15] They are represented along the entire supply chain of primary resources through the transformation to the final distribution of electricity.

3.3.2 Key assumptions

Structure and temporal resolution

The model was calibrated to reflect electricity production and consumption levels in 2019 based on data retrieved from Statistics Mauritius. Figure 3.6 illustrates the power mix for both islands that year for a total installed capacity of 821 MW and 13.9 MW in Mauritius and Rodrigues. Moreover, a general discount rate of 8%[16] is applied. We also carry out a sensitivity analysis to investigate the impact of general discount rates on the power system costs and generation portfolio. These are detailed in subsection 3.4.4.

[14] As a partial equilibrium model, the RoM-TIMES does not model the economic interactions outside of the power sector.

[15] Both power systems are relatively small, and computation time is not an issue.

[16] Baumol (1968) suggests a discount rate within the range of 4.5-9%. Drouineau (2011) used a discount rate of 7% in her study of Reunion Island. Timmons et al. (2019) applied a discount rate of 8% for Mauritius.

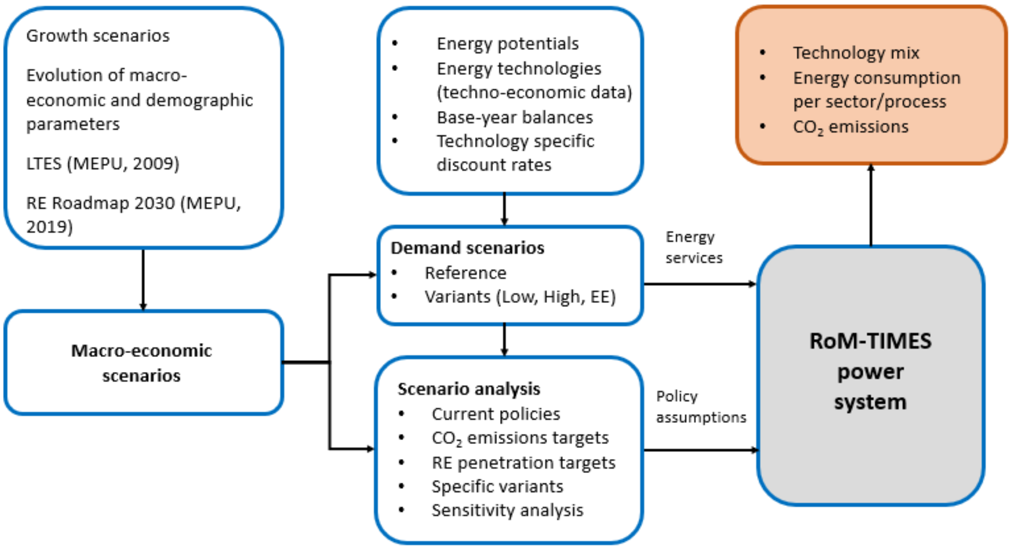
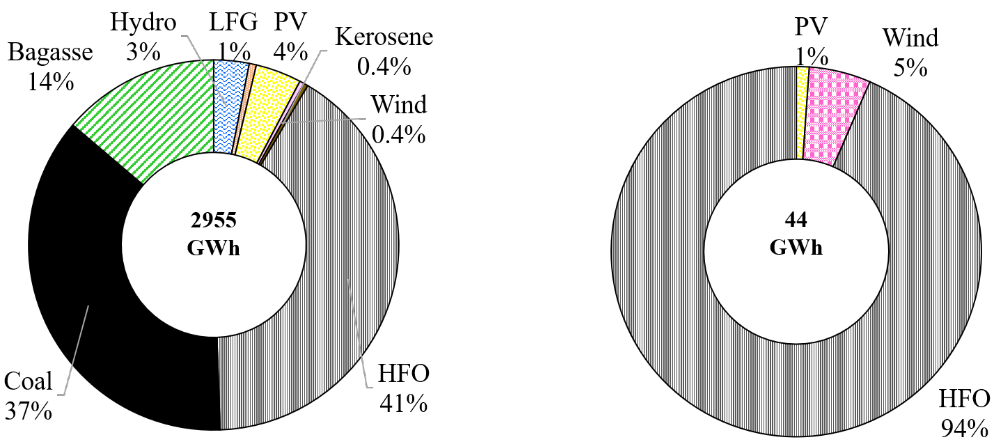


Figure 3.5: Overview of the main exogenous inputs considered in RoM-TIMES

Source: the authors.



(a) Mauritius

(b) Rodrigues

Figure 3.6: Power generation mix in the RoM

Source: the authors.

The modelling horizon spans from 2019 to 2050 and considers decision years every year. These years correspond to those in which investment decisions and capacity increments are made. At a finer scale, the decomposition of each year is carried out on ten timeslices obtained by considering a summer period and a winter period. In each of them, five time steps are identified in a typical day. Based on load curves for both regions in 2019 (Figure 3.7), a typical 24-hour day is cut into ten timeslices (TS) to represent peak demand periods during the day (D1-D5) and at night (N1-N5) in summer (S) and winter (D). See Tables C.1 and C.2 in Appendix C for more details. Peak demand for the year 2019 was 507.2 MW in Mauritius and 7.6 MW in Rodrigues. Therefore, the power generation fleet should be sized according to peak demand, depending on electricity usage. As these are isolated systems, it is important to ensure that the installed capacity exceeds the peak demand at all times to avoid the risk of non-supply of electricity.

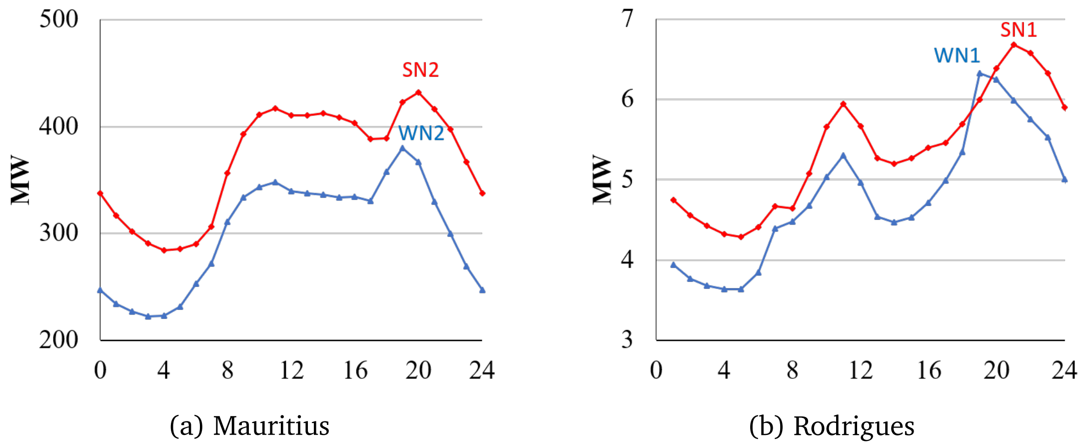


Figure 3.7: Daily load curves

Source: the authors.

We also consider emission factors for stationary combustion per unit of energy (kt/TJ) for each technology (see Table C.3 in Appendix C). We assume carbon neutrality[17] for bagasse, biomass and fuelwood in the RoM-TIMES model. Costs were converted into 2019 euros. See Appendix C for more details on RE potentials (Table C.4) and techno-economic parameters (Table C.5) for the RoM.

Long-term electricity demand

Based on past trends, electricity demand is likely to increase in the future, exerting more pressure on current and future power systems to securely deliver reliable and affordable electricity. As a result, assessing the future evolution of electricity demand is paramount in determining future requirements in generation capacity, investments, and tailoring particular energy and climate policies, including electricity conservation, to achieve stated policy targets. Energy demand projections thus have important policy implications, considering their strategic nature and importance to domestic economies.

The literature on energy demand projections and forecasting includes, but is not limited to, time series models based on past trends (Amarawickrama & Hunt, 2008), regression and econometric models (Zachariadis, 2010; Adom & Bekoe, 2012; Khalifa et al., 2019), machine learning and artificial neural networks (Geem & Roper, 2009), and Grey prediction models (Lee & Tong, 2011). Suganthi & Samuel (2012) presented a comprehensive review of various energy demand models to forecast energy demand's long-term evolution. The authors found that econometric models were the most popular,

[17]The carbon neutrality assumption refers to the fact that biomass combustion emissions are offset by upstream sequestration (ADEME, 2014).

especially to link energy demand with GDP, energy price, gross output and population indicators. To the best of our knowledge, no scenario-based approach for electricity demand projections exist. Moreover, comprehensive national projections for electricity demand for Rodrigues and Mauritius are not readily available.[18]

In the RoM-TIMES model, electricity consumption is estimated over 1978-2019 using a dynamic regression model. The ARDL bounds test approach to cointegration in Chapter 2 suggests that real GDP per capita, real electricity price and real exports of goods and services per capita were the forcing variables that drove electricity consumption in the long run. However, national projections for GDP, electricity price and exports are not currently available for Mauritius for the forecast period. We thus retrieved GDP per capita growth rates for Mauritius from Fouré et al. (2012). Then, using extrapolated growth rates, we computed future values for electricity price and exports per capita based on the historical data series. Projections for the latter variables will be updated when data become available. Consequently, electricity price and exports per capita are set to increase at an annual rate of 1.8% and 2.4%, respectively, based on the calculated compound annual growth rates between 1990 and 2019.

Mauritius's electricity consumption is then projected using the estimated coefficients from the model that capture the dynamics between electricity consumption and its main drivers (GDP per capita, electricity price, and exports per capita). Projections for the main drivers are obtained by extrapolating historical average growth rates over 2020-2050 (see Figure 3.8). Sufficient data were not available for Rodrigues. Electricity demand was thus projected by simply extrapolating historical trends. Table 3.1 provides electricity demand forecasts over 2019-2050 for milestone years.[19]

Table 3.1: Electricity demand (GWh) in the reference scenario

Region	2019	2020	2025	2030	2035	2040	2045	2050
Mauritius	2,814.4	2,939.2	3,511.5	4,097.0	4,171.3	5,368.2	6,051.7	6,779.0
Rodrigues	37.6	45.8	52.4	58.9	65.4	72.0	77.2	85.1

Note: In comparison, electricity demand in Mauritius amounted to 3,775 GWh in 2030 in MEPU (2019) and 4,011 GWh in 2040 in Timmons et al. (2019).
Source: the authors.

3.3.3 Scenarios

Achieving sustainable energy and low-carbon pathways involves the deep restructuring of socio-economic systems. In addition, its medium and long term conditions of implementation present risks and opportunities that need to be anticipated (Colin et al., 2019). Scenarios are useful for energy planning and management as they are a means to

[18]The network operator does not publicly disclose this information.
[19]Please note that energy-saving and efficiency are not considered in this study.

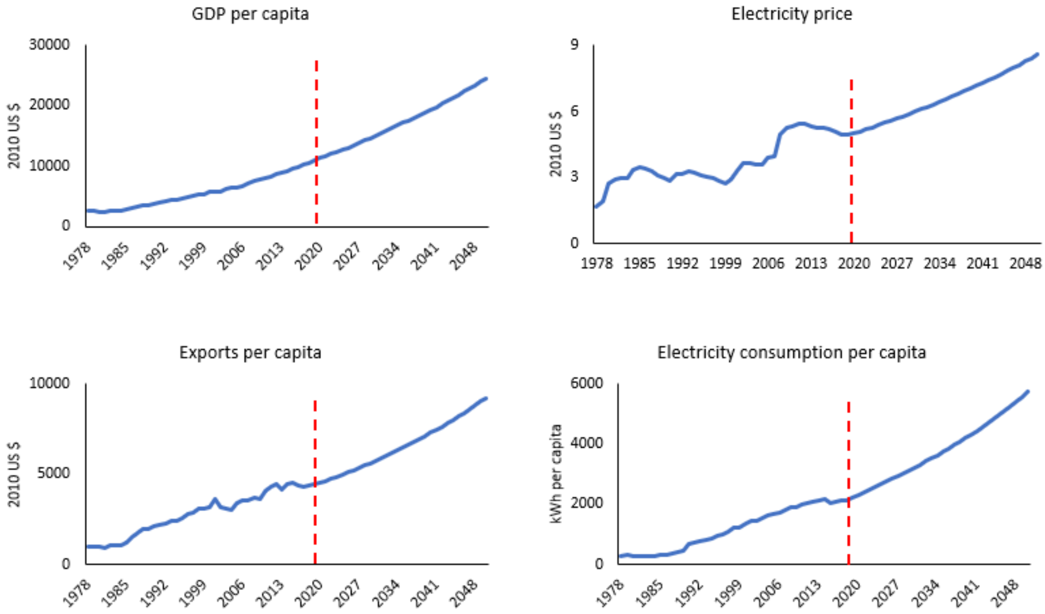


Figure 3.8: Projections for electricity consumption and its drivers

Source: the authors.

portray the future and explore a range of future uncertainties. This chapter aims to assess the impact of existing policy frameworks and announced policy intentions relative to sustainable energy and climate mitigation. Three main scenarios are investigated:

3.3.3.1 Business-As-Usual

In the reference scenario, denoted **BAU**, electricity demand is determined by historical trends and continues to grow over the modelling horizon with limited energy efficiency improvements. There is no incentive or willingness to integrate RE beyond the current penetration rate into the island power systems. Efforts to mitigate CO_2 emissions are close to historical trends and are not compatible with the NDC target. Current features of the power generation portfolio are extended over the modelling horizon.

3.3.3.2 Renewable energy penetration

In the **35RE** scenario, both island power systems are expected to deliver at least 35% renewable energy penetration by 2025. RE technology costs are assumed to gradually drop over the modelling horizon, especially for the less mature ones such as wind offshore and wave energy. Suitable financing conditions for investments in RE projects and technological progress are necessary for this transition. Following (MEPU, 2019), the RE share in the power generation mix increases by five percentage points to reach 40% by 2030, and an additional ten percentage points are modelled by 2050. Compared to the government's current prospective work (MEPU, 2019), we offer a broader spectrum by exploring the role of technologies and potential investment requirements beyond 2030.

3.3.3.3 GHG emissions reduction

The **30GHG** scenario aligns with the announced national NDC target following the Paris Agreement. A 30% reduction target is modelled in the 30GHG scenario[20] to set the maximum emissions allowed for 2030 compared to emission levels in the reference scenario. In this scenario, efforts are primarily diverted towards CO_2 emissions reduction. We model the reduction constraint of an additional 20 percentage points by the end of 2050 to discourage the use of existing thermal power stations and investment in fossil fuel-based technologies beyond 2030.

3.4 Results and discussion

3.4.1 Power generation mix

In Mauritius, electricity generation reaches 4,304 GWh in 2030 and continues to grow at an average annual rate of 3% onwards across all scenarios to reach 7,121 GWh by 2050. In Rodrigues, total electricity generation at the end of the modelling horizon reaches approximately 100 GWh, representing a 6% average annual increase to meet growing electricity demand. Electricity supply growth thus reflects the assumptions about electricity demand presented in Table 3.1 throughout the modelling horizon.

Figures 3.9 and 3.10 compare the evolution of the power generation mix across the three scenarios for Mauritius and Rodrigues. Without policy intervention, the BAU scenario, as illustrated in Figure 3.9, naturally integrates renewables (solar PV, imported biomass and LFG). However, fossil fuels play an important role at the end of the modelling horizon on both islands. In Mauritius, electricity generation from HFO power plants remains constant throughout the study period, except for a drop around 2040, and is displaced by co-fired coal/bagasse power plants. On the other hand, the share of solar PV increases moderately until 2030 and becomes the second-largest power generation technology from that point. Decreasing costs of the technology and the favourable conditions on the island support its penetration into the grid.

In Rodrigues Island, HFO accounts for approximately 42% of total electricity generation by 2050 (Figure 3.10) in the BAU scenario. The share of domestic fuelwood remains constant throughout the study period and plays an essential role in replacing HFO power plants. Renewable energy accounts for 58% (of which 24% of solar PV) by 2050.

[20] This target will be updated when the new NDC for the RoM is announced.

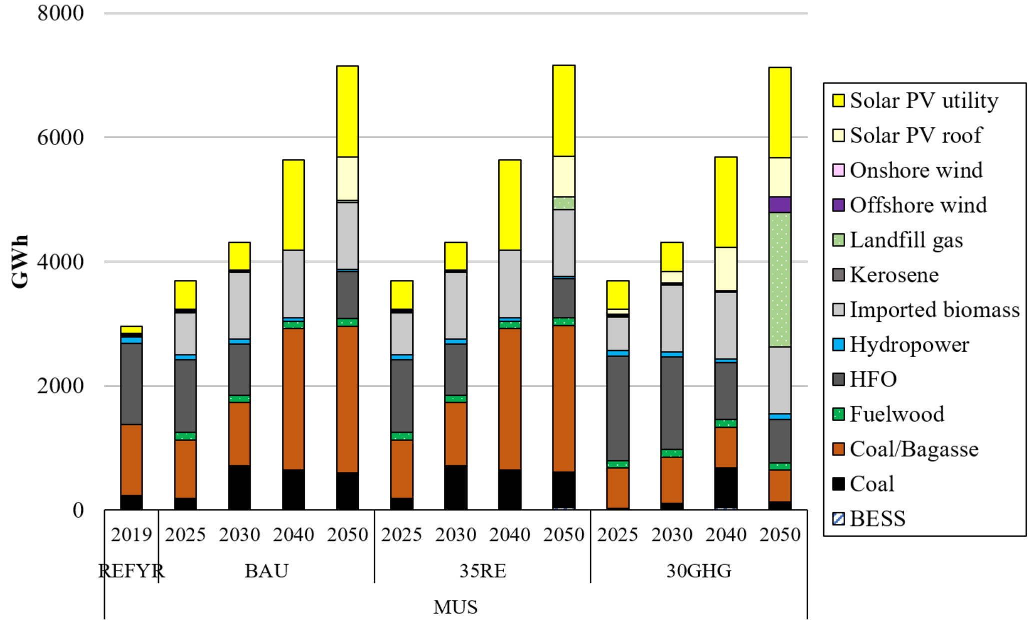


Figure 3.9: Electricity generation in Mauritius

Source: the authors.

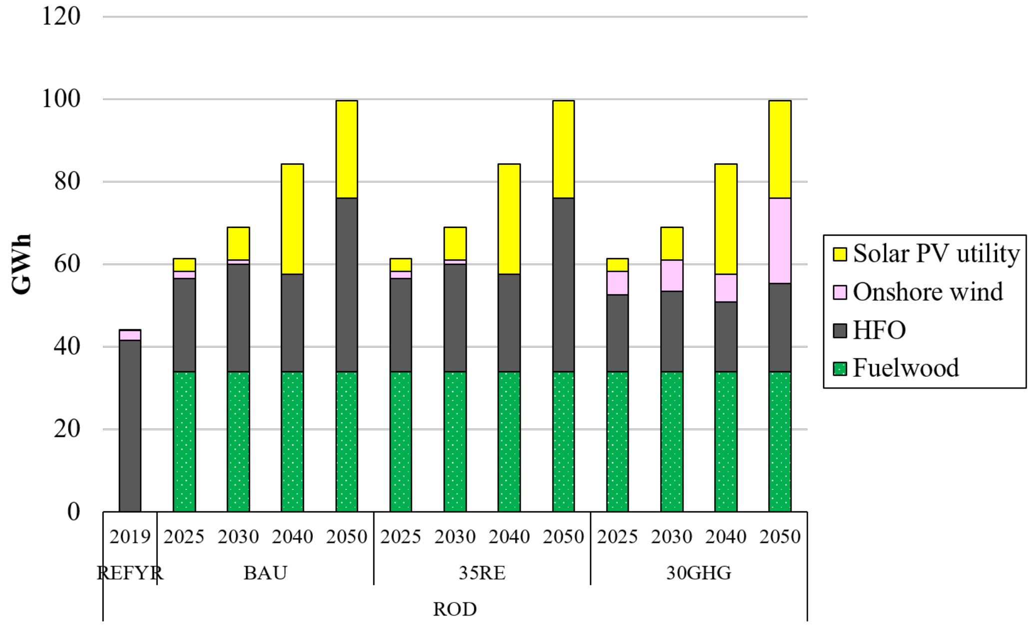


Figure 3.10: Electricity generation in Rodrigues

Source: the authors.

The results do not significantly change in the 35RE scenario for Mauritius. They indicate a relatively slight difference in power generation of 168 GWh sourced from landfill gas and electricity discharged by battery systems in 2050 when RE penetration targets of 50% are established. Solar PV and biomass are associated with other RE sources to achieve RE targets and a cost-effective power system. These results corroborate the findings in Timmons et al. (2019) and Shea & Ramgolam (2019), who highlight the contribution of these two RE sources to the energy transition in Mauritius. The same can be observed in Rodrigues, where the 35RE scenario generates the same results, suggesting that the 35% RE target set by the government of Mauritius is not ambitious enough and needs to be revised upwards.

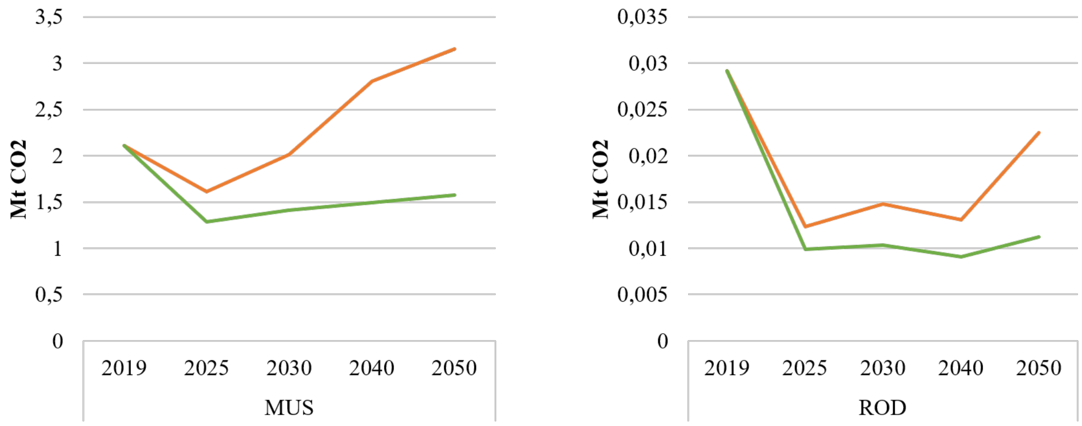
Setting CO_2 emissions reduction targets in the 30GHG scenario changes both island power systems. In Mauritius, fuel switching between coal-fired plants and HFO occurs due to the lower-emitting factor of HFO between 2030 and 2040. Higher decarbonisation requirements to meet the 50% emissions reduction target by the end of the modelling horizon pushes forward landfill gas and, to some extent, offshore wind in 2050. Variable renewable energy makes up 33% of the total by that year, and renewable electricity generation accounts for more than 80% of total generation. Although the share of VRE increases in the power generation mix, storage technologies only play a minor role around 2040 when more solar PV is integrated.

In Rodrigues, the most salient feature is the significant deployment of onshore wind energy compared to the BAU scenario. Fuel switching occurs between HFO and onshore wind to achieve emissions reduction targets. From 2040 onwards, solar PV and onshore wind share in the power generation mix reaches a 45% penetration rate. By the end of the modelling horizon, renewable energy is expected to reach almost 80%. Although the 30GHG scenario does not depict a fully renewable trajectory due to the activity of HFO power plants throughout the modelling horizon, the latter is less carbon-intensive compared to both the BAU and 35RE scenarios in Rodrigues. Moreover, the power generation portfolio is more diversified.

3.4.2 CO_2 emissions and mitigation efforts to decarbonise the power mix

The emissions trajectories across the three scenarios are illustrated in Figure 3.11. Total CO_2 emissions in the BAU scenario reach 2.11 Mt by 2030 and reaches 3.15 Mt by 2050, representing a 1.5-fold increase over the period. Thus, relative to the reference year, emissions almost doubled over the modelling horizon. The same holds for the 35RE scenario, which follows the same emissions' trajectory as the BAU scenario. However, the emissions' trajectory in the BAU scenario merges with that of the 35RE. This shows that the 35RE scenario is not ambitious enough and does not lead to any transformation compared to BAU. As a result, RE targets are not compatible with the NDC pledges made by the RoM in this case. On the other hand, both constrained scenarios result in a drop in CO_2 emissions, although the 30GHG scenario allows for more stringent cuts than the 35RE scenario.

The drop in CO_2 emissions between 2019 and 2025 for Mauritius in BAU and 35RE



(a) Mauritius　　(b) Rodrigues

Figure 3.11: Emissions trajectories across all scenarios in million tonnes CO_2

Source: the authors.

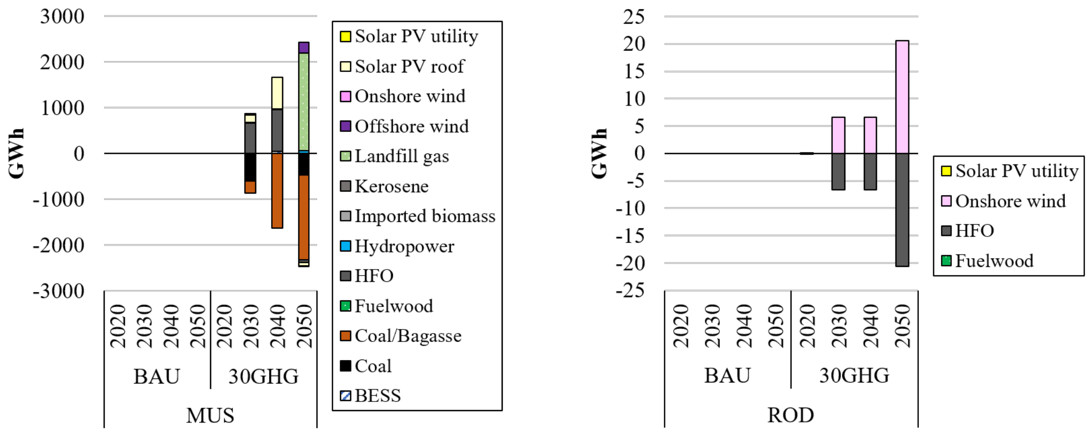
scenarios is due to a fuel switch from coal to bagasse in co-fired power plants to meet RE penetration targets in 2025. In Rodrigues, the initial 94% of electricity generation sourced from HFO power plants in 2019 sharply drops to 37% to integrate more renewables (fuelwood and solar PV) in 2025.

Overall, transitioning to a less carbon-intensive power system requires fuel switching and an increased share of low-carbon/zero-emission technologies. This can be observed for both power systems in the RoM-TIMES. Compared to the BAU scenario, over the period from 2019 to 2050, a total of 24.4 Mt of cumulative CO_2 emissions can be avoided in Mauritius following the establishment of emission reduction targets. As shown in Figure 3.12, avoidance is mainly achieved by substituting coal-fired power plants with HFO plants and a solar PV roof between 2030 and 2040 and by integrating landfill gas and offshore wind by 2050. In Rodrigues, a total of 0.14 Mt of CO_2 can be avoided over the modelling horizon. HFO plants are replaced by up to 21 GWh of onshore wind by 2050.

3.4.3 Economic impact

The total discounted system cost for the BAU scenario in the RoM amounts to 2,366 billion euros, with 98% of total costs supported by Mauritius. Consequently, introducing RE penetration targets in the 35RE scenario does not significantly impact the total system costs for both islands. On the other hand, the 30GHG scenario is significantly more expensive than the BAU scenario for Mauritius and Rodrigues, indicating the relatively higher costs (+4% and +6%, respectively) of achieving CO_2 emissions reduction targets on the islands.

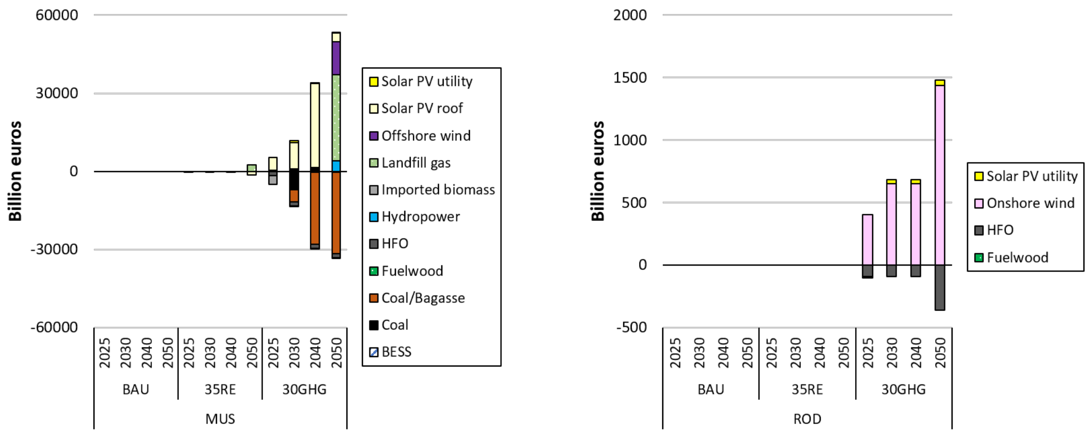
Figure 3.13 shows the total undiscounted investment costs for both islands. In Mau-



(a) Mauritius (b) Rodrigues

Figure 3.12: Difference in power generation in the constrained scenarios w.r.t the BAU scenario

Source: the authors.



(a) Mauritius (b) Rodrigues

Figure 3.13: Total undiscounted investment costs by energy type in billions of euros

Source: the authors.

ritius, the required investment costs in the 35RE scenario do not differ from the BAU scenario. On the other hand, the 30GHG scenario is markedly more capital-intensive than the BAU scenario (+3.95%) due to the new capacity deployment of solar PV roof, landfill gas and offshore wind for a total capacity of 440 MW, 315 MW and 58 MW, respectively for the whole period. In Rodrigues, investment costs differ considerably. Substantial investment is required in the 30GHG scenario compared to the BAU scenario (+30%) due to a larger capacity installation of capital-intensive onshore wind turbines of 16 MW.

3.4.4 Sensitivity analysis for the general discount rate

The choice of the general discount rate (DR) has important implications for the power system and underlying associated costs (García-Gusano et al., 2016). Besides the 8% DR chosen in this study, we investigate the potential impact of varying degrees of DR for the RoM-TIMES model, i.e. 3% (DR-3), 5% (DR-5) and 10% (DR-10). These values are primarily based on the Bank of Mauritius interest rates in the RoM in 2019. On average, the key repo rate[21] stood at 3% and the prime lending rate between 5% and 8% in the RoM in 2019.[22] We believe these are reasonable range indications to carry out a sensitivity analysis. This range corresponds to DR values frequently used in the literature, as shown in Table 3.2.

Overall, we observe that higher discount rates tend to drive down total discounted system costs. However, there is no difference in the total system costs in the BAU and 35RE scenario variants for Mauritius and Rodrigues. Table 3.3 summarises the impacts following a change in the general discount rate.[23]

[21] The repo rate, or the repurchase rate, is the key monetary policy rate of interest at which the central bank makes short-term loans to banks, essentially to control credit availability, inflation, and the economic growth (https://www.financialexpress.com/what-is/repo-rate-meaning/1748807/, accessed 21/06/21).

[22] https://www.bom.mu/sites/default/files/int1219.pdf (accessed 16/03/2021)

[23] Refer to Appendix E for all figures relative to the sensitivity analysis.

Table 3.2: General discount rates in selected energy optimization models

Existing studies	Region/Country	SDR	Modelling horizon	Comments
Weisser (2004a)	Rodrigues Island	7% and 15%	2001-2015	Weisser (2004a) used a Discounted Cash Flow analysis to investigate the impacts of different electricity supply scenarios.
Loulou & Labriet (2008)	Multi-regional model (ETSAP-TIAM)	5%	2005-2100	The World is divided in 16 regions in the current version.
Drouineau (2011)	Réunion Island	7%	2008-2030	
Kannan & Turton (2011)	Switzerland (STEM-E)	3%	2000-2110	Single region covering the electricity sector.
Lind & Rosenberg (2013)	Norway (TIMES-Norway)	7%	2006-2050	
Daly & Fais (2014)	United Kingdom (UKTM)	3.5%	2010-2100	
Vaillancourt et al. (2014)	Canada (TIMES-Canada)	5%	2007-2050	
Simoes et al. (2013)	Europe (JRC-TIMES-EU)	5%	2005-2075	
García-Gusano et al. (2016)	Norway (TIMES-Norway) + Multi-regional model (ETSAP-TIAM)	5%	2010-2050	Conducted a sensitivity analysis ranging from 3 to 15%. Recommended the use of a DR of 4-5%
Timmons et al. (2019)	Mauritius (OSeMOSYS)	8%	2016 and 2040	

Source: the authors.

Table 3.3: Results of sensitivity analysis across scenarios w.r.t respective reference scenarios

Scenarios	Mauritius	Rodrigues
BAU variants	Significant changes are reported for the highest (DR-10) and the lowest (DR-3) discount rates. A 3% DR favours solar PV roof and, to a lesser extent, WGS and batteries from 2020 to 2040 to replace co-fired coal/bagasse plants. By the end of the modelling horizon, landfill gas becomes the preferred technology option to decarbonise the power generation mix at the expense of HFO plants. The magnitude of change is highest when fuel switching occurs in 2040, where 726 GWh of electricity sourced from co-fired plants is sourced from solar PV and WGS instead. The same trends can be observed when a 5% DR is selected, except that WGS is not considered.	There are no significant changes except that both DR-10 and DR-3 variants slightly favour HFO instead of solar PV early in 2020.
35RE variants	Once again, the lowest DRs (i.e. DR-3 and DR-5) account for the most significant changes in the power generation portfolio. Overall, similar trends can be observed to the BAU scenario variants, where coal power plants are replaced by solar PV roof for the most part.	There are no significant changes except that both DR-10 and DR-3 variants slightly favour HFO instead of solar PV early in 2020.
30GHG variants	The most salient feature is the difference in power generation in the DR-3 variant concerning the reference 30GHG scenario. In 2040, a total of 743 GWh of electricity sourced from HFO plants is replaced by landfill gas, co-fired plants, and to a lesser extent, solar PV and offshore wind.	Significant changes are reported for the highest (DR-10) and the lowest (DR-3) discount rates. At a 10% DR, HFO plants marginally replace wind onshore. At a 3% DR, the opposite is observed where onshore wind becomes a more interesting technology option. Again, the difference in power generation is marginal (approx. 0.8 GWh)

Source: the authors.

Overall, the sensitivity analysis, particularly in Rodrigues, reveals that a lower discount rate favours low-carbon and carbon-neutral technologies depending on the scenario under investigation when a cap on emissions levels is set. As a result, offshore wind becomes a technically reliable, economically viable technological option. In Mauritius, considerable fuel switching occurs when the discount rate is at its lowest, i.e. 3%. Although insightful, the sensitivity analysis carried out in this chapter is limited in its scope. The main idea was to investigate the impact of varying but constant discount rates on the future generation portfolio and understand to what extent this might affect the decision-making process when considering which technology options should be given priority. Several studies have considered declining discount rates over time so that future generations are weighted more.[24] However, undertaking such a study goes beyond the scope of this chapter and will be considered for future research.

3.4.5 Discussion

3.4.5.1 Reaching targets

As mentioned above, the current RE penetration target of 35% in 2025 and 40% in 2030 is incompatible with the RoM's NDC pledge. A vital factor to consider is that mature and cost-competitive RE technologies will drive the transition, supported by less mature ones like offshore wind. The 30GHG scenario is more likely to shape a sustainable energy future compatible with energy and climate imperatives. Newly installed renewable power capacity becomes cost-competitive, even when cheap power generation options are available, illustrating the importance of renewables in the future power mix. Consequently, reaching energy and climate targets does not necessarily mean more economic compromise regarding additional clean investments for Mauritius.

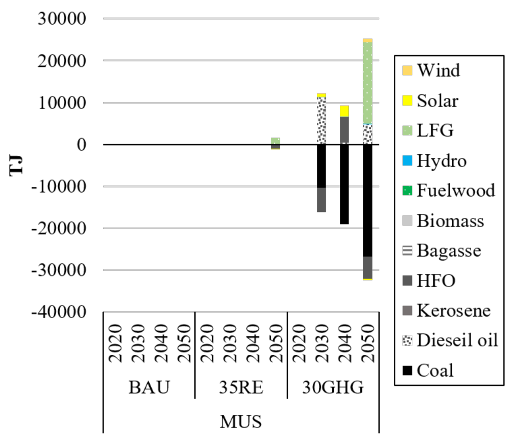
Furthermore, the central role played by fuelwood in Rodrigues' power generation mix, regardless of the scenarios considered, calls for the consideration of several parameters. First, Rodrigues is particularly limited in surface area, implying a trade-off between agriculture and land area dedicated to deploying RE projects, including solar and wind farms. The energy transition, although necessary, will have to align with the national development agendas of these territories without hindering their growth and socio-economic development (Atteridge et al., 2020). Third, with fewer technology options and an almost exclusively fossil-based power mix, Rodrigues will have to mobilise climate financing like the UNDP and the Green Climate Fund that support climate mitigation efforts through NDC implementation. No single energy source is the absolute winner; the optimal mix minimises costs, meets energy demand and achieves the desired targets. Instead, the deployment of renewable technologies must be supported

[24] See Pearce et al. (2003) and Groom et al. (2005) for discussions on this specific issue.

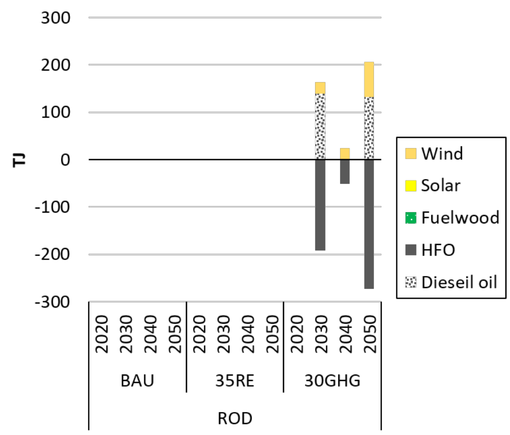
by enabling technologies that cater for system flexibility and prevent significant system failures.

3.4.5.2 Energy security

In this study, the power systems progressively become more diverse as targets become more stringent in constrained scenarios. Policymakers should thus work towards maintaining this level of diversity and balance, as a diverse power system acts as a bulwark against major external shocks that could potentially disrupt the supply chain. In addition, transitioning to a low-carbon energy system implies switching from high-carbon content technologies to low-carbon/carbon-neutral technologies.



(a) Mauritius



(b) Rodrigues

Figure 3.14: Difference in primary energy supply (TJ) requirements w.r.t the BAU scenario

Source: the authors.

Figure 3.14 illustrates the primary energy supply requirements for power generation in Mauritius and Rodrigues. As a result, the energy systems in both islands will rely less on imported fossil fuels, especially more polluting ones (such as coal for Mauritius and HFO for Rodrigues), to meet their primary energy requirement. This is a crucial benefit for a small island state like the RoM, which has historically relied heavily on imported fossil fuels and has been exposed to energy price fluctuations on international energy markets and supply chain disruptions. However, the question of old dependencies versus new ones remains. Indeed, the results show that 15% of the electricity production in 2050 comes from imported biomass, which may be a barrier for Mauritius if it aspires to electricity autonomy one day. As fossil fuels such as coal are phased out, the share of imported biomass increases.

3.5 Conclusion and policy implications

Our work explored sustainable and low-emission pathways for two island power systems in the Republic of Mauritius (RoM) based on a cost-optimisation approach. We focused on established policy targets relative to RE penetration to promote sustainable energy and climate mitigation to curb CO_2 emissions in Mauritius and Rodrigues.

The study shows that renewable electricity generation substantially increases throughout the modelling horizon in both power systems to reach over 87% in Mauritius and 79% in Rodrigues by 2050 when emissions reduction targets are set. The successful transition of the Rodrigues power system to a low-carbon pathway relies on onshore wind and fuelwood. However, Rodrigues's projected biomass-dominated electricity mix remains uncertain since its potential still needs to be assessed. Other islands with similar characteristics, such as El-Hierro in the Canary Islands, could serve as an example to develop a coherent energy strategy, which does not exist currently.

In Mauritius, CO_2 emissions are effectively reduced by switching fuel from coal-fired plants to renewable energy, in the form of solar PV earlier on, and landfill gas by the end of the modelling horizon. We can therefore deduce that RE penetration targets will not help islands in the RoM curb CO_2 emissions by 30% by 2030. Moreover, based on the model's assumptions and despite increasing generation from renewables, similarly rigorous RE penetration targets are not compatible with current NDC pledges. This situation will become even more irrelevant when the country's new NDC is announced, considering that recently updated NDCs are more stringent than previous ones.

The explicit bound on CO_2 emissions in the 30GHG scenario appears to be more suitable for long-term emission reductions. When the RoM's new NDC target is revised upwards, introducing a CO_2 tax might be considered a powerful policy instrument to further curb CO_2 emissions in the power sector in the RoM. The challenge would be to discuss which levers would facilitate the fulfilment of the announced objectives and, in particular, to assess whether a carbon tax is a viable policy instrument in the RoM. A scenario modelling a carbon tax could be investigated to estimate the optimal tax level to be introduced to finance more ambitious climate targets. However, a carbon tax alone is not enough to accelerate the energy transition. This policy instrument must be accompanied by other measures, including a demand-side policy focused on demand management and energy efficiency.

Mauritius and Rodrigues Island can reduce their dependence on energy imports for electricity generation based on the gradual fuel switch from HFO and coal to domestic energy sources within the optimisation framework and modelling horizon. The 30GHG scenario enhances the diversification of the power generation portfolios compared to the baseline scenario. Energy independence and generation mix diversity are indicators that convey information about a power system's global performance. As discussed in Genave et al. (2020), these two indicators, along with others, including CO_2 intensity of primary energy, contribute to a power system's relative energy vulnerability. The extent to which small island developing states, including the Republic of Mauritius, can mitigate energy vulnerability through cost-optimal power system energy transition constitutes an interesting avenue for future research.

Main conclusion

> *"Pragmatism suggests that when the thesis and the anti-thesis are equally justified, perhaps it is wise to select the synthesis."*
>
> *(Rao, 2007, p.1623)*

Summary of work

This thesis investigated issues pertaining to the economy-energy-environment nexus in small island developing states (SIDS). To this end, we sought to answer the following question: **To what extent can SIDS, in responding to the imperatives of climate change, reduce their energy vulnerability?** To answer this fundamental question, this thesis was built around two main axes, namely **energy vulnerability** and **energy transition**. On the one hand, we looked at the factors contributing to the vulnerability of island energy systems for a group of SIDS in chapter 1. On the other hand, we set out the issues regarding the energy transition in the context of a case study on the Republic of Mauritius (RoM) in chapters 2 and 3. The main objective was to assess the prospects for the evolution of electricity demand and supply as well as CO_2 emissions in the long term. This thesis highlighted the relevance of energy-related issues for policymakers, particularly regarding the type of energy transition that can be expected in the RoM, given the vulnerability of island energy systems.

Contributions and policy implications

Chapter 1: Measuring energy vulnerability in small island developing states

The energy transition is a means to reduce energy vulnerability through the reduction of CO_2 emissions. Energy systems play a crucial role in the fight against climate change, mainly through greenhouse gas mitigation strategies. The aim was to carry out a diagnosis to understand the factors that can weaken the energy systems of these small territories. Firstly, we defined a conceptual framework to understand better the phenomenon of energy vulnerability: this is the *degree of sensitivity of energy systems to external shocks and internal disturbances that can hinder their functioning*. Secondly, we developed a composite index for 36 SIDS. This index reflects the dimensions of energy vulnerability and allows the phenomenon to be measured.

The results showed that the environmental dimension measured by the carbon content of primary energy was the main factor of vulnerability in most of the territories studied. This observation leads to the need to adopt a strategy to reduce greenhouse gas (GHG) emissions, which coincides with the countries' nationally determined contributions (NDCs) and is part of the energy transition process. Furthermore, it is interesting that the poorest countries are not necessarily the most vulnerable. The synthetic index proposed in this thesis measures the degree of sensitivity to shocks. However, some SIDS, although considered as "less advanced", have better performances on specific dimensions, especially the environmental and economic dimensions, mainly due to their low dependence on fossil fuel imports. They are therefore less exposed to the fluctuations in world energy markets.

Our contribution to the literature is based on three main points. First, we proposed a conceptual framework that has provided a new definition of energy vulnerability. This conceptual framework is based on an already well-established literature in the field of SIDS: economic vulnerability. Second, from a methodological point of view, we have constructed a composite index to measure this phenomenon. The originality of our approach lies in the fact that we have combined data-driven methods to establish the hierarchical structure of our index. This allowed us to assess the contribution of the different dimensions to vulnerability. Furthermore, although our study focused on SIDS, the proposed index can be calculated for other territories.

The results of Chapter 1 show that for many SIDS, the reduction of energy vulnerability requires the reduction of greenhouse gas emissions. In this context, an energy transition appears to be a means of achieving the reduction objective while improving energy performance in other dimensions. This argument could be put forward in the context of international negotiations on the allocation of aid to support the "low carbon" transition.

Chapter 2: The main drivers of electricity consumption in the Republic of Mauritius

Energy planning and management require a good understanding of the dynamics of energy demand (electricity in our case). Prospective tools generally use pilots for long-term energy demand, even though this is one of the critical parameters of the model. This demand is considered exogenous, and demand dynamics are often not addressed in prospective studies. This demand will notably condition investment choices in installed capacities intended to satisfy it. It is therefore essential to identify the factors that can influence this demand. We have chosen the Republic of Mauritius as a case study to analyse the main determinants of electricity consumption. The results of our study confirm the existence of a long-term equilibrium relationship between electricity consumption, GDP per capita, electricity price and exports per capita. Knowledge of this relationship allows public decision-makers to develop coherent energy, economic and trade policies to influence behaviour and consumption patterns without hampering the socio-economic development of the territory.

The literature on the issue of the relationship between energy/electricity consumption and other economic variables is abundant in developed and emerging countries (Smyth & Narayan, 2015; Payne, 2010a; De Vita et al., 2006; Zachariadis, 2010; Blázquez et al., 2013; Tsani, 2010; Wang et al., 2011; Zhang, 2011). Unfortunately, this literature has no consensus on the nature and magnitude of the relationship between the variables. However, it can be observed that this literature is relatively poor when it comes to SIDS (Sultan, 2012; Narayan & Singh, 2007; Katircioglu, 2013; Mishra et al., 2009). However, the knowledge gained on the main determinants of electricity consumption is of paramount importance for these small territories, subject to a continuous increase in their energy needs (transport, electricity production, etc.).

Moreover, the study carried out in this thesis has led to interesting results, especially concerning the causal relationship between the different variables. In particular, our results highlighted the absence of causality between electricity consumption and GDP per capita on the one hand and exports per capita on the other hand. We also showed that electricity consumption is inelastic to its own price in the short and long run. Therefore, a policy aimed at, for example, raising prices to influence consumer behaviour is unlikely to have the desired effect. Under these circumstances, energy efficiency and demand-side management measures should be promoted or reinforced.

Chapter 3: The energy transition in the Republic of Mauritius

The CO_2 emissions reduction target is most likely to shape a sustainable energy future for the two island power systems in the Republic of Mauritius. The intervention of public decision-makers amounts to making public policy choices once diagnoses have been made and objectives have been set. In the context of this thesis, we have highlighted areas that require particular attention from policymakers. We have focused here on the supply side of the energy transition. Furthermore, in the context of an energy transition, we wanted to assess the different future trajectories of the electricity production mix in the Republic of Mauritius. In particular, we modelled other targets for renewable energy penetration and GHG emissions reduction set by the Mauritian government. We aimed to compare these targets to a reference scenario and measure their impacts on the future evolution of the power mix of Mauritius and Rodrigues.

The prospective study conducted in chapter 3 was not intended to propose future forecasts but to explore future trajectories of the power generation mix. This exercise allowed us to understand the issues related to investment needs, the optimal deployment rate of technologies, and the consideration of environmental, social and technical constraints. We highlighted the importance of the prospective tool in the planning of energy systems (or sub-sectors such as electricity). The collaboration with the network operator allowed us to make a fair breakdown of the power system. Indeed, the technological richness of the RoM-TIMES model enabled technologies to be modelled at the scale of each production unit.

Our work showed that the GHG emission reduction target is the most likely to ensure a sustainable energy future, particularly in Mauritius. Indeed, the latter makes it possible to achieve higher renewable energy penetration rates and progressively decarbonise the electricity mix in line with the commitment made by the RoM under the Paris Agreement. Our study also suggested that the energy transition aimed at achieving the stated objectives is essentially based on technologies that are already mature and commercially viable, such as solar photovoltaic, onshore wind and biomass. However, the energy transition is not just a technological transition. Social, political and regulatory shifts must accompany the energy transition to be successful. Hence the importance of adopting a holistic approach.

Main lessons of the thesis

The research conducted in this thesis showed that island territories have a strong interest in engaging in the energy transition, particularly through climate change mitigation strategies. The relative energy vulnerability studied and measured in this thesis justifies aid allocation for climate change adaptation in SIDS. This conclusion is in line with the work of Betzold & Weiler (2017), Klöck & Nunn (2019), and Scandurra et al. (2020) who found that the most vulnerable countries benefit most from climate change adaptation aid.

The prospective study carried out in chapter 3 was used to understand the different energy needs and challenges for Mauritius and Rodrigues. It is necessary to evaluate renewable energy potential in these two territories, particularly in Rodrigues. The lack of diversity of energy sources for electricity generation demonstrates how vulnerable the island's electricity system is in the event of a disruption in the petroleum supply chain. To the best of our knowledge, there is no regional strategy or energy roadmap for Rodrigues Island, although an energy autonomy target has been announced in the past. The prospective modelling exercise carried out in this thesis has helped clarify the issue of possible future trajectories of the electricity mix. Local biomass (fuelwood) is expected to play an essential role in meeting electricity demand over the next 30 years. A more detailed study of its potential and the means of sustaining its production must be carried out while meeting the environmental requirements in line with the sector's sustainable development.

Moreover, the Republic of Mauritius has committed itself at the international level to reduce its GHG emissions by 30% by 2030. In this sense, carbon pricing could be a means to achieve this objective. The introduction of a carbon tax, which does not yet exist in the RoM, would constitute a means of internalising the negative externalities associated with energy use and ultimately encourage reduction behaviour. In addition, this tax would encourage public and private actors to invest in cleaner technologies.

Limitations and future research developments

In this thesis, we have analysed different facets of the same problem, namely the capacity of island energy systems to respond to the challenge of climate change, primarily through the energy transition. This raises new issues that could be interesting to study. In addition, some of the points raised deserve to be studied in greater depth.

The composite index proposed in chapter 1 is a static index. It only gives a fixed image of the situation of the small island developing states for the year 2015. A study based on several periods allowing the values of this index to be compared, for example, every three years, following the example of the economic vulnerability index calculated by the United Nations, could be envisaged to assess the progress of the territories. This would be of particular interest to policymakers as it would indicate the direction of change over time and identify longer-term trends. This dynamic approach could be used provided that the data needed to compute the composite index are updated regularly.

We estimated the aggregate electricity consumption in chapter 2. Consequently, the factors explaining consumer preferences at the micro-economic level could not be analysed. Indeed, the econometric study was based on the hypothesis of a representative consumer whose demand is influenced by economic aggregates. Moreover, the choice of using past growth rates of these variables to generate their future trajectories can be questioned. However, sensitivity analyses regarding the evolution of future demand are carried out.

Chapter 3 focused on the power system and gave only a limited overview of substitution possibilities between technologies. However, the prospective study could be extended to the whole energy sector. Moreover, the RoM-TIMES model, based on partial equilibrium analysis, ignores potential interactions with other markets in the Mauritian economy.

We will now outline three future research developments that constitute interesting research avenues to be explored.

1. **To what extent does the energy transition reduce energy vulnerability?**
   We plan to use the results of the RoM-TIMES model presented in chapter 3 to study this issue. The sensitivity analysis presented in chapter 1 demonstrated the possibility of reducing energy vulnerability by improving performance on some dimensions, especially the environmental dimension. The latter, measured by the carbon content of primary energy, was identified as the main source of vulnerability for most SIDS in our sample. In this context, several critical outputs of the RoM-TIMES model are identified. These correspond in particular to the indicators used in the construction of the composite energy vulnerability index in chapter 1 (Figure 1): CO_2 emissions trajectories (carbon content of primary energy); the supply of fossil fuels (energy import dependency); the composition of the electricity mix (energy mix diversity); the efficiency of the productive system (overall system conversion efficiency); the supply of primary energy (primary energy supply per capita); and the energy intensity of the economy (final energy intensity of GDP).

   Furthermore, a comparison can be made between the outputs of the 35RE and 30GHG scenarios modelled under TIMES.

2. **To what extent is a system-wide energy transition technically feasible and economically viable?**
   The island's energy balance demonstrates the increased dependence of the Republic of Mauritius on imported fossil fuels. Indeed, in 2020, 87% of primary energy supply needs were met by imported coal and petroleum products (SM, 2021). Final energy consumption was also highly carbon-intensive, all sectors combined. The transport sector was one of the primary consumers of fossil fuels (48.6%), followed by the industrial sector (22.2%).

   Since the activities linked to the combustion of fossil fuels are the main emitters of greenhouse gases, an energy transition extending to all sectors of the Mauritian economy (including the transport, industrial, residential, commercial and agricultural sectors) is necessary for it to be successful. Furthermore, such a modelling exercise requires a large amount of data to be collected and processed, especially concerning the techno-economic characteristics of the modelled technolo-

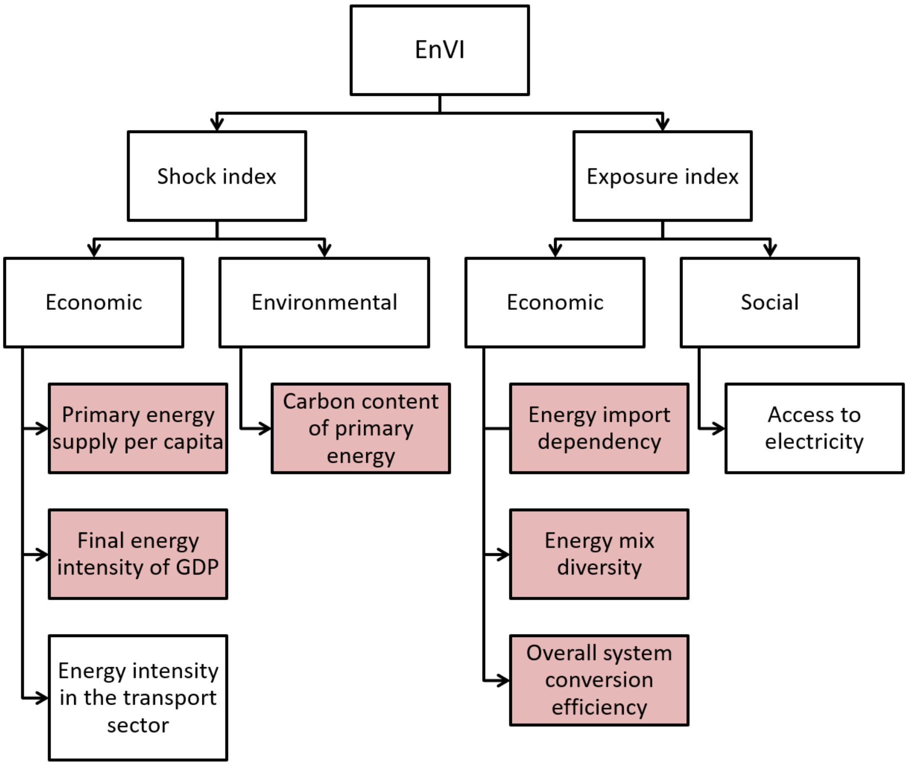


Figure 1: Indicators of the composite index of energy vulnerability corresponding to key outputs of the RoM-TIMES model

Source: the author.

gies. Therefore, collaboration with key stakeholders in the Republic of Mauritius is essential for completing this project. In addition, there is a need to ensure coordination between public authorities, particularly between the Ministry of Energy and related parastatal bodies (MARENA, CEB, EEMO and URA), and private actors, especially independent power producers and potential investors (national or international).

While the renewable energy penetration target is well established for the electricity sector, the Republic is still struggling to develop a real national and regional strategy regarding the roadmap for a low-carbon energy sector. The importance of such a prospective study has been underlined by international institutions such as the International Renewable Energy Agency (IRENA) in the framework of its "SIDS Lighthouses Initiative" framework.[25] The implementation of the recommendations made in such a study could benefit from technical and financial support from the IRENA.

3. **What are the macroeconomic impacts of the energy transition in Mauritius?** The Republic of Mauritius adopted a 2025 vision in 2009 and a 2030 vision in 2015 to promote RE integration in its energy mix. This small island state's desire

[25] SIDS Lighthouses, https://islands.irena.org/

to adopt a sustainable and long-term approach correspond to already established energy and climate objectives. The prospective exercise through a "bottom-up" model makes it possible to capture the technological substitutions which take place from one scenario to another, considering the constraints imposed. However, it cannot apprehend the effects of this transition on the major economic aggregates. What are the conditions for the implementation of such a transition? Which policy instruments should be used to facilitate the energy transition? What will be the effects of these instruments on the economy considered?

These essential questions could be addressed with the help of computable general equilibrium (CGE) models whose purpose is to represent and simulate the transactions between the markets of an economy (Zantman, 1995; Decaluwé et al., 2001). These models are based on the social accounting matrix (SAM), which constitutes the accounting basis of the country under consideration. They allow the simulation of an exogenous shock or an economic policy with a general equilibrium effect in the economy. Developing a CGE model for the Republic of Mauritius constitutes a complementary contribution to the TIMES model. This family of models refers to a "top-down" approach that allows the study of interdependencies between different economic agents and sectors.

For instance, the costs of reducing greenhouse gas emissions through introducing a carbon tax can be investigated. Unfortunately, this instrument has not yet been introduced in the Republic. Still, it is of interest given that it is at the centre of policy debates on reducing CO_2 emissions in many countries and international institutions.

Conclusion générale

> *"Pragmatism suggests that when the thesis and the anti-thesis are equally justified, perhaps it is wise to select the synthesis."*
>
> *(Rao, 2007, p.1623)*

Synthèse des travaux

La présente thèse étudie les enjeux relatifs au nexus économie-énergie-environnement dans les petites économies insulaires en développement (PEID). Pour cela, nous avons cherché à répondre à la question suivante : **dans quelle mesure les PEID, en répondant aux impératifs du changement climatique, peuvent réduire leur vulnérabilité énergétique ?** Pour répondre à cette question fondamentale, cette thèse s'est construite autour de deux axes principaux, à savoir la **vulnérabilité énergétique** et la **transition énergétique**. D'une part, nous nous sommes intéressés dans le chapitre 1 aux facteurs contribuant à la vulnérabilité des systèmes énergétiques insulaires pour un groupe de PEID. D'autre part, nous avons exposé dans les chapitres 2 et 3 les enjeux relatifs à la transition énergétique dans le cadre d'une étude de cas sur la République de Maurice (RdM). Il s'agissait principalement d'évaluer les perspectives d'évolution de la demande et de l'offre d'électricité ainsi que les émissions de CO_2 à long-terme. À travers cette thèse, nous avons souligné la pertinence des questions liées à l'énergie pour les décideurs publics, notamment en ce qui concerne le type de transition énergétique que l'on peut espérer dans la RdM compte tenu de la vulnérabilité des systèmes énergétiques insulaires.

Contributions et implications de politiques publiques

Chapitre 1: Mesure de la vulnérabilité énergétique dans les petites économies insulaires en développement

La transition énergétique constitue un moyen de réduire la vulnérabilité énergétique à travers la diminution des émissions de CO_2. Les systèmes énergétiques jouent un rôle prépondérant dans la lutte contre le changement climatique, notamment à travers les stratégies d'atténuation des émissions de gaz à effet de serre. Il était question de faire un diagnostic pour comprendre les facteurs pouvant fragiliser les systèmes énergétiques de ces petits territoires. Dans un premier temps, nous avons défini un cadre conceptuel pour mieux appréhender le phénomène de vulnérabilité énergétique : il s'agit du *degré de sensibilité des systèmes énergétiques aux chocs externes et perturbations internes pouvant entraver le fonctionnement de ces derniers*. Dans un second temps, nous avons développé un indice synthétique pour 36 PEID. Ce dernier reflète les différentes dimensions de la vulnérabilité énergétique et permet de mesurer le phénomène.

Les résultats démontrent que la dimension environnementale mesurée par l'intensité carbone de l'énergie primaire est le principal facteur de vulnérabilité dans la majorité des territoires étudiés. De ce constat découle la nécessité d'adopter une stratégie de réduction des émissions de gaz à effet de serre (GES), cette nécessité coïncidant avec les contributions déterminées au niveau national des pays et s'inscrivant dans le processus de transition énergétique. Par ailleurs, il est intéressant de souligner que les pays les plus pauvres ne sont pas forcément les plus vulnérables. L'indice synthétique proposé dans cette thèse mesure le degré de sensibilité des territoires aux chocs. Or, certains PEID, bien que considérés comme "moins avancés" ont de meilleures performances sur certaines dimensions, notamment environnementale ou encore économique, principalement dues à leur faible dépendance vis-à-vis des importations d'énergies fossiles. Ils sont donc moins exposés aux aléas sur les marchés mondiaux de l'énergie.

Notre contribution à la littérature s'articule autour de trois principaux points. Premièrement, nous avons proposé un cadre conceptuel qui nous a permis de donner une nouvelle définition de la vulnérabilité énergétique. Ce cadre conceptuel est basé sur une littérature déjà bien établie dans le champ des études relatives aux petites économies insulaires en développement : celle de la vulnérabilité économique. Deuxièmement, d'un point de vue méthodologique, nous avons construit un indice synthétique pour mesurer ce phénomène. L'originalité de notre approche tient du fait que nous avons combiné des méthodes orientées par les données pour établir la structure hiérarchique de notre indice. Ce dernier permet de ce fait d'évaluer la contribution des différentes dimensions à la vulnérabilité. Par ailleurs, bien que notre étude se soit intéressée aux PEID, l'indice proposé peut être calculé pour d'autres territoires.

Les résultats du chapitre 1 montrent que pour nombre de PEID, la réduction de la vulnérabilité énergétique passe par la diminution des émissions de gaz à effet de serre. Dans ce cadre, une transition énergétique apparaît comme un moyen d'atteindre l'objectif de réduction tout en améliorant la performance énergétique dans d'autres dimensions. Cet argument pourrait être avancé dans le cadre des négociations internationales relatives à l'allocation des aides visant à soutenir la transition "bas carbone".

Chapitre 2 : Les principaux déterminants de la consommation d'électricité dans la République de Maurice

La planification et le "management" de l'énergie nécessitent une bonne compréhension de la dynamique de la demande d'énergie (électricité dans notre cas). Les outils prospectifs utilisent généralement des pilotes pour la demande énergétique à long terme, alors qu'il s'agit d'un des paramètres clés du modèle. Cette demande est considérée comme exogène, et la dynamique de la demande n'est souvent pas abordée dans les études prospectives. Cette demande va notamment conditionner les choix d'investissement dans des capacités installées destinées à la satisfaire. Il est donc primordial d'identifier les facteurs pouvant influencer cette demande. Nous avons choisi la République de Maurice comme étude de cas pour analyser les principaux déterminants de la consommation d'électricité. Les résultats de notre étude confirment l'existence d'une relation d'équilibre de long terme entre consommation d'électricité, le PIB par habitant, le prix moyen de l'électricité et les exportations par tête. La connaissance de cette relation permet aux décideurs publics d'élaborer des politiques énergétiques, économiques et commerciales cohérentes dans le but d'influencer les comportements et les habitudes de consommation sans pour autant entraver le développement socioéconomique du territoire.

La littérature sur la question de la relation entre consommation d'énergie/d'électricité et d'autres variables économiques est abondante dans les pays développés et émergents (Smyth & Narayan, 2015; Payne, 2010a; De Vita et al., 2006; Zachariadis, 2010; Blázquez et al., 2013; Tsani, 2010; Wang et al., 2011; Zhang, 2011). Cette littérature ne fait pour l'instant pas consensus s'agissant de la nature et de l'amplitude de la relation entre les variables. On observe cependant que cette littérature est relativement pauvre lorsqu'il s'agit des PEID (Sultan, 2012; Narayan & Singh, 2007; Katircioglu, 2013; Mishra et al., 2009). Les connaissances acquises sur les principaux déterminants de la consommation d'électricité sont pourtant d'une importance capitale pour ces petits territoires qui sont soumis à une augmentation continue de leurs besoins en énergie (transport, production d'électricité, etc.).

L'étude menée dans cette thèse a, par ailleurs, abouti à des résultats intéressants, notamment en ce qui concerne la relation causale entre les différentes variables. En particulier, nos résultats soulignent l'absence de causalité entre la consommation d'électricité et le PIB par habitant d'une part et les exportations par tête d'autre part. Nous montrons par ailleurs que la consommation est inélastique au prix moyen de l'électricité à court et à long terme. Une politique visant par exemple à hausser les prix pour influencer le comportement des consommateurs ne devrait pas avoir l'effet escompté. Dans ces conditions, les mesures d'efficacité énergétique et de maîtrise de la demande devraient être promues ou renforcées.

Chapitre 3 : La transition énergétique dans la République de Maurice

L'objectif de réduction des émissions de CO_2 est le plus à même de façonner un avenir énergétique durable pour les deux systèmes électriques insulaires de la République de Maurice. Nous nous sommes intéressés ici à l'aspect "offre" de la transition énergétique. En outre, dans le contexte d'une transition énergétique, nous avons voulu évaluer les différentes trajectoires futures de mix de production électrique dans la République de Maurice. En particulier, nous avons modélisé différents objectifs de pénétration d'énergies renouvelables et de réduction d'émissions de gaz à effet de serre affichés par le gouvernement Mauricien. Notre but était de comparer ces objectifs à un scénario de référence et à mesurer leurs impacts sur l'évolution future des mix électriques de Maurice et de Rodrigues. Il ressort de nos travaux que l'objectif de réduction des émissions de GES est le plus susceptible d'assurer un futur énergétique durable, notamment à Maurice. En effet, ce dernier permet de réaliser à la fois des taux de pénétration d'énergies renouvelables supérieurs et de progressivement décarboner les mix électriques compatibles à l'engagement pris par l'État lors de l'Accord de Paris.

Notre étude suggère également que la transition énergétique visant à atteindre les objectifs affichés se base essentiellement sur des technologies déjà matures et commercialisées telles que le photovoltaïque, l'éolien terrestre ou encore la biomasse. Cependant, la transition énergétique n'est pas qu'une transition technologique. Pour qu'elle soit réussie, elle doit être accompagnée de transitions sociale, politique et réglementaire. D'où l'importance d'adopter une approche holistique.

L'intervention des décideurs publics revient à faire des choix de politiques publiques lorsque des diagnostics ont été réalisés et que des objectifs ont été fixés. Dans le cadre de cette thèse, nous avons notamment souligné des domaines qui nécessitent une attention particulière de la part des décideurs publics. L'étude prospective menée dans le chapitre 3 n'avait pas vocation à proposer des prévisions de l'avenir, mais avait pour but d'explorer les trajectoires futures de mix électriques. Nous avons fait le choix dans ce dernier chapitre d'évaluer l'impact de deux objectifs fixés par le gouvernement mauricien sur l'évolution possible des mix électriques de Maurice et de Rodrigues. Cet exercice permet d'appréhender les questions relatives aux besoins d'investissement, au rythme de déploiement optimal des technologies, ou encore la prise en compte des contraintes environnementales, sociales et techniques. Nous mettons en exergue l'importance de l'outil prospectif dans la planification des systèmes énergétiques (ou des sous-secteurs tels que l'électricité). La collaboration avec l'opérateur de réseau nous a permis d'effectuer un découpage fin du système électrique. En effet, la richesse technologique du modèle RoM-TIMES permet de modéliser les technologies à l'échelle de l'unité de production.

Enseignements principaux de la thèse

Au regard des travaux de recherche menés dans cette thèse, il apparaît que les territoires insulaires ont tout intérêt à s'engager dans la transition énergétique, notamment au travers de stratégies d'atténuation du changement climatique. La relative vulnérabilité énergétique étudiée et mesurée dans cette thèse justifie l'allocation de l'aide au titre de l'adaptation au changement climatique dans les PEID. Cette conclusion s'inscrit dans la lignée des travaux de Betzold & Weiler (2017), Klöck & Nunn (2019), et Scandurra et al. (2020) qui constatent que les pays les plus vulnérables bénéficient le plus des aides d'adaptation au changement climatique.

L'étude prospective effectuée dans le chapitre 3 a quant à elle servi à comprendre les différents besoins et enjeux énergétiques pour Maurice et Rodrigues. Il est nécessaire d'évaluer le potentiel d'énergies renouvelables dans ces deux territoires, en particulier à Rodrigues. La concentration des sources d'énergies pour la production d'électricité démontre à quel point le système électrique de l'île est vulnérable en cas de rupture dans la chaîne d'approvisionnement en produits pétroliers. À ce jour, il n'existe pas de stratégie régionale ou de feuille de route énergétique pour Rodrigues alors même qu'une vision d'autonomie énergétique avait été annoncée par le passé. L'exercice de modélisation prospective effectué dans cette thèse a permis de défricher la question concernant les trajectoires futures possibles de mix électrique. La biomasse locale (le bois-énergie) devrait jouer un rôle important dans la satisfaction de la demande d'électricité au cours des trente prochaines années. Une étude plus poussée sur son potentiel ainsi que les moyens de pérenniser sa production doit être effectuée. Cette étude devra notamment répondre à des exigences environnementales dans le cadre d'un développement durable de la filière.

Par ailleurs, la République de Maurice s'est engagée au niveau international à réduire ses émissions de GES de 30 % d'ici à 2030. En ce sens, la tarification du carbone pourrait être un moyen d'atteindre cet objectif. L'introduction d'une taxe carbone, qui n'existe pas encore dans la RdM, constituerait un moyen d'internaliser les externalités négatives associées à l'utilisation de l'énergie, et *in fine* inciter les comportements de réduction. En outre, cette taxe conduirait les acteurs publics et privés à investir dans des technologies plus propres.

Limites et perspectives de recherche

Nous avons analysé dans cette thèse différentes facettes d'un même problème, à savoir la capacité des systèmes énergétiques insulaires à répondre au défi du changement climatique, notamment par la transition énergétique. Cela soulève de nouvelles problématiques qu'il pourrait être intéressant d'étudier. Par ailleurs, certains points évoqués mériteraient d'être approfondis.

L'indice synthétique proposé au chapitre 1 est un indice statique. Il ne donne qu'une image figée de la situation des petites économies insulaires pour l'année 2015. Une étude basée sur plusieurs périodes permettant de comparer les valeurs de cet indice, par exemple tous les trois ans, à l'instar de l'indice de vulnérabilité économique calculé par les Nations Unis, pourrait être envisagée afin d'évaluer la progression des territoires. Cela aurait un intérêt particulier pour les décideurs publics en indiquant la direction du changement au fil du temps et en permettant l'identification de tendances à plus long-terme. Cette approche dynamique pourrait être employée sous réserve que les données nécessaires au calcul de l'indice synthétique soient actualisées régulièrement.

Nous avons estimé dans le chapitre 2 la consommation d'électricité agrégée. De ce fait, les facteurs permettant d'expliquer les préférences des consommateurs au niveau microéconomique n'ont pu être analysés. En effet, l'étude économétrique réalisée repose sur l'hypothèse d'un consommateur représentatif dont la demande est influencée par des agrégats économiques. Par ailleurs, le choix d'utiliser les taux de croissances passés de ces variables pour générer leurs trajectoires futures peut être contesté bien que des analyses de sensibilité relatives à l'évolution de la demande future soient effectuées.

Le chapitre 3 se concentre sur le système électrique et ne donne qu'un aperçu limité des possibilités de substitution entre technologies. Une étude prospective pourrait être étendue à tout le secteur énergétique. De plus, le modèle RoM-TIMES, basé sur une analyse en équilibre partiel, ignore les interactions potentielles avec d'autres marchés de l'économie mauricienne. Nous allons à présent exposer trois perspectives de recherche qu'il nous semblerait important d'explorer.

1. **Dans quelle mesure la transition énergétique permet-elle de réduire la vulnérabilité énergétique ?**

Nous envisageons d'utiliser les résultats du modèle RoM-TIMES présentés au chapitre 3 pour étudier cette question. L'analyse de sensibilité présentée dans au chapitre 1 a démontré la possibilité de réduire la vulnérabilité énergétique en améliorant les performances sur certaines dimensions, notamment celle environnementale. Cette dernière, mesurée par le contenu carbone en énergie primaire, a été identifiée comme la principale source de vulnérabilité pour la majorité des PEID de notre échantillon. Dans ce cadre, certains outputs clés du modèle RoM-TIMES sont identifiés. Ces derniers correspondent notamment aux indicateurs utilisés dans la construction de l'indice synthétique de vulnérabilité énergétique au chapitre 1 : la trajectoire des émissions de CO_2 (contenu carbone de l'énergie primaire); l'approvisionnement en énergies fossiles (dépendance vis-à-vis des importations d'énergies fossiles); la composition du mix électrique (diversité du mix électrique); l'efficacité du système productif (efficacité globale de la conversion du système); l'approvisionnement en énergie primaire (l'offre d'énergie primaire par tête) et l'intensité énergétique de l'économie (intensité de l'énergie finale du PIB).

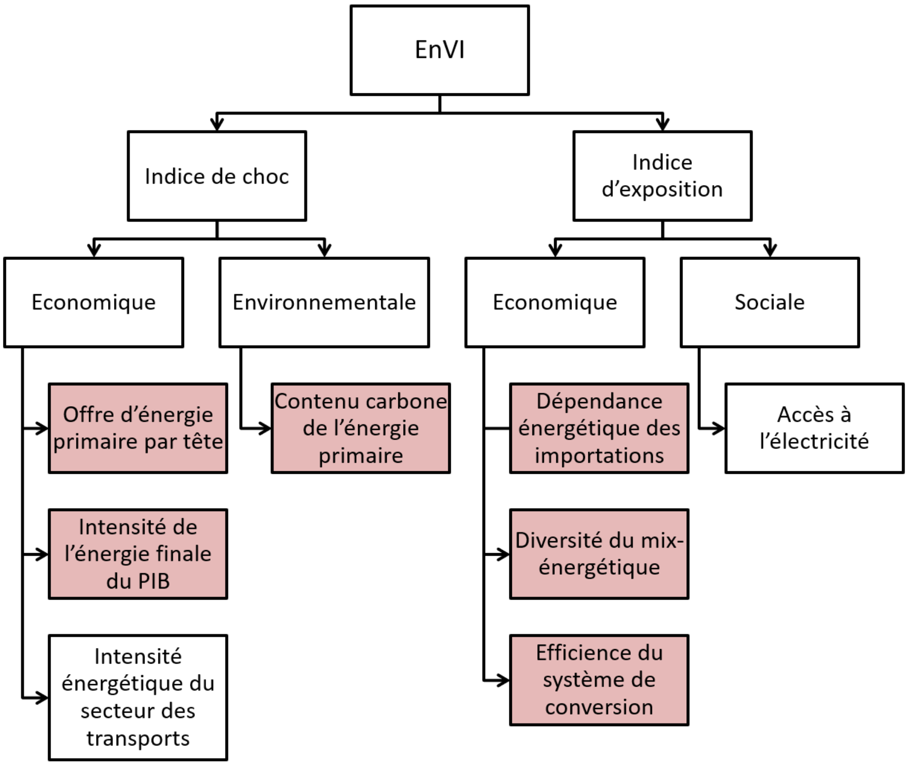


Figure 1: Indicateurs de l'indice synthétique de vulnérabilité énergétique correspondant outputs clés du modèle RoM-TIMES

Source : l'auteure.

Par ailleurs, une comparaison peut être effectuée entre les résultats des scénarii 35RE et 30GHG modélisés sous TIMES.

2. **Dans quelle mesure une transition énergétique étendue à tout le système énergétique est-elle techniquement faisable et économiquement viable ?**
La balance énergétique de l'île démontre la dépendance accrue de la République de Maurice vis-à-vis des énergies fossiles importées. En effet, en 2020, 87 % des besoins d'approvisionnement en énergie primaire étaient satisfaits par les importations de charbon et de produits pétroliers (SM, 2021). La consommation d'énergie finale est également fortement carbonée, et ce, tous secteurs confondus. Le secteur des transports est notamment l'un des principaux consommateurs d'énergies fossiles (48.6 %) suivi du secteur industriel (22.2 %). Si les activités liées à la combustion des énergies fossiles sont les principales émettrices de gaz à effet de serre, une transition énergétique s'étendant à tous les secteurs de l'économie mauricienne est cependant nécessaire pour qu'elle soit réussie. Cela inclut les secteurs des transports, industriel, résidentiel, commercial et agricole. Un tel exercice de modélisation requiert une importante quantité de données à collecter et à traiter, notamment en ce qui concerne les caractéristiques technico-économiques des technologies modélisées. Une collaboration avec les principaux acteurs de la République de Maurice est indispensable pour mener à bien ce projet. En outre, il est nécessaire d'assurer la coordination entre les instances publiques, notamment le Ministère de l'Énergie et les établissements parapublics associés (MARENA, CEB, EEMO et URA), et les acteurs privés, notamment les producteurs indépendants d'électricité et les investisseurs potentiels (nationaux ou internationaux).

   Si l'objectif de pénétration d'énergie renouvelable est bien établi pour le secteur électrique, La République peine encore à élaborer une réelle stratégie nationale et régionale en ce qui concerne la feuille de route pour un secteur énergétique bas-carbone. L'importance d'une telle étude prospective a notamment été soulignée par des institutions internationales telles que l'International Renewable Energy Agency (IRENA) dans le cadre de son programme « SIDS Lighthouses Initiative ».[26] La mise en oeuvre des recommandations formulées dans une telle étude pourrait bénéficier d'un appui technique et financier de l'IRENA. .

3. **Quels sont les impacts macroéconomiques de la transition énergétique dans La République de Maurice ?**
La République de Maurice s'est dotée en 2009 d'une vision à horizon 2025 puis en 2015 d'une vision à horizon 2030 pour promouvoir l'intégration des énergies renouvelables dans son mix énergétique. La volonté de ce petit territoire insulaire en développement de s'inscrire dans une démarche durable et à long terme renvoie à des objectifs énergétiques et climatiques déjà établis. L'exercice prospectif

[26] SIDS Lighthouses, https://islands.irena.org/

au travers d'un modèle « bottom-up » permet de capturer les substitutions technologiques qui s'opèrent d'un scénario à l'autre compte tenu des contraintes imposées mais n'est pas en mesure d'appréhender les effets de cette transition sur les grands agrégats économiques. Quelles sont les conditions de la mise en œuvre d'une telle transition ? Quels instruments politiques pour faciliter la transition énergétique ? Quels seront les effets de ces instruments sur l'économie considérée ?

Ces questions importantes pourraient être abordées à l'aide des modèles d'équilibre général calculable (MEGC) dont l'objet consiste à représenter et simuler les transactions entre les marchés d'une économie (Zantman, 1995; Decaluwé et al., 2001). Ces modèles s'appuient sur la matrice de comptabilité sociale (MCS) qui constitue la base comptable du pays considéré. Ils permetttent de simuler un choc exogène ou une politique économique qui a un effet d'équilibre général dans l'économie. L'élaboration d'un MEGC pour la République de Maurice constitue un apport complémentaire au modèle TIMES. Cette famille de modèles renvoie à une approche « top-down » qui permet l'étude des interdépendances entre différents agents économiques et secteurs.

Par exemple, les coûts de réduction des émissions de gaz à effet de serre à travers l'introduction d'une taxe carbone peuvent être évalués. Cet instrument n'a pas encore été introduit dans La République mais il présente un intérêt certain compte tenu de la place centrale qu'il occupe dans les débats de politique de réduction des émissions de CO_2 dans de nombreux pays et institutions internationales.

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Appendices

Appendix for Chapter 1

Appendix A

Table A.1: Basic indicators for SIDS in 2015

Country	Code	Pop density (pop/km^2)	GDP per cap ($ PPP)	Status
Atlantic, Indian Ocean, and South China Sea (AIMS)				
Singapore	SGP	7713.3	83,342	NOI
Bahrain	BHR	1763.3	43,927	NOE
Seychelles	SYC	206.5	24,857	NOI
Mauritius	MUS	620.4	18,879	NOI
Maldives	MDV	1516.4	12,684	NOI
Cape Verde	CPV	130.2	6,007	NOI
Sao Tomé and Principe	STP	207.7	2,890	NOI
Guinea-Bissau	GNB	61.8	1,474	NOI
Comoros	COM	417.8	2,494	NOI
Caribbean				
Trinidad and Tobago	TTO	267.1	31,460	NOE
Bahamas	BHS	37.4	29,366	NOI
St. Kitts and Nevis	KNA	196.9	27,179	NOI
Antigua and Barbuda	ATG	212.7	21,426	NOI
Barbados	BRB	663.6	16,396	NOI
Suriname	SUR	3.6	14,488	NOE
Dominican Republic	DOM	212.8	13,717	NOI
Grenada	GRD	322.4	12,436	NOI
St. Lucia	LCA	293.7	11,568	NOI
St. Vincent and the Grenadines	VCT	279.8	10,472	NOI
Dominica	DMA	94.9	10,215	NOI
Belize	BLZ	15.8	7,977	NOI
Jamaica	JAM	266.9	8,047	NOI
Guyana	GUY	3.9	7,087	NOI
Cuba	CUB	108.9	6,523	NOI
Haiti	HTI	388.1	1,654	NOI
Pacific				
Palau	PLW	38.4	17,132	NOI
Fiji	FJI	47.5	8,776	NOI
Timor-Leste	TLS	80.5	7,657	NOE
Samoa	WSM	68.4	5,567	NOI
Tonga	TON	140	5,477	NOI
Papua New Guinea	PNG	17.9	3,820	NOE
Tuvalu	TUV	370	3,389	NOI
Micronesia (Fed. States of)	FSM	155.6	3137	NOI
Vanuatu	VUT	22.2	2,739	NOI
Solomon Islands	SLB	21.5	2,094	NOI
Kiribati	KIR	136.9	1,976	NOI

Note: Data for the computation of population density were retrieved from the World Development Indicators of the World Bank and World Population Prospects: The 2019 revision. Data for GDP per capita expressed in constant 2011 international dollars purchasing power parity (PPP) were retrieved from the World Development Indicators of the World Bank. NOI stands for net oil importer and NOE for net oil exporter.

Appendix B

Table B.1: Initial set of 21 variables

Dimension	Code	Name	(E) or (S)	Data source
Social	SOC1	Access to electricity	E	World Bank (SE4ALL)[a]; UN statistics (SDGs)[b]
	SOC2	Access to clean fuels and technologies	E	
	SOC3	Remoteness	E	UNCDP (LCD data)
Economic	ECO1	Primary energy supply per capita	S**	UN Energy Balances (2015); UN Statistics Division (National Accounts Estimates of Main Aggregates)[c]
	ECO2	Final energy intensity per capita	S	
	ECO4	Primary energy supply per unit of GDP	S**	
	ECO5	Final energy intensity of GDP	S	
	ECO7	Energy intensity in the agricultural sector	S	
	ECO8	Energy intensity in the service/commercial sector	S	
	ECO9	Energy intensity in the manufacturing sector	S	
	ECO10	Energy intensity in the transport sector	S	
	ECO11	Renewable energy as a share of TFEC	E	World Bank (SE4ALL); UN statistics (SDGs)
	ECO12	Renewable energy as a share of total electricity generated	E	
	ECO13	Energy import dependency	E	UN Energy Balances (2015)[d]
	ECO14	Energy mix diversity	E**	
	ECO15	Energy bill	S	
	ECO16	Overall system conversion efficiency	E	
	ECO17	Overall self-sufficiency	E	
Environmental	ENV1	CO_2 emissions per capita	S	EDGAR
	ENV2	CO_2 emissions per unit of GDP	S	
	ENV3	CO_2 content of primary energy	S	EDGAR; UN Energy Balances (2015)

Note: TFEC stands for Total Final Energy Consumption; E stands for Exposure and S for Shock.
** Based on d'Artigues & Vignolo (2012).
[a] https://datacatalog.worldbank.org/dataset/sustainable-energy-all (accessed on 18/03/2019).
[b] https://unstats.un.org/sdgs/indicators/database (accessed on 18/03/2019).
[c] https://unstats.un.org/unsd/snaama/downloads (accessed on 18/03/2019).
[d] https://read.un-ilibrary.org/natural-resources-water-and-energy/2015-energy-balances_5869b981-en#page1 (accessed on 18/03/2019).

Table B.2: Descriptive statistics of energy vulnerability variables (N = 36)

Code	Unit	Formula	Min	Max	Std. Dev.	Data sources
ECO1	toe/cap	TPES/population	0.16	14.22	2.760	United Nations Energy Balances 2015 edition; United Nations World Population Prospects: The 2019 Revision
ECO5	toe/1,000 $ PPP	TFC/GDP	0.013	0.319	0.061	United Nations Energy Balances 2015 edition; World Development Indicators of The World Bank
ECO10	toe/1,000 $ PPP	Energy use/gross value added (transport)	0.072	2.07	0.399	United Nations Energy Balances 2015 edition; National Accounts Estimates of Main Aggregates
ECO13	toe	Energy imports/TPES	0.176	5.79	0.895	United Nations Energy Balances 2015 edition
ECO14	toe	$SWI = -\sum p_i ln(p_i)$	0	1.158	0.335	United Nations Energy Balances 2015 edition
ECO16	%	(TFC/TPES)*100	20.98	89.93	14.134	United Nations Energy Balances 2015 edition
ENV3	ton CO_2/toe	Total CO_2 emissions/TPES	0.44	5.48	1.322	United Nations Energy Balances 2015 edition; EDGAR 2016 edition
SOC1	%	% of population with access to electricity	14.66	100	24.474	The World Bank SE4ALL 2015

Note: (*) indicates that several countries have the same value in a dimension.
U = undesirable; D = desirable indicators; S = shock; E = exposure
TPES = total primary energy supply; TFC = total final energy consumption
Total CO_2 emissions for Tuvalu were retrieved from the World Development Indicators of the World Bank for 2014.

Appendix C

Table C.1: Raw data on the eight selected indicators

Country	ECO1	ECO5	ECO10	ECO13	ECO14	ECO16	ENV3	SOC1
ATG	1.997	0.058	0.664	1.319	0.000	60.10	2.152	97.35
BHS	2.158	0.056	0.200	1.084	0.011	75.81	4.998	100
BHR	10.080	0.102	0.537	0.819	0.349	33.26	1.601	100
BRB	1.385	0.058	0.264	1.330	0.272	68.33	3.598	100
BLZ	0.979	0.102	0.772	0.613	0.962	82.61	2.891	92.21
CPV	0.398	0.049	0.326	1.324	0.606	74.31	0.477	92.61
COM	0.158	0.044	0.130	0.492	0.691	68.82	0.880	77.84
CUB	1.012	0.085	0.074	0.678	0.629	53.83	3.008	100
DMA	0.898	0.049	0.331	0.950	0.263	55.86	2.665	100
DOM	0.762	0.038	0.280	0.989	0.929	64.60	3.098	100
FJI	1.043	0.076	0.494	0.929	0.604	63.19	1.662	98.64
GRD	0.881	0.050	0.370	0.926	0.277	71.15	5.272	92.34
GNB	0.417	0.263	0.613	0.176	0.439	89.92	0.440	14.65
GUY	1.075	0.117	0.636	0.816	0.513	77.07	3.573	84.24
HTI	0.399	0.182	0.330	0.229	0.543	75.48	0.546	38.69
JAM	0.895	0.080	0.518	1.096	0.445	70.69	3.549	98.20
KIR	0.188	0.067	0.530	0.982	0.196	69.46	2.210	84.93
MDV	0.990	0.066	0.605	1.174	0.060	84.15	2.382	100
MUS	1.262	0.038	0.367	1.134	1.029	56.41	2.038	98.78
FSM	0.496	0.121	2.071	1.007	0.076	73.09	2.785	75.43
PLW	4.240	0.184	1.702	1.204	0.000	73.08	0.485	99.28
PNG	0.468	0.090	0.633	0.526	1.158	72.85	2.084	22.93
KNA	1.564	0.032	0.278	1.054	0.061	55.35	2.323	100
LCA	0.804	0.045	0.237	1.027	0.078	63.24	3.871	97.76
VCT	0.734	0.052	0.457	0.953	0.224	72.41	4.149	100
WSM	0.693	0.096	0.660	0.837	0.657	73.86	1.103	100
STP	0.321	0.081	0.333	0.780	0.715	72.86	0.876	65.44
SYC	1.584	0.044	0.220	2.403	0.063	67.92	3.452	100
SGP	5.266	0.037	0.072	5.861	0.792	35.80	1.648	100
SLB	0.240	0.098	0.094	0.518	0.701	83.89	2.057	55.10
SUR	1.257	0.069	0.629	0.790	0.574	79.26	3.320	87.17
TLS	0.159	0.013	0.466	0.906	0.349	61.08	2.356	63.39
TON	0.396	0.057	0.830	1.117	0.110	75.64	5.481	97.02
TTO	14.218	0.319	0.368	0.210	0.294	20.98	1.811	100
TUV	0.308	0.056	0.644	0.951	0.195	61.53	3.221	99.42
VUT	0.253	0.080	0.410	0.835	0.700	84.25	1.748	57.82

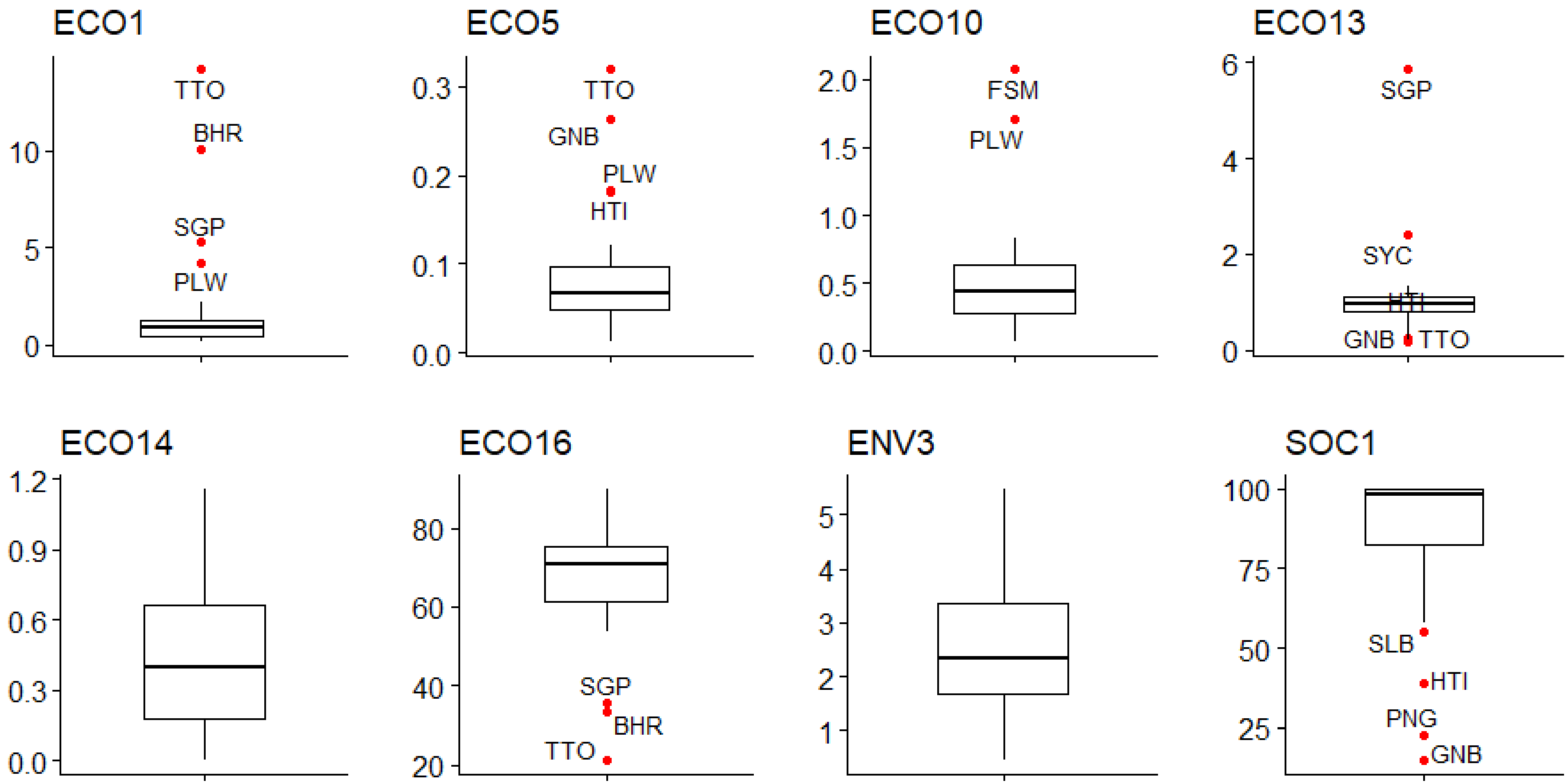

Figure C.1: Distribution of original indicator values with outliers marked with dots

Appendix D

We show in the following example the interest of the BoD model for the construction of composite indices. In particular, we discuss issues regarding normalization, weighting, and benchmarking. Suppose we have five countries (A, B, C, D and E) and two sub-indicators (Ind1 and Ind2). The following Table D.1 provides corresponding indicator values (selected randomly) for each country.

Table D.1: Raw data

Countries	Ind1	Ind2
A	79	0.3
B	67	0.5
C	78	0.4
D	63	0.7
E	55	0.6
Min	55	0.3
Max	79	0.7
Std. Dev.	10.2	0.2

We consider the following alternatives to construct our composite index (C1):

a. Arithmetic average (with implicit equal weighting)

b. Arithmetic average with unequal weighting (75% Ind1 and 25% Ind2)

c. Arithmetic average with normalized values (min-max procedure)

d. Standard BoD model

e. Standard BoD model with normalized values (min-max procedure)

CI scores under the different alternatives (CI-a to CI-e) are reported in Table D.2.

Normalization

We first compare CI-c and CI-d, i.e. the CI scores obtained under the arithmetic average with normalised values and the standard BoD model. Overall, countries D and E remain the leader and the laggard respectively. On the other hand, countries A and C are put in a more favourable position while country B is worst off when noralised values are used in the BoD model. Second, we compared the standard BoD models (CI-d and CI-e) with and without normalized values. Although the CI scores differ slightly, country rankings are not impacted. Furthelaggard,rmore, using the min-max procedure to re-scale sub-indicators in the BoD models is not required since the BoD model is unit invariant

Table D.2: Composite index scores

Country	CI-a	CI-b	CI-c	CI-d	CI-e
A	39.7	59.3	0.5	1.000	1.000
B	33.8	50.4	0.5	0.939	0.786
C	39.2	58.6	0.6	1.000	1.000
D	31.9	47.4	0.7	1.000	1.000
E	27.8	41.4	0.4	0.867	0.750
Min	27.8	41.4	0.4	0.867	0.750
Max	39.7	59.3	0.7	1.000	1.000
SD	5.0	7.6	0.1	0.059	0.128

due to endogenously determined weights. Therefore, normalization procedure becomes redundant.

Weighting

We consider the impacts of weighting schemes (equal weighting, unequal weighing and endogenously determined weights) on the CI scores, rankings and % contribution of the two sub-indicators. We thus compare CI-a, CI-b and CI-d. Please note that under CI-a, an equal weight of 0.5 is assigned to each sub-indicator. Under CI-b, an unequal weighting scheme is assigned (i.e. 75% Ind1 and 25% Ind2). Under the standard BoD model (CI-d), endogenously determined weights are assigned.

We observe from Table D.3 that the set of weights are more flexible under the standard BoD model regardless of the measurement units with CI-scores in the [0;1]. interval. Moreover, the contribution of the two sub-indicators (% contrib) are more balanced when weights are determined endogenously as shown in Table D.4.

Table D.3: Impacts of weights on CI scores

Countries	Arithmetic average (equal weighting					Arithmetic average (unequal weighting)					Standard BoD				
	Ind1	WInd1	Ind2	WInd2	CI-a	Ind1	WInd1	Ind2	WInd2	CI-b	Ind1	WInd1	Ind2	WInd2	CI-d
A	79	0.5	0.3	0.5	39.7	79	0.75	0.3	0.25	59.3	79	0.01266	0.3	0.0001	1.000
B	67	0.5	0.5	0.5	33.8	67	0.75	0.5	0.25	50.4	67	0.01020	0.5	0.5102	0.939
C	78	0.5	0.4	0.5	39.2	78	0.75	0.4	0.25	58.6	78	0.01020	0.4	0.5102	1.000
D	63	0.5	0.7	0.5	31.9	63	0.75	0.7	0.25	47.4	63	0.01020	0.7	0.5102	1.000
E	55	0.5	0.6	0.5	27.8	55	0.75	0.6	0.25	41.4	55	0.01020	0.6	0.5102	0.867

Note: WInd1 and WInd2 refer to the weights assigned to Ind1 and Ind2 respectively. The CI score is then obtained by linear aggregation. For instance, the score of country A under the standard BoD model is obtained as follows: $[(79 \times 0.01266) + (0.3 \times 0.0001)]$.

Table D.4: Sub-indicator shares and % contribution of each sub-indicator

Countries	Arithmetic average					Arithmetic average with unequal weighting					Standard BoD				
	sub WInd1	% contrib	Sub WInd2	% contrib	CI-a	sub WInd1	% contrib	Sub WInd2	% contrib	CI-b	sub WInd1	% contrib	Sub WInd2	% contrib	CI-d
A	39.5	99.6%	0.150	0.4%	39.7	59.3	99.9%	0.075	0.1%	59.3	1.000	100.0%	0.000	0.0%	1.000
B	33.5	99.3%	0.250	0.7%	33.8	50.3	99.8%	0.125	0.2%	50.4	0.684	72.8%	0.255	27.2%	0.939
C	39.0	99.5%	0.200	0.5%	39.2	58.5	99.8%	0.100	0.2%	58.6	0.796	79.6%	0.204	20.4%	1.000
D	31.5	98.9%	0.350	1.1%	31.9	47.3	99.6%	0.175	0.4%	47.4	0.643	64.3%	0.357	35.7%	1.000
E	27.5	98.9%	0.300	1.1%	27.8	41.3	99.6%	0.150	0.4%	41.4	0.561	64.7%	0.306	35.3%	0.867

Note: subW1nd1 and subWInd2 represent the sub-indicator shares of Ind1 and Ind2. These are obtained by multiplying the respective indicator values by their corresponding indicator weights. For instance, subWInd1 for country A under the standard BoD model is obtained as follows: 79×0.01266. The % contribution of Ind1 is then obtained by dividing the sub-indicator share (subWInd1) by the CI score (i.e. $\frac{1}{1} \times 100 = 100\%$).

Table D.5: Assigning the set of weights of efficient countries to others

Country	Standard BoD					Weights of A					Weights of C					Weights of D				
	Ind1	WInd1	Ind2	WInd2	CI-d	Ind1	WInd1	Ind2	WInd2	Score_A	Ind1	WInd1	Ind2	WInd2	Score_C	Ind1	WInd1	Ind2	WInd2	Score_D
A	79.0	0.0127	0.3	0.0001	1.000	79.0	0.0127	0.3	0.0001	1.000	79.0	0.0102	0.3	0.5102	0.959	79.0	0.0102	0.3	0.5102	0.959
B	67.0	0.0102	0.5	0.5102	0.939	67.0	0.0127	0.5	0.0001	0.848	67.0	0.0102	0.5	0.5102	0.939	67.0	0.0102	0.5	0.5102	0.939
C	78.0	0.0102	0.4	0.5102	1.000	78.0	0.0127	0.4	0.0001	0.987	78.0	0.0102	0.4	0.5102	1.000	78.0	0.0102	0.4	0.5102	1.000
D	63.0	0.0102	0.7	0.5102	1.000	63.0	0.0127	0.7	0.0001	0.798	63.0	0.0102	0.7	0.5102	1.000	63.0	0.0102	0.7	0.5102	1.000
E	55.0	0.0102	0.6	0.5102	0.867	55.0	0.0127	0.6	0.0001	0.696	55.0	0.0102	0.6	0.5102	0.867	55.0	0.0102	0.6	0.5102	0.867

Let us now consider the claim that the best set of weights are allocated to each coutry when using the BoD model. The results are reported in Table D.5. We observe that all other countries are worst off with the set of weights of A. C and D are not on the effiency frontier (i.e they do not have an optimal score of 1). On the other hand, Country A is worst off with the set of weights of C and D. The CI scores obtained when the weights of C and D are assigned are similar since both countries were assigned the same set of weights under the standard BoD model.

Benchmarking

Figure D.1 illustrates the benchmark idea behind the BoD model. A, C and D have an optimal score of one and are therefore located on the efficiency frontier. On the other hand, B and E are underperforming countries. Therefore, if we refer to Table D.6, country B's score is computed based on the performances of C and D in particular (i.e $0.524 + 0.415 = 0.939$). B' lies between C and D when projecting B on the efficiency frontier (i.e. the effort required for B to become efficient). On the other hand, E is closer to D. Consequently, E should benchmark best practices from D.

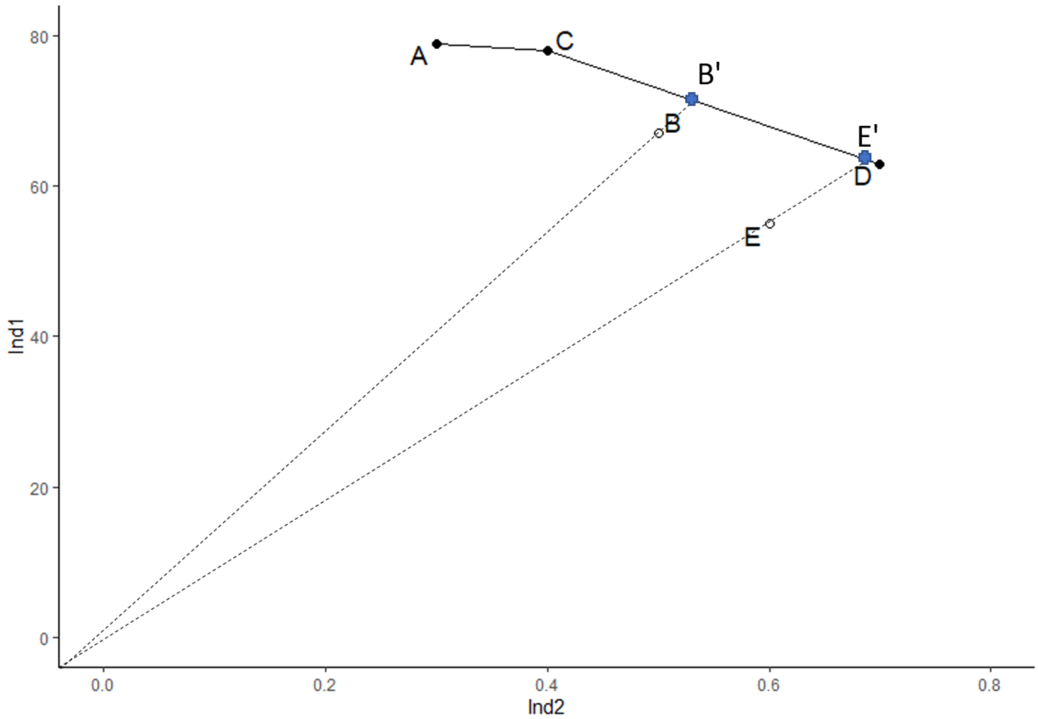

Figure D.1: Efficient versus underperforming countries under the standard BoD model (CI-d)

Table D.6: Country benchmarks

Benchmarks	A	B	C	D	E
A	1				
B			0.524	0.415	
C			1		
D				1	
E			0.024	0.844	

Appendix E

Table E.1: Confidence intervals for SIDS MLBoD scores

Country	MLBoD score	Lower bound	Upper bound
Cape Verde	1.0000	1.0000	1.0000
Comoros	0.8427	0.7758	0.9079
Samoa	0.8377	0.7537	0.9150
Palau	0.7979	0.7177	0.8713
Fiji	0.7183	0.6160	0.7870
Sao Tome and Principe	0.7119	0.6220	0.7946
Maldives	0.6899	0.6262	0.7369
Mauritius	0.6661	0.5984	0.7139
St.Kitts and Nevis	0.6433	0.5919	0.6805
Dominica	0.6401	0.5889	0.6769
Haiti	0.6328	0.5198	0.7363
Dominican Rep.	0.6322	0.5860	0.6652
Cuba	0.6256	0.5811	0.6577
Tuvalu	0.6217	0.5769	0.6536
Antigua and Barbuda	0.6099	0.5634	0.6435
Belize	0.6097	0.5687	0.6396
Kiribati	0.6000	0.5337	0.6467
Singapore	0.5987	0.5511	0.6333
Barbados	0.5986	0.5646	0.6231
Seychelles	0.5973	0.5627	0.6224
St. Vincent and the Grenadines	0.5959	0.5627	0.6197
Jamaica	0.5947	0.5588	0.6204
St. Lucia	0.5822	0.5501	0.6055
Bahamas	0.5680	0.5439	0.5851
Bahrain	0.5638	0.5356	0.5837
Tonga	0.5553	0.5308	0.5726
Suriname	0.5545	0.5241	0.5763
Vanuatu	0.5435	0.4887	0.5804
Guinea-Bissau	0.5409	0.4314	0.6345
Trinidad and Tobago	0.5304	0.5118	0.5427
Guyana	0.5289	0.5021	0.5481
Grenada	0.5252	0.5030	0.5408
Solomon Islands	0.5181	0.4702	0.5508
Micronesia	0.4866	0.4601	0.5059
Timor-Leste	0.4356	0.4055	0.4580
Papua New Guinea	0.2929	0.2793	0.3029

Appendix F

Table F.1: Contribution (%) of dimensions and sub-indices to energy vulnerability

SIDS	Sub-components		Exposure		Shock	
	Exposure	Shock	D1	D2	D3	D4
ATG	65%	35%	35%	65%	61%	39%
BHS	65%	35%	46%	54%	65%	35%
BHR	65%	35%	35%	65%	37%	63%
BRB	65%	35%	37%	63%	64%	36%
BLZ	65%	35%	64%	36%	63%	37%
CPV	65%	35%	35%	65%	52%	48%
COM	65%	35%	51%	49%	65%	35%
CUB	65%	35%	35%	65%	65%	35%
DMA	65%	35%	35%	65%	63%	37%
DOM	65%	35%	37%	63%	65%	35%
FJI	65%	35%	35%	65%	61%	39%
GRD	65%	35%	46%	54%	65%	35%
GNB	65%	35%	65%	35%	35%	65%
GUY	65%	35%	65%	35%	63%	37%
HTI	65%	35%	63%	37%	52%	48%
JAM	65%	35%	37%	63%	64%	36%
KIR	65%	35%	58%	42%	65%	35%
MDV	65%	35%	60%	40%	63%	37%
MUS	65%	35%	35%	65%	63%	37%
FSM	65%	35%	65%	35%	61%	39%
PLW	65%	35%	35%	65%	35%	65%
PNG	65%	35%	65%	35%	63%	37%
KNA	65%	35%	35%	65%	63%	37%
LCA	65%	35%	35%	65%	65%	35%
VCT	65%	35%	37%	63%	65%	35%
WSM	65%	35%	35%	65%	53%	47%
STP	65%	35%	61%	39%	58%	42%
SYC	65%	35%	37%	63%	64%	36%
SGP	65%	35%	35%	65%	37%	63%
SLB	65%	35%	65%	35%	65%	35%
SUR	65%	35%	65%	35%	63%	37%
TLS	65%	35%	64%	36%	65%	35%
TON	65%	35%	46%	54%	65%	35%
TTO	65%	35%	35%	65%	37%	63%
TUV	65%	35%	35%	65%	65%	35%
VUT	65%	35%	65%	35%	62%	38%

Appendix G

Table G.1: Composite index scores and country rankings across methods

SIDS	Direct approach		Hybrid approach			Indirect approach		
	Score	Rank	Score	Rank	Shift	Score	Rank	Shift
ATG	0.610	16	0.528	24	-8	0.913	19	+5
BHS	0.568	24	0.531	23	+1	0.868	28	-5
BHR	0.564	25	0.535	19	+6	0.905	24	-5
BRB	0.599	17	0.556	15	+2	0.921	16	-1
BLZ	0.610	15	0.667	7	+8	0.979	7	0
CPV	1.000	1	1.000	1	0	1.000	1	0
COM	0.843	2	1.000	1	+1	0.998	4	-3
CUB	0.626	13	0.631	9	+4	0.966	8	+1
DMA	0.640	10	0.593	13	-3	0.948	13	0
DOM	0.632	12	0.682	5	+7	0.993	5	0
FJI	0.718	6	0.670	6	0	0.982	6	0
GRD	0.525	32	0.486	31	+1	0.830	34	-3
GNB	0.541	29	0.361	35	-6	0.856	31	+4
GUY	0.529	31	0.484	32	-1	0.863	29	+3
HTI	0.633	11	0.487	30	-19	0.907	22	+8
JAM	0.595	22	0.560	14	+8	0.908	20	-6
KIR	0.600	21	0.501	28	-7	0.896	27	+1
MDV	0.690	7	0.614	10	-3	0.959	9	+1
MUS	0.666	8	0.730	4	+4	1.000	1	+3
FSM	0.487	34	0.367	34	0	0.761	36	-2
PLW	0.798	4	0.599	12	-8	0.955	12	0
PNG	0.293	36	0.407	33	+3	0.842	32	+1
KNA	0.643	9	0.606	11	-2	0.956	10	+1
LCA	0.582	23	0.532	22	+1	0.900	26	-4
VCT	0.596	20	0.552	16	+4	0.905	25	-9
WSM	0.838	3	0.745	3	0	1.000	1	+2
STP	0.712	5	0.648	8	-3	0.956	11	-3
SYC	0.597	18	0.508	27	-9	0.907	21	+6
SGP	0.599	19	0.545	18	+1	0.945	14	+4
SLB	0.518	33	0.534	21	+12	0.922	15	+6
SUR	0.555	27	0.545	20	+7	0.907	23	-3
TLS	0.436	35	0.360	36	-1	0.861	30	+6
TON	0.555	26	0.493	29	-3	0.815	35	-6
TTO	0.530	30	0.515	26	+4	0.835	33	-7
TUV	0.622	14	0.548	17	-3	0.917	18	-1
VUT	0.544	28	0.519	25	+3	0.918	17	+8
Mean	0.614		0.573			0.917		
Std. Dev.	0.122		0.139			0.058		
$\overline{R_s}$					4.25			3.28

Note: Country rankings under the hybrid approach are used to compute shifts in ranks.

Table G.2: Contribution of dimensions to energy vulnerability (sensitivity analysis)

SIDS	Direct approach				Hybrid approach				Indirect approach			
	D1	D2	D3	D4	D1	D2	D3	D4	D1	D2	D3	D4
ATG	35%	65%	61%	39%	35%	65%	63%	37%	54%	46%	89%	11%
BHS	46%	54%	65%	35%	35%	65%	65%	35%	62%	38%	88%	12%
BHR	35%	65%	37%	63%	35%	65%	58%	42%	46%	54%	90%	10%
BRB	37%	63%	64%	36%	35%	65%	65%	35%	64%	36%	87%	13%
BLZ	64%	36%	63%	37%	65%	35%	64%	36%	69%	31%	77%	23%
CPV	35%	65%	52%	48%	35%	65%	65%	35%	29%	71%	87%	13%
COM	51%	49%	65%	35%	52%	48%	54%	46%	50%	50%	87%	13%
CUB	35%	65%	65%	35%	35%	65%	65%	35%	66%	34%	91%	9%
DMA	35%	65%	63%	37%	35%	65%	65%	35%	60%	40%	89%	11%
DOM	37%	63%	65%	35%	42%	58%	65%	35%	72%	28%	76%	24%
FJI	35%	65%	61%	39%	35%	65%	56%	44%	58%	42%	91%	9%
GRD	46%	54%	65%	35%	35%	65%	65%	35%	59%	41%	88%	12%
GNB	65%	35%	35%	65%	65%	35%	35%	65%	40%	60%	69%	31%
GUY	65%	35%	63%	37%	60%	40%	64%	36%	70%	30%	73%	27%
HTI	63%	37%	52%	48%	64%	36%	45%	55%	41%	59%	73%	27%
JAM	37%	63%	64%	36%	35%	65%	65%	35%	62%	38%	88%	12%
KIR	58%	42%	65%	35%	35%	65%	64%	36%	55%	45%	88%	12%
MDV	60%	40%	63%	37%	35%	65%	64%	36%	57%	43%	86%	14%
MUS	35%	65%	63%	37%	54%	46%	64%	36%	66%	34%	90%	10%
FSM	65%	35%	61%	39%	35%	65%	59%	41%	69%	31%	75%	25%
PLW	35%	65%	35%	65%	35%	65%	35%	65%	33%	67%	86%	14%
PNG	65%	35%	63%	37%	65%	35%	63%	37%	67%	33%	81%	19%
KNA	35%	65%	63%	37%	35%	65%	65%	35%	59%	41%	90%	10%
LCA	35%	65%	65%	35%	35%	65%	65%	35%	64%	36%	88%	12%
VCT	37%	63%	65%	35%	35%	65%	65%	35%	58%	42%	89%	11%
WSM	35%	65%	53%	47%	35%	65%	52%	48%	52%	48%	89%	11%
STP	61%	39%	58%	42%	60%	40%	52%	48%	53%	47%	82%	18%
SYC	37%	63%	64%	36%	35%	65%	65%	35%	60%	40%	86%	14%
SGP	35%	65%	37%	63%	35%	65%	62%	38%	59%	41%	89%	11%
SLB	65%	35%	65%	35%	65%	35%	65%	35%	72%	28%	69%	31%
SUR	65%	35%	63%	37%	58%	42%	65%	35%	69%	31%	74%	26%
TLS	64%	36%	65%	35%	42%	58%	65%	35%	57%	43%	83%	17%
TON	46%	54%	65%	35%	35%	65%	65%	35%	54%	46%	89%	11%
TTO	35%	65%	37%	63%	35%	65%	50%	50%	44%	56%	90%	10%
TUV	35%	65%	65%	35%	35%	65%	65%	35%	59%	41%	89%	11%
VUT	65%	35%	62%	38%	65%	35%	64%	36%	68%	32%	69%	31%

Appendix for Chapter 2

Appendix A

Table A.1: Raw data of selected time series

Year	TECPC (kWh/cap)	GDPPC (US $/cap)	EP (US $)	EXPPC (US $/cap)
1978	279.59	2583.64	0.5	1003.33
1979	309.51	2628.35	0.65	1018.51
1980	299.16	2324.38	1.03	1020.51
1981	295.78	2424.91	1.22	955.27
1982	294.20	2527.12	1.33	1038.00
1983	301.49	2513.60	1.37	1037.98
1984	301.32	2604.32	1.59	1069.52
1985	313.56	2762.76	1.72	1187.53
1986	347.15	3008.82	1.71	1496.31
1987	388.00	3251.92	1.7	1755.46
1988	436.14	3448.94	1.69	1954.34
1989	482.28	3575.45	1.7	1999.61
1990	670.59	3805.21	1.71	2148.20
1991	728.79	3931.32	1.96	2217.71
1992	780.13	4132.62	2.05	2261.22
1993	820.14	4291.47	2.19	2384.26
1994	857.26	4406.84	2.19	2419.76
1995	945.25	4556.44	2.16	2562.59
1996	1021.17	4762.09	2.17	2804.07
1997	1108.61	4970.31	2.2	2866.86
1998	1205.60	5216.96	2.14	3073.14
1999	1226.96	5285.55	2.11	3076.19
2000	1363.25	5663.19	2.31	3176.01
2001	1453.66	5806.71	2.71	3630.09
2002	1473.49	5859.66	3.03	3177.81
2003	1561.77	6162.12	3.09	3101.07
2004	1614.25	6388.75	3.14	3008.84
2005	1683.69	6463.92	3.25	3396.26
2006	1743.12	6746.89	3.6	3542.32
2007	1816.67	7100.86	3.79	3577.88
2008	1881.65	7456.37	4.9	3672.79
2009	1907.12	7683.12	5.15	3602.20
2010	1995.36	8000.38	5.31	4099.20
2011	2025.70	8313.27	5.64	4307.33
2012	2075.04	8580.09	5.71	4448.88
2013	2148.33	8848.89	5.67	4175.86
2014	2182.51	9163.63	5.73	4430.97
2015	2026.00	9476.67	5.74	4506.96
2016	2067.00	9833.61	5.73	4347.60
2017	2114.00	10199.48	5.72	4301.56
2018	2139.00	10577.20	5.73	4396.04
2019	2222.00	10949.24	5.78	4417.05

Appendix B

Table B.1: Model specification in selected studies

Authors	DV	Functional form
Al-Faris (2002)	AEC	$\Delta Q_t = \alpha_0 + \alpha_1 \Delta X_t + \alpha_2 \Delta \mathrm{Pe}_t + \alpha_3 \Delta \mathrm{PI}_t + \alpha_4 \ell_{t-1}$
Narayan (2005)	REC	$ln\ \mathrm{EC}_t = \alpha_0 + \alpha_1 lnY_t + \alpha_2 ln\mathrm{EP}_t + \alpha_3 ln\mathrm{GP}_t + \alpha_4 ln\mathrm{TM}_t + \varepsilon_t$
De Vita et al. (2006)	EC	$\mathrm{ed}_t = \alpha + \beta_1 y_t + \beta_2 p_t + \beta_3 x_t + \mu_t$
Narayan & Singh (2007)	AEC	$\Delta \mathrm{lnE}_t = a_{0E} + \sum_{i=1}^{n} b_{iE} \Delta lnE_{t-i} + \sum_{i=1}^{n} c_{iE} \Delta \mathrm{lnY}_{t-i} + \sum_{i=1}^{n} d_{iE} \Delta lnL_{t-i} + \varpi_{1E} \mathrm{lnE}_{t-1} + \varpi_{2E} \mathrm{lnY}_{t-1} + \varpi_{3E} \mathrm{lnL}_{t-1} + \varepsilon_{1t}$
Zachariadis & Pashourtidou (2007)	AEC	$\Delta e_t = \alpha_{01} + \alpha_{11} \Delta e_{t-1} + \alpha_{21} \Delta y_{t-1} + \alpha_{31} \Delta p_{t-1} + \alpha_{41} \Delta \mathrm{tdd}_t + \alpha_{51}(e_{t-1} + \mathrm{by}_{t-1} + \mathrm{cp}_{t-1} + d) + u_{1t}$
Halicioglu (2007)	REC	$ln\ C_t = \alpha_0 + \alpha_1 lnY_t + \alpha_2 lnP_t + \alpha_3 U_t + \varepsilon_t$
Amusa et al. (2009)	AEC	$\mathrm{ec}_t = \alpha + \beta_1 y_t + \beta_2 p_t + \mu_t$
Mishra et al. (2009)	EC	$\mathrm{EC}_{i,t} = \alpha_i + \beta_i \mathrm{GDP}_{i,t} + \phi_{i,t} lnU_t + \varepsilon_{i,t}$
Odhiambo (2009)	AEC	$\Delta \mathrm{lnELEC}_t = \delta_0 + \sum_{i=1}^{n} \delta_{1i} \Delta ln\mathrm{ELEC}_{t-i} + \sum_{i=0}^{n} \delta_{2i} \Delta lny_{t-i} + \delta_3 \mathrm{lny}_{t-1} + \delta_4 \mathrm{lnELEC}_{t-1} + \mu_t$
Jamil & Ahmad (2010)	AEC	$\Delta E_t = \alpha_1 + \sum_{i=1}^{l} \beta_{1i} \Delta E_{t-i} + \sum_{i=1}^{m} \gamma_{1i} \Delta Y_{t-i} + \sum_{i=1}^{n} \delta_{1i} \Delta P_{t-i} + \phi_1 \mathrm{ECT}_{r,\ t-1} + \mu_{1t}$
Sadorsky (2010)	EC	$e_{it} = \alpha e_{it-1} + \beta_1 y_{it} + \beta_2 p_{it} + \beta_3 d_{it} + \nu_i + \psi_t + \varepsilon_{it}$
Jamil & Ahmad (2011)	AEC	$ln(E_t) = \beta_1 + \beta_2 ln(Y_t) + \beta_3 ln(P_t) + \beta_4 ln(Pd_t) + \beta_5 ln(K_t) + \beta_6 ln(T_t) + \mu_i$
Kumar (2011)	EC	$\Delta \mathrm{lnE}_t = \beta_0 + \beta_1 \mathrm{lnE}_{t-1} + \beta_2 \mathrm{lnY}_{t-1} + \beta_3 \mathrm{lnP}_{t-1} + \sum_{i=1}^{n} \lambda_i \Delta \mathrm{lnE}_{t-i} + \sum_{i=0}^{m} \gamma_i \Delta \mathrm{lnY}_{t-i} + \sum_{i=0}^{j} T_i \Delta \mathrm{lnP}_{t-i} + \varepsilon_t$
Sadorsky (2011)	EC	$e_{it} = \beta_{1i} y_{it} + \beta_{2i} p_{it} + \beta_{3i} o_{it} + \nu_i + \varepsilon_{it}$
Adom et al. (2012)	REC	$\mathrm{EC}_t = \alpha + \beta_1 \mathrm{PY}_t + \beta_2 \mathrm{IE}_t + \beta_3 \mathrm{IV}_t + \beta_4 U_t + \varepsilon_t$
Ghani (2012)	EC	$E_{it} = \lambda_0 + \lambda_{1i} + \lambda_{2t} + \lambda_3 \mathrm{LIB}_{it} + \lambda_4 Y_{it} + \lambda_5 \mathrm{LIB}_{it} * Y_{it} + \lambda_6 \mathrm{KL}_{it} + \lambda_7 \mathrm{LIB}_{it} * \mathrm{KL}_{it} + \eta_{it}$
Jiang & Lin (2012)	PEC	$LQ = c + \beta_1 LY + \beta_2 LM + \beta_3 LC + \beta_4 LEF + \beta_5 P$
Shahbaz & Lean (2012)	EC	$\Delta \mathrm{ENC}_t = \alpha_1 + \alpha_T T + \alpha_{ENC} \mathrm{ENC}_{t-1} + \alpha_{GDPC} \mathrm{GDPC}_{t-1} + \alpha_{FD} \mathrm{FD}_{t-1} + \alpha_{IND} \mathrm{IND}_{t-1} + \alpha_{URB} \mathrm{URB}_{t-1} + \sum_{i=1}^{p} \alpha_i \Delta \mathrm{ENC}_{t-i} + \sum_{j=0}^{q} \alpha_j \Delta \mathrm{GDPC}_{t-j} + \sum_{k=0}^{r} \alpha_k \Delta \mathrm{FD}_{t-k} + \sum_{l=0}^{s} \alpha_l \Delta \mathrm{IND}_{t-l} + \sum_{m=0}^{t} \alpha_m \Delta \mathrm{URB}_{t-m} + \mu_t$
Zaman et al. (2012)	AEC	$\Delta ln(ELEC)_t = \beta_0 + \beta_1 ln(ELEC)_{t-1} + \beta_2 ln(RGDPPC)_{t-1} + \beta_3 ln(FDI)_{t-1} + \beta_4 ln(POP)_{t-1} + \sum_{i=1}^{p} \beta_5 \Delta ln(ELEC)_{t-i} + \sum_{i=0}^{q} \beta_6 \Delta ln(RGDPPC)_{t-i} + \sum_{i=0}^{r} \beta_7 \Delta ln(FDI)_{t-i} + \sum_{i=0}^{s} \beta_8 \Delta ln(POP)_{t-i} + u_t$
Adom & Bekoe (2013)	AEC	$\mathrm{EC}_t = \alpha + \beta_1 \mathrm{PY}_t + \beta_2 \mathrm{IE}_t + \beta_3 \mathrm{IV}_t + \beta_4 U_t + \varepsilon_t$
Al-mulali & Lee (2013)	PEC	$\mathrm{LEC}_{it} = \beta_0 + \beta_1 \mathrm{LFD}_{it} + \beta_2 \mathrm{LGDP}_{it} + \beta_3 \mathrm{LUR}_{it} + \beta_4 \mathrm{LTD}_{it} + u_{it}$
Blázquez et al. (2013)	AEC	$lnE_{it} = \beta_0 + \beta_E lnE_{it-1} + \beta_{PE} ln\mathrm{PE}_{it} + \beta_Y lnY_{it} + \beta_{POP} ln\mathrm{POP}_{it} + \beta_{HS} \mathrm{lnHS}_{it} + \beta_{GAS} \mathrm{GAS}_{it} + \beta_{HDD} ln\mathrm{HDD}_{it} + \beta_{CDD} ln\mathrm{CDD}_{it} + \beta_{DT} \mathrm{DT}_t + \varepsilon_t$
Islam et al. (2013)	EC	$ln\mathrm{EC}_t = \delta_0 + \delta_{GDP} ln\mathrm{GDP}_t + \delta_{POP} ln\mathrm{POP}_t + \delta_{FD} ln\mathrm{FD}_t + \mu_t$
Mudakkar et al. (2013)	EC	$ln\mathrm{EC}_t = \alpha_0 + \alpha_1 ln\mathrm{GDP}_t + \alpha_2 ln\mathrm{REP}_t + \alpha_3 ln\mathrm{FDI}_t + \alpha_4 ln\mathrm{FD}_t + e_t$
Nasreen & Anwar (2014)	EC	$\mathrm{EN}_{it} = \alpha_{1i} Y_{it} + \alpha_{2i} T_{it} + \alpha_{3i} \mathrm{EP}_{it} + W_i + u_{it}$
Omri & Nguyen (2014)	RE	$g\mathrm{RE}_t = \alpha_0 + \alpha_1 gCO2_t + \alpha_2 g\mathrm{ROP}_t + \alpha_3 gY_t + \alpha_4 \mathrm{TO}_t + \varepsilon_t$
Sbia et al. (2014)	EC	$lnE_t = \beta_1 + \beta_2 lnF_t + \beta_3 lnG_t + \beta_4 ln\mathrm{TR}_t + \beta_5 lnC_t + \beta_6 lnY_t + \mu_i$
Tang & Tan (2014)	EC	$ln\mathrm{EC}_t = \alpha_0 + \alpha_2 ln\mathrm{GDP}_t + \alpha_3 ln\mathrm{RELP}_t + \alpha_3 ln\mathrm{FDI}_t + \alpha_4 ln\mathrm{FD}_t + \varepsilon_t$
Abidin et al. (2015)	EC	$ln(EC)_t = \alpha_0 + \alpha_1 ln(FDI)_t + \alpha_2 ln(TR)_t + \alpha_3 ln(FD)_t + \varepsilon_t$
Leitão (2015)	EC	$E_t = \alpha_0 + \alpha_1 Y + \alpha_2 FDI + \alpha_3 CO2 + \alpha_4 OT + \alpha_5 PolG + \mu_{it}$
Adom (2017)	AEC	$ln\ E_{it} = \alpha_i + \beta_i lnP_{Et} + \phi_i lnP_{Ot} + \delta_i lnY_t + \varepsilon_{it}$
Arif et al. (2017)	EC	$ln\mathrm{EC}_{it} = \beta_{1i} + \beta_{2i} ln\mathrm{TO}_{it} + \beta_{3i} ln\mathrm{GDP}_{it} + \beta_{4i} ln\mathrm{EP}_{it} + \epsilon_{it}$
Peñasco et al. (2017)	IEC	$ln\ E_{it} = \alpha_i + \beta_1 lnE_{it-1} + \beta_2 lnY + \beta_3 lnp_{it} + \varepsilon_{it}$
Salim et al. (2017)	EC	$C_t = \beta_1 + \beta_2 y_t + \beta_3 t_t + \beta_4 f_t + \mu_t$
Al-Bajjali & Shamayleh (2018)	AEC	$lnAEC = \alpha + \beta_1 lnGDP + \sigma_1 lnEP + \varphi_1 lnPOP + \psi_1 lnURB + \rho_1 lnIVA + \mu_1 lnAWC + \varepsilon$
Haider et al. (2019)	EC	$ln\mathrm{EC}_t = \beta_1 + \beta_2 lnY_t + \beta_3 lnU_t + \beta_4 lnI_t + \varepsilon_t$
Shahbaz et al. (2019)	EC	$ln\mathrm{EC}_t = \beta_0 + \beta_1 lnE_t + \beta_2 lnD_t + \beta_3 lnP_t + \beta_4 lnY_t + \beta_5 lnR_t + \mu_t$
Wang et al. (2020)	REC	$ln(\mathrm{Ene}_{it}) = \alpha_i + \beta_1 ln(P_{it}) + \beta_2 ln(A_{it}) + \beta_3 ln(\mathrm{Urb}_{it}) + u_{it}$
Zhao et al. (2020)	EC	$\mathrm{REC}_t \mid \mathrm{NREC}_t \mid \mathrm{PEC}_t = f(\mathrm{FD}_t, \mathrm{PI}_t, \mathrm{TECH}_t,\ \mathrm{TO}_t,\ \varepsilon_t)$

Note: EC stands for electricity consumption, AEC stands for aggregate electricity consumption, IEC stands for industrial electricity consumption, PEC stands for primary energy consumption, and REC stands for residential electricity consumption. For readability issues, individual description of all variables used in the studies presented above was not included.

Appendix C

Suppose we have an ARDL (1,1) model with Y_t the dependent variable and X_t the explanatory (independent) variable. The ARDL model is expressed as follows:

$$Y_t = \alpha + \beta\, Y_{t-1} + \delta_0 X_t + \delta_1 X_{t-1} + \varepsilon_t \tag{C.1}$$

Equation C.1 implies that Y_t is explained by its first lag Y_{t-1}, the current (X_t) and first lagged value (X_{t-1}) of X.

Let's assume that our variables are integrated of order one (non-stationary), i.e. I(1) and are cointegrated. First, we subtract Y_{t-1} from both sides as in Equation C.2. We then add and subtract $\delta_0 X_{t-1}$ on the right hand-side to derive the short and long-run estimates of X_t as in Equation C.3. The error correction model (ECM) representation of the underlying ARDL (1,1) model is given by Equation C.4.

$$Y_t - Y_{t-1} = \alpha + \beta\, Y_{t-1} - Y_{t-1} + \delta_0 X_t - \delta_0 X_{t-1} + \delta_1 X_{t-1} + \delta_0 X_{t-1} + \varepsilon_t \tag{C.2}$$

$$\Delta Y_t = \alpha + (\beta - 1) Y_{t-1} + \delta_0 \Delta X_t + (\delta_1 + \delta_0) X_{t-1} + \varepsilon_t \tag{C.3}$$

$$\Delta Y_t = -(1 - \beta)\left[Y_{t-1} - \frac{\alpha}{(1-\beta)} + \frac{(\delta_1 + \delta_0)}{(1-\beta)} X_{t-1} \right] + \delta_0 \Delta X_t + \varepsilon_t \tag{C.4}$$

Where $(1 - \beta)$ represents the adjustment parameter; the parameters in [] represent the error correction term, i.e. deviation of Y_{t-1} from its long-run equilibrium. Thus, for Y_{t-1} to error-correct, $(1 - \beta) < 0$, i.e. the adjustment parameter must be negative and statistically signifant for the error-correction mechanism to function.

Appendix D

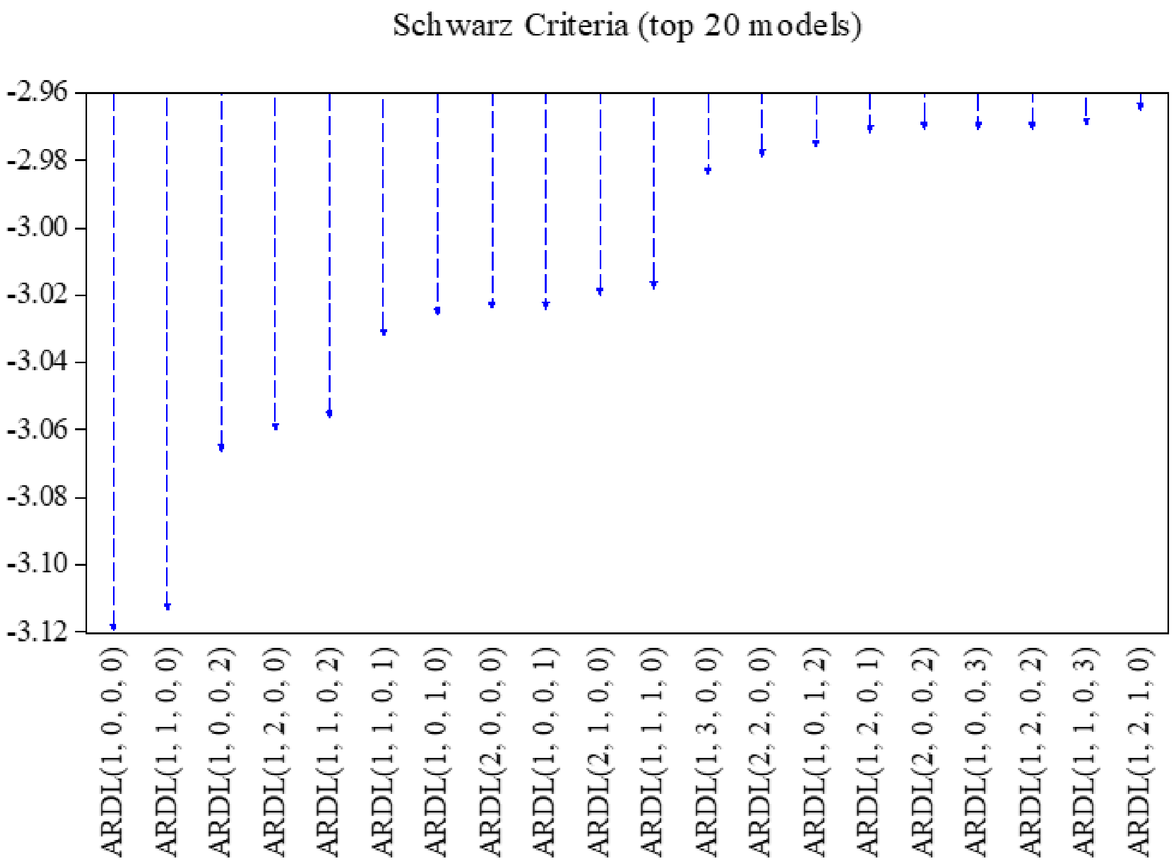

Figure D.1: ARDL model selection based on the Schwarz criterion (SIC)

Figure D.2 shows the residual plots of the ARDL (1,0,0,0) model. The top left plot shows that residuals have linear patterns. The Q-Q plot shows that residuals are roughly normally distributed although we acknowledge the presence of three outliers. The scale-location plot checks heteroscedasticity and shows that residuals are homoscedastic. The bottom right plot detects the presence of outliers in a linear regression model. Points outside the dotted line of the Cook's distance indicate that deleting them would change the model a lot.

Table D.1: ARDL (1,0,0,0) analysis

Variable	Coefficient	Std. Error	t-Statistic	Prob.
$tecpc(-1)$	0.789360	0.059011	13.37642	0.0000
$gdppc$	0.072662	0.071713	1.013238	0.3177
ep	-0.138045	0.049107	-2.811122	0.0079
$exppc$	0.280250	0.054667	5.126509	0.0000
c	-1.151637	0.399950	-2.879449	0.0067
R-squared	0.997094	Mean dependent var		6.896986
Adjusted R-squared	0.996771	S.D. dependent var		0.738449
S.E. of regression	0.041961	Akaike info criterion		-3.390294
Sum squared residuals	0.063387	Schwarz criterion		-3.181322
Log-likelihood	74.50104	Hannan-Quinn criterion		-3.314198
F-statistic	3088.028	Durbin-Watson stat		1.968303
Prob(F-statistic)	0.000000			

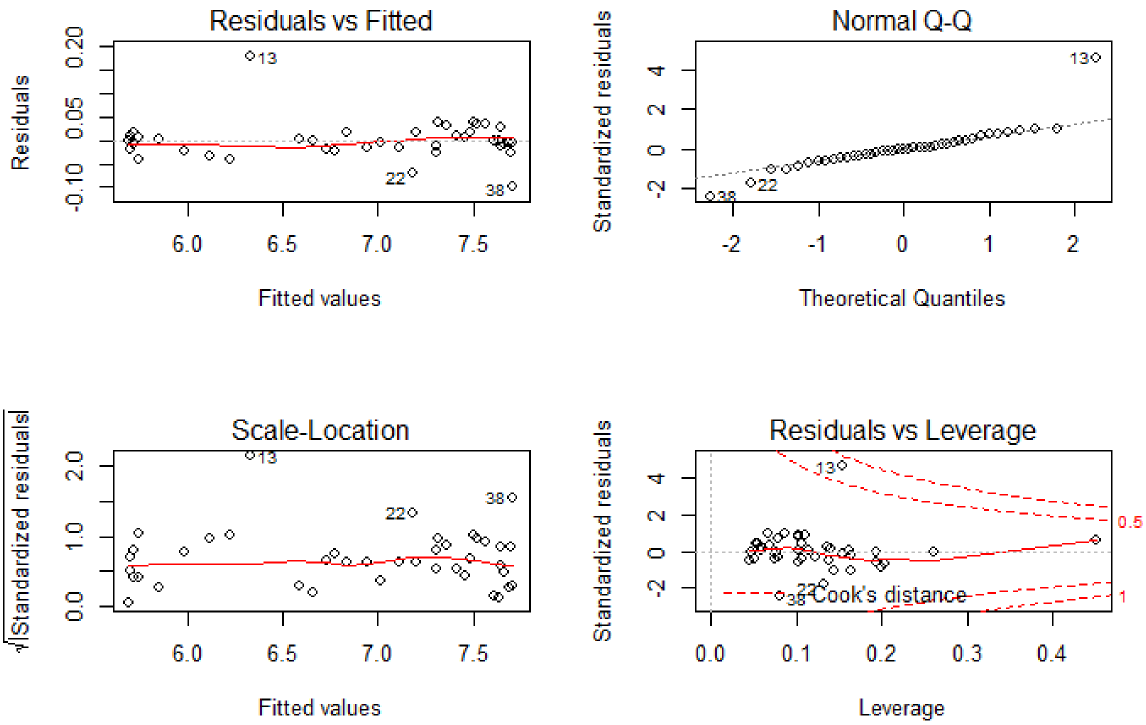

Figure D.2: Regression plots of the ARDL (1,0,0,0) model

Appendix E

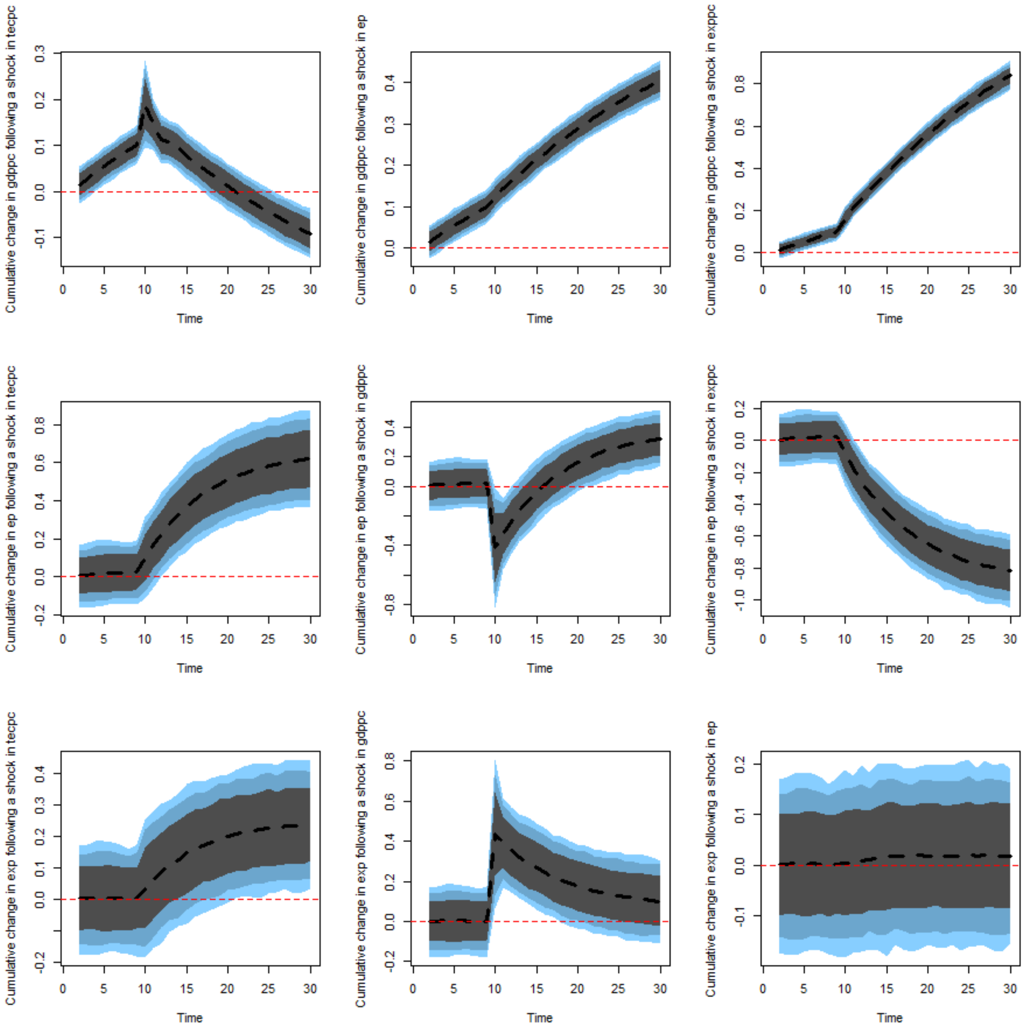

Figure E.1: Response from $gdppc$ (row 1), ep (row 2) and $exppc$ (row 3) following a change in the shock variables

Appendix F

Table F.1: Diagnostic tests for the augmented VAR (2) model

Serial correlation (Portmanteau test)	189.95 [0.9522]
Heteroscedasticity (ARCH test)	188.08 [0.7173]
Normality (Jarque-Bera test)	98.782 [2.2e-16]***

Note: *** denotes rejection of the null hypothesis at 1% significance level; p-values in []

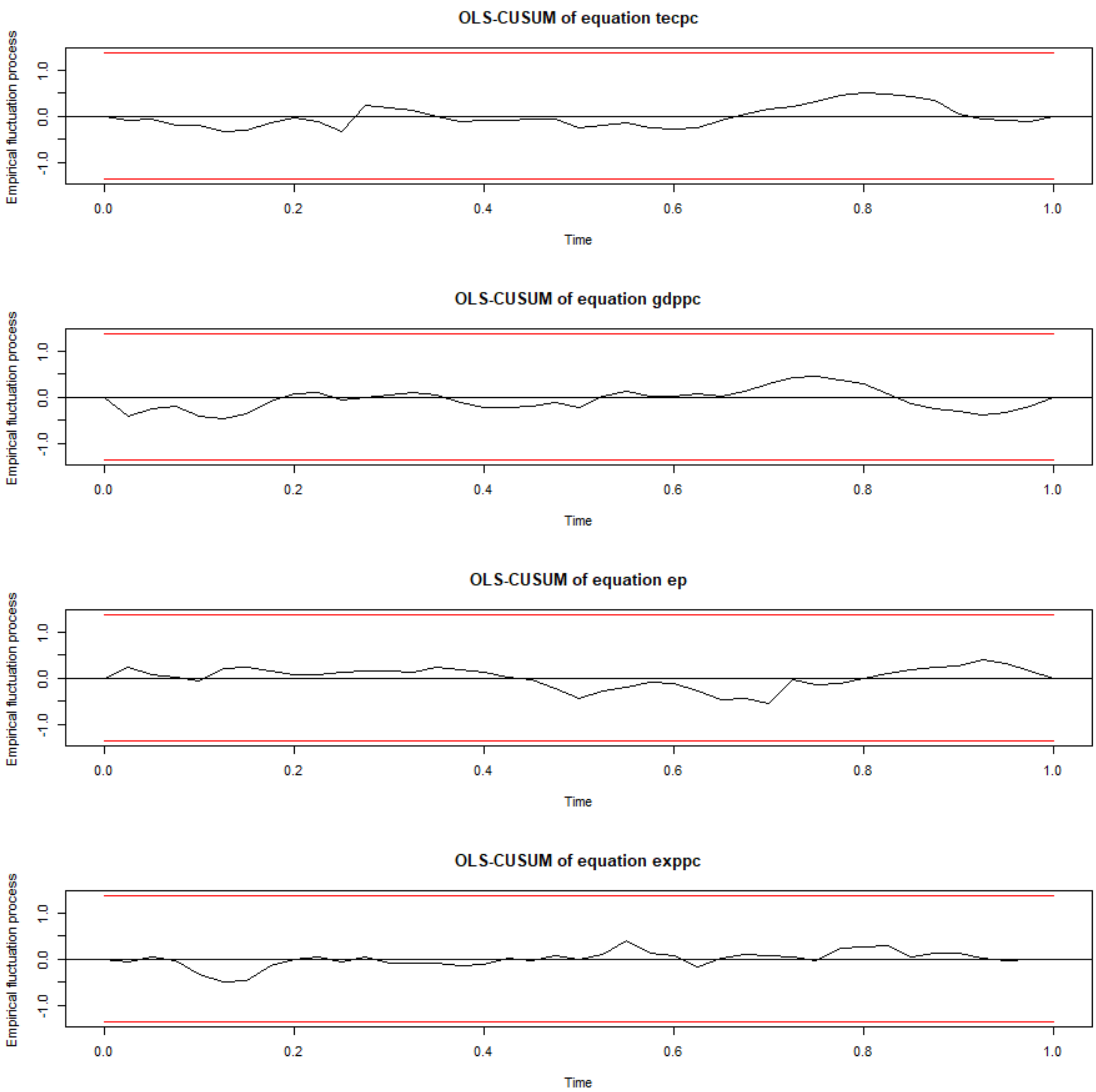

Figure F.1: Stability plots for the augmented VAR (2) model

Appendix for Chapter 3

Appendix A

Table A.1: Energy balance for the Republic of Mauritius in 2019

ktoe	FOSSIL								RENEWABLE									
	Coal	Petroleum products (PP)						Total PP									**Elec**	Total
		Diesel	Gasolene	Jet A1	Kerosene	HFO	LPG		Fuel Wood	Charcoal	Hydro	Wind	LFG	Solar PV	Bagasse	Total RE		
PRIMARY SUPPLY AND PRODUCTION																		
Local resources									5		8	1	2	11	177	204		204
Imports	727	337	198	299	14	816	189	1853										2580
Exports		-143		-152		-499	-67	-861										-861
Stock variation	-316	29	11	7	-10	-12	-31	-7										-323
TPER	**412**	**224**	**209**	**153**	**4**	**304**	**91**	**984**	**5**	**0**	**8**	**1**	**2**	**11**	**177**	**204**		**1600**
SECONDARY ENERGY PRODUCTION																		
CEB		-1			-4	-262		-267			-8					-9	**126**	-150
IPPs	-393							-393				-1	-2	-11	-160	-174	**153**	-808
Other transformation									-1									
Used-on works									0								**-4**	-4
Total secondary production	**-393**	**-1**			**-4**	**-262**		**-267**	**-1**		**-8**	**-1**	**-2**	**-11**	**-160**	**-183**	**275**	**-569**
Losses																	**-16**	-16
Total final distribution	**18**	**223**	**209**	**153**	**0**	**42**	**91**	**718**	**4**	**0**	**0**	**0**	**0**	**0**	**17**	**21**	**259**	**1016**
FINAL ENERGY CONSUMPTION																		
Manufacturing	18	38				37	7	83							17	17	**85**	203
Transport		183	209	153		4	3	552										552
Commercial							24	24									**87**	111
Residential							56	56	4							4	**81**	141
Agriculture		2						2									**2**	4
Other																	**4**	4
TFEC	**18**	**223**	**209**	**153**	**0**	**42**	**91**	**718**	**4**	**0**	**0**	**0**	**0**	**0**	**17**	**21**	**259**	**1016**

Note: 1 ktoe = 11.63 GWh - Unit converter and glossary, IEA (https://www.iea.org/reports/unit-converter-and-glossary, accessed 29/01/2020).

Appendix B

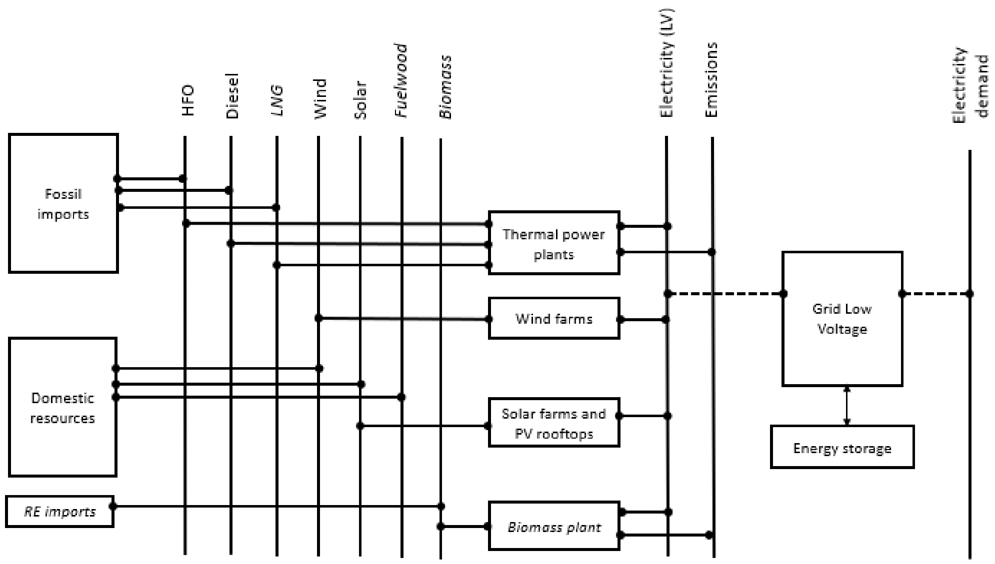

Figure B.1: Rodrigues' reference energy system

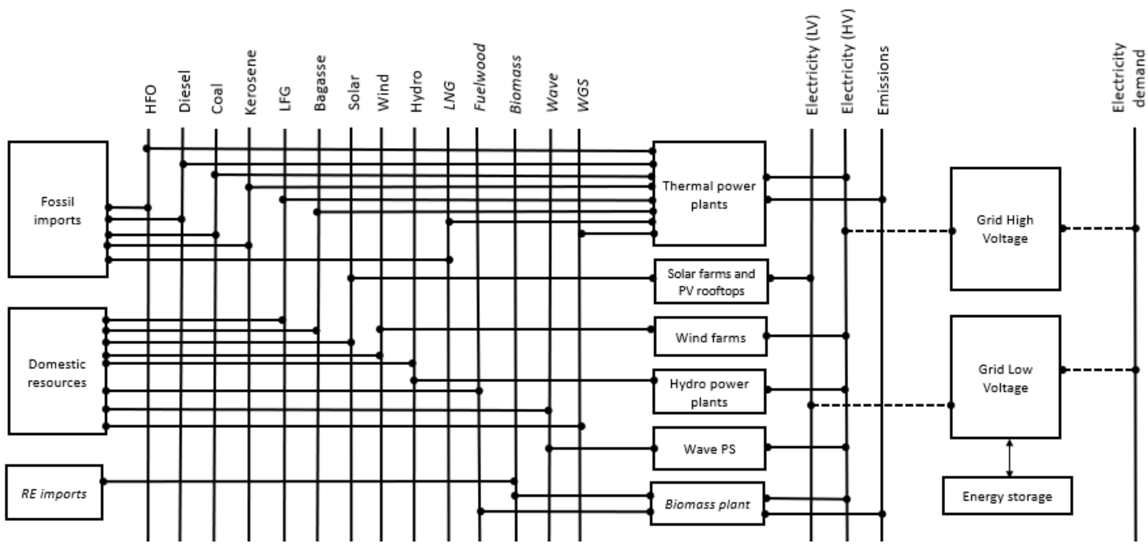

Figure B.2: Mauritius' reference energy system

Table B.1: Commodities in the RoM-TIMES model

Scenario	Region	Sector	Sets	Commodity	Unit	Type	TimeSlice	Description
BASE	MUS	TOT	.ENV.	ELCCH4	kt	ENV	-	CH4 Emissions
BASE	MUS	TOT	.ENV.	ELCCO2	kt	ENV	-	CO2 Emissions
BASE	MUS	TOT	.ENV.	ELCN2O	kt	ENV	-	N2O Emissions
BASE	MUS	TOT	.NRG.	COA	TJ	NRG	ANNUAL	Coal
BASE	MUS	TOT	.NRG.	DIE	TJ	NRG	ANNUAL	Diesel
BASE	MUS	TOT	.NRG.	ELCHV	TJ	NRG	DAYNITE	Electricity High Voltage
BASE	MUS	TOT	.NRG.	ELCLV	TJ	NRG	DAYNITE	Electricity Low Voltage
BASE	MUS	TOT	.NRG.	KERO	TJ	NRG	ANNUAL	Kerosene
BASE	MUS	TOT	.NRG.	OILHFO	TJ	NRG	ANNUAL	Heavy Fuel Oil
BASE	MUS	TOT	.NRG.	RENBAG	TJ	NRG	SEASON	Bagasse
BASE	MUS	TOT	.NRG.	RENHYDRO	TJ	NRG	ANNUAL	Hydro
BASE	MUS	TOT	.NRG.	RENLFG	TJ	NRG	ANNUAL	Landfill Gas
BASE	MUS	TOT	.NRG.	RENSOL	TJ	NRG	DAYNITE	Solar PV
BASE	MUS	TOT	.NRG.	RENWIN	TJ	NRG	ANNUAL	Wind
BASE	MUS	TOT	.NRG.	TFCELC	TJ	NRG	DAYNITE	Total Final Electricity Consumption
BASE	ROD	TOT	.ENV.	ELCCH4	kt	ENV	-	CH4 Emissions
BASE	ROD	TOT	.ENV.	ELCCO2	kt	ENV	-	CO2 Emissions
BASE	ROD	TOT	.ENV.	ELCN2O	kt	ENV	-	N2O Emissions
BASE	ROD	TOT	.NRG.	DIE	TJ	NRG	ANNUAL	Diesel
BASE	ROD	TOT	.NRG.	ELCLV	TJ	NRG	DAYNITE	Electricity Low Voltage
BASE	ROD	TOT	.NRG.	OILHFO	TJ	NRG	ANNUAL	Heavy Fuel Oil
BASE	ROD	TOT	.NRG.	RENSOL	TJ	NRG	DAYNITE	Solar PV
BASE	ROD	TOT	.NRG.	RENWIN	TJ	NRG	ANNUAL	Wind
BASE	ROD	TOT	.NRG.	TFCELC	TJ	NRG	DAYNITE	Total Final Electricity Consumption
B-NT-BIOMASS	MUS	TOT	.NRG.	RENBIOMASS	TJ	NRG	ANNUAL	Biomass
B-NT-BIOMASS	MUS	TOT	.NRG.	RENFWOO	TJ	NRG	ANNUAL	Fuelwood
B-NT-BIOMASS	MUS	TOT	.NRG.	RENWGS	TJ	NRG	ANNUAL	Waste-to-Energy
B-NT-BIOMASS	ROD	TOT	.NRG.	RENBIOMASS	TJ	NRG	ANNUAL	Biomass
B-NT-BIOMASS	ROD	TOT	.NRG.	RENFWOO	TJ	NRG	ANNUAL	Fuelwood
B-NT-GEO	MUS	TOT	.NRG.	RENGEO	TJ	NRG	ANNUAL	Geothermal energy
B-NT-LNG	MUS	TOT	.NRG.	LNG	TJ	NRG	ANNUAL	Liquified Natural Gas
B-NT-LNG	ROD	TOT	.NRG.	LNG	TJ	NRG	ANNUAL	Liquified Natural Gas
B-NT-OCE	MUS	TOT	.NRG.	RENWAVE	TJ	NRG	ANNUAL	Wave Energy

Table B.2: Processes in the RoM-TIMES model

Scenario	Region	Sector	Sets	Process	ActUnit	CapUnit	Type	PrimaryCG	TimeSlice	Description
BASE	MUS	TOT	.ELE.	EUCOALBAGALT	TJ	MW	ELE	ELCHV	DAYNITE	Alteo Cogeneration
BASE	MUS	TOT	.ELE.	EUCOALBAGOM	TJ	MW	ELE	ELCHV	DAYNITE	Omnicane Cogeneration
BASE	MUS	TOT	.ELE.	EUCOALBAGTER	TJ	MW	ELE	ELCHV	DAYNITE	Terragen Cogeneration
BASE	MUS	TOT	.ELE.	EUCOALOM	TJ	MW	ELE	ELCHV	DAYNITE	Omnicane Coal-fired PS
BASE	MUS	TOT	.ELE.	EUHYDDAMCH	TJ	MW	ELE	ELCHV	DAYNITE	Champagne Dam
BASE	MUS	TOT	.ELE.	EUHYDDAMMD	TJ	MW	ELE	ELCHV	DAYNITE	Midlands Dam
BASE	MUS	TOT	.ELE.	EUHYDDAMMG	TJ	MW	ELE	ELCHV	DAYNITE	Magenta Dam
BASE	MUS	TOT	.ELE.	EUHYDRESLF	TJ	MW	ELE	ELCHV	DAYNITE	La Ferme Dam
BASE	MUS	TOT	.ELE.	EUHYDRESLN	TJ	MW	ELE	ELCHV	DAYNITE	La Nicolière Reservoir
BASE	MUS	TOT	.ELE.	EUHYDRESLV	TJ	MW	ELE	ELCHV	DAYNITE	Le Val Reservoir
BASE	MUS	TOT	.ELE.	EUHYDRESTF	TJ	MW	ELE	ELCHV	DAYNITE	Tamarind Falls Reservoir
BASE	MUS	TOT	.ELE.	EUHYDRUNCC	TJ	MW	ELE	ELCHV	DAYNITE	Cascade Run of River
BASE	MUS	TOT	.ELE.	EUHYDRUNFE	TJ	MW	ELE	ELCHV	DAYNITE	Ferney Run of River
BASE	MUS	TOT	.ELE.	EUHYDRUNR	TJ	MW	ELE	ELCHV	DAYNITE	A.I A Run of River
BASE	MUS	TOT	.ELE.	EUKERNIGT	TJ	MW	ELE	ELCHV	DAYNITE	Nicolay Kerosene
BASE	MUS	TOT	.ELE.	EULFGSL	TJ	MW	ELE	ELCHV	DAYNITE	Sotravic LFG
BASE	MUS	TOT	.ELE.	EUOILHFOFG	TJ	MW	ELE	ELCHV	DAYNITE	Fort George HFO
BASE	MUS	TOT	.ELE.	EUOILHFOFVWS	TJ	MW	ELE	ELCHV	DAYNITE	Fort Victoria HFO
BASE	MUS	TOT	.ELE.	EUOILHFOSLPS	TJ	MW	ELE	ELCHV	DAYNITE	Saint Louis HFO
BASE	MUS	TOT	.ELE.	EUSOLPVHVAK	TJ	MW	ELE	ELCHV	DAYNITE	AKUO Henrietta PV Farm
BASE	MUS	TOT	.ELE.	EUSOLPVHVCEB	TJ	MW	ELE	ELCHV	DAYNITE	CEB Green Scheme
BASE	MUS	TOT	.ELE.	EUSOLPVHVHL	TJ	MW	ELE	ELCHV	DAYNITE	Helios PV Farm
BASE	MUS	TOT	.ELE.	EUSOLPVHVSF	TJ	MW	ELE	ELCHV	DAYNITE	Solar field PV Farm
BASE	MUS	TOT	.ELE.	EUSOLPVHVSK	TJ	MW	ELE	ELCHV	DAYNITE	Sarako PV Farm

Table B.2 Processes in the RoM-TIMES model *(cont.)*

Scenario	Region	Sector	Sets	Process	ActUnit	CapUnit	Type	PrimaryCG	TimeSlice	Description
BASE	MUS	TOT	.ELE.	EUSOLPVHVSYNEP	TJ	MW	ELE	ELCHV	DAYNITE	SynnoveEP PV Plant
BASE	MUS	TOT	.ELE.	EUSOLPVHVSYNPR	TJ	MW	ELE	ELCHV	DAYNITE	SynnovePR PV Plant
BASE	MUS	TOT	.ELE.	EUSOLPVHVVG	TJ	MW	ELE	ELCHV	DAYNITE	Voltas Green PV Farm
BASE	MUS	TOT	.ELE.	EUSOLPVHVVY	TJ	MW	ELE	ELCHV	DAYNITE	Voltas Yellow PV Farm
BASE	MUS	TOT	.ELE.	EUSOLPVLVFGPS	TJ	MW	ELE	ELCLV	DAYNITE	CEB FGPS rooftop
BASE	MUS	TOT	.ELE.	EUSOLPVLVFVPS	TJ	MW	ELE	ELCLV	DAYNITE	CEB FVPS rooftop
BASE	MUS	TOT	.ELE.	EUSOLPVLVMCB	TJ	MW	ELE	ELCLV	DAYNITE	MCB Saint Jean rooftop
BASE	MUS	TOT	.ELE.	EUSOLPVLVMSDGNET	TJ	MW	ELE	ELCLV	DAYNITE	MSDG Net Metering
BASE	MUS	TOT	.ELE.	EUSOLPVLVSSDG	TJ	MW	ELE	ELCLV	DAYNITE	SSDG rooftop
BASE	MUS	TOT	.ELE.	EUSOLPVLVSUPERU	TJ	MW	ELE	ELCLV	DAYNITE	Super U Flacq rooftop
BASE	MUS	TOT	.ELE.	EUWINONEPR	TJ	MW	ELE	ELCHV	DAYNITE	Eole PDR Onshore
BASE	MUS	TOT	.ELE.	GRIDHV	TJ	MW	ELE	TFCELC	DAYNITE	Grid High Voltage
BASE	MUS	TOT	.ELE.	GRIDLV	TJ	MW	ELE	TFCELC	DAYNITE	Grid Low Voltage
BASE	MUS	TOT	.IMP.	IMPDEMZ	PJ	-	IRE	DEM	ANNUAL	Dummy Import of DEM
BASE	MUS	TOT	.IMP.	IMPMATZ	Mt	-	IRE	MAT	ANNUAL	Dummy Import of MAT
BASE	MUS	TOT	.IMP.	IMPNRGZ	PJ	-	IRE	NRG	ANNUAL	Dummy Import of NRG
BASE	MUS	TOT	.IMP.IRE.	IMPCOA	TJ	Tja	IRE	COA	ANNUAL	Coal Imports
BASE	MUS	TOT	.IMP.IRE.	IMPDIE	TJ	Tja	IRE	DIE	ANNUAL	Diesel Imports
BASE	MUS	TOT	.IMP.IRE.	IMPKERO	TJ	Tja	IRE	KERO	ANNUAL	Kerosene Imports
BASE	MUS	TOT	.IMP.IRE.	IMPOILHFO	TJ	Tja	IRE	OILHFO	ANNUAL	Heavy Fuel Oil Imports
BASE	MUS	TOT	.MIN.IRE.	MINRENBAG	TJ	Tja	IRE	RENBAG	SEASON	Bagasse Potential
BASE	MUS	TOT	.MIN.IRE.	MINRENHYDRO	TJ	Tja	IRE	RENHYDRO	ANNUAL	Hydro Potential
BASE	MUS	TOT	.MIN.IRE.	MINRENLFG	TJ	Tja	IRE	RENLFG	ANNUAL	Lanfill Gas Potential
BASE	MUS	TOT	.MIN.IRE.	MINRENSOL	TJ	Tja	IRE	RENSOL	DAYNITE	Solar PV Potential
BASE	MUS	TOT	.MIN.IRE.	MINRENWIN	TJ	Tja	IRE	RENWIN	ANNUAL	Wind Potential

Table B.2 Processes in the RoM-TIMES model *(cont.)*

Scenario	Region	Sector	Sets	Process	ActUnit	CapUnit	Type	PrimaryCG	TimeSlice	Description
BASE	ROD	TOT	.ELE.	EUOILHFO	TJ	MW	ELE	ELCLV	DAYNITE	Pointe Monier HFO PS
BASE	ROD	TOT	.ELE.	EUOILHFODIE	TJ	MW	ELE	ELCLV	DAYNITE	Port Mathurin HFO PS
BASE	ROD	TOT	.ELE.	EUSOLPVLVGRE	TJ	MW	ELE	ELCLV	DAYNITE	Grenade PV Farm
BASE	ROD	TOT	.ELE.	EUWINONGRE	TJ	MW	ELE	ELCLV	DAYNITE	Grenade Wind Onshore
BASE	ROD	TOT	.ELE.	EUWINONTRF	TJ	MW	ELE	ELCLV	DAYNITE	Trefles Wind Onshore
BASE	ROD	TOT	.ELE.	GRIDLV	TJ	MW	ELE	TFCELC	DAYNITE	Grid Low Voltage
BASE	ROD	TOT	.IMP.	IMPDEMZ	PJ	-	IRE	DEM	ANNUAL	Dummy Import of DEM
BASE	ROD	TOT	.IMP.	IMPMATZ	Mt	-	IRE	MAT	ANNUAL	Dummy Import of MAT
BASE	ROD	TOT	.IMP.	IMPNRGZ	PJ	-	IRE	NRG	ANNUAL	Dummy Import of NRG
BASE	ROD	TOT	.IMP.IRE.	IMPDIE	TJ	Tja	IRE	DIE	ANNUAL	Diesel Imports
BASE	ROD	TOT	.IMP.IRE.	IMPOILHFO	TJ	Tja	IRE	OILHFO	ANNUAL	Heavy Fuel Oil Imports
BASE	ROD	TOT	.MIN.IRE.	MINRENSOL	TJ	Tja	IRE	RENSOL	DAYNITE	Solar PV Potential
BASE	ROD	TOT	.MIN.IRE.	MINRENWIN	TJ	Tja	IRE	RENWIN	ANNUAL	Wind Potential
B-NT-BIOMASS	MUS	TOT	.ELE.DSCINV.	ENBIOMASS2	TJ	MW	ELE	ELCHV	DAYNITE	Biomass PS MUS
B-NT-BIOMASS	MUS	TOT	.ELE.DSCINV.	ENFWOO2	TJ	MW	ELE	ELCHV	DAYNITE	Fuelwood PS MUS
B-NT-BIOMASS	MUS	TOT	.ELE.DSCINV.	ENLFG21	TJ	MW	ELE	ELCHV	DAYNITE	Sotravic21 New
B-NT-BIOMASS	MUS	TOT	.ELE.DSCINV.	ENWGS1	TJ	MW	ELE	ELCHV	DAYNITE	WGS Chaumière 24 MW
B-NT-BIOMASS	MUS	TOT	.IMP.IRE.	IMPRENBIOMASS	TJ	TJa	IRE	RENBIOMASS	ANNUAL	Biomass Imports
B-NT-BIOMASS	MUS	TOT	.MIN.IRE.	MINRENFWOO	TJ	TJa	IRE	RENFWOO	ANNUAL	Fuelwood Potential
B-NT-BIOMASS	MUS	TOT	.MIN.IRE.	MINRENWGS	TJ	TJa	IRE	RENWGS	ANNUAL	WtE Potential
B-NT-BIOMASS	ROD	TOT	.ELE.DSCINV.	ENBIOMASS1	TJ	MW	ELE	ELCLV	DAYNITE	Biomass PS ROD
B-NT-BIOMASS	ROD	TOT	.ELE.DSCINV.	ENFWOO1	TJ	MW	ELE	ELCLV	DAYNITE	Fuelwood PS ROD
B-NT-BIOMASS	ROD	TOT	.IMP.IRE.	IMPRENBIOMASS	TJ	TJa	IRE	RENBIOMASS	ANNUAL	Biomass Imports
B-NT-BIOMASS	ROD	TOT	.MIN.IRE.	MINRENFWOO	TJ	TJa	IRE	RENFWOO	ANNUAL	Fuelwood Potential
B-NT-COAL	MUS	TOT	.ELE.DSCINV.	ENCOAL1	TJ	MW	ELE	ELCHV	DAYNITE	Coal PP Pte aux Caves

Table B.2 Processes in the RoM-TIMES model *(cont.)*

Scenario	Region	Sector	Sets	Process	ActUnit	CapUnit	Type	PrimaryCG	TimeSlice	Description
B-NT-COAL	MUS	TOT	.ELE.DSCINV.	ENCOALBAG1	TJ	MW	ELE	ELCHV	DAYNITE	New coal-bag power plant
B-NT-GEO	MUS	TOT	.ELE.DSCINV.	ENGEO1	TJ	MW	ELE	ELCHV	DAYNITE	Nouvelle Découverte geo site
B-NT-GEO	MUS	TOT	.MIN.IRE.	MINRENGEO	TJ	TJa	IRE	RENGEO	ANNUAL	Geothermal potential
B-NT-HFO	MUS	TOT	.ELE.DSCINV.	ENOILHFO1	TJ	MW	ELE	ELCHV	DAYNITE	New HFO PS
B-NT-HFO	MUS	TOT	.ELE.DSCINV.	ENOILHFODIE1	TJ	MW	ELE	ELCHV	DAYNITE	New HFO DIE PS MUS
B-NT-HFO	ROD	TOT	.ELE.DSCINV.	ENOILHFODIE2	TJ	MW	ELE	ELCLV	DAYNITE	New HFO DIE PS ROD
B-NT-HYDRO	MUS	TOT	.ELE.DSCINV.	ENHYDDAM1	TJ	MW	ELE	ELCHV	DAYNITE	Bagatelle Dam 0.35 MW
B-NT-LNG	MUS	TOT	.ELE.DSCINV.	ENLNG1	TJ	MW	ELE	ELCHV	DAYNITE	LNG Fort George OCGT
B-NT-LNG	MUS	TOT	.ELE.DSCINV.	ENLNG2	TJ	MW	ELE	ELCHV	DAYNITE	LNG Fort George OCGT
B-NT-LNG	MUS	TOT	.ELE.DSCINV.	ENLNG3	TJ	MW	ELE	ELCHV	DAYNITE	LNG Fort George CCST
B-NT-LNG	MUS	TOT	.IMP.IRE.	IMPLNG	TJ	TJa	IRE	LNG	ANNUAL	LNG Imports
B-NT-LNG	ROD	TOT	.ELE.DSCINV.	ENLNGROD	TJ	MW	ELE	ELCLV	DAYNITE	LNG PS ROD
B-NT-LNG	ROD	TOT	.IMP.IRE.	IMPLNG	TJ	TJa	IRE	LNG	ANNUAL	LNG Imports
B-NT-OCE	MUS	TOT	.ELE.DSCINV.	ENWAVE1	TJ	MW	ELE	ELCHV	DAYNITE	WAVE 2030 15.5 MW
B-NT-OCE	MUS	TOT	.MIN.IRE.	MINRENWAVE	TJ	TJa	IRE	RENWAVE	ANNUAL	Wave Energy Potential
B-NT-SOL	MUS	TOT	.ELE.	ENSOLPVHVAH	TJ	MW	ELE	ELCHV	DAYNITE	Anahita PV farm 10.3 MW
B-NT-SOL	MUS	TOT	.ELE.	ENSOLPVHVHE1	TJ	MW	ELE	ELCHV	DAYNITE	CEB Henrietta PV farm
B-NT-SOL	MUS	TOT	.ELE.	ENSOLPVHVHE2	TJ	MW	ELE	ELCHV	DAYNITE	CEB Henrietta PV farm
B-NT-SOL	MUS	TOT	.ELE.	ENSOLPVHVQV	TJ	MW	ELE	ELCHV	DAYNITE	Queen Victoria PV farm
B-NT-SOL	MUS	TOT	.ELE.	ENSOLPVLVNGOCI	TJ	MW	ELE	ELCLV	DAYNITE	PV kits NGOCI 2 MW
B-NT-SOL	MUS	TOT	.ELE.	ENSOLPVLVPOOR	TJ	MW	ELE	ELCLV	DAYNITE	PV kits POOR 10 MW
B-NT-SOL	MUS	TOT	.ELE.	ENSOLPVLVPSEM	TJ	MW	ELE	ELCLV	DAYNITE	PV kits PSE 10 MW
B-NT-SOL	MUS	TOT	.ELE.	ENSOLPVLVRG	TJ	MW	ELE	ELCLV	DAYNITE	PV kits RG 4 MW
B-NT-SOL	MUS	TOT	.ELE.	ENSOLPVLVSC	TJ	MW	ELE	ELCLV	DAYNITE	SSDG/MSDG SC 15 MW
B-NT-SOL	MUS	TOT	.ELE.	ENSOLPVLVSME	TJ	MW	ELE	ELCLV	DAYNITE	PV kits SME 4 MW

Table B.2 Processes in the RoM-TIMES model *(cont.)*

Scenario	Region	Sector	Sets	Process	ActUnit	CapUnit	Type	PrimaryCG	TimeSlice	Description
B-NT-SOL	ROD	TOT	.ELE.	ENSOLPVLVPSER	TJ	MW	ELE	ELCLV	DAYNITE	PV kits PSE 1 MW ROD
B-NT-SOL	ROD	TOT	.ELE.	ENSOLPVLVRCO	TJ	MW	ELE	ELCLV	DAYNITE	Solar Farm R.Coco 100 KW
B-NT-STG	MUS	TOT	.ELE.STGTSS.	ENBESS01	TJ	TJa	ELE	ELCLV	DAYNITE	BESS 2,24 MW Henrietta
B-NT-STG	MUS	TOT	.ELE.STGTSS.	ENBESS02	TJ	TJa	ELE	ELCLV	DAYNITE	BESS 2,24 MW Amaury
B-NT-STG	MUS	TOT	.ELE.STGTSS.	ENBESS03	TJ	TJa	ELE	ELCLV	DAYNITE	BESS 4,48 MW Jin Fei
B-NT-STG	MUS	TOT	.ELE.STGTSS.	ENBESS04	TJ	TJa	ELE	ELCLV	DAYNITE	BESS 2,24 MW La TK
B-NT-STG	MUS	TOT	.ELE.STGTSS.	ENBESS05	TJ	TJa	ELE	ELCLV	DAYNITE	BESS 4,48 MW Anahita
B-NT-STG	MUS	TOT	.ELE.STGTSS.	ENBESS06	TJ	TJa	ELE	ELCLV	DAYNITE	BESS 4,48 MW Wooton
B-NT-STG	ROD	TOT	.ELE.STGTSS.	ENBESS07	TJ	TJa	ELE	ELCLV	DAYNITE	BESS 1 MW Rodrigues
B-NT-WIN	MUS	TOT	.ELE.	ENWINOF1	TJ	MW	ELE	ELCHV	DAYNITE	Wind Offshore 10 MW
B-NT-WIN	MUS	TOT	.ELE.	ENWINOF2	TJ	MW	ELE	ELCHV	DAYNITE	Wind Offshore 10 MW
B-NT-WIN	MUS	TOT	.ELE.	ENWINOF3	TJ	MW	ELE	ELCHV	DAYNITE	Wind Offshore 10 MW
B-NT-WIN	MUS	TOT	.ELE.	ENWINON1	TJ	MW	ELE	ELCHV	DAYNITE	Wind Onshore CPP 29,4 MW
B-NT-WIN	MUS	TOT	.ELE.	ENWINON2	TJ	MW	ELE	ELCHV	DAYNITE	Wind Onshore 20 MW
B-NT-WIN	ROD	TOT	.ELE.	ENWINON3	TJ	MW	ELE	ELCLV	DAYNITE	Wind Onshore 20 MW

Appendix C

Table C.1: Time slices for Mauritius

Winter				Summer			
TS	Hours	FR-TS	FR-Energy	TS	Hours	FR-TS	FR-Energy
WN5	0-4	0.084	0.057	SN5	0-4	0.083	0.076
WD1	4-7	0.063	0.046	SD1	4-7	0.062	0.054
WD2	7-10	0.063	0.059	SD2	7-10	0.062	0.068
WD3	10-13	0.063	0.064	SD3	10-13	0.062	0.077
WD4	13-16	0.063	0.062	SD4	13-16	0.062	0.076
WD5	16-18	0.042	0.042	SD5	16-18	0.041	0.049
WN1	18-19	0.021	0.023	SN1	18-19	0.021	0.025
WN2	19-20	0.021	0.023	SN2	19-20	0.021	0.027
WN3	20-22	0.042	0.041	SN3	20-22	0.041	0.052
WN4	22-24	0.042	0.034	SN4	22-24	0.041	0.046

Table C.2: Time slices for Rodrigues

Winter				Summer			
TS	Hours	FR-TS	FR-Energy	TS	Hours	FR-TS	FR-Energy
WN5	0-5	0.105	0.079	SN5	0-5	0.103	0.094
WD1	5-8	0.063	0.055	SD1	5-8	0.062	0.059
WD2	8-12	0.084	0.083	SD2	8-12	0.083	0.093
WD3	12-15	0.063	0.058	SD3	12-15	0.062	0.067
WD4	15-17	0.042	0.042	SD4	15-17	0.041	0.046
WD5	17-18.5	0.032	0.038	SD5	17-18.5	0.031	0.038
WN1	18.5-19.5	0.021	0.025	SN1	18.5-19.5	0.021	0.028
WN2	19.5-21	0.032	0.034	SN2	19.5-21	0.031	0.040
WN3	21-23	0.042	0.038	SN3	21-23	0.041	0.046
WN4	23-24	0.021	0.017	SN4	23-24	0.021	0.021

Table C.3: GHG emission factors from stationary combustion in kt/TJ

Fuel type	CO_2	CH_4	N_2O	Source
Coal (sub-bituminous)	0.0961	0.000001	0.0000015	MESD (2017)
Diesel Oil	0.0741	0.000003	0.0000006	MESD (2017)
Heavy fuel oil	0.0774	0.000003	0.0000006	MESD (2017)
Kerosene	0.0719	0.000003	0.0000006	MESD (2017)
Landfill gas	0.0546	0.000001	0.0000001	IPCC (2006)
WGS	0.092	0.00003	0.000004	IPCC (2006)
LNG	0.0561	0.000001	0.000003	IPCC (2006)
Fuelwood	-	0.00003	0.000004	IPCC (2006)
Bagasse	-	0.00003	0.000004	MESD (2017)
Imported biomass	-	0.00003	0.000004	IPCC (2006)

Table C.4: Renewable energy potential

Technologies	Capacity (MW)		Activity (GWh)	
	2030	2050	2030	2050
Solar PV SSDG	540.7	1359.45	804.6	-
Solar PV Utility	320.1	641.51	466.4	-
Wind Onshore	56	120.74	86	-
Wind Offshore	22	57	90	-
Wave	22	57	30	-
WGS	20	51.8	140	-
Hydro	61	61	93	-
Bagasse	-	-	-	-
Landfill gas	4	-	23	-
Fuelwood	-	-	123.3	
Imported biomass	-	-	1077	
BESS	18	-	-	-
Fuelwood and imported biomass - ROD	-	-	34.04	
Solar PV - ROD	-	-	5	15

Note: Resource potential (activity and capacity) up to 2030 was retrieved from MEPU (2009). Data on power plant activity for fuelwood and imported biomass were retrieved from Timmons et al. (2019). Please note that fuelwood in this paper corresponds to domestic wood chips potential in Timmons et al. (2019). Maximum capacity beyond 2030 is from the authors' calculations, where the assumed deployment rate is based on past trends $x1.5$.

Table C.5: Techno-economic parameters considered in the RoM-TIMES model

Energy source	Life	AFA	EFF		CAPEX (K€/TJ)		OPEX (K€/TJ)		Import price/ Extraction cost (K€/TJ)
			Existing	New	2030	2050	Fixed	Variable	
Hydro	50	[0.13 - 0.39]	1	1	4807.08	3605.31	[50.28 – 62.85]	0	-
Solar PV Roof	25	[0.10 - 0.18]	1	1	1881.44	496.7	5.42	0	-
Solar PV Utility	25	[0.13 – 0.21]	1	1	1188.17	313.68	10.84	0	-
Wave	20	0.29	-	1	4451	3115.70	178.04	0	-
Wind Onshore	20	[0.14 – 0.22]	1	1	2134.7	1183.48	52.97	0	-
Wind Offshore	20	0.5	1	1	4005.90	2220.87	214.63	0	-
Landfill gas	13	0.66	0.33	0.4	1503.55	845.75	271.51	0	-
WGS	28	0.79	-	0.25	5875.32	3304.87	235.9	3.56	-
Coal	33	0.82	0.26	0.31	1585.45	-	62.35	4.46	0.00127
HFO	33	[0.30 - 0.54]	0.44	0.53	1924.61	-	67.21	15.04	0.01409
LNG	25	0.5	-	0.4	1090.90	531.81	19.95	23.96	0.000018
Coal/bagasse	33	[0.54 - 0.68]	0.26/0.24	0.31/0.28	1554.29	-	62.95	4.46	-
Kerosene	25	0.02	0.26	-	-	-	6.70	0.47	0.02248
BESS	15	0.25	-	0.94	771.36	289.76	2.05	0	-
Fuelwood	33	0.5	-	0.4	1650	928.13	41.69	0.12	0.00000
Imported biomass	33	0.5	-	0.4	1650	928.13	41.69	0.12	0.00025

Note: All costs are converted into costs are expressed in 2019 prices. The authors calculate AFA and EFF for all existing technologies values based on available data for the reference year 2019. Values for fuelwood and imported biomass are retrieved from IRENA (2019). A 20% improvement is applied to the new EFF. CAPEX and OPEX values are retrieved from Shea & Ramgolam (2019) except for the following technologies: LNG retrieved from Poten & Partners (2019); BESS retrieved from IRENA (2017). Import prices are computed and converted in 2019 prices by the authors based on energy data available from SM (2020a) except for LNG, which are retrieved from Poten & Partners (2019) and imported biomass retrieved from Timmons et al. (2019). Extraction costs for domestic fuelwood are retrieved from Timmons et al. (2019).

Appendix D

Table D.1: Main results across modelled scenarios

Indicators	Mauritius							Rodrigues						
	REFYR	**BAU**		**35RE**		**30GHG**		**REFYR**	**BAU**		**35RE**		**30GHG**	
	2019	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2019**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Electricity demand (GWh)	2814.4	4097	6779	4097	6779	4097	6779	37.6	58.9	85.1	58.9	85.1	58.9	85.1
RE penetration rate (%)	24%	48%	53%	48%	53%	55%	89%	6%	62%	58%	62%	58%	72%	79%
of which imported biomass	-	*25%*	*15%*	*25%*	*15%*	*25%*	*15%*	-	-	-	-	-	-	-
RE installed capacity (MW) exclu. bagasse	161.765	544.52	1384.89	544.52	1384.89	664.57	1715.88	1.365	13.35	22.77	13.35	22.77	17.3	35
of which VRE (MW)	*97.875*	*221.25*	*1082.99*	*221.25*	*1058.84*	*338.92*	*1092.71*	*1.365*	*5.576*	*15*	*5.576*	*15*	*9.52*	*27.23*
Storage (MW)	-	-	15.57	-	14.72	3.58	15.70	-	-	-	-	-	-	-
Emissions (Mt)	2.11	2.01	3.14	2.01	3.15	1.41	1.57	0.029	0.015	0.022	0.015	0.022	0.01	0.011
Fossil fuel supply (TJ)	23918.4	22006.88	33542.1	22006.88	32557.67	17127.02	6253.69	376.99	190.99	289.96	190.99	289.96	139.645	132.61
Imported biomass (TJ)	-	9683	9693	9693	9693	9693	9693	-	-	-	-	-	-	-

Appendix E

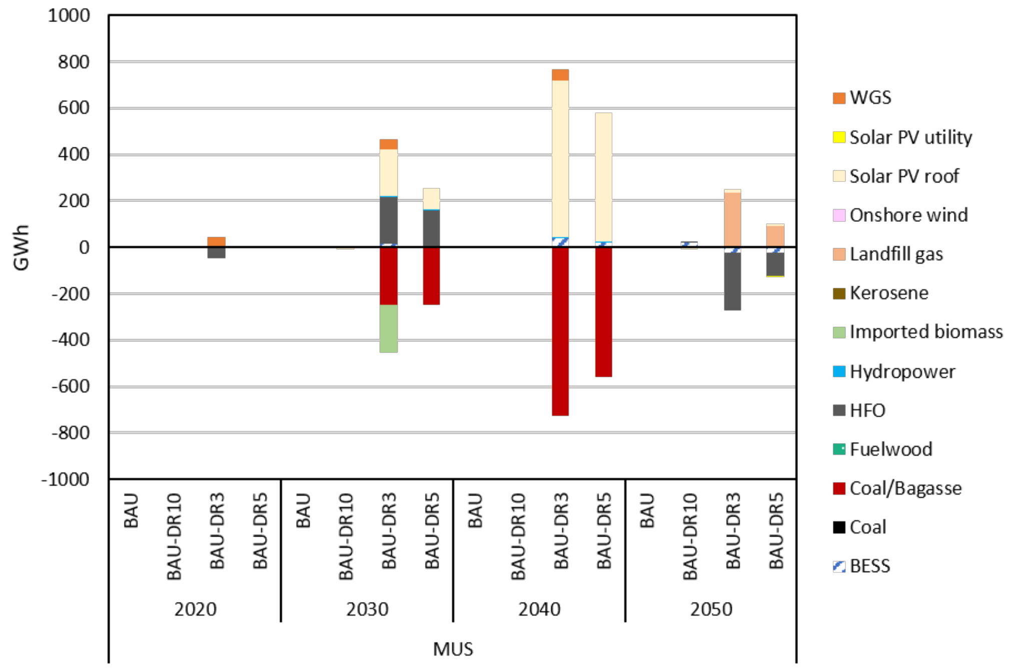

Figure E.1: Difference in electricity generation (GWh) w.r.t the BAU scenario across variants for Mauritius

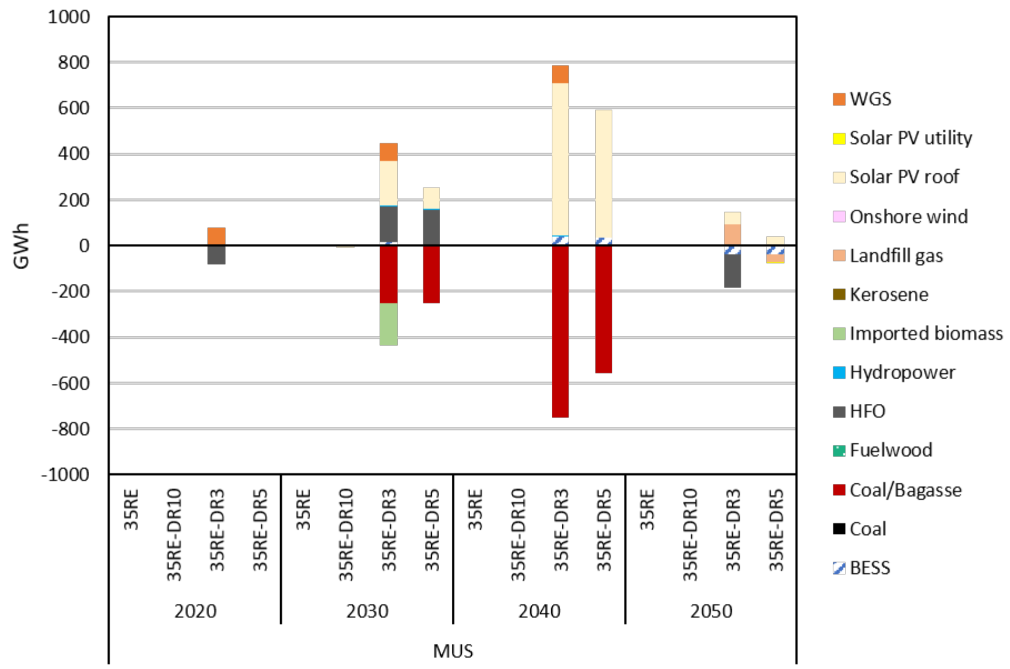

Figure E.2: Difference in electricity generation (GWh) w.r.t the 35RE scenario across variants for Mauritius

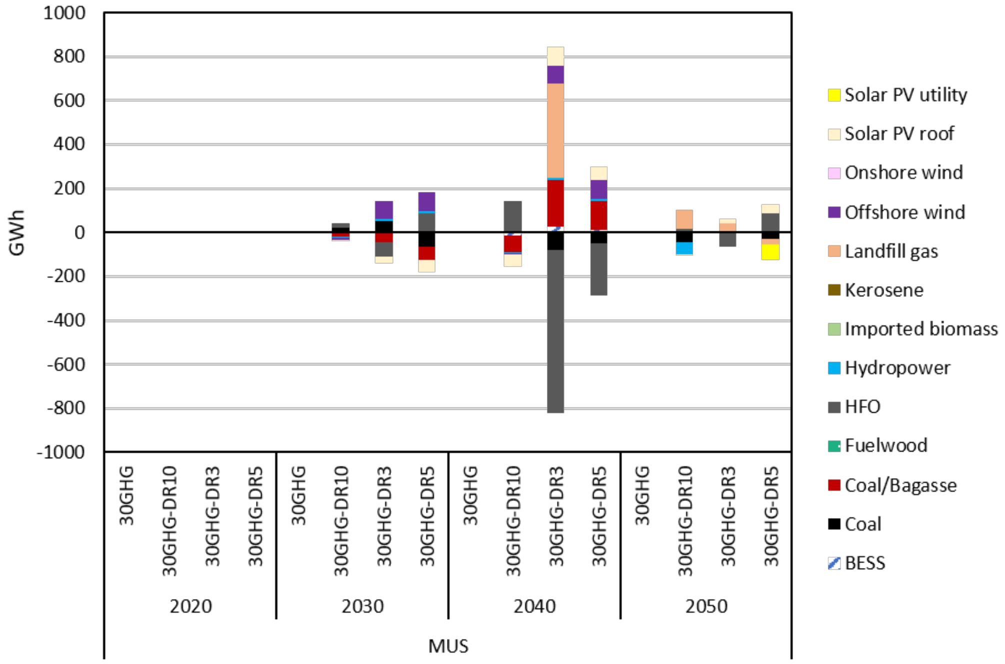

Figure E.3: Difference in electricity generation (GWh) w.r.t the 30GHG scenario across variants for Mauritius

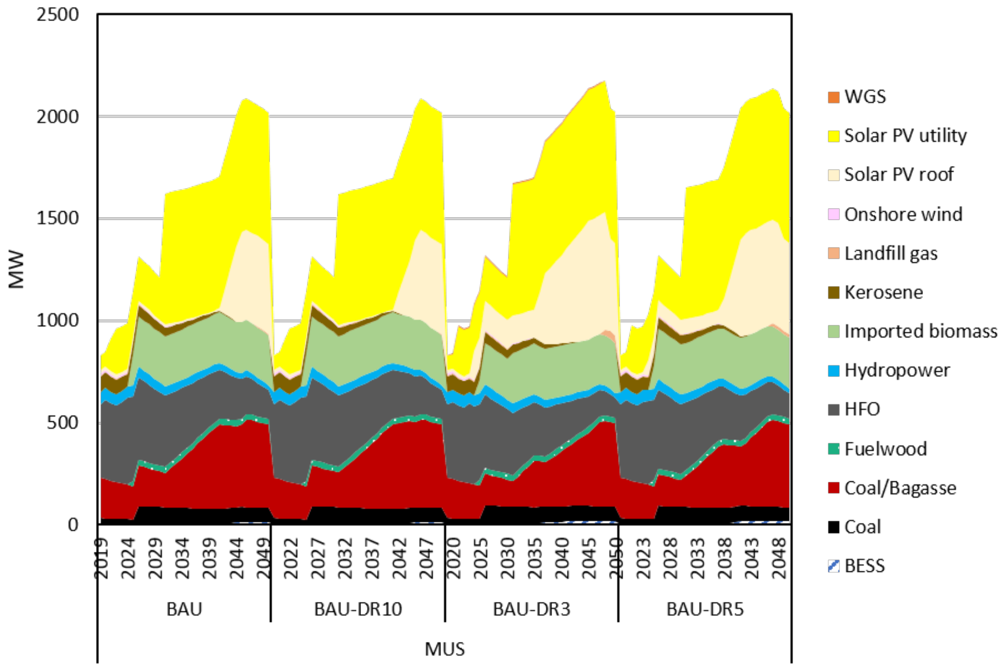

Figure E.4: Installed capacity (MW) across BAU scenario variants for Mauritius

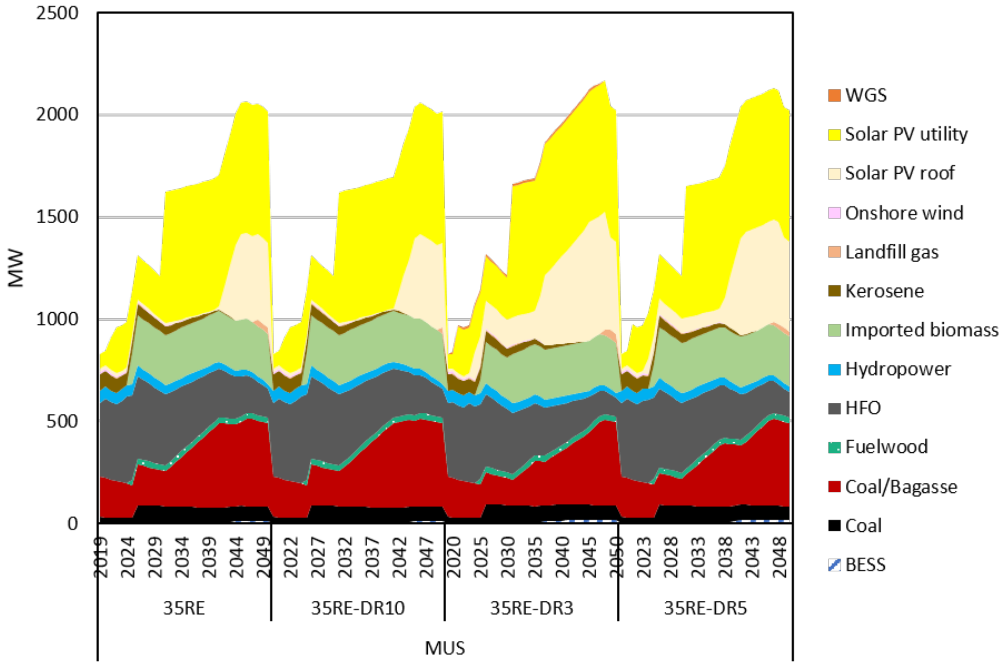

Figure E.5: Installed capacity (MW) across 35RE scenario variants for Mauritius

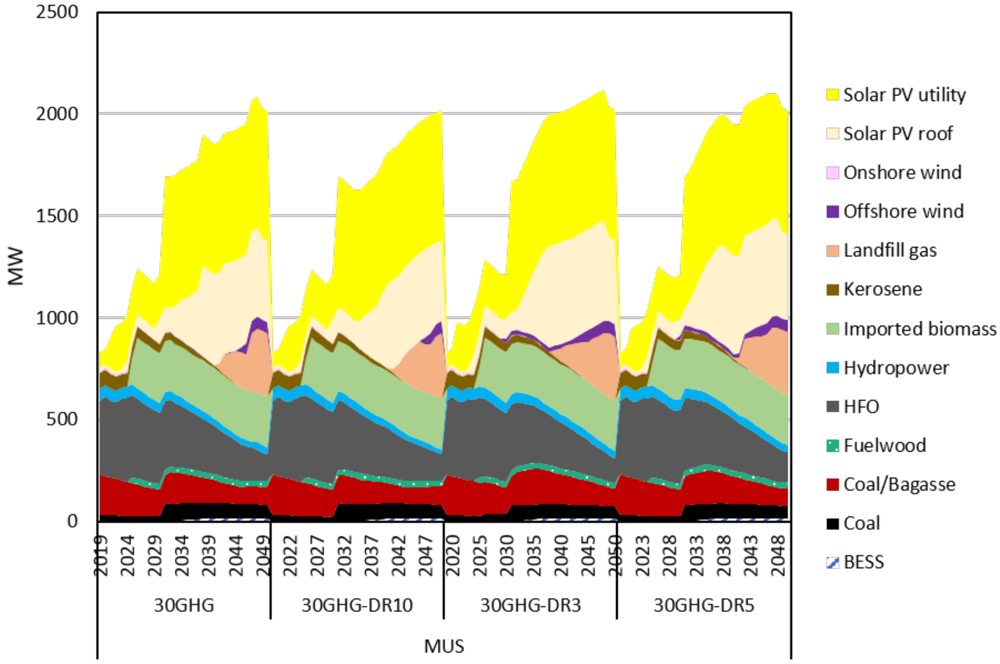

Figure E.6: Installed capacity (MW) across 30GHG scenario variants for Mauritius