Europa-Universität Flensburg

RENEWABLE ENERGY FOR SUSTAINABLE DEVELOPMENT:

Reviewing the Nicaraguan Energy Transition, its Challenges and Opportunities

Cumulative Dissertation

BY MARÍA MERCEDES VANEGAS CANTARERO

Cover Photos:

<u>Front</u>:
Wind turbines in Rivas, Nicaragua

<u>Back</u>:
Lake Apanás reservoir in Jinotega, Nicaragua

RENEWABLE ENERGY FOR SUSTAINABLE DEVELOPMENT: REVIEWING THE NICARAGUAN ENERGY TRANSITION, ITS CHALLENGES AND OPPORTUNITIES

By
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Submitted in partial fulfillment of the requirements for the degree of
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Dedication

To *Julio Vanegas* and *Lubina Cantarero*

Ustedes siempre han sido los principales promotores de mis sueños. Esto es por y para ustedes.

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"Scheiß auf den Kommerz. Lass uns was Richtiges machen."

Reiner Lemoine (1949 – 2006)

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Declaration

I hereby affirm that the present work was written by me alone, using no sources or aids other than those referenced in it. All of the materials taken directly or indirectly from external sources (including electronic sources, the Internet and oral communication) are marked as such, without exception and with a precise indication of the source. Core dissertation content has not been used previously for another thesis or work submitted in order to obtain an academic qualification. In particular, I have not received the help of a so-called "doctoral consultant" ("Promotionsberaterinnen/Promotionsberater"). Third parties have neither directly nor indirectly received money or goods with a monetary value from me in exchange for work related to the content of the herewith submitted dissertation. The work has not been submitted, in its present form or a similar form, to any other examination authority, either in Germany or abroad. I have been informed of what it means to submit an affidavit in lieu of an oath, of the penal consequences of a §§156,161 StGB [German Criminal Code].

03.09.2020

María M. Vanegas Cantarero

Date

Declaration on cumulative dissertation papers (resolution of the EUF dated: 31.05.2017)

I declare that the following specialist articles:

- "Reviewing the Nicaraguan transition to a renewable energy systems: Why is 'business as usual' no longer an option?" published in the journal Energy Policy
- "Decarbonizing the transport sector: The Promethean responsibility of Nicaragua" published in the Journal of Environmental Management
- "Of renewable energy, energy democracy and sustainable development: A roadmap to accelerate the energy transition in developing countries" published in the journal Energy Research & Social Sciences

submitted in the doctoral procedure by María Mercedes Vanegas Cantarero at the EUF are and were not part of a dissertation at any other university/college (this includes current, proposed or completed dissertations). Furthermore, the author of this dissertation has not previously attempted to earn a doctoral degree.

03.09.2020

María M. Vanegas Cantarero

Date

List of Abbreviations

ADF	Augmented Dickey Fuller
AIC	Akaike's Information Criterion
AGT	Automated Gateway Transit
ALBA	Alianza Bolivariana de las Americas (Bolivarian Alliance of the Americas)
APRODELBO	Asociacion Pro-desarrollo de Servicio Electrico Bocay (Bocay Electrical Service Development Association)
ARDL	Autoregressive Distributed Lag
AsoFenix	Asociacion Fenix (Fenix Association)
ATDER-BL	Asociacion de Trabajadores de Desarrollo Rural - Benjamin Linder (Association of Rural Development Workers - Benjamin Linder)
BCN	Central Bank of Nicaragua
BRT	Bus Rapid Transit
CARICOM	Caribbean Community and Common Market
CFLs	Compact Fluorescent Lamps
CIA	Central Intelligence Agency
CNDC	Centro Nacional de Despacho de Carga (National Load Dispatch Center)
CNE	Comision Nacional de Energia (National Energy Commission)
DNP	Distribuidora Nicaragüense de Petroleo (Nicaraguan Oil Distributor)
ECM	Error Correction Model
EKC	Environmental Kuznets Curve
ENATREL	Empresa Nacional de Transmision Electrica (National Electricity Transmission Company)
ENEL	Empresa Nicaragüense de Electricidad (Nicaraguan Electricity Company)
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
gha	Global Hectare
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German Corporation for International Cooperation)

HQ	Hannah Quinn Information Criterion
IEA	International Energy Agency
INE	Instituto Nacional de Energia (National Energy Institute)
INETER	Instituto Nicaragüense de Estudios Territoriales (Nicaraguan Institute of Territorial Studies)
INTUR	Instituto Nicaragüense de Turismo (Nicaraguan Institute of Tourism)
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
kboe	Thousands of barrels of oil equivalent
LEAP	Long-range Energy Alternatives Planning
LPG	Liquid Petroleum Gas
MEM	Ministerio de Energia y Minas (Ministry of Energy and Mines)
MIF	Multilateral Investment Fund
$MtCO_2$	Metric tons of carbon dioxide
NDC	Nationally Determined Contribution
NGO	Non-governmental Organisation
PDVSA	Petroleos de Venezuela (Petroleums of Venezuela)
PERZA	Proyecto de Electrificacion Rural para Zonas Aisladas Off-grid Rural Electrification Project
PNESER	Programa Nacional de Electrificacion Sostenible y Energias Renovables (Sustainable Electrification and Renewable Energy Programme)
PPP	Purchasing Power Parity
PV	Photovoltaic
RE	Renewable Energy
RENOVABLES	Asociacion Nicaragüense de Energia Renovable (Nicaraguan Association for Renewable Energy)
RQ	Research Question
SDGs	Sustainable Development Goals
SE4All	Sustainable Energy for All
SES	Smart Energy Systems
SIC	Schwarz's Information Criterion
T-Y	Toda-Yamamoto
TFEC	Total Final Energy Consumption
TPES	Total Primary Energy Supply
UNDP	United Nations Development Programme
UN ECLAC	United Nations Economic Commission for Latin American

	and the Caribbean
UNESCO	United Nations Educational, Scientific and Cultural Organization
V2G	Vehicle-to-Grid
VAR	Vector Autoregressive
WJP	World Justice Project

Abstract

Background. Energy is fundamental for development. In the last decades, fossil fuels have been the primary source of energy powering economies around the world. Paradoxically, these sources of energy have become the main source of human-induced climate change. Renewable energy has been appointed among the primary strategies to tackle the current climate crisis and build more resilient and sustainable energy systems. Countries around the world aim to transition to low-carbon energy systems to support sustainable development. Recently, developing and emerging economies have been leading investment in renewable energy. Due to the modest size of most of these economies, transitioning to sustainable and renewable energy systems could be a swift and less resource-intensive process, once the adequate strategies and policies are in place.

Nicaragua actively invested in renewable energy capacity in the last decade, positioning itself among the early leaders of the energy transition in Latin America. With a vast renewable energy potential, Nicaragua more than quintupled its electricity generation from clean energy sources between 2000 and 2017. Furthermore, using the distributed nature of renewable energy sources to its advantage, the country provided access to modern energy to nearly 98% of its population in 2019. This is a significant increase from 54% in 2006. However, progress has slowed down and investment in renewable energy has fallen to virtually zero since 2015. Furthermore, decarbonisation efforts are focused on the power sector and neglect other carbon-intensive sectors. This single-sector approach restricts the sustainability of the Nicaraguan economy and limits the country's energy transition.

Aims. 1) To examine the Nicaraguan energy system and its vision of a transition to renewable energy, identifying key drivers and challenges. 2) To study the energy-growth nexus in the context of Nicaragua and identify the role of renewable energy in the country's strategies for sustainable development. 3) To develop alternative energy pathways for Nicaragua based on a smart energy systems approach and the principles of energy justice and democracy to accelerate the uptake of renewable energy in the country, reduce greenhouse gas emissions and foster sustainable development. 4) To perform a techno-economic evaluation of the energy pathways developed. 5) To provide recommendations to aid a swift, just and democratic transformation of the

Nicaraguan energy system.

Methods. A convergent parallel mixed methods approach integrating both qualitative and quantitative data. The current situation of the Nicaraguan energy system is defined through desk research, reviewing policies and legislation, plans and strategies, as well as statistics and operational data. This information is used to build both econometric and energy models. Time-series econometric techniques, particularly an autoregressive distributed lag model and a vector autoregressive model, were employed to study the dynamics between selected economic and energy-related variables and identify the role of renewable energy in Nicaragua's recent economic development. Two energy modelling tools (EnergyPLAN and LEAP) were used to simulate the Nicaraguan energy system and design alternative energy pathways leading to a more sustainable and renewable energy system. Finally, interviews were carried out along with a review of scientific and grey literature to better understand the concepts of energy justice and energy democracy, which recently have been attracting attention in Nicaragua.

Results. Renewable energy has contributed to mitigating environmental degradation in Nicaragua while fostering economic development. Such energy sources have modestly supported the decoupling of the historical correlation between economic development and environmental degradation in the country. This research found that the potential to curb environmental degradation via renewable energy increases in the long-run and, therefore, it is fundamental to continue promoting the transformation of the Nicaraguan energy system.

Renewable energy must be integrated into all economic sectors to decarbonise the Nicaraguan energy system. For this, alternative energy pathways must be considered. Adopting new technologies in the transport sector may contribute to this purpose. Battery-electric vehicles, an electric public transport system in the Nicaraguan capital, and the production and local consumption of electrofuels are some strategies to introduce renewable energy into the Nicaraguan transport sector and significantly reduce greenhouse gas emissions. Furthermore, community energy projects were identified as an effective strategy to enable access to modern energy services, tackle the issues of energy poverty and social exclusion, and create opportunities for sustainable development. However, these projects lack support from the central government and are in a disadvantage when competing for support with incumbent energy sources

such as oil and its derivatives.

Conclusion. Renewable energy is playing an important role in dissociating economic development from environmental degradation. With more than 50% of the current electricity being generated from renewable energy sources, the next steps for Nicaragua's transition should involve both a cross-sectoral and decentralised approach to energy planning. Thereby, renewable energy can be integrated into highly oil-dependent economic sectors such as transport and industry. The country should adopt technologies to increase the uptake of renewable energy and leapfrog the resource-intensive development path followed by its forerunners. Nonetheless, plans and strategies should address the co-produced nature of the energy transition and enable citizen participation in the formulation and evaluation of energy and development strategies, as well as participatory decision-making. Finally, future energy plans and policies should be established as part of a politically agnostic development agenda and be measured and tracked in a multi-dimensional framework to secure progress in all facets of the energy transition.

Keywords: Nicaragua; Renewable energy; Smart energy system; Energy justice; Energy democracy; Sustainable development

Zusammenfassung

Einleitung. Energie ist von grundlegender Bedeutung für den wirtschaftlichen Wachstum. Eine der Haupttriebkräfte dieser Entwicklung ist der enorme Verbrauch von fossilen Brennstoffen, die die Volkswirtschaften auf der ganzen Welt antreibt. Mittlerweile ist dieser Verbrauch die hauptsächliche Quelle des vom Menschen verursachten Klimawandels. Erneuerbare Energien wurden zu einer der wichtigsten Strategien zur Bewältigung der gegenwärtigen Klimakrise und zum Aufbau widerstandsfähigerer und nachhaltigerer Energiesysteme ernannt. Länder auf der ganzen Welt streben den Übergang zu kohlenstoffarmen Energiesystemen an, um die nachhaltige Entwicklung zu unterstützen. In den letzten Jahren wurden Schwellen- und Entwicklungsländer durch ihre Investitionen in erneuerbare Energien zum Vorreiter. Aufgrund der bescheidenen Größe der meisten dieser Volkswirtschaften kann ein Übergang zu nachhaltigen und erneuerbaren Energiesystemen rasch und mit weniger Ressourcen erreicht werden, sobald die entsprechenden Strategien und Politiken vorhanden sind.

Mit einem enormen Potenzial an erneuerbaren Energien hat Nicaragua die Stromerzeugung aus sauberen Energiequellen zwischen 2000 und 2017 mehr als verfünffacht. Darüber hinaus nutzte das Land die dezentrale Natur der erneuerbaren Energiequellen zu ihrem Vorteil und verschaffte 2019 fast 98% seiner Bevölkerung Zugang zu moderner Energie. Dies ist ein signifikanter Anstieg von 54% im Jahr 2006. Der Fortschritt hat sich jedoch verlangsamt, und die Investitionen in erneuerbare Energien sind seit 2015 praktisch auf Null zurückgegangen. Darüber hinaus konzentrieren sich die Bemühungen zur Dekarbonisierung auf den Stromsektor und vernachlässigen andere kohlenstoffintensive Sektoren. Dieser Ein-Sektor-Ansatz schränkt die Nachhaltigkeit der nicaraguanischen Wirtschaft ein und schränkt die Energiewende des Landes ein.

Zielsetzungen. 1) Untersuchung des nicaraguanischen Energiesystems und dessen Vision eines Übergangs zu erneuerbaren Energien sowie Ermittlung der wichtigsten Triebkräfte und Herausforderungen. 2) Charakterisierung des Zusammenhanges zwischen Energie und Wachstum im Kontext Nicaraguas und die Identifizierung der Rolle der erneuerbaren Energien in den Strategien für nachhaltige Entwicklung. 3) Entwicklung von alternativen Energieplänen für Nicaragua, die auf dem Ansatz smarte Energiesysteme und den Prinzipien von Energiegerechtigkeit und Demokratie basieren, um die Einführung erneuerbarer Energien im Land zu beschleunigen, die Treibhausgasemissionen zu reduzieren und eine nachhaltige Entwicklung zu fördern. 4) Erstellung einer techno-ökonomischen Bewertung der entwickelten Energiepläne. 5) Erarbeitung von Empfehlungen bezüglich der nicaraguanischen Energieperspektive und eines zügigen, gerechten und demokratischen Umbaus des nicaraguanischen Energiesystems.

Methoden. Ein konvergentes paralleles Design mit gemischter Methode, das sowohl qualitative als auch quantitative Daten integriert. Die aktuelle Situation des nicaraguanischen Energiesystems wird durch Schreibtischforschung definiert, wobei Informationen über Politik und Gesetzgebung, Pläne und Strategien sowie Statistiken und operative Daten gesammelt werden. Diese Informationen werden verwendet, um sowohl ökonometrische als auch Energiemodelle zu erstellen. Zeitreihen-ökonometrische Techniken, insbesondere ein autoregressiv-distributed-lag-Modell und ein vektor-autoregressives Modell, wurden eingesetzt, um die Dynamik zwischen ausgewählten wirtschaftlichen und energiebezogenen Variablen zu untersuchen und die Rolle der erneuerbaren Energien in der Entwicklung Nicaraguas zu identifizieren. Zusätzlich wurden zwei Energiemodelle (EnergyPLAN und LEAP) eingesetzt, um das Energiesystem Nicaraguas zu simulieren und alternative Energiepläne zu erstellen, die zu einem nachhaltigeren und erneuerbaren Energiesystem führen. Schließlich wurden Interviews und eine Literaturrecherche durchgeführt, um die Konzepte der Energiegerechtigkeit und der Energiedemokratie, die in letzter Zeit in Nicaragua Aufmerksamkeit erregt haben, besser zu verstehen.

Ergebnisse. Erneuerbare Energien haben dazu beigetragen, die Umweltschädigung in Nicaragua einzudämmen und gleichzeitig die wirtschaftliche Entwicklung zu fördern. Diese Energiequellen haben in bescheidenem Maße dazu beigetragen, den historischen Zusammenhang zwischen wirtschaftlicher Entwicklung und Umweltschädigung im Land zu entkoppeln. Diese Untersuchung ergab, dass das Potenzial zur Eindämmung der Umweltzerstörung durch erneuerbare Energien langfristig zunimmt und es daher von grundlegender Bedeutung ist, die Transformation des nicaraguanischen Energiesystems weiter zu fördern.

Erneuerbare Energien müssen in alle Wirtschaftssektoren integriert werden, um das nicaraguanische Energiesystem zu dekarbonisieren. Dazu müssen alternative Energierouten in Betracht gezogen werden. Die Einführung neuer Technologien im Verkehrssektor kann zu diesem Zweck beitragen. Batterie-elektrische Fahrzeuge, ein elektrisches öffentliches Verkehrssystem in der nicaraguanischen Hauptstadt und die Produktion und der lokale Verbrauch von Elektrokraftstoffen sind einige Strategien, um erneuerbare Energien in den nicaraguanischen Verkehrssektor einzuführen und die Treibhausgasemissionen deutlich zu reduzieren. Darüber hinaus wurden Energiegemeinschaftsprojekte als eine wirksame Strategie identifiziert, um den Zugang zu modernen Energiedienstleistungen zu ermöglichen, die Probleme der Energiearmut und der sozialen Ausgrenzung anzugehen und Möglichkeiten für eine nachhaltige Entwicklung zu schaffen. Diesen Projekten mangelt es jedoch an Unterstützung der Zentralregierung, somit sind sie im Nachteil beim Wettbewerb um Unterstützung gegenüber den etablierten Energiequellen wie Öl und dessen Derivatprodukten.

Fazit. Erneuerbare Energien spielen eine wichtige Rolle bei der Abkopplung der wirtschaftlichen Entwicklung von der Umweltschädigung. Daher sind weitere Förderung und Integration ratsam. Da derzeit mehr als 50% des Stroms aus erneuerbaren Energiequellen erzeugt wird, sollten die nächsten Schritte für den Übergang Nicaraguas einen sektorübergreifenden Ansatz zur Energieplanung beinhalten. Auf diese Weise können erneuerbare Energien in stark ölabhängigen Wirtschaftssektoren wie Verkehr und Industrie integriert werden. Das Land sollte Technologien einführen, um den Einsatz erneuerbarer Energien zu erhöhen und den ressourcen-intensiven Entwicklungsweg, den seine Vorgänger beschritten haben, zu vermeiden. Allerdings sollten die Pläne und Strategien die ko-produzierte Natur der Energiewende berücksichtigen und die Beteiligung der Bürger an der Formulierung und Bewertung von Energie- und Entwicklungsstrategien sowie eine partizipatorische Entscheidungsfindung ermöglichen. Schließlich sollten zukünftige Energiepläne und -politiken als Teil einer politisch agnostischen Entwicklungsagenda aufgestellt und in einem mehrdimensionalen Rahmen gemessen und verfolgt werden, um Fortschritte in allen Bereichen der Energiewende zu sichern.

Stichwörter: Nicaragua; Erneuerbare Energien; Intelligentes Energiesystem; Energiegerechtigkeit; Energiedemokratie; Nachhaltige Entwicklung

Resumen Ejecutivo

Introducción. La energía es fundamental para el desarrollo. En las últimas décadas, los combustibles fósiles han sido la principal fuente de energía que ha impulsado las economías de todo el mundo. Paradójicamente, estas fuentes de energía se han convertido en la principal fuente de cambio climático inducido por el hombre. La energía renovable ha sido identificada como una de las principales estrategias para hacer frente a la actual crisis climática y construir sistemas energéticos más resilientes y sostenibles. Los países de todo el mundo se han puesto como objetivo crear economías con bajos niveles de emisiones de carbono para apoyar el desarrollo sostenible. Recientemente, las economías en desarrollo y emergentes han estado liderando la inversión en energía renovable. Debido al modesto tamaño de la mayoría de esas economías, la transición a sistemas de energía sostenible y renovable podría llevarse a cabo rápidamente y con menos recursos une vez que se establezcan las estrategias y políticas adecuadas.

Nicaragua invirtió activamente en capacidad instalada de energías renovables en la última década, posicionándose entre los primeros líderes de la transición energética en América Latina. Con un vasto potencial de energía renovable, Nicaragua quintuplicó sz generación de electricidad a partir de fuentes de energía limpia entre los años 2000 y 2017. Además, aprovechando la naturaleza distribuida de las fuentes de energía renovable, el país proporcionó acceso a energía moderna a casi el 98% de su población en 2019. Este es un aumento significativo con respecto al 54% de 2006. Sin embargo, el progreso se ha ralentizado y la invesión en energía renovable ha caído prácticamente a cero desde 2015. Además, los esfuerzos para descarbonizar el sistema energético se centran en el sector electricidad y descuidan otros sectores que tienen una huella de carbono significativa. Este enfoque monosectorial restringe la sostenibilidad de la economía nicaragüense y limita la transición energética del país.

Objetivos. 1) Examinar el sistema energético nicaragüense y su visión de la transición hacia las energías renovables, identificando los principales impulsadores y desafíos para dicho cambio. 2) Estudiar el nexo entre energía y crecimiento económico en el contexto de Nicaragua e identificar el papel de la energía renovable en las estrategias de desarrollo sostenible del país. 3) Desarrollar estrategias energéticas alternativas para Nicaragua basadas en un enfoque de sistemas inteligentes de energía y en los principios de justicia y democracia energética para acelerar la adopción de estas fuentes en el país, reducir las emisiones de gases de efecto invernadero y fomentar el desarrollo sostenible. 4) Realizar una evaluación tecno-económica de las estrategias energéticas desarrolladas. 5) Formular recomendaciones para acudar a una transformación rápida, justa y democrática del sistema energético nicaragüense.

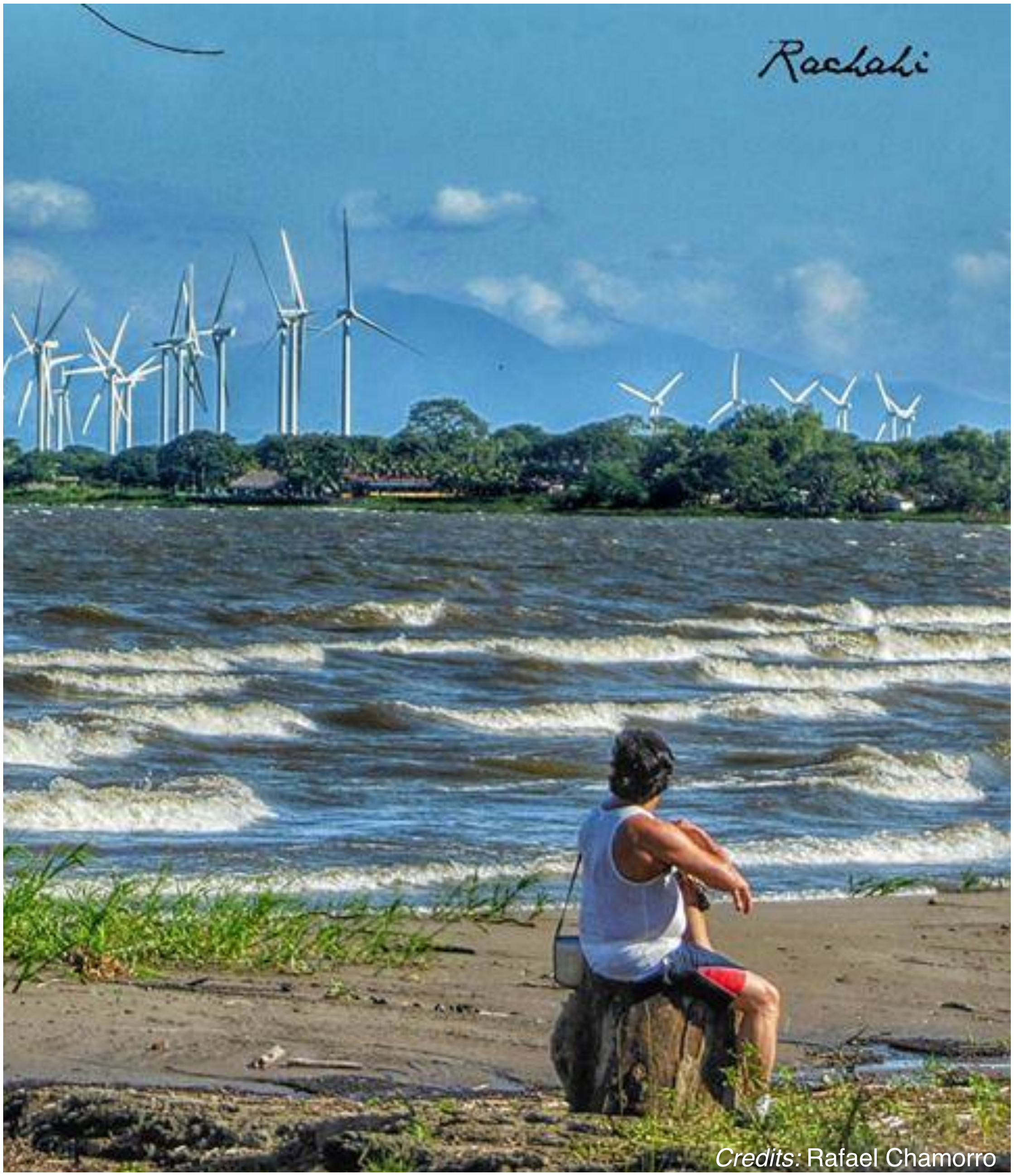
Metodología. Un enfoque paralelo convergente de métodos mixtos que integra datos cualitativos y cuantitativos. La situación actual del sistema energético nicaragüense se definió mediante investigaciones documentales, reuniendo información referente a políticas y legislación, planes y estrategias, así como estadísticas y datos operacionales. Esa información fue utilizada para elaborar modelos econométricos y energéticos. Se analizaron series de tiempo con métodos econométricos, en particular un modelo autorregresivo de retardos distribuidos y un modelo vectorial autorregresivo, para estudiar la dinámica entre determinadas variables económicas y otras relacionadas con el sector energía e identificar el papel de la energía renovable en el desarrollo de Nicaragua. Se utilizaron dos herramientas de modelización energética (EnergyPLAN y LEAP) para simular el sistema energético nicaragüense y diseñar estrategias energéticas alternativas que conduzcan a un sistema energético más sostenible y renovable. Por último, se realizaron entrevistas y se revisó la literatura científica reciente para comprender mejor los conceptos de justicia y democracia energética, que recientemente han venido resonando en Nicaragua.

Resultados. La energía renovable ha contribuido a mitigar la degradación del medio ambiente en Nicaragua, al mismo tiempo que ha fomentado el desarrollo económico. Esas fuentes de energía han apoyado modestamente la desvinculación de la correlación histórica entre el desarrollo económico y la degradación ambiental en el país. En esta investigación se comprobó que las posibilidades de frenar la degradación ambiental mediante la energía renocable aumentan a largo plazo y, por lo tanto, es fundamental seguir promoviendo la transformación del sistema energético nicaragüense.

La energía renovable debe integrarse en todos los sectores económicos para descarbonizar el sistema energético nicaragüense. Para ello, se deben considerar estrategias alternativas para la planeación energética. La adopción de nuevas tecnologías en el sector transporte puede contribuir a este propósito. Los vehículos eléctricos a batería, un sistema de transporte público eléctrico en la capital nicaragüense y la producción y consumo local de electrocombustibles son algunas de las estrategias para introducir energía renovable en el sector transporte nicaragüense y reducir significativamente las emisiones de gases de efecto invernadero. Además, se determinó que los proyectos comunitarios de energía son una estrategia eficaz para permitir el acceso a servicios energéticos modernos, abordar los problemas de pobreza energética y exclusión social y crear oportunidades para el desarrollo sostenible. Sin embargo, esos proyectos carecen de apoyo del gobierno central y se encuentran en desventaja cuando compiten por este apoyo con las fuentes de energía tradicionales, como el petróleo y sus derivados.

Conclusiones. La energía renovable está desempeñando un papel importante en la disociación entre el desarrollo económico y la degradación ambiental. Dado que más del 50% de la electricidad actual se genera a partir de fuentes de energía renovable, los próximos pasos para la transición energética en Nicaragua deberían implicar un enfoque intersectorial para la planificación energética. De este modo, la energía renovable puede integrarse en sectores económicos altamente dependientes del petróleo, como el transporte y la industria. El país debería adoptar tecnologías modernas para aumentar el uso de energía renovable y evitar el camino hacia el desarrollo que han seguido sus precursores caracterizado por la sobreexplotación de recursos. No obstante, los planes y estrategias deberían tener en cuenta el carácter coproducido de la transición energética y permitir la participación ciudadana en la formulación y evaluación de estrategias de energía y desarrollo, así como la implementación de procesos de toma de decisiones participativos. Por último, los planes y políticas energéticas futuras deben establecerse como parte de una agenda de desarrollo políticamente agnóstica y debe dárseles seguimiento en un marco multidimensional para asegurar el progreso en todas las áreas de la transición energética.

Palabras clave: Nicaragua; Energía renovable; Sistema inteligente de energía; Justicia energética; Democracia energética; Desarrollo sostenible



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Chapter 1

Introduction

1.1 Background

Energy is fundamental for development. Its benefits range from the creation of economic opportunities and jobs, through the empowerment of women, children and youth, to the improvement of health and education. Nevertheless, energy consumption, especially fossil fuel combustion, is closely linked to environmental degradation. This has been the largest source of greenhouse gas (GHG) emissions in the last 40 years [Edenhofer et al., 2014].

Around the globe, the decarbonization of the energy systems through renewable energy has been appointed as one of the key strategies to mitigate climate change and thus, curtail global warming and environmental degradation [Edenhofer et al., 2014]. Furthermore, renewable energy has been described as a means for sustainable development due to their potential contribution to attaining social inclusion, affordable energy access, energy security, reduction of environmental and health impacts and economic development [Sathaye et al., 2011].

Clean-energy technologies and the momentum created by the Paris climate agreement and the Sustainable Development Goals have led to a revolution in the power sector which is driving rapid change towards a renewable energy future. Scientific research appoints Smart Energy Systems (SES) as the future of energy systems. SES are capable of integrating high shares of intermittent renewable energy into the energy systems to fuel sectors other than electricity (e.g. heating, cooling, industry, transport) through radical technological changes such as electric vehicles, heat pumps, or electrolysers, thereby enhancing and guaranteeing efficiency, sustainability and affordability [Lund et al., 2017].

Although clean-energy technologies have been traditionally developed and manufactured by developed nations, developing and emerging economies are driving the renewables revolution. In recent years, these economies have invested more in clean-energy technologies than developed nations, when viewed on a per gross domestic product basis [Frankfurt School - UNEP Centre/BNEF, 2020; REN21, 2020]. Developing nations that are endowed with sufficient domestic renewable resources to meet their energy needs may have a latent comparative advantage that, if used properly, can lead to an increase in competitiveness, industrial upgrading, innovation and economic growth [Lin, 2016].

Table 1.1
Country profile: Nicaragua

Indicator	**Nicaragua**	**Latin American Average**
Gross domestic product (GDP), PPP, 2019 (current international $)[1]	37.69 billion	10.86 billion
Growth rate at constant prices, 2019 (%)	-3.9	0.0
Population, 2019 (Thousands of persons)	6,546	648,121
Literacy rate of people ages 15 years and over, 2015 & 2018 respectively (%)	82.6	93.9
Unemployment rate, 2019 (%)	5.4	8.0
Poverty headcount ratio at $3.20 a day (2011 PPP), 2014 & 2018 respectively (% of population)[1]	12.8	10.4
Proportion of the population using safely managed drinking water services, 2017 (%)	51.6	74.3
Proportion of the population with primary reliance on clean flues and technology, 2018 (%)	48.0	88.0

Indicator	Nicaragua	Latin American Average
Proportion of population with access to electricity, 2017 (%)	86.8	98.2
Renewable proportion of final energy consumption, 2017 (%)	47.15	20.40
Carbon dioxide (CO_2) emissions per GDP, 2016 (Tonnes of CO_2 per US$ 1,000 of GDP)	0.48	0.45
Energy intensity of GDP, 2015 (kboe equivalent per US$1M of GDP in constant 2010 prices)	1.55	0.80
Ecological footprint, 2016 (gha)[2]	10,816,913	n/a[3]

Source: Main indicators retrieved from UN ECLAC, 2020a (unless otherwise stated herein).

[1] Alternative Source: World Bank Group (2020)

[2] Alternative Source: Global Footprint Network (2019)

[3] N/A = not available or not applicable.

In 2018, Nicaragua was the third most impoverished country in Latin America (excluding the Caribbean), yet the second-fastest growing economy among the Central American countries [World Bank Group, 2020]. This recently experienced economic growth has coincided with high levels of fossil fuel consumption, overuse of natural resources and significant environmental degradation. CO_2 emissions and the ecological footprint of Nicaragua, both indicators of environmental degradation, have been rising [Global Footprint Network, 2019; World Bank Group, 2020]. Despite the economic prosperity, most of Nicaragua's development indicators (see Table 1.1) are underperforming in comparison with the Latin American average. Literacy, poverty and access to modern and safely managed basic services remain development challenges for the country. Nevertheless, Nicaragua was among the region's first newcomers to the renewable energy transition in the past decade. The country invested 1.6 billion dollars between 2006 and 2013 to integrate more renewable energies into its energy system [MIF et al., 2014]. Consequently, the use of clean electricity per capita doubled between 2005 and 2013 [World Bank Group, 2020]. Currently, more than half of the electricity in Nicaragua is generated using domestic renewable resources (approx.

56.8% in 2019) [INE, 2020c].

Nicaragua's interest in clean energy is part of its efforts to tackle the energy trilemma, i.e., energy security, energy poverty and environmental sustainability. The country seeks to power the economy with domestic renewable resources instead of imported oil and its derivatives. The question remains whether renewable energy will be able to replace fossil fuels in their role as an engine for economic development in Nicaragua and whether they can curb the associated negative environmental impact.

To date, the country has seized approx. 30% of its renewable energy potential for electricity generation[1] and has used the distributed nature of these clean-energy resources to its advantage. The Sustainable Electrification and Renewable Energy Programme (PNESER) has used distributed renewable generation since 2011 to provide electricity to remote and rural areas within Nicaragua. It has been funded by a portfolio of multi-lateral and international development agencies and has aided to increase the share of the population with access to electricity from 72.4% in 2011 to 97.2% in 2019 [MEM, 2020c]. The country aims to reach 99.9% in 2021 [Ibid].

While successfully exploiting its renewable energy potential, some regions in Nicaragua have simultaneously tackled sustainable development challenges. Small rural communities have established micro or mini-grids to supply modern energy, thereby enabling the empowerment of women and children, raising awareness of environmental issues, climate change and sustainability, building capacity, creating new income-generating opportunities and easing the access to basic services such as health and education [Allen et al., 2019, Colbert, 2017]. In these communities, energy users have become "energy citizens" rather than just consumers. Research on this regard has shown that community energy offers two main benefits: i) creating the capacity to transform the current energy infrastructure through collaborative work and citizen engagement in energy planning and decision-making and ii) enabling an opportunity to revitalize the local economy [Burke and Stephens, 2017, Islar and Busch, 2016, Van Veelen, 2018]. Small rural and remote communities across Nicaragua are embracing renewable energy for sustainable development.

[1]Nicaragua's renewable energy potential is estimated at approx. 5,500 MW and includes large-scale hydropower, run-of-river hydropower, onshore wind, solar, biomass and geothermal [IRENA, 2015, Marandin, 2015, PRONicaragua, 2012].

In the utility market, since 2013, Nicaragua has been generating more than half of its electricity requirements from renewable energy sources [IEA, 2020], with the highest annual average seen in 2018, 59.2% of the total electricity [MEM, 2020a]. At times, Nicaragua has generated over 90% of its electricity in a day from renewable energy sources [ENATREL, 2020]. Onshore wind is the most relevant renewable energy source currently. The increased integration of renewable energy into the Nicaraguan energy system has decreased the country's oil bill[2] from $1,097 million in 2014 to $936 million in 2018 [UN ECLAC, 2019]. Finally, the annual average wholesale electricity price[2] has decreased from $125/MWh in 2010 to $92/MWh in June 2020 [ENATREL, 2020]. The Nicaraguan central government aims to expand the country's renewable installed capacity adding approx. 1.2 GW by 2033 and generating 70% of its electricity from these energy sources that year [MEM, 2018a].

The country seemed to be making adequate efforts to transform its power system. However, as will be further explained in the coming section, these efforts may not be sufficient to limit global warming to 1.5°C.

1.2 Problem Statement

The Intergovernmental Panel on Climate Change (IPCC) [2018], the International Energy Agency (IEA) [2019] and the United Nations (UN) [2018] agree that the world is not on track to either limit global warming to 1.5°C or meet the Sustainable Development Goals. The IPCC 1.5°C pathways, with no or limited overshoot, estimate that renewable energy sources are expected to supply 70–85% of the global electricity in 2050, i.e., the global share of electricity generation from renewable energy sources must increase by approx. 4 times relative to 2017 [based on IEA, 2019].

Rapid integration of renewable energy sources into the global energy system is required to limit global warming. Most of the parties to the Paris Agreement [United Nations, 2015a] outlined actions to address climate change focusing on renewable energy and energy efficiency [United Nations, 2016]. Nicaragua, having ratified the Paris Agreement only in October 2017 and presented its Nationally Determined Contribution (NDC) in September 2018, set a target of 60% renewable electricity by 2030

[2] These prices are not indexed, i.e., they are not adjusted for the effects of inflation.

[Central Government of Nicaragua, 2018]. Unfortunately, since 2013, the growth rate of renewable energy generation in the country has stalled. The outstanding growth rates witnessed between 2011 and 2013 (26% and 21% annually respectively) have decreased significantly to an average of 5% annually between 2015 and 2018 [IEA, 2020; MEM, 2020a]. Furthermore, investment in clean energy has fallen from approx. $ 270 million in 2010 to virtually zero since 2015 [Bloomberg New Energy Finance and UKAid, 2019]. The stagnation of renewable energy investments and slower growth of renewable electricity generation, graphically depicted in Figure 1.1, coupled with the unstable political circumstances in the last two years, has led to investors being cautious and the expansion of the renewable installed capacity being nearly paused.

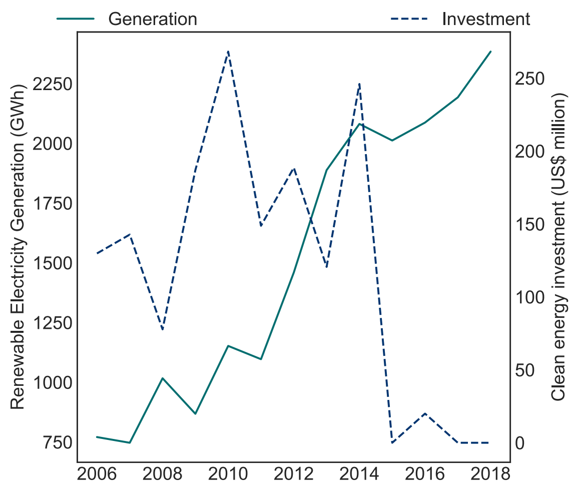


Figure 1.1: Renewable electricity generation growth compared to clean energy investment in Nicaragua

Source: Author based on INE [2019d] and Bloomberg New Energy Finance and UKAid [2019].

Furthermore, since Nicaragua's energy-related NDC focuses solely on the power sector, it can be said that the country's decarbonization efforts pivot around renewable electricity. Current energy policies and mandates focus solely on the power sector and neglect other important sectors, namely residential (cooking) and transport. These two energy sectors represented approx. three-quarters of the final energy consumed in the country in 2017 [MEM, 2018b]. The single-sector approach adopted by the Nicaraguan central government restricts the sustainability of the Nicaraguan economy and limits the country's capability to deal with climate risks and impacts.

Additionally, the top-down approach of the Nicaraguan central government to the energy transition accentuates the urban-rural divide in the country. With nearly 40% of the Nicaraguan population living in rural areas and only 71% of this population having access to electricity (opposed to 100% in urban areas), the current vision of the energy transition in the country seems to neglect social justice concerns. Lack of access to modern forms of energy, under-consumption and poverty increase the complexity of this transformative process [Herington et al., 2017]. These energy challenges heighten the fewer educational and limited income-generating opportunities as well as the heavier environmental and health burdens in rural areas [Sovacool et al., 2016]. Hence, the energy transition should be seen as an opportunity to streamline sustainable development aided by renewable energy technologies.

In this sense, the experiences of countries such as Denmark [Lund, 2000], Germany [Morris and Jungjohann, 2016], Scotland [Van Veelen, 2018] and Mauritius [Atlas of Utopias, 2018] have shown that citizen engagement is fundamental to reshape the current energy systems and accelerate the energy transition. Although some small rural communities in Nicaragua have actively adopted renewable energy, most Nicaraguans could be labelled as apathetic regarding energy-related issues. The country has adopted a centralized, top-down approach for the energy transition with little to no citizen consultation. Most major energy projects in the last decades have been the result of negotiations between central governments and private investors and such decisions have been surrounded by claims of corruption and lack of transparency [Olivares, 2016, Rojo-Martín, 2019].

1.3 Research Questions

Considering the Nicaraguan context and the challenges described above, this thesis aims at answering the following main research question:

How can Nicaragua accelerate its transition to a sustainable and renewable energy system while tackling sustainable development challenges such as poverty and environmental degradation?

The research will be directed and shaped by the following sub-questions:

1. What is driving the transformation of the Nicaraguan energy system?
2. How is the energy transition currently envisioned in the context of the Nicaraguan energy system?
3. How does the envisioned energy transition contribute to sustainable development in Nicaragua?
4. What are the main challenges that Nicaragua faces for the transformation of its energy system?
5. What are the most promising approaches to deal with those challenges? i.e., how have other nations/regions attempted to address those challenges?
6. What alternative energy pathways can be designed for Nicaragua considering the challenges and opportunities previously identified?
7. Would a smart energy systems approach be a techno-economically feasible alternative for the country's energy transition?

1.4 Structure of the Thesis

As depicted in Figure 1.2, this dissertation is divided into seven chapters. The following two chapters will elaborate on the trends and most relevant scientific literature regarding the transition to renewable energy systems and energy planning approaches for sustainable energy systems. Chapter 2 condenses promising approaches to transform energy systems and aid the energy transition, thereby contributing to answering one of the research questions stated in section 1.3. Chapter 3 outlines the theories and scientific research shaping the current global energy transition whilst Chapter 4 outlines the key methods used to answer the research questions. Next, Chapter 5 describes the state of affairs of the Nicaraguan energy system and contributes to describing the Nicaraguan energy transition outlook. Chapter 6 presents the main results and insight derived from the research conducted within this doctoral project. The results are derived from the different publications that form this dissertation and that can be found in Annexes. All publications aim to contribute to the questions mentioned in section 1.3. Finally, Chapter 7 summarizes conclusions and recommendations to accelerate the transition to a renewable and sustainable energy system in Nicaragua.

The motivation behind this dissertation is to contribute to the understanding of how developing nations with sufficient indigenous renewable resources can transform their energy systems and design sustainable and renewable energy systems. As mentioned previously, the research questions guide the methods and approach chosen for this work and are concretely purposed to contribute to the field in the following ways:

- Provide an overview of state-of-the-art solutions and trends for designing sustainable and renewable energy systems based on the smart energy system approach.
- Highlight the key role of energy in sustainable development processes and provide evidence of the opportunities enabled by renewable energy in particular.
- Design potential strategies to leapfrog the energy-intensive development paths that developed countries have followed until now and create synergies between the energy transition and sustainable development.
- Emphasize the crucial role of energy citizens in reshaping current energy systems and tackling development challenges.

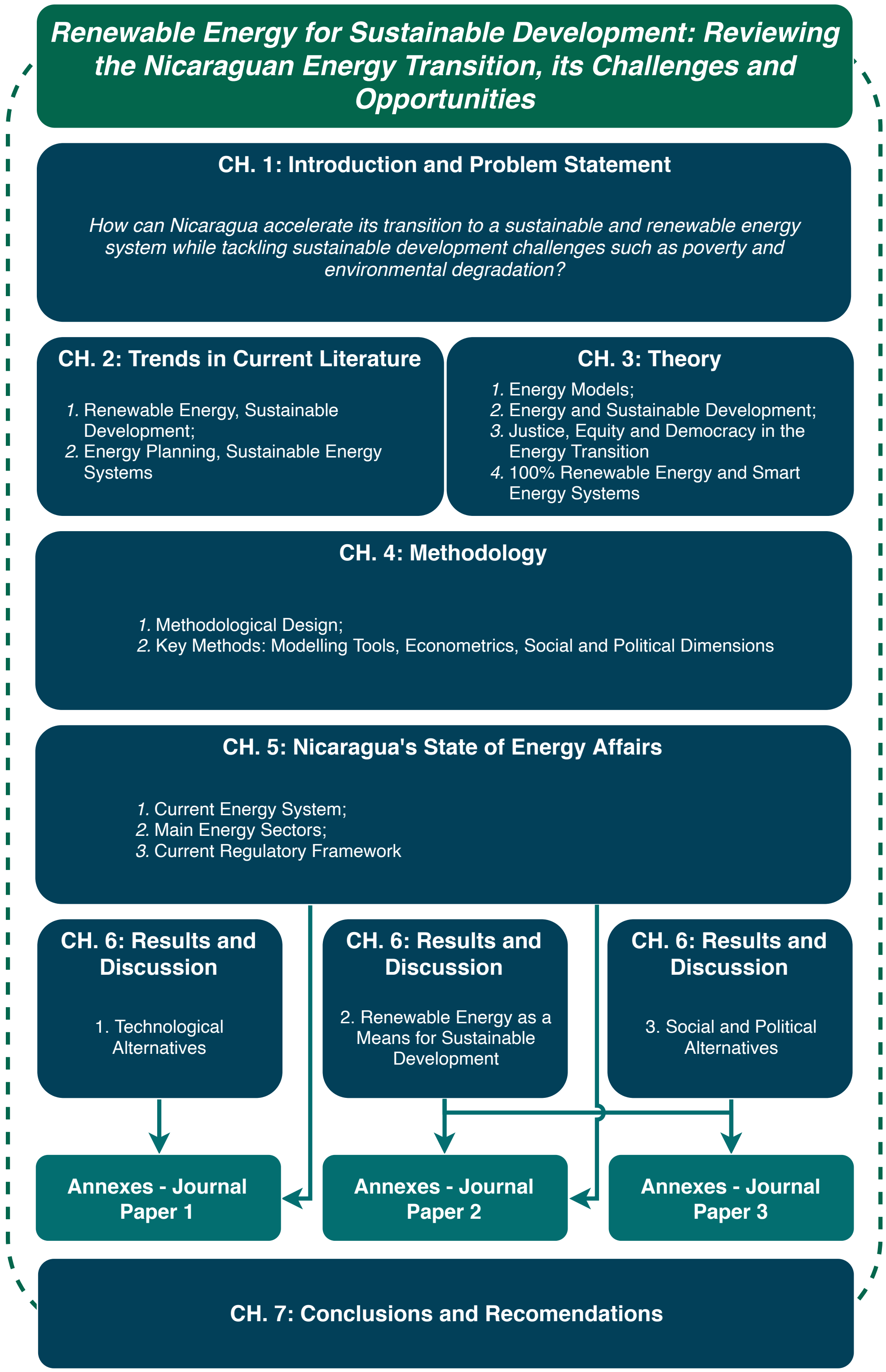


Figure 1.2: Structure of this thesis

Chapter 2

Trends in Current Literature

The transition to sustainable and renewable energy systems is a complex subject that has attracted much attention, particularly in the last decade. It involves transformations and developments in different dimensions, across different sectors within economies and societies and at different scales. This chapter presents a comprehensive interpretation of the current energy transition based on the outcomes of a bibliometric analysis and a meta-ethnography. This review aids in the characterization of sustainable and renewable energy systems, the identification of the tools and strategies available for the design and planning of such systems and the assessment of these systems' contribution to sustainable development.

Table 2.1
Algorithms used in the Scopus web search

1	*("renewable energy" AND "energy transition" AND "sustainable development") AND DOCTYPE(ar OR cp) AND (LIMIT-TO(LANGUAGE, "English") AND (LIMIT-TO(PUBYEAR,2019) OR ... LIMIT-TO(PUBYEAR,2015) ... OR LIMIT-TO(PUBYEAR,2010)))*
2	*(("smart energy system" OR "renewable energy system" OR "low-carbon") AND ("energy planning" OR "energy modelling" OR "energy modeling") AND "scenario" AND DOCTYPE(ar OR cp) AND LIMIT-TO(LANGUAGE, "English") AND (LIMIT-TO(PUBYEAR,2019) OR ... LIMIT-TO(PUBYEAR,2015) ... OR LIMIT-TO(PUBYEAR,2010)))*

Relevant documents were searched for in the Scopus database. Using the algorithms described in Table 2.1, peer-reviewed articles published between 2010 and November 15th, 2019 were gathered. The searches were limited to articles and conference papers written in English. Search 1 resulted in 126 documents and search 2 in 146 documents. The annual production for both searches is presented in Figure 2.1. As seen, the studies discussing the transition to renewable energy systems for sustainable development have been growing continuously at an annual average rate of approx. 40% between 2010 and 2019. The studies focusing on planning and designing sustainable and renewable energy systems have experienced a more modest increase of approx. 26% annually.

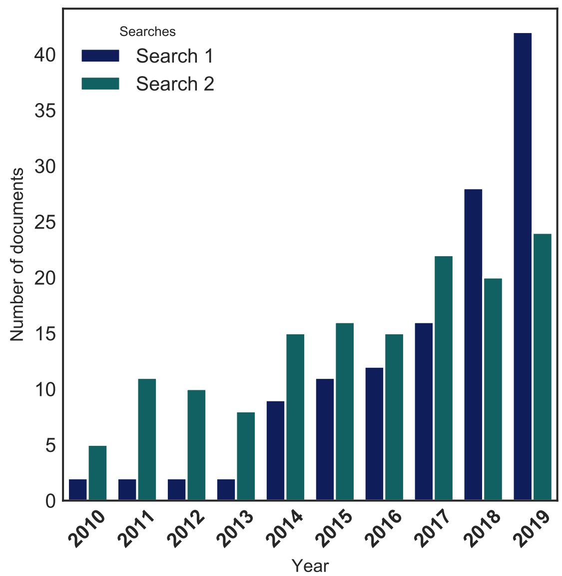


Figure 2.1: Number of annual scientific documents published per search

2.1 Transition to Renewable Energy Systems for Sustainable Development

The vast majority of studies resulting from the first search draw special attention to renewable energy sources as alternatives to fossil fuels in energy systems. The energy transition is seen among scholars as a means to reduce carbon emissions, tackle climate change and improve the efficiency and sustainability of the global economy.

Scouting through the set of 126 documents resulting from this search, five research streams can be identified. These include studies:

- Focusing on technical aspects of renewable energy systems,
- Discussing the political or institutional dimension of such systems,
- Assessing the economics of the decarbonisation of the current energy systems,
- Reviewing the social implications of the energy transition and
- Offering a comprehensive view of the transformation of the energy systems.

Figure 2.2 summarizes the topics found among the papers. The first subgroup represents slightly over one-third of the total number of documents and approximately 73% of these studies focus on renewable energy technologies such as wind power [Olaofe, 2018], biomass [Ketzer et al., 2017] and/or solar power [Hansen et al., 2018]. There is a strong emphasis on energy planning among the studies in this subgroup and the concept of *Smart Energy Systems* (SES) and/or the notion of *synergies* or *interlinkages* between energy sectors, economy, environment and society are beginning to resound [Dincer and Acar, 2018, Farfan et al., 2019, Scharl and Praktiknjo, 2019]. These interactions can potentially facilitate tackling challenges related to both sustainable development and the energy trilemma. The second subgroup represents roughly one-third of the total number of documents and focuses on regulations and institutions required for the energy transition. The highlights in this subgroup are local governance [Hamman, 2019] and citizens empowerment [Mullally et al., 2018]. In this regard, the concept of community renewable energy is reviewed or visited in approximately one-quarter of the studies in this subgroup [Mahzouni, 2019, Roesler and Hassler, 2019]. The third subgroup accounts for one-fifth of the total documents drawn in this search and entails econometric analyses looking into the effects of the energy transition into local economies [Lin and Omoju, 2017, Waziri et al., 2018], life-cycle assessments of clean-energy technologies [Weldu and Assefa, 2017], business models to further integrate renewable energy into current energy systems [Gsodam et al., 2015] and energy market analyses and tools to aid the energy transition [Loßner et al., 2017]. Although largely underrepresented, the fourth subgroup revises the social side of the energy transition. These studies represent a modest 6% of the total number of documents and focus mainly on issues of public acceptance [Süsser and Kannen, 2017] and social innovation [Hölsgens et al., 2018]. Finally, roughly 5% of the

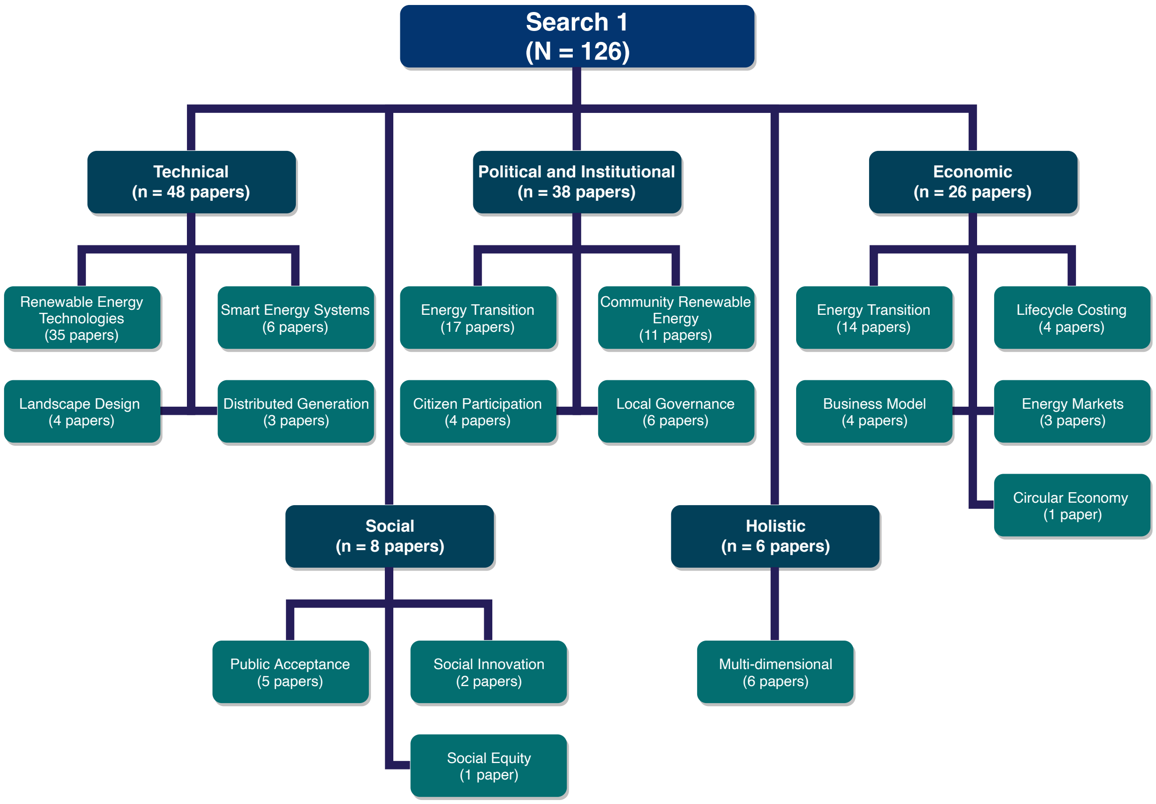


Figure 2.2: Thematic distribution of the papers resulting from search 1

papers present a comprehensive and holistic view of the energy transition [Ciriminna et al., 2018].

Although there seems to be a consensus among the scientific literature regarding the need for a comprehensive and holistic approach to the energy transition, much of the focus lays on the technical and economic aspects of the alternatives available for such process. The political aspects are not as predominant; however, these have been considered and discussed significantly more often than the social aspects in the studies reviewed.

In terms of methodologies, the approaches adopted by the authors vary vastly. However, long-term energy planning/policy-making and the modelling of energy systems are the most common choices to answer the different research questions posed in the studies reviewed. Most studies perform techno-economic evaluations of the energy alternatives being considered. In some occasions, the assessments attempt to integrate social and environmental impacts. In these cases, the evaluations are based on, for example, the number of direct green jobs created [Sun et al., 2016] and CO_2 emissions [Marchi et al., 2018].

Geographically, the most commonly revised case among all studies is Germany [Busch and McCormick, 2014, Hake et al., 2015]. At least 1 in 6 papers reviews a German case study either at the local or national level. Studies reviewing the Global South focus on emerging markets [1] such as China [Zhu et al., 2019], Mexico [Vidal-Amaro and Sheinbaum-Pardo, 2018], South Africa [Prentice et al., 2018], India [Amrutha et al., 2018], Turkey [Yelmen and Tarık Çakir, 2016] and the Philippines [Ocon and Bertheau, 2019]. Low- and middle-income countries such as Senegal [Thiam et al., 2012], Venezuela [Pietrosemoli and Rodríguez-Monroy, 2019], Morocco [Chachdi and Mokadmi, 2015], Vietnam [Shem et al., 2019], Armenia, Moldova [Spiesberger and Schoenbeck, 2019] and Nicaragua [Meza et al., 2019] have been also visited in the scientific literature albeit less recurrently.

2.2 Planning the Transition to Sustainable Energy Systems

To pinpoint the strategies and pathways being considered for the transition to sustainable energy systems, a second search among the scientific literature was performed. Employing the second algorithm described in Table 2.1, a systematic examination of the energy plans available in the scientific literature was carried out. This time, the resulting papers were surveyed and only those meeting the following criteria were included in the review:

- The study performs techno-economic analyses of energy pathways or strategies;
- Energy models or scenarios considering energy systems or sectors are constructed;
- The energy systems or sectors simulated are at least at a micro-grid level; and
- The models or scenarios have a medium or long-term time horizon.

[1] See MSCI Country Classification Standard [2019]

The objective is to identify the trends in energy pathways and strategies being considered in the current literature, their scale and their scope. Editorials or studies performing literature reviews were excluded from the review. A total of 21 articles were not included based on the criteria here defined.

From the 125 remaining articles, the vast majority (approx. 75%) aim to aid the transition to low-carbon energy systems or economies. An additional 12% of these articles review decarbonisation pathways and an approximately equal share of documents aim to design energy systems that are more energy-efficient than the current ones. Regarding the focus of the articles, approximately 44% of the studies perform a holistic assessment of the energy system and the energy pathways, i.e., they consider at least three energy sectors such as electricity, heating and transport sector and enable synergies between them that improve the overall efficiency of the system [Connolly et al., 2011, Krey et al., 2014, Phdungsilp, 2010]. However, approximately 39% of the studies focus solely on the electricity sector [Bagheri et al., 2018, Hu et al., 2011, Nelson et al., 2012]. The latter includes more studies published recently (within the last three years) than the former. This hints to the narrow focus on the power sector and the relevance of electricity in decarbonisation strategies. Also, important focus points among the scientific literature have been wind and solar energy. These two renewable resources seem to be considered as the backbone of the energy transition.

Half of the studies used well-established bottom-up tools such as EnergyPLAN [Connolly et al., 2011], LEAP [Phdungsilp, 2010], MARKAL [Jablonski et al., 2010], TIMES [McCollum et al., 2012], HOMER [Babatunde et al., 2019] or MESSAGE [Aryanpur et al., 2019]. EnergyPLAN and LEAP are notably the two most frequently used energy tools among the articles reviewed. However, there is an emerging interest for open-source models such as OSeMOSYS [Howells et al., 2011], SWITCH [Johnston et al., 2019, Nelson et al., 2012], Balmorel [Wiese et al., 2018], PyPSA [Brown et al., 2017], or oemof [Hilpert et al., 2018]. Moreover, approximately one-third of the articles introduced and tested a self-developed model [Bassi et al., 2010, Richardson and Harvey, 2015, Walnum et al., 2019]. This is linked to the latent need to plan energy strategies or pathways at different geographical and temporal scales to address different energy challenges and make energy planning and policy-making more inclusive processes.

Most commonly, the papers assess medium- and/or long-term strategies (i.e., plans for 2030 or 2050) either at the national or local level. China [Hu et al., 2011, Wu and Xu, 2013], the United Kingdom [Chaudry et al., 2014, Liu and Mancarella, 2016] and the United States [McCollum et al., 2012, Nelson et al., 2012] are the most commonly studied national and local cases. The Global South is well represented with 33 studies reviewing national cases from 18 different nations and 15 studies reviewing local cases corresponding to 13 localities in 8 different countries. The vast majority of these studies present potential energy pathways for low-carbon energy systems or decarbonisation. The regions represented among these studies include Asia, Africa and Latin America and the Caribbean.

The different results from the 125 papers reviewed provide the following insight regarding the energy transition:

- The main motivation for the energy transition is curtailing carbon emissions and limiting global warming;
- Renewable electricity is the preferred energy carrier for the energy transition;
- Wind and solar energy, in particular, are the foundation of low-carbon energy systems in the future;
- Energy efficiency and management are crucial for the integration of renewable energy into future energy systems;
- The potential synergies between the different economic and energy sectors alongside technological advances have gained momentum and found relevance in the framework of smart energy systems;
- In emerging and developed economies, where energy demand is increasing rapidly, higher shares of renewable energy do not translate into lower fossil fuels consumption and, thus, carbon sequestration technologies and strategies might be necessary;
- Notably, bottom-up energy models are often used to simulate energy strategies or plans and policies and explore different scenarios;
- Techno-economic analyses are the most common assessment method to decide between energy pathways;

- The energy transition is being shaped by energy policies and initiatives that focus significantly on the economics of future energy systems;
- The social impacts of the energy transition are being gradually included in energy planning, as well as in policy- and decision-making processes;
- China is the country being most often studied in this review of energy planning literature, surpassing the UK, the US, Italy, Europe and Denmark; however,
- Other developing countries are also evaluating decarbonisation pathways.

The following section expands on some of the key concepts found among the papers reviewed and identify and elaborate on theories and concepts available currently among the scientific community in relation to the energy transition. Furthermore, the theories found to be relevant to answer the research questions belonging to this thesis are described.

Chapter 3

Theoretical Framework

The previous literature review showed that the energy transition entails more than the shift from traditional fossil-fuel-based energy systems to renewable energy systems. There are political, social, environmental and economic aspects to this transition that need to be integrated into a holistic approach to energy planning. Research on this regard has progressed in the last decades. The coming section describes some of the most relevant discoveries and theories relating these topics. These discoveries and theories serve as a theoretical foundation to answer the research questions outlined in section 1.3.

3.1 Energy Models: Designing the Transition

The energy transition carries along the need for new and improved energy and environmental policies. As previously mentioned, the first and foremost motivation for the energy transition is curtailing global GHG emissions and limiting global warming. The literature review presented in Chapter 2 pointed out energy planning as the most common strategy to design and shape the energy transition. Scholars and policy-makers continuously develop energy models, scenarios and visions to channel the efforts and initiatives to transform the current energy systems into sustainable energy systems. Ringkjøb et al. (2018) provided a recent review of computer tools used for modelling energy and electricity systems with large shares of variable renewable energy. The information available for this study was valid up to April 2017. The authors reviewed 71 tools used at least once in publications since 2012 including RETScreen, HOMER, LEAP, energyPRO, EnergyPLAN, MARKAL/TIMES, BALMOREL, NEMS, OSeMOSYS, SWITCH, among others. The tools reviewed in the study were diverse in terms of their geographical scope (i.e., national, regional, island), temporal resolution (i.e., hourly, weekly, monthly, annually, or user-defined) and the methodologies used (i.e., simulation, optimisation, or equilibrium models). Consistent with other reviews such as the ones performed by Connolly et al. (2010), Pfenninger et al. (2014) and Després et al. (2015), as well as the literature review from Chapter 2, Ringkjøb et al. found that most models can be classified depending on their purpose, approach, or methodology. First, four general purposes were identified:

- *Power System Analysis Models.* Given the predominant role of electricity in the energy transition, computer tools have been developed to study power systems in detail and to deal with common issues of these systems including power flows or dynamic stability.
- *Operation Optimisation Models.* These tools optimise the operation of an energy system based on simulations of such system and from a technological perspective. The optimisation criteria include fuel savings, CO_2 emissions, reserve capacity, minimisation of import/export, elimination of excess power generation, among others (cf. Østergaard, 2009).
- *Investment Optimisation Models.* In these cases, the system is optimised from an economic perspective. The evaluation criteria include total energy system costs, capacity costs, societal costs, among other costs (cf. Østergaard, 2009).
- *Scenario Models.* In these cases, the computer tools create a long-term scenario (20 - 50 years) by combining the results of shorter, usually 1-year, time-steps scenarios. These models are generally used to study the impact of various policies.

Second, three different approaches were identified:

- *Top-down Models.* Based on a top-down approach, these tools breakdown a system to gain insight into its subsystems. In these cases, macroeconomic data is used to determine growth in energy demand and prices.

- *Bottom-up Models*. Contrarily, bottom-up tools piece together a system and, thus, start by identifying a mix of technologies and their investment options giving rise to an energy system.

- *Hybrids*. These models combine the capabilities of top-down and bottom-up tools.

Lastly, three major methodologies were identified:

- *Simulation Models*. The computer tools aim to simulate the operation of an energy system in specific (sometimes user-defined) time-steps, e.g., hourly or seasonally. These are often bottom-up models testing various impacts and developments of scenarios.

- *Equilibrium Models*. Equilibrium models aim to explain the dynamics of supply, demand and prices in an economy where several markets interact (general) or with a single-market emphasis (partial).

- *Optimisation Models*. These models generally use a linear programming approach to either maximise or minimize a feature, e.g., minimising the total energy system costs or maximising the share of renewable energy in the energy mix.

According to the literature review from Chapter 2, the most common application of the modelling tools was found to be for exploring and evaluating alternative energy futures, i.e., the construction of scenarios, that simulate the implementation of energy or environmental policies. In line with the findings from the literature review, Nielsen and Karlsson (2007) found that most energy scenarios focus on future economic or technical developments and lack details regarding the specific social and political assumptions considered for the construction of the scenarios. Furthermore, the literature review showed that, although social and environmental criteria are being increasingly included in scientific studies, they fall far behind techno-economic criteria.

3.2 Energy and Sustainable Development

The strong link between economics and energy policy and planning is reflected in the importance of techno-economic analyses for the energy transition. However, given the nature of renewable energy, the energy transition can potentially have a strong link with sustainable development as well. By enabling access to clean energy in remote or alienated areas, renewable energy contributes to improving standards of living and reducing poverty levels. Furthermore, new or higher income opportunities as well as services such as healthcare and potable water are made available with affordable energy. And, lastly, clean energy reduces the level of air pollution and, thus, the negative health impacts from fuels such as traditional biomass. These are amongst the wide range of benefits of the energy transition and they exhibit the strong relationship between energy policy and planning and sustainable development.

Energy has been fundamental for development. Prior to the establishment of the 2030 Agenda and the Sustainable Development Goals [United Nations, 2015b], the link between economic development and energy policy and planning converged on a discipline termed "energy-based economic development" by Carley et al. [2011]. The aim was to integrate the efforts to increase energy efficiency and improve energy security into the endeavours of job creation and retention and economic development. This discipline gave room to the analysis of the energy - growth nexus. Testing and evidence presented four possible hypotheses explaining the nature of this nexus. Bhattacharya et al. (2016) describe these hypotheses as follows:

- *Growth Hypothesis.* Energy is a major source of input for development processes. A uni-directional causality from energy consumption to economic growth is evidenced and, thus, energy conservation policies are expected to have a negative impact on economic growth.
- *Conservation Hypothesis.* Economic growth stimulates energy consumption. In this case, energy conservation policies are not expected to have a negative impact on economic growth given that the uni-directional causality runs from economic growth to energy consumption.
- *Feedback Hypothesis.* Any change in energy consumption is expected to affect economic growth with a reverse effect, i.e., there is a bi-directional causality

between energy consumption and economic growth.

- *Neutrality Hypothesis.* In this case, energy consumption and economic growth are independent and, thus, are not expected to affect each other.

After the adoption of the 2030 Agenda for Sustainable Development, energy (renewable energy in particular) regained attention. Sustainable Development Goal 7 seeks to *"(e)nsure access to affordable, reliable, sustainable and modern energy for all"* [United Nations, 2015b] and is closely related to other economic, social and environmental goals defined within the 2030 Agenda [Friends of Europe, 2019]. Especially with the increased concerns over environmental degradation and the constant threat of global warming, the relationship between energy and the environment has begun to be more often studied. Based on the Environmental Kuznets Curve (EKC) hypothesis (cf. Dinda, 2004), which postulates an inverted-U-shaped relationship between different pollutants and per capita income, the energy-environment-income nexus has been investigated. Some scholars see energy as the key source of CO_2 emissions and, thus, as an indicator of environmental pressure (e.g., Luzzati and Orsini, 2009 and Pablo-Romero and De Jesús, 2016). Others consider the effect of energy consumption on the environment and the economy and, thus, see energy as an explanatory variable in their econometric models (e.g., Apergis and Payne, 2009 and Al-Mulali et al., 2016). In both cases, the findings vary across countries or regions and time-periods. The literature has not reached a consensus on the nature of the energy-environment-income nexus; however, the key role of energy in development processes is widely acknowledged.

3.3 Justice, Equity and Democracy in the Energy Transition

Referring back to the steam age and the industrial revolution and later to the invention of the internal combustion engine and the oil era, throughout history, energy transitions have been accompanied by political and social transformations. The current energy transition is also such a case. However, based on the chaotic experiences from the past, this time, society demands equity, participation and transparency [Healy and Barry, 2017, Szulecki, 2018].

Energy justice emerges as a response to these claims of society. Energy justice has aided the identification of injustices such as energy poverty[1] and lack of access to clean, modern energy and to the design and implementation of processes to avoid, redress and tackle until-now marginalised sections of society [Jenkins et al., 2016]. Sovacool and Dworkin (2015) presented an energy justice framework seeking to assist energy planners and consumers in making more informed energy choices. The key elements suggested by the authors to be promoted in energy decision-making processes include (1) availability, (2) affordability, (3) due process, (4) good governance, (5) sustainability, (6) intergenerational equity, (7) intragenerational equity and (8) responsibility.

To address some of these elements, the scientific community has brought attention to the notions of energy citizenship, community energy and energy democracy in the framework of the energy transition. First, Devine-Wright (2004) introduced the concept of energy citizenship to describe the active role of the public in the energy transition. This call for action is framed by the desire for equity and justice and the awareness of the responsibility for climate change across society. Energy citizenship became an integral element of UK energy policy and gave room to collective energy actions, including acts of consumption and the setting up of community renewable energy projects such as energy cooperatives [Devine-Wright, 2012].

In countries such as Germany, Scotland and Denmark, energy citizenship and community energy have been key in the bottom-up fight against global warming and have had strong political influence leading to the democratization of the energy sector [Lund, 2000, Morris and Jungjohann, 2016, Slee, 2015]. Energy democracy has emerged as a social movement defined along three dimensions, namely popular sovereignty, participatory governance and civic ownership [Szulecki, 2018]. Its advocates argue that the current energy transition implies a political struggle to resist the fossil-fuel-dominant energy agenda and integrate more renewable energy. It is necessary to develop new policies and strengthen the existing ones to support a democratic and inclusive transformation of the energy sector [Burke and Stephens, 2017, 2018]. Without a supportive and enabling legal framework, renewable energy systems alone would not guarantee more democratic energy futures [Burke and Stephens, 2018].

[1] *"Energy poverty is a distinct form of poverty associated with a range of adverse consequences for people's health and well being – with respiratory and cardiac illnesses and mental health, exacerbated due to low temperatures and stress associated with unaffordable energy bills"* [European Commission, Directorate General for Energy, 2019].

Sustainable energy systems based on renewable energy and the principles of energy justice and democracy create an opportunity for sustainable development and to, simultaneously, curb global warming. The Choice Awareness Theory proposed by Lund (2014a) presents a plan based on the four strategies described in Figure 3.1 to raise societal awareness of energy choices and increase public involvement in energy policy and decision-making, thereby enabling society to counter the influence and interests of fossil-fuel organizations and providing room for sustainable energy solutions.

The implementation of these strategies has aided Denmark to significantly reduce its reliance on imported coal and increase the share of renewable energy - particularly onshore wind - in the electricity mix[2]. Denmark has set the highly ambitious target of supplying all its final energy needs from renewable energy sources by 2050 [REN21, 2020]. Many countries around the world are attempting to emulate this target and, thus, the notion of 100% renewable energy systems has attracted much attention.

3.4 100% Renewable Energy and Smart Energy Systems

The notion of 100% renewable energy systems implies using clean energy sources to meet the energy needs of all economic sectors: residential, industry, services, agriculture and transport. It would require technical alternatives to integrate renewable energy into sectors where electricity is not a common energy carrier. Furthermore, it entails the integration of large amounts of variable renewable energy into the power grid increasing uncertainty of supply and threatening grid stability. It also may require additional transmission capacity alongside enhanced systems for voltage control to bring electricity to where it will be needed.

The case of Denmark is one of a few success stories where large shares of variable renewable energy have been integrated into existing energy systems. Research suggests more and more often that 100% renewable energy systems are not only technically feasible in the future but may even be economically advantageous compared to current energy systems [Mathiesen et al., 2011, Thellufsen et al., 2020]. Such systems

[2]Denmark produced 23.6 TWh of electricity from coal in 1990 and 6.4 TWh in 2018. In contrast, the country generated 610 GWh of electricity from wind in 1990 and 13.9 TWh in 2018 [IEA, 2019].

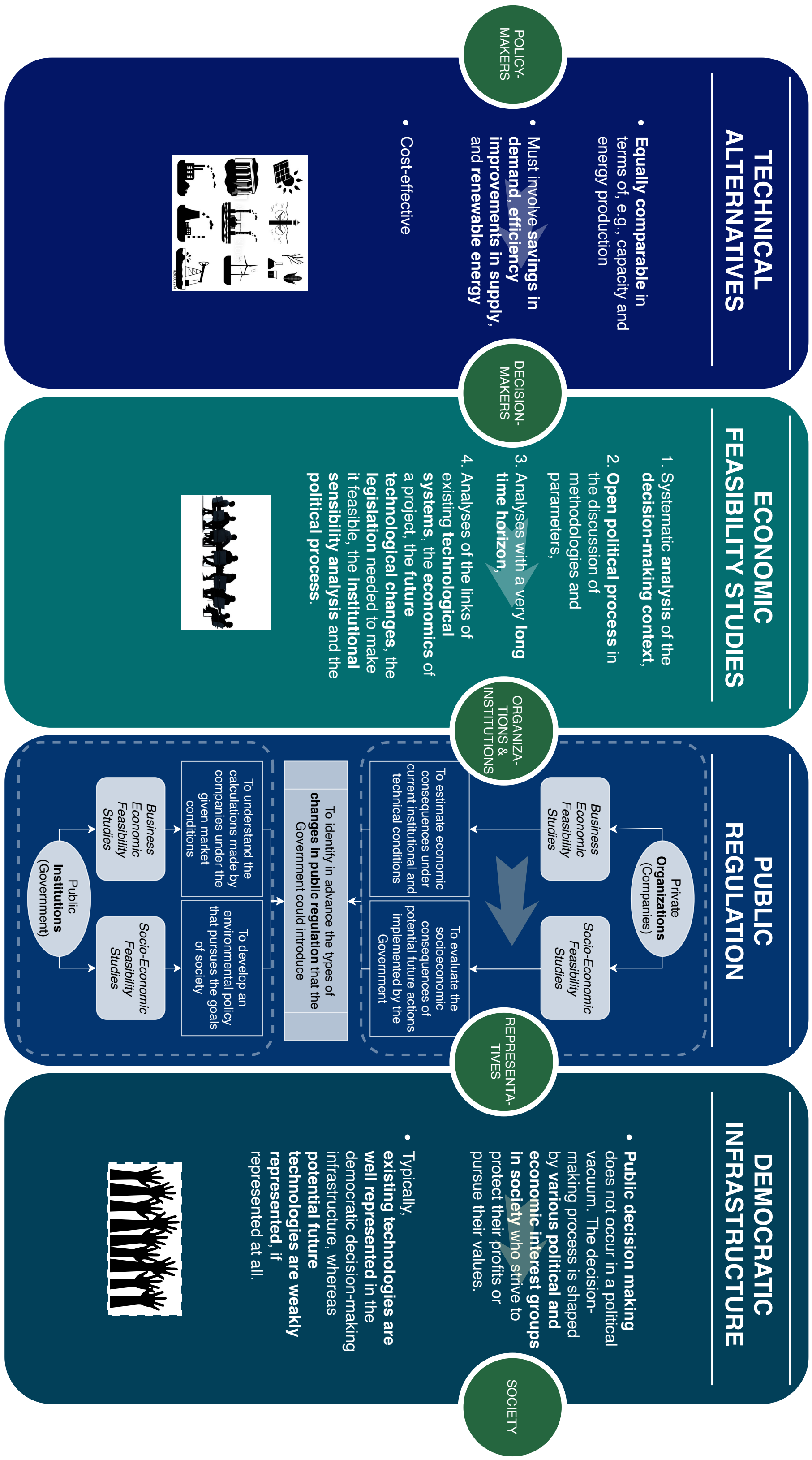


Figure 3.1: Choice awareness strategies

Source: Author based on Lund 2014b

have been studied in Denmark [Korberg et al., 2020, Lund and Mathiesen, 2009], Ireland [Connolly et al., 2011, Thellufsen et al., 2019] and also the European Union [Connolly et al., 2016, Möller et al., 2019].

Two key features of the energy systems suggested in the scientific literature for a transition to 100% renewable energy are sector coupling and enhanced power system flexibility. Synergies between energy sub-sectors (i.e., buildings, heating, cooling, power, transport and industry) enable more effective and least-cost solutions to add flexibility to sustainable energy systems. The combination of innovative grid infrastructures for electricity, gas and heating and cooling with storage technologies allows an integrated holistic approach to find favourable solutions for each energy sub-sector and the energy system as a whole. This approach has been described as *"Smart Energy System"* [Lund et al., 2017].

The smart energy systems approach takes advantage of technological advancements such as heat pumps, batteries, demand-side response devices, power-to-X applications and smart grids to guarantee grid stability and avoid curtailing renewable energy. These technologies may represent a disruption for incumbent energy market players and current business models. These smart energy systems require supporting and enabling regulatory and legal frameworks [Heldeweg, 2017], behavioural and organisational changes [Khansari et al., 2017], as well as new business strategies [Liang et al., 2020] and infrastructure [Howard et al., 2020]. However, they represent a paradigm shift that encourages citizens participation [Costanza et al., 2014, Goulden et al., 2014], thereby raising societal awareness and acceptance of renewable energy choices [Hvelplund et al., 2013, van der Werff and Steg, 2016].

Chapter 4

Methodology

Having the theoretical framework described in the previous chapter as a foundation, this section describes the mixture of methods used to answer the research questions outlined in Chapter 1. The overall methodology and its linkages to the research questions, results and publications are depicted in Figure 4.1.

4.1 Methodological Design

Aiming to provide a holistic perspective of the Nicaraguan energy transition, this dissertation uses a mixed-methods approach. In such an approach, both qualitative and quantitative data are concurrently collected and integrated into the analysis. This form of research methodology originated in the late 1980s and early 1990s and has, since then, evolved and gained popularity [Creswell, 2014]. It offers the advantages of both types of research while minimizing the limitations of both approaches. Given the intricate nature of energy research, the choice of mixed methods is deemed as appropriate to draw on both quantitative and qualitative data, thereby obtaining a more complete understanding of the research questions. Nevertheless, it must be born in mind that this research approach requires extensive data collection and time-intensive analyses of both quantitative and qualitative data. Thus, the researcher is expected to be familiar with both types of analyses, raising the level of expertise required and the complexity of the research.

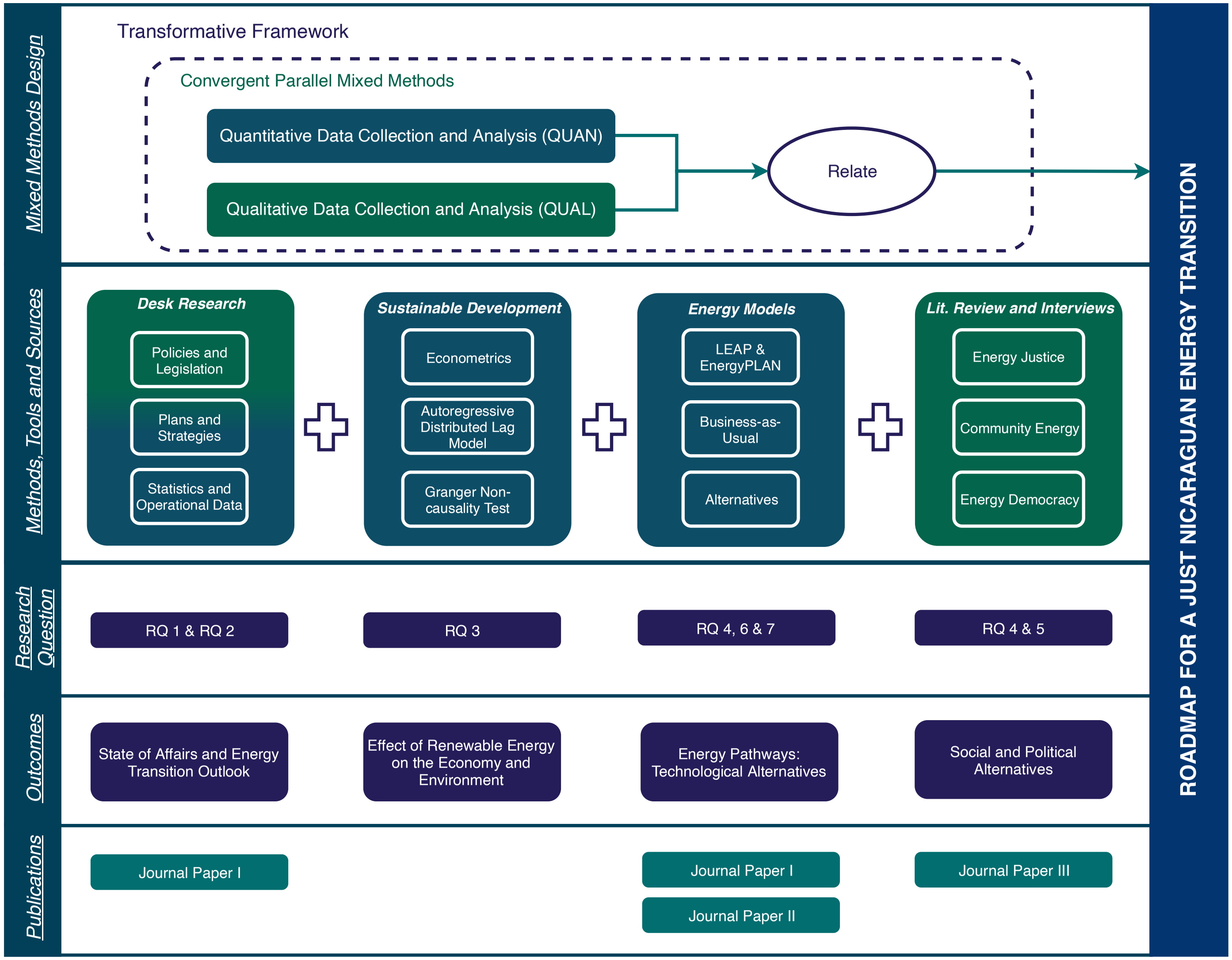


Figure 4.1: Layout of the research methodology followed in this dissertation including design, selected methods and tools as well as outcomes and publications resulting from its implementation.

Both types of data are collected in parallel based on the concepts described in the theoretical framework (see Chapter 3), i.e., a convergent parallel mixed-methods design is adopted. The findings derived from the analysis of the two forms of data are merged later in a joint display that in this thesis takes the form of a road map for a just Nicaraguan energy transition. This dissertation uses a transformative framework through the mixed methods research to advocate for a sustainable, just and democratic future energy system in Nicaragua. Thus, the results can be seen as a call for action to reshape the Nicaraguan energy system.

The transformative mixed methods design is selected since it can be really useful and recommended in analyzing the risks or impacts for evaluation of past or present policies in science and technology, thereby seeking to avoid to reproduce the faults and failures of old models that did not work, notably within the post-positivist or constructivist paradigms [Creswell, 2014, Sweetman et al., 2010].

4.2 Key Methods

The key analytical methods and tools selected for this mixed-methods study are described below.

4.2.1 Energy Planning and Modelling Tools

The first step is to conduct desk research and gather secondary data regarding the status-quo of the Nicaraguan energy system. The objective is to recreate the existing state of affairs and define a reference state to which alternative energy pathways can be compared. This implies identifying relevant sources of information and analysing the data gathered. The findings serve as input for the first two publications associated with this dissertation.

The second step is to construct the energy models and scenarios that will enable the assessment of alternative energy pathways for Nicaragua. With aid from the insight derived from the literature review presented in Chapter 2, two energy modelling tools are selected for this research project: EnergyPLAN [Aalborg University, 2019] and LEAP [Heaps, 2016]. These tools are chosen given their capability to:

- Consider energy demand for all energy sub-sectors, namely electricity, cooling and heating, transport, residential and industry.
- Account for the high variability of the natural cycles of some renewable energy sources such as wind, solar, wave and tidal stream and, thus, work in hourly time-steps ensuring that the balance between supply and demand is met at all times.
- Consider the intensity of the use of resources, cost-effectiveness and socio-economic effects.
- Simulate energy trading alternatives within the energy system, i.e., import and export of electricity.
- Optimize the combination of energy technologies used based on both technical capacity and investment and production costs.
- Include environmental impacts in the analysis in the form of emission levels or global warming potential.
- Construct and compare different scenarios in the medium and long-term.
- Deal with and account for the characteristics and conditions of energy systems in developing countries such as wide use of non-commercial fuels such as traditional firewood, weak information systems available and fast integration of renewable energy technologies into the energy system.

The Long-Range Energy Alternatives Planning (LEAP) modelling tool is a simulation and optimization software published by the Stockholm Environment Institute. LEAP uses a hybrid approach, i.e., top-down and bottom-up approaches, and enables the construction of yearly scenarios for, typically, a 20-50 years horizon [Ringkjøb et al., 2018]. It has been commonly used to simulate national energy systems considering all conventional and renewable energy generation technologies and all demand sectors, making it appropriate for the evaluation of energy and climate protection policies. The market is modelled in a way that seeks to guarantee the supply-demand balance at all times. For all years and scenarios, annual costs are estimated including investment, operation and maintenance, fuel and carbon.

EnergyPLAN is a scenario and investment-decision support tool developed at the Department of Development and Planning at Aalborg University. EnergyPLAN uses a bottom-up approach to make hourly simulations for a 1-year horizon [Ringkjøb et al., 2018]. It has been typically used to simulate local and national energy systems including all electricity generation technologies and all demand sectors; however, unlike LEAP, EnergyPLAN enables the simulation of imports and exports of electricity and includes a wide range of technologies for the sectoral integration of energy systems. These features aid the integration of higher shares of variable renewable energy into the energy systems. Finally, the simulations can be evaluated based on technical and operational criteria such as excess of electricity generated, total primary energy, or CO_2 emissions and economic criteria such as investment costs, operation and maintenance costs, fuel costs, carbon and taxes.

Both tools are used complementarily in this research project to assess different aspects of the Nicaraguan energy system. On the one hand, LEAP can simulate transformation processes of primary energy such as refining and charcoal production as well as model generation from individual power plants. Additionally, this tool provides separate emission estimates from energy demand and transformation processes. On the other hand, EnergyPLAN can enable more detailed simulations of the Nicaraguan power sector. This tool allows a detailed examination of the seasonal variation in electricity generation from variable renewable energy sources such as biomass, wind and solar. Furthermore, EnergyPLAN can be used to perform sensitivity analyses exploring the effects of interest rates and carbon taxes on the unit-cost of electricity and the Nicaraguan electricity generation mix.

Based on the trends identified amongst the current scientific literature as well as insight derived from the desk research, a set of alternative energy pathways for Nicaragua are developed. The aim is to explore smart energy system alternatives for the Nicaraguan energy system. The results from the simulations are assessed and compared in terms of energy supply and demand, GHG and CO_2 emissions, electricity generation from renewable energy sources and annual costs. The energy pathways explored and the insight that is derived from these simulations form part of the first and second publication associated with this dissertation.

4.2.2 Econometrics for Renewable Energy and Sustainable Development

Having identified the potential contribution of renewable energy sources to the transformation of the Nicaraguan energy system, it is important to assess the effect of the relatively recent adoption of clean energy technologies in Nicaragua on both the economy and the environment that may be driving this transformative process. In this case, two hypotheses are tested: the Environmental Kuznets Curve (EKC) hypothesis and the energy-growth nexus. The models are constructed using secondary economic data. This represents a challenge on its own given the history of political and economic instability in Nicaragua limiting data availability. However, the chosen methods and tools account for this limitation.

$$\ln EF_t = \beta_0 + \beta_1 \ln GDPpc_t + \beta_2 \ln RE_t + \beta_3 \ln AGRO_t + \beta_4 \ln URB_t + \epsilon_t \tag{4.1}$$

The representation of the EKC hypothesis presented in this dissertation differs from the "generic" representation found in the literature. This is to account for the singularities of the Nicaraguan economy, energy system and history. The model presented in Equation 4.1 is constructed to represent the relationship between ecological footprint (EF), income in terms of gross domestic product per capita ($GDPpc$), renewable energy use (RE), urbanization growth rate (URB) and the transition to a service economy measured in terms of the agricultural production index ($AGRO$). The data is retrieved from the Global Footprint Network (see Global Footprint Network, 2019) and the World Development Indicators database (see World Bank Group, 2020). Neither the quadratic nor the cubic term of income, generally included in models studying the EKC hypothesis, are present. These terms are omitted to avoid issues of multicollinearity. In this case, the validity of the EKC hypothesis is verified if the short-run income elasticity is greater than the long-run income elasticity, as per Narayan and Narayan's approach (2010).

The methodology employed to test the EKC hypothesis also differs from the bulk of literature on this regard. The EKC hypothesis is tested through a cointegration and autoregressive distributed lag (ARDL) bounds test as proposed by Pesaran and Shin (1998) and Pesaran et al. (2001). This methodology offers a series of advantages: it can be used with a mixture of I(0) and I(1) data; it involves a single-equation set-up making its implementation and interpretation much simpler and individual lag-lengths can be assigned to the variables in the model, thereby accounting for the differences in the trends of the economic data used. The ARDL equation is specified as in Equation 4.2.

$$\Delta \ln EF_t = \alpha_0 + \sum_{k=1}^{\pi_1} \alpha_{1k} \Delta \ln EF_{t-k} + \sum_{k=0}^{\pi_2} \alpha_{2k} \Delta \ln GDPpc_{t-k} + \sum_{k=0}^{\pi_3} \alpha_{3k} \Delta \ln RE_{t-k} + \sum_{k=0}^{\pi_4} \alpha_{4k} \Delta \ln AGRO_{t-k} + \sum_{k=0}^{\pi_5} \alpha_{5k} \Delta \ln URB_{t-k} + \varnothing_1 \ln EF_{t-1} + \varnothing_2 \ln GDPpc_{t-1} + \varnothing_3 \ln RE_{t-1} + \varnothing_4 \ln AGRO_{t-1} + \varnothing_5 \ln URB_{t-1} + e_t \quad (4.2)$$

To deal with the problem of data stationarity, Perron's (1989) modified Augmented Dickey-Fuller (ADF) test is performed to examine the order of integration of the variables. The tests allow for structural breaks in order to avoid spurious results due to the occurrence of structural shocks in the time series, as is expected due to Nicaragua's history. The model is initially examined for multiple breakpoints applying the test suggested by Bai and Perron (1998) and applying the "minimum Schwarz Information Criterion (SIC)" rule proposed by Liu et al. (1997). Dummies corresponding to the identified breakpoints are added to the model, where necessary. The optimal lag length ($\pi_1 ... \pi_5$) for the conditional error correction model (ECM) is determined using Akaike's Information Criterion (AIC). Furthermore, the Breusch-Pagan-Godfrey test and the serial correlation Lagrange Multiplier test [Breusch and Pagan, 1979; Godfrey, 1978] are employed to deal with the lack of diagnostic statistics of the regression residuals and the key assumption in the bounds testing methodology of the errors in the ECM model being serially independent.

The bounds testing procedure is based on the F-test. As in conventional cointegration testing, the null hypothesis is defined as $H_0 : \varnothing_0 = \varnothing_1 = \varnothing_2 = \varnothing_3 = \varnothing_4 = \varnothing_5 = 0$ and represents no cointegration, i.e., the absence of a long-run equilibrium relationship between the variables. Thus, rejecting H_0 implies that a long-run relationship exists. To draw the inference of cointegration, the F-statistics are compared with the tabulated critical values. Since the F-test used has non-standard distribution, two "bounds" of critical values have been computed for small sample sizes by Narayan (2005). The lower bound assumes that all variables are I(0) whilst the upper bound assumes that all variables are I(1). There is cointegration if the calculated F-statistic exceeds the upper critical value. The test is inconclusive if the F-statistic falls within the two bounds of critical values. And there is no cointegration if the F-statistic falls below the lower critical value.

The short-run equation is derived from Equation 4.2 and specified as in Equation 4.3. ECT_{t-1} is the ECM term lagged one period. If there is a long-run relationship, this term indicates how fast the variables return to their equilibrium in the long-run from the short-run [Zambrano-Monserrate et al., 2018]. For this, θ must be negative and highly significant.

$$\begin{aligned}\Delta \ln EF_t = \alpha_0 &+ \sum_{k=1}^{\pi_1} \alpha_{1k} \Delta \ln EF_{t-k} + \sum_{k=0}^{\pi_2} \alpha_{2k} \Delta \ln GDPpc_{t-k} + \sum_{k=0}^{\pi_3} \alpha_{3k} \Delta \ln RE_{t-k} \\ &+ \sum_{k=0}^{\pi_4} \alpha_{4k} \Delta \ln AGRO_{t-k} + \sum_{k=0}^{\pi_5} \alpha_{5k} \Delta \ln URB_{t-k} + \theta ECT_{t-1} + e_t \quad (4.3)\end{aligned}$$

The energy-growth nexus is examined through a Granger non-causality test using the methodology proposed by Toda and Yamamoto (1995). This test can be complementary to the EKC hypothesis test and contributes to deal with the simultaneity and irreversibility issue raised by Stern (1998), thereby allowing for an impact of the environment on the economy and not only of the economy on the environment as originally suggested by the EKC hypothesis model. The Toda-Yamamoto (T-Y) methodology is selected given its ability to ensure that the Wald-test statistic obtained during the Granger test is asymptotically chi-square. With this methodology, Vector AutoRegressive (VAR) models in levels can be formulated to test general restrictions on the parameter matrices even if the processes may be integrated or cointegrated, i.e., even if the data is non-stationary. Equations 4.4 through 4.8 show the VAR models formulated for this thesis.

$$\begin{aligned}\ln EF_t = \psi_0 + \alpha_1 \ln EF_{t-1} + ... + \alpha_p \ln EF_{t-p} + \gamma_1 \ln GDPpc_{t-1} \\ + ... + \gamma_p \ln GDPpc_{t-p} + \eta_1 \ln RE_{t-1} + ... + \eta_p \ln RE_{t-p} \\ + \lambda_1 \ln URB_{t-1} + ... + \lambda_p \ln URB_{t-p} + \sigma_1 \ln AGRO_{t-1} \\ + ... + \sigma_p \ln AGRO_{t-p} + \varepsilon_{1t}\end{aligned} \tag{4.4}$$

$$\begin{aligned}\ln GDPpc_t = \zeta_0 + \theta_1 \ln GDPpc_{t-1} + ... + \theta_p \ln GDPpc_{t-p} + \iota_1 \ln EF_{t-1} \\ + ... + \iota_p \ln EF_{t-p} + \mu_1 \ln RE_{t-1} + ... + \mu_p \ln RE_{t-p} \\ + \nu_1 \ln URB_{t-1} + ... + \nu_p \ln URB_{t-p} + \xi_1 \ln AGRO_{t-1} \\ + ... + \xi_p \ln AGRO_{t-p} + \varepsilon_{2t}\end{aligned} \tag{4.5}$$

$$\begin{aligned}\ln RE_t = \beta_0 + \pi_1 \ln RE_{t-1} + ... + \pi_p \ln RE_{t-p} + \varpi_1 \ln EF_{t-1} \\ + ... + \varpi_p \ln EF_{t-p} + \rho_1 \ln GDPpc_{t-1} + ... + \rho_p \ln GDPpc_{t-p} \\ + \varrho_1 \ln URB_{t-1} + ... + \varrho_p \ln URB_{t-p} + \varsigma_1 \ln AGRO_{t-1} \\ + ... + \varsigma_p \ln AGRO_{t-p} + \varepsilon_{3t}\end{aligned} \tag{4.6}$$

$$\begin{aligned}\ln URB_t = \tau_0 + \phi_1 \ln URB_{t-1} + ... + \phi_p \ln URB_{t-p} + \chi_1 \ln EF_{t-1} \\ + ... + \chi_p \ln EF_{t-p} + \psi_1 \ln GDPpc_{t-1} + ... + \psi_p \ln GDPpc_{t-p} \\ + \delta_1 \ln RE_{t-1} + ... + \delta_p \ln RE_{t-p} + \vartheta_1 \ln AGRO_{t-1} \\ + ... + \vartheta_p \ln AGRO_{t-p} + \varepsilon_{4t}\end{aligned} \tag{4.7}$$

$$
\begin{aligned}
\ln AGRO_t = \beta_0 + \kappa_1 \ln AGRO_{t-1} + ... + \kappa_p \ln AGRO_{t-p} + \gamma_1 \ln EF_{t-1} \\
+ ... + \gamma_p \ln EF_{t-p} \\
+ \iota_1 \ln GDPpc_{t-1} + ... + \iota_p \ln GDPpc_{t-p} + \eta_1 \ln RE_{t-1} \\
+ ... + \eta_p \ln RE_{t-p} + \rho_1 \ln URB_{t-1} + ... + \rho_p \ln URB_{t-p} + \varepsilon_{5t} \quad (4.8)
\end{aligned}
$$

Subsequently, the optimal lag length is selected using the usual information criteria: Schwarz Information Criterion (SIC), Akaike Information Criterion (AIC), Hannah Quinn Information Criterion (HQ), among others. This is done ensuring that there was no serial correlation in the residuals. Although all information criteria perform similarly, SIC has shown a relatively better performance in lag-choice accuracy in many situations, e.g., when sample size, stability, variance structure and forecast horizon have been varied [Scott Hacker and Hatemi-J, 2008]. AIC has shown good lag-choosing and forecasting properties as well. Therefore, these two are selected to define the optimal lag length.

Next, a modified Wald test is estimated. The correct order of the system (k) is augmented by the maximal order of integration (d_{max}). Then, the VAR ($k + d_{max}$) is estimated with the coefficients of the last lagged d_max vector being ignored. In this way, the Wald test statistic is asymptotically chi-square distributed with degrees of freedom under the null regardless of whether the process is stationary. The T-Y method avoids potential unit root and cointegration test bias. In each case, the null hypothesis $H_0 : a_1 = a_2 = ... = a_p = 0$ is tested against the alternative H_A : *not* H_0. A rejection of H_0 implies that there is Granger causality and one of the four hypotheses described in Chapter 3 can be confirmed.

4.2.3 The Social and Political Side of the Energy Transition

As was evidenced through the literature review, the social and political side of the energy transition are being included more and more often in scientific writings. On the one hand, it could be argued that addressing these aspects of the energy transition as well as the technical and economic aspects can accelerate the transformation of the energy systems and contribute to the achievement of the Sustainable Development

Goals (SDGs) [Cherp et al., 2018, Sovacool, 2014, Sovacool et al., 2018]. On the other hand, it could also be argued that the adoption of the SDGs requires addressing the social, political, economic and technical dimensions in research and policy-making to accelerate their implementation and seize their transformative potential [Allen et al., 2018, McKenzie and Abdulkadri, 2018].

The present research seeks to address the social and political dimensions of the Nicaraguan energy transition along with the techno-economic aspects of such transformation. To do so, a thorough literature review is carried out along with interviews with key stakeholders in the country. This review facilitates the identification of the current challenges and opportunities faced by developing countries such as Nicaragua for their energy transitions and is a fundamental part of the contribution of the final publication associated with this dissertation. The literature review is based on a bibliometric analysis, i.e., a statistical evaluation of published scientific articles studying the social and political side of the energy transition with a particular emphasis on developing countries. The bibliometric analysis is performed with support from the *bibliometrix* R-package, an open-source application designed for science mapping analysis [Aria and Cuccurullo, 2017]. The review draws and highlights good practices and lessons learned from relevant case studies found in the current literature, thereby contributing to answering some of the research questions in Chapter 1. The review includes not only techno-economic issues relevant to the energy transitions in developing countries but approaches to, simultaneously, deal with the socio-politics of this transformation of the energy systems. The two main outcomes include a holistic roadmap of alternatives to accelerate the energy transition addressing simultaneously the technological, social and political dimensions as well as a monitoring and evaluation framework to track progress.

Finally, the interviews aimed at better understanding the Nicaraguan energy system, the role of renewable energy and the benefits of development projects promoting clean energy in the country. The interviews are mostly directed to non-governmental organisations working in the fields of renewable energy and development in Nicaragua such as GIZ, Renovables, Hivos and BlueEnergy. They consist of the set of questions described in Appendix D. The same Appendix lists the interviewees. These interviews provide an empirical perspective of the Nicaraguan energy transition and are relevant for the design of future energy pathways to swiftly transform the Nicaraguan energy system.

Chapter 5

Nicaragua's State of Energy Affairs

Understanding the status quo is a key step before exploring new energy pathways for Nicaragua. This chapter presents a snapshot of the current state of affairs in the Nicaraguan energy sector. The structure of the energy system is reviewed as well as its historical development and the regulatory framework shaping it. A detailed description of the main energy markets is also provided. This snapshot enables the identification of key challenges and opportunities that must be addressed when seeking to accelerate the Nicaraguan energy transition. The insight derived from the review carried out for this chapter aids in answering some of the research questions presented in Chapter 1 and constitutes the underlying foundation of the energy scenarios that will be explored later in Chapter 6.

5.1 Country Profile

Nicaragua is the largest of the six Central American countries, bordered by Honduras to the north, Costa Rica to the south, the Caribbean to the east and the Pacific Ocean to the west. With approximately 6 million inhabitants and a total area of 120,340 km^2 [World Bank Group, 2020], Nicaragua is the least densely populated country in the Central American subregion. It has experienced several periods of political unrest and economic crisis and has often been hit by natural disasters. These events have shaped the status-quo: Nicaragua is one of the poorest nations in the western hemisphere. Its economy is the smallest among the six neighbouring countries, yet the second most carbon-intensive [World Bank Group, 2020]. In 2017, Nicaragua's economic output was derived from services (60%), industry (24.4%) and agriculture (15.5%) [CIA, 2020]. Agricultural and textile products accounted for approximately 50% of the country's exports in the same year [CIA, 2020]. The most prominent industries are food, chemical and metal products, oil refining, cement, beverages, footwear and tobacco.

Nicaragua has a significant amount of natural resources ranging from the two largest lakes in Central America, through lagoons and active volcanoes, to the second-largest rainforest in the western hemisphere [FAO, 2015, INETER, 2019, UNESCO, 2011]. Seizing this potential, Nicaragua has developed a robust eco-tourism industry that represented 3.7% of the country's gross domestic product (GDP) in 2017 [BCN, 2018, p. 8]. Tourism generated approximately 840 million dollars in 2017; 300 million dollars more than the country's main export: coffee [INTUR, 2018, p. 77]. Additional to boosting tourism, Nicaragua's vast natural resources grant the country a technical renewable energy potential estimated in approximately 5,500 MW that includes hydropower, geothermal, wind, solar and biomass [IRENA, 2015, Marandin, 2015, PRONicaragua, 2012]. Unfortunately, this potential has long been underexploited.

5.2 The Current Energy System

Despite the variety of energy resources available, Nicaragua's main primary energy sources have long been biomass, in the form of traditional firewood and vegetable waste and oil. Biomass accounted for 61.1% of the total primary energy supply (TPES) in 2017 and 41.8% of the total final energy consumption (TFEC) [MEM, 2018b, p. 45, 48]. Although oil accounted for 28.4% of the country's TPES in 2017 [MEM, 2018b, p. 45], it is the main source of energy consumed in Nicaragua, accounting for 46% of the country's TFEC [MEM, 2018b, p. 48].

The high usage of both traditional firewood and oil contribute to the country's relatively high carbon intensity and high energy-related costs. The fact that Nicaragua has always relied on imported oil (as it has no reserves of its own) aggravates this situation. In 2017, the oil bill represented 5.9% of Nicaragua's GDP and amounted to 130 dollars per capita [UN ECLAC, 2018, p. 55]. Historically, the residential and the transport sectors have been the main energy consumers, being responsible for approximately 73% of the energy used in 2017 in the country [MEM, 2018b, p. 49]. The residential sector's main energy source in 2017 was traditional firewood, which accounted for 84.8% of the sector's energy use, followed by electricity, which accounted for a moderate 9.4% of the sector's total energy consumption [MEM, 2018b, p. 49]. The transport sector, however, relies entirely on oil derivatives, namely diesel, gasoline and kerosene. Traditionally, the most consumed fuel in this sector has been diesel, which accounted for 53.3% of the sector's consumption in 2017 [MEM, 2018b, p. 49].

Other economic sectors are also reliant on biomass and oil derivatives; however, their energy mixes are slightly more diverse. Nicaraguan industry has been traditionally reliant on electricity, diesel and firewood, with these three fuels accounting for approximately 70% of the sector's energy consumption in 2017 [MEM, 2018b, p. 50]. Commerce and services have customarily relied mostly on electricity, diesel and liquid petroleum gas (LPG), with these fuels accounting for 75.9% of the sector's energy use in 2017 [MEM, 2018b, p. 50]. Agriculture consumes primarily biomass, diesel and electricity. These three categories represented 93% of the sector's energy consumption in 2017 [MEM, 2018b, p. 51].

Traditional firewood and oil derivatives are neither sustainable nor clean energy sources, yet they have been fundamental for economic growth in the country. There is a statistically significant strong positive association between GDP per capita (measured in current US dollars) and energy consumption per capita (measured in kg of oil equivalent) in Nicaragua evidenced by a Pearson correlation coefficient of 0.53 (p-value = 0.0002)[1]. As can be seen in Figure 5.1, the energy intensity of the Nicaraguan economy is currently above that of more developed countries such as Germany, the United Kingdom or Costa Rica and above the average of low-middle income countries and Latin American countries (excluding high-income countries). Given the predominant roles of traditional firewood and oil derivatives in Nicaragua's total final energy consumption, it can be argued that this high energy intensity is largely due to the consumption of these unsustainable fuels. Nonetheless, after the decade of civil unrest experienced in the 1980s, the country began to see a decline in its energy intensity explained by lower consumption of oil derivatives in the Nicaraguan industry and an increase in electricity consumption [ECLAC, 2015]. Furthermore, Nicaragua began

[1] Estimated using time series between 1990 and 2016 from the World Development Indicators [World Bank Group, 2020]

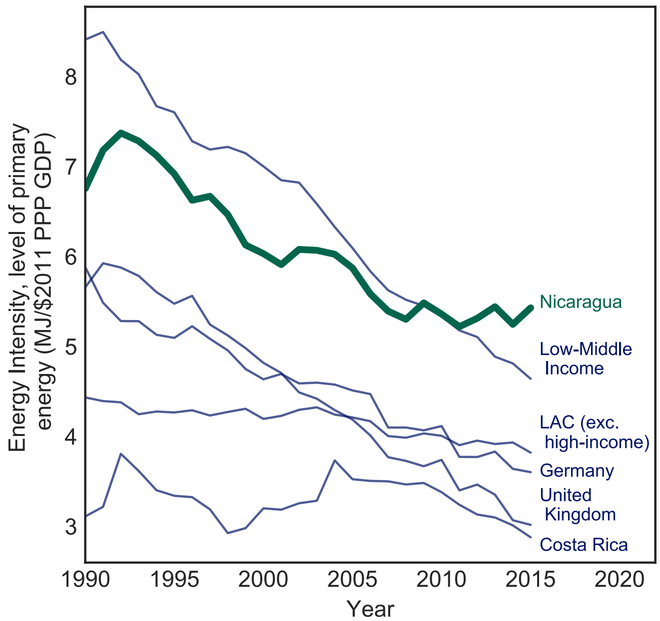


Figure 5.1: Evolution of energy intensity in different countries compared to Nicaragua

Source: Author based on the World Bank Group [2020]

investing in energy efficiency measures, primarily (albeit not exclusively) in the power sector that have led to the decrease in energy intensity seen in recent years. Finally, in the last decade, the emerging interest in renewable energy technologies and the high rate of economic growth in the country have further contributed to lower levels of energy intensity [ECLAC, 2015].

5.3 The Hydrocarbon Sector

Nicaragua has long been an acute oil consumer. In April 1963, Esso Standard Oil - a subsidiary of ExxonMobil - opened the country's only oil refinery to date with an estimated capacity of 20,000 barrels per day. Historically, the refinery has been the largest player in the Nicaraguan hydrocarbon market. With an average effective production of 13,787 barrels per day in 2018, the refinery met approximately 42% of the country's needs that year [MEM, 2019, p. 13, 15]. Puma Energy, the owner of ExxonMobil's operations and shares in Central America since 2012 [El Nuevo Diario, 2012], was responsible for all oil imports in 2018, which summed 4.74 million barrels [MEM, 2019, p. 12]. In recent decades, this oil has come mostly from Venezuela, given Nicaragua's participation in the Petrocaribe Agreement. This agreement enables member countries to purchase oil and/or its derivatives from Venezuela with a preferential payment arrangement: between 5% and 50% of the oil bill (depending on the price of oil at the time of purchase) must be paid in 90 days and the remainder through a 25-year financing agreement at interest rates of 1% and with a 2-year grace period [CARICOM, 2013]. Nicaragua's membership in the Bolivarian Alliance of the Americas (ALBA) has been a source of development aid channelled through private mechanisms as a parallel budget. It has been seen as a political tool for Venezuela's foreign policy since this nation has provided billions in social development projects to several nations in Latin America and the Caribbean, winning their favour and support and preventing opposing viewpoints to Venezuela [De la Fuente, 2011]. The secrecy surrounding Venezuelan financial aid and the financial activities of Albanisa, a private company owned by Venezuela's state oil company PDVSA and its counterpart in Nicaragua Petronic, have been a reason for criticism and distrust [Chamorro, 2016].

Since 2014, nevertheless, due to the crisis in Venezuela, Nicaragua has been importing oil from other countries in the American continent such as Mexico, Ecuador, the United States and Colombia. Since 2017, the U.S. is the main source of oil for Nicaragua and, in 2018, this nation was also the primary source of other derivatives such as LPG, gasoline (both regular and premium), diesel and solvents. From the 12.12 million barrels of oil and its derivatives imported in 2018, approximately 56% came from the U.S. and 13.6% from Venezuela [MEM, 2019, p. 9]. Diesel is by far the most consumed oil derivate acquainting for 35.5% of the country's oil derivatives demand [MEM, 2019, p. 16]. Fuel oil, gasoline, LPG, kerosene, coke and others acquainted for 23.98%, 23.07%, 11.86%, 1.7%, 2.8% and 1.09% respectively [MEM, 2019, p. 16]. Diesel and fuel oil are the two main fossil fuels used for electricity generation in Nicaragua.

5.4 The Power Sector

Slightly over one-third of the electricity used in Nicaragua in 2019 was consumed by the residential sector [INE, 2020b]. Nicaragua has a high electrical coverage index for a developing country, 97.2% of the households had access to electricity in 2019 [MEM, 2020c]. The average Nicaraguan household used approximately 91 kWh/month[2] in 2019, i.e., approximately 1,095 kWh/year. From the total electricity sales within Nicaragua, roughly 3,470 GWh in 2019 [INE, 2020b], about one fifth corresponded to consumption in industry and another similar share corresponded to commerce and services [INE, 2020b]. The remaining share corresponded to irrigation, pumping, street lighting, among others [INE, 2020b].

When it comes to supply, out of the approximately 4,582 GWh of electricity produced in 2019, less than half was produced using oil derivatives [INE, 2020c]. Renewable energy was responsible for approximately 57% of the electricity generated in Nicaragua in 2019 [INE, 2020c]. Biomass power plants (generating from sugar cane bagasse and other vegetable waste) were the main renewable generators accounting for 18.6% of the total electricity produced but closely followed by geothermal power plants (17.2%) and wind power plants (16.1%), whilst hydropower plants and solar photovoltaic accounted for 5% and 0.5% respectively [INE, 2020c].

Nicaragua has virtually 1,600 MW available for electricity generation [INE, 2020d], more than twice the maximum demand in 2019 [INE, 2020e]. Thermal power plants using diesel and fuel oil account for 54.4% of the installed capacity, whilst the remaining share accounts for renewable energy installed capacity. Nicaragua exploited approximately 30% of its technical renewable potential in 2019.

Despite the sub-utilization of its renewable potential, Nicaragua has long used renewable energy sources to partially meet the country's electricity needs. There is a record of the active role played by renewable energy since as early as 1945 [UN ECLAC, 1966, p. 153]. With a hydropower installed capacity of 8.7 MW at that time, 50.4% of Nicaragua's electricity was being generated from renewable energy sources, whilst the remaining 49.6% came from thermal power plants using imported fossil fuels [UN ECLAC, 1966, p. 158]. Nonetheless, and not much different from

[2] Own estimation based on data from INE [2020a, 2020b].

the current situation, the amount of electricity consumed in 1945 was equivalent to 10.1% of the total energy used by Nicaragua [UN ECLAC, 1966, p. 156]. This figure shows the low level of electricity consumption in the country; the lowest among the six Central American countries in 2016 according to official records [UN ECLAC, 2020a] and estimated at 564.2 kWh/capita in 2019[3].

5.5 Institutional and Legal Framework

The Nicaraguan energy system is currently regulated and monitored by the Nicaraguan Energy Institute [*Instituto Nicaragüense de Energía* in Spanish] (INE). The Ministry of Energy and Mines [*Ministerio de Energía y Minas* in Spanish] (MEM) is responsible for planning development strategies and policy-making. The energy sector has been opened to the involvement of private companies only since the mid-90s. Currently, there are private companies involved in activities such as electricity generation, import/export of oil and its derivatives, refining and distribution and commercialization of energy (see Figure 5.2). The state remains an important player, nevertheless, partaking in the generation of electricity through the Nicaraguan Electricity Company [*Empresa Nicaragüense de Electricidad* in Spanish] (ENEL), the operation and administration of the electricity market through the National Load Dispatch Center [*Centro Nacional de Despacho de Carga* in Spanish] (CNDC), the transmission of electricity and the management of all transmission networks through the National Electricity Transmission Company [*Empresa Nacional de Transmisión Eléctrica* in Spanish] (ENATREL) and the import/export of oil and its derivatives through the Nicaraguan Oil Distributor [*Distribuidora Nicaragüense de Petróleo* in Spanish] (DNP).

After democracy was established at the beginning of the 1990s, a series of reform processes started in Nicaragua, which extended to both the power and hydrocarbon sectors. The Hydrocarbon Supply Law [1997] was an effort from the Nicaraguan government to establish the legal regime for the activities, participants and facilities that belong to the hydrocarbon supply chain in the country. As a result, the partaking of private actors in the hydrocarbon market activities was regulated through a system of licenses. The state, nevertheless, sets the maximum sale prices of gasoline,

[3]Own estimation based on data from INE [2020b] and CIA [2020].

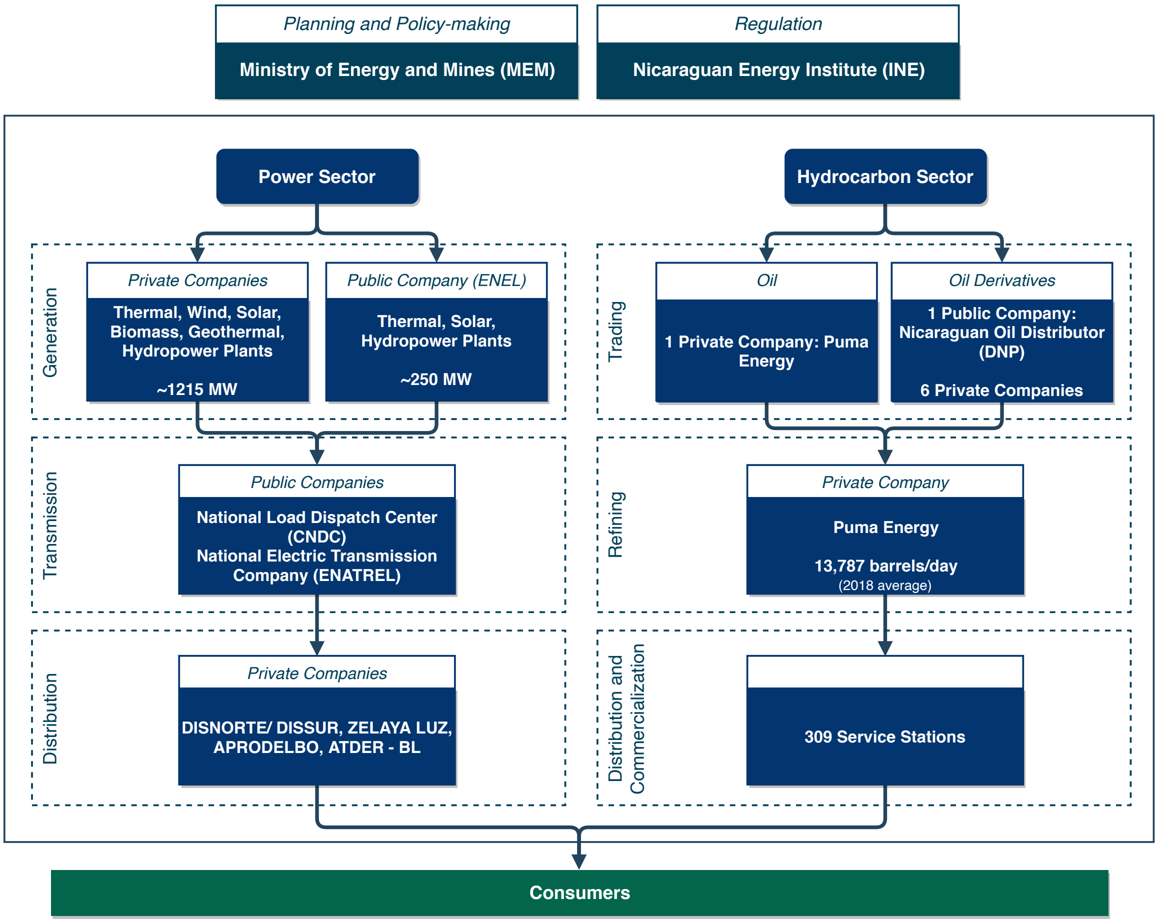


Figure 5.2: Structure of the Nicaraguan energy market

Source: Author based on INE [2020d], MEM [2019] and UN ECLAC [2018].

diesel, kerosene and LPG. The Electricity Industry Act [1998] represents the efforts of the Nicaraguan government to reform and privatize the power sector. This law is fundamental as it establishes the legal framework for all activities in the power sector: generation, transmission, distribution, commercialization and trading. The act sought to create a wholesale market with multiple generating companies compensated following a spot price determined by the highest marginal cost of production at any given hour; a contracts market involving generating companies, distribution companies and large consumers, which provides protection against variabilities in the spot market; and a regulated market of end-users, served by distribution companies at prices set by a regulator. The reform enabled the privatization of some generating assets. However, the absence of policies defining water rights or regulating protected areas led to a lack of interest from the private sector on hydro assets. Most large hydropower plants and thermal power plants remained in public ownership.

The continuous increases in the international oil price at the beginning of the 2000s had important repercussions in the Nicaraguan energy system due to the high reliance of the country on oil. Firstly, both transport fuels and electricity rates were impacted. Disagreements within the Executive and the Legislative bodies developed and escalated due to the reluctance of the regulator to transfer to end consumers the rise in oil prices. There was an underlying profound political crisis that prevented solutions and aided the failure of the reforms. The political crisis repelled potential investment which, in conjunction with the worsened state of existing old generating assets, low rainfall levels limiting electricity generation from hydropower and high transmission and distribution losses in the power system exacerbated the insecurity of supply. The energy crisis led to daily blackouts lasting between 8 and 12 hours.

Amid this national energy crisis, Law N° 554 – also known as the Energy Stability Act [2005] – was passed. The law declared a state of "national energy crisis", which was meant to remain in place for as long as the international oil price was higher than 50 US dollars per barrel or more than 50% of the country's electricity was generated using fossil fuels. The Energy Stability Act sought to regulate energy prices to alleviate the effect of high international oil prices on the Nicaraguan economy. As a result, energy efficiency measures were implemented in different economic sectors, electricity tariff subsidies were applied for residential clients with monthly consumption of 150 kWh or less, a subsidy was destined for inland public transport and investment in renewable energy was declared as a special priority for the country. Additionally, the act established an Energy Crisis Fund aimed to finance the subsidies and an Energy Investment Development Fund to fund research and pre-feasibility studies to expand the renewable installed capacity in the country.

The crisis was offset with investment from Venezuela on fuel oil-based power plants in the framework of the Petrocaribe Agreement. Nonetheless, law bills were passed to promote and regulate the exploitation of the vast renewable energy potential of the country. For example, Law N° 443 on Exploration and Exploitation of Geothermal Resources [2002] was passed aiming to establish the basic requirements and considerations to seize Nicaragua's geothermal potential for electricity generation. Similarly, Law N° 467 for the Promotion of the Hydroelectric Sub-sector [2003] sought to stimulate the generation of electricity sustainably using hydraulic sources. Law N° 532 for the Promotion of Electricity Generation from Renewable Sources was passed in 2005 to promote investment in renewable installed capacity. This is the main renewables-related policy in the country and it establishes fiscal, economic and financial incentives along with grid benefits to foster the development of clean energy. These incentives and benefits include value-added tax exemption, income tax exemption, import duty exemption, exemption of local taxes, preferential dispatch, among others. With the passing of this law, the interest and support for the integration of renewable energy have increased significantly. The country has recently updated its goal to generate 70% of its electricity from renewable energy sources in 2033 [MEM, 2018a].

5.6 Historical Development of the Power Sector

Traditionally, capacity expansions in Nicaragua have been a reactive response to growing demand and unsatisfied energy requirements. This continual lack of long-term planning in the power sector has led to investment in internal combustion units as an immediate solution to unmet energy needs. Nicaragua has made scattered attempts to seize its renewable potential for electricity generation. However, it is only until recently that renewable energy has been seen as an alternative to ensure the security of supply and reduce energy imports. As seen in Figure 5.3, the development of the country's renewable installed capacity for electricity generation has grown significantly and continuously since 2010.

The development of renewable energy in Nicaragua began in 1965 when the first large-scale hydropower plant with 50 MW installed capacity was inaugurated [UN ECLAC, 1991, p. 17]. Later, in 1983, Nicaragua seized the geothermal potential on the slopes of the Momotombo volcano and began producing electricity from a 35 MW geothermal power plant [CNE, 2001, p. 27]. In 1996, Nicaragua's two largest sugar mills began selling their excess electricity produced from sugar cane bagasse to the national grid [Van Den Broek et al., 2000]. Electricity was produced from wind turbines for the first time in Nicaragua in 2009 with the inauguration of a 40 MW wind park [PRONicaragua, 2014]. More recently, in 2014, Nicaragua introduced 1.38 MW installed capacity of solar photovoltaic to the national electricity grid [MEM, 2015, p. 11]. This development and diversification of the Nicaraguan power sector have continued and the country was positioned among the top 10 countries in the world with the highest share of electricity generation from variable renewable energy

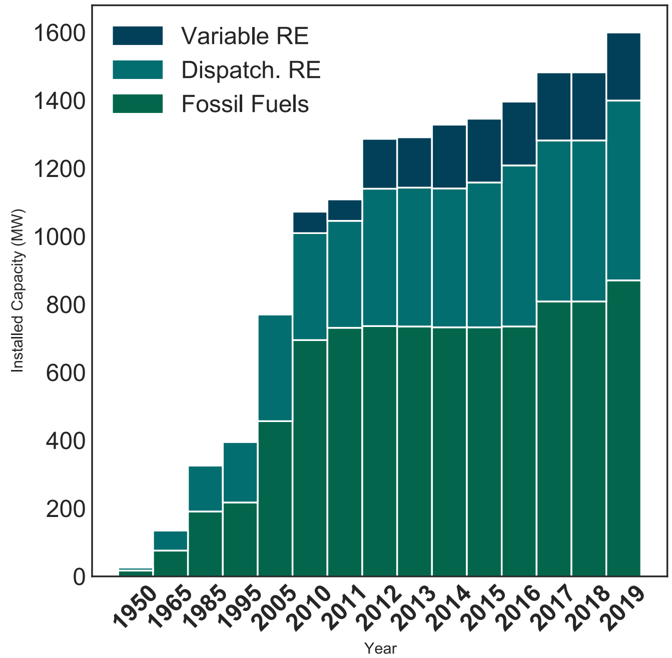


Figure 5.3: Evolution of the installed capacity for electricity generation in Nicaragua

Source: Author based on ECLAC [1966, p. 156], ECLAC [1991, p. 17], MEM [2018c, p. 68] and INE [2020d].

in 2018 [REN21, 2019, p. 43].

The expansion of the installed capacity with renewable energy has led to lower consumption of fossil fuels. This situation, combined with lower oil prices, has reduced the country's vulnerability to the volatility of oil prices. An indicator of this is the correlation between electricity prices in the Nicaraguan wholesale market and electricity generation from renewable energy which has increased from -0.12 in 2010 to -0.78 in 2018 (see Figures 5.4(a) and 5.4(b)). The negative association suggests that the more electricity is generated from clean sources, the lower the wholesale prices will be. Moreover, the increase in the strength of this association hints to the important role that renewable energy has acquired in recent years in Nicaragua.

Unfortunately, the current electricity tariffs in Nicaragua do not reflect the favourable effect of the integration of renewable energy. Despite the higher penetration of renewables in the Nicaraguan electricity mix, the average electricity prices for the end consumer have remained among the highest in the Central American region (see Figure

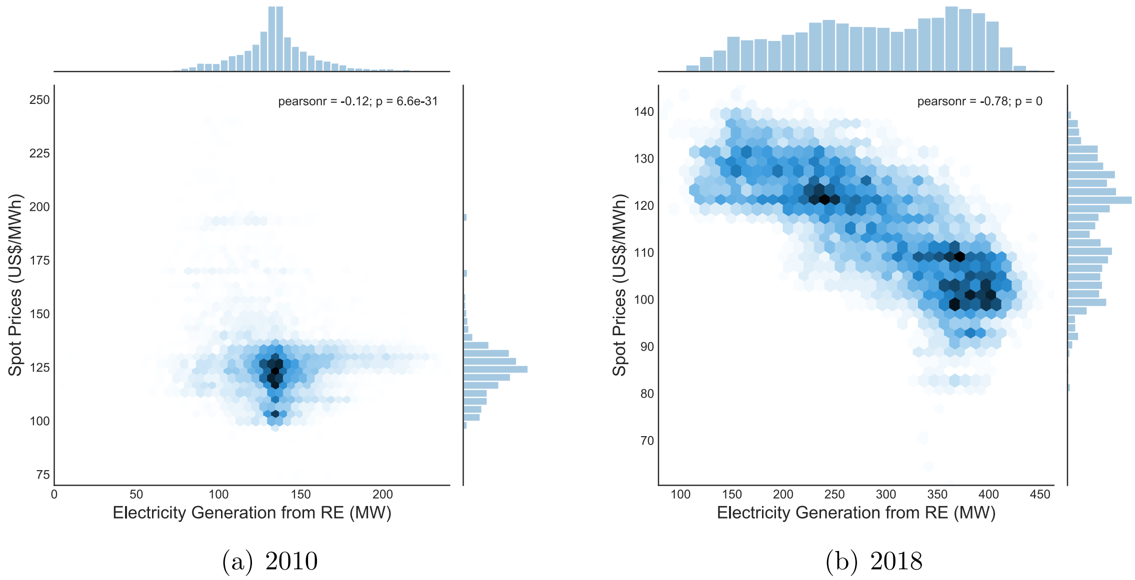


Figure 5.4: Pearson correlation between electricity generation from renewable energy and wholesale electricity prices in selected years

Source: Author based on official data [ENATREL, 2020].

5.5). In 2019, the average household electricity tariff in the country was 20 ¢/kWh [INE, 2020f]. This is comparable to the price paid by Finnish or Luxembourgian households in 2019 [Eurostat, 2020].

5.7 Tariff Scheme and Financial Sustainability of the Power Sector

As is usual in many countries, electricity prices in the wholesale market are estimated on an hourly basis and are equal to the marginal cost in an unconstrained spot (or over-the-counter) market. Generation costs are transferred to the consumers with some levelling intended to reduce volatility and foster investment in generation. The differences (either positive or negative) accumulate and are supposed to be balanced through appropriate tariff adjustments. In the case of Nicaragua, the Electricity Industry Act established a wholesale market and its pricing rules. The pricing strategy is intricately regulated by INE and tariffs are adjusted periodically (typically every

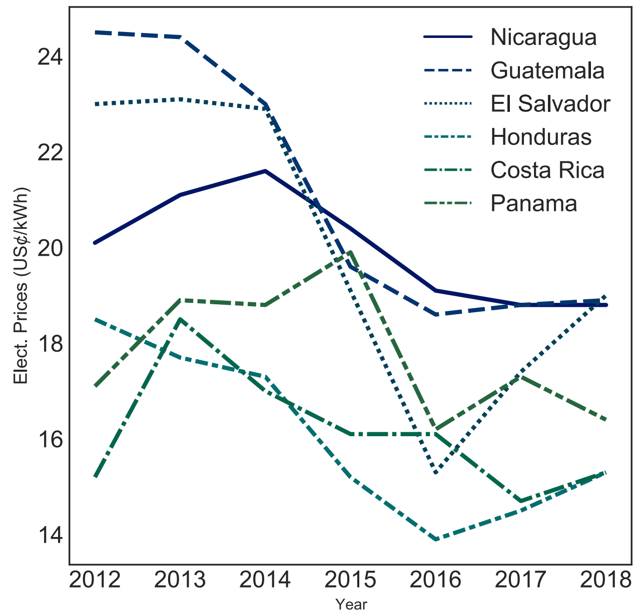


Figure 5.5: Nominal electricity prices in selected Central American countries.

Source: Author based on data gathered by ECLAC [2020b].

2-5 years) in agreement with the distributors. However, there has been a lack of investment in infrastructure maintenance and upgrading despite both tariff increases and government subsidies [Cupples, 2011]. One of the main financial challenges facing the Nicaraguan power sector is that tariffs do not account for the high transmission and distribution losses (approx. 21% in 2019 [INE, 2020h]). Unfortunately, the financial information publicly available hinders a detailed analysis of the situation.

The approved tariffs encompass the costs of purchasing energy and wholesale power, a charge for street lighting and charges associated to distribution networks, operation and maintenance, energy and power losses characteristic of an efficient distributor (i.e., 2-5%), the costs of access to and use of transmission networks, invoicing and marketing expenses and the costs of normal capital or profit. A simplified breakdown of the typical charges applicable to a residential household and a medium-size industry in December 2018 are shown in Figure 5.6. The industrial customer in Figure 5.6 and other types of customers are subjected to additional charges according to the legislation. These include a charge per unit of energy consumption (possibly per hour block, i.e., peak or off-peak), per unit of maximum contracted power (also possibly per hour block), for fixing and guaranteeing the permanent availability of the service

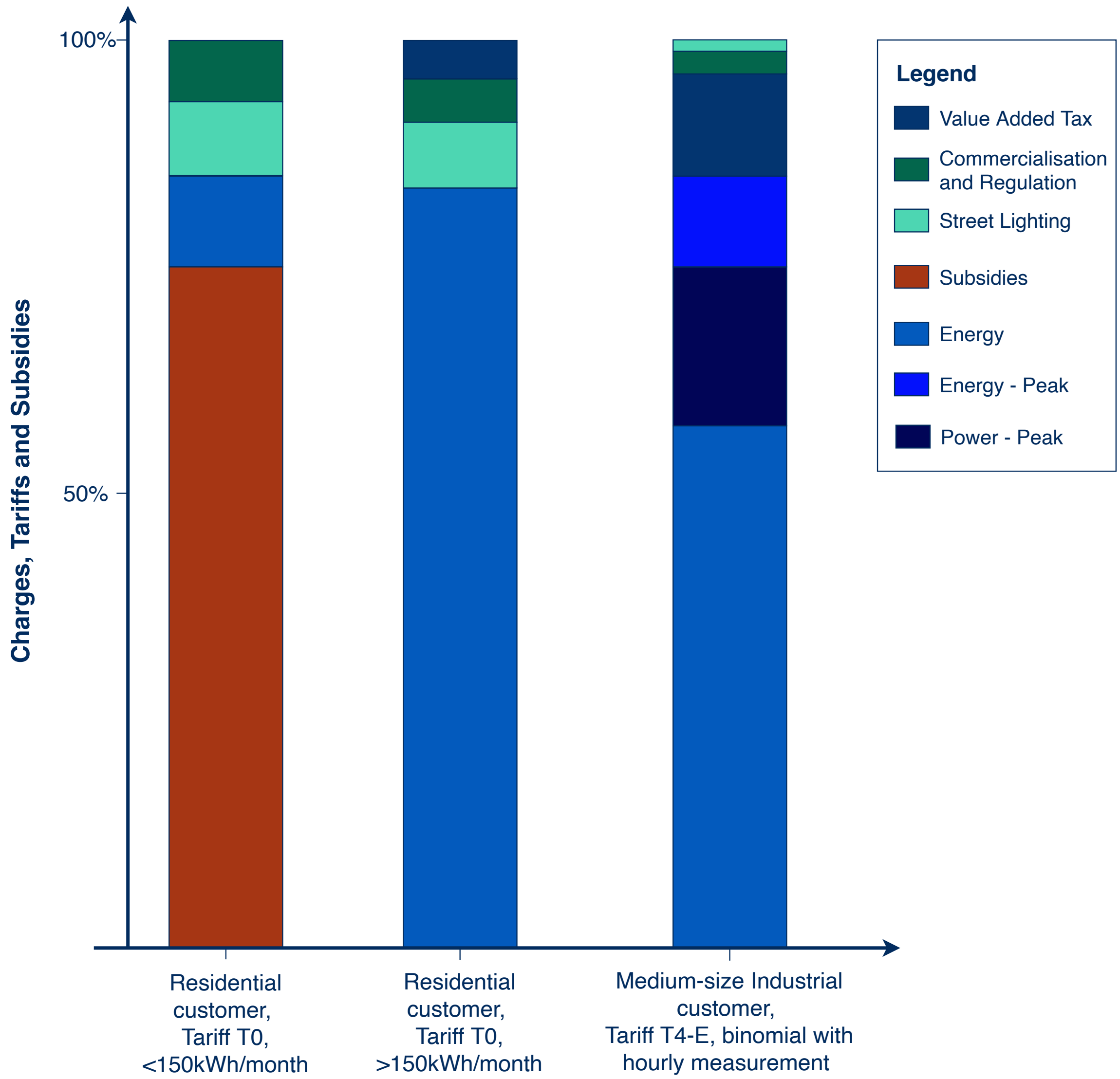


Figure 5.6: Consumer price cost breakdown in 2018 for residential customers (tariff T0) and medium-size industries (tariff T4-E).

Source: Author based on INE [2019a].

and for user connection. End consumers are categorized according to their demand characteristics into classes and tariffs for each customer class are estimated according to their corresponding load curves. As a result, there were 10 different low-voltage customer classes with 43 energy tariffs and 19 power tariffs in total as well as 7 different medium-voltage customer classes with 46 energy tariffs and 26 power tariffs in total in July 2019 [INE, 2019a].

Additional to this tariff segregation, within the customer class corresponding to households, another differentiation that responds to different types of subsidies applied to alleviate the increase in the tariffs due to increases in the oil price. These subsidies have been applied since 2005. Some of the subsidies represent discounts in the approved tariffs whilst others imply exemptions from tax payments. Figure 5.6 shows the structure of the tariffs and charges applicable to two types of households: one consuming less than 150 kWh/month (on the left) and another one consuming more than 150 kWh/month (on the right). In 2017, those Nicaraguan households consuming less or equal to 150 kWh/month were entitled to a subsidy equivalent to 52.8% of the approved electricity tariff [Nicaragua National Assembly, 2015]. These households have also subsidies on the charges for commercialization and street lighting which in 2017 were equivalent to discounts of 30.2% and 22% respectively [Nicaragua National Assembly, 2015]. And, lastly, there are reductions of the value-added tax for households depending on their consumption range. Until 2018, households consuming 300 kWh/month or less were exempt from this tax and households consuming more than 300 kWh/month paid a 7% tax, as opposed to the 15% that should have been lawfully charged [Nicaragua National Assembly, 2015]. The subsidies to those households consuming less or equal to 150 kWh/month totalled 43.9 million dollars in 2019 [INE, 2020g].

Table 5.1

Scheduled reductions to households' subsidies in electricity consumption in Nicaragua

Range of Consumption	Share of electricity tariff being subsidized (%)					
	2017	2018	2019	2020	2021	2022
0 - 25 kWh	52.8	52.8	52.8	52.8	50	50
26 - 50 kWh	52.8	52.8	52.8	52.8	50	50
51 - 75 kWh	52.8	52.8	52.8	52.8	50	45
76 - 100 kWh	52.8	52.8	52.8	52.8	50	45
101 - 125 kWh	52.8	50	40	35	30	25
126 - 150 kWh	52.8	40	30	25	25	25

Source: Author based on current legislation (Law N° 971 [2018], Law N° 898 [2015]).

Legal reforms set in motion gradual cutbacks to these subsidies in 2018. The discounts from the approved tariffs will be slowly reduced as shown in Table 5.1. There are similar reduction plans for the subsidies on commercialization and street lighting seeking to phaseout the benefits for people consuming more than 100 kWh/month by

2022. The benefit regarding the value-added tax exemption/reduction has now been restructured and will only be perceived by those households consuming less than 300 kWh/month.

In summary, the Nicaraguan energy system faces important challenges that include financial sustainability, the stability of the legal framework and the need for reliable regulation, guaranteeing the security of supply, lack of transparency and simplicity in regulatory processes and general institutional weaknesses. These challenges hinder competitiveness and productivity in the country and affect the well-being and purchasing power of the Nicaraguan households, thereby threatening the opportunity for sustainable development. With the drive of the present-day transition to renewable energy in the country, these challenges cannot be neglected or overlooked.

Chapter 6

Main Results and Discussion

The objective of this dissertation is to identify key strategies to accelerate the Nicaraguan transition to a sustainable and renewable energy system while tackling sustainable development challenges. This endeavour might seem cumbersome. Nevertheless, the research performed has made it possible to pinpoint a set of key alternatives for the Nicaraguan case. The alternatives are divided into three categories: technology, development economics and society and politics. The findings and contributions of this dissertation are summarized in this chapter.

6.1 Technological Alternatives

As previously discussed in Chapter 5, Nicaragua directed its efforts to restructuring the country's power sector after a severe energy crisis between 2005 and 2006. Among the reforms, Nicaragua's renewable energy potential was set to be better exploited. The country established a supporting legal framework that contributed to managing the risks for new and private investors in the Nicaraguan power sector. The strategy successfully attracted funding for new renewable installed capacity. Nevertheless, it was only until 2013 when these energy sources began significantly increasing its share in the Nicaraguan energy mix and replacing thermal energy for electricity generation.

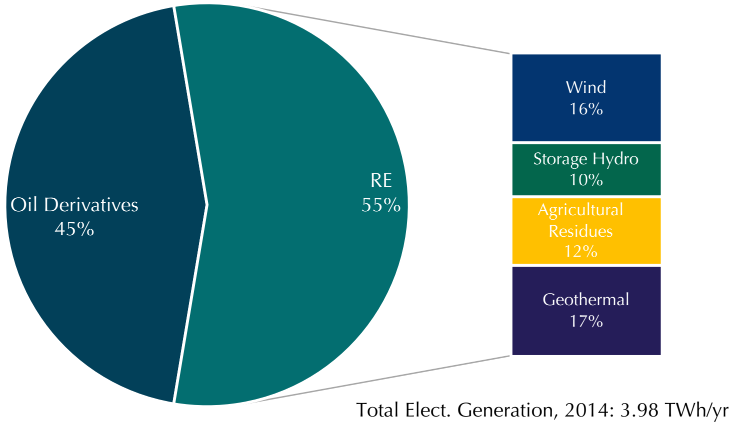
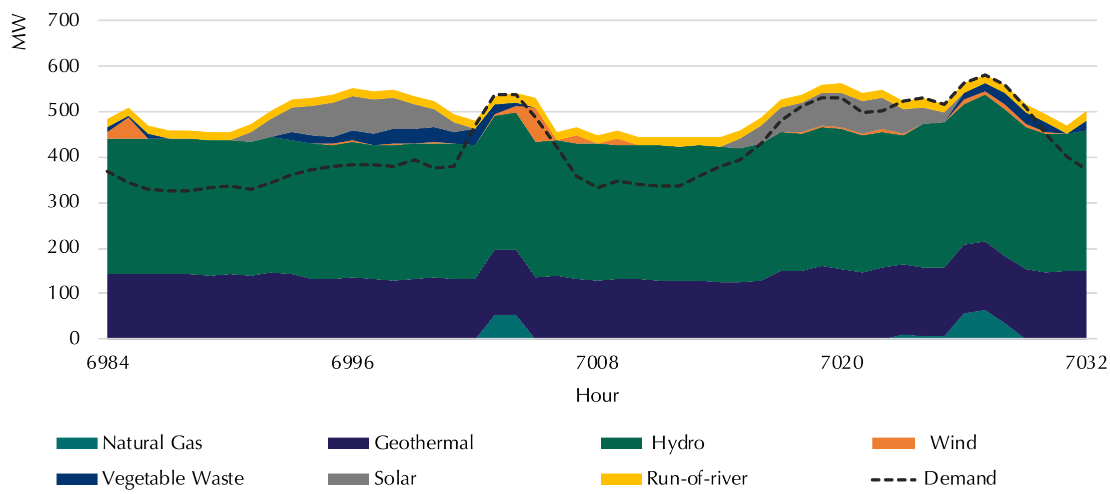


Figure 6.1: Electricity generation matrix, Nicaragua 2014

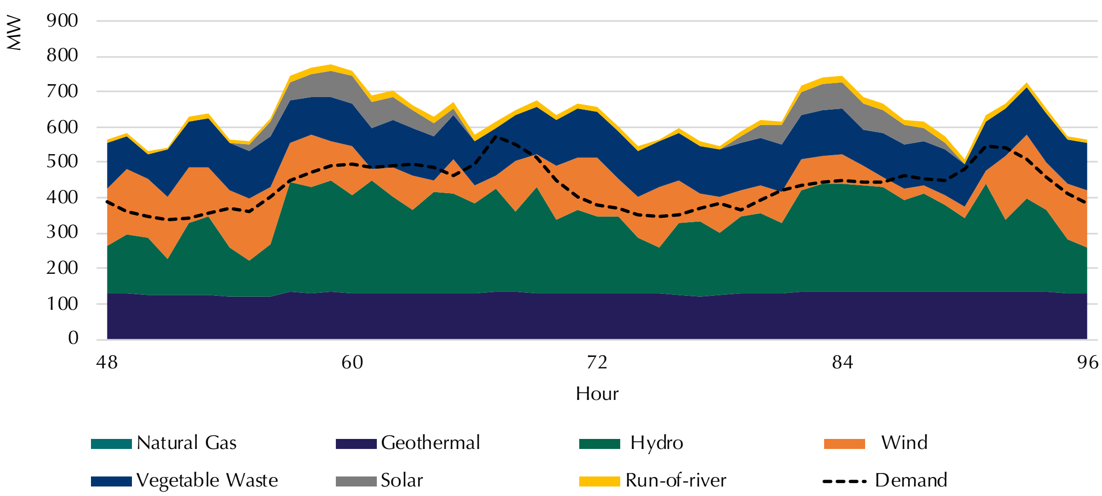
Source: Based on the results from Vanegas Cantarero [2018]

The country aims to generate 70% of its electricity from clean energy sources by 2033 [MEM, 2018a]. Renewable installed capacity is expected to increase by 944 MW between 2019 and 2033, thereby diversifying the country's electricity matrix and seizing, primarily, the country's hydro, solar and wind energy potential (although expansions in biomass and geothermal capacity are planned as well).

While reviewing a previous yet comparable version of Nicaragua's renewable energy expansion plan, the analysis presented in Paper 1 [Vanegas Cantarero, 2018] indicates that the country's promotion of clean energy could lead to supplying nearly 90% of the electricity in 2030 from renewable energy sources. In such a situation, variable renewable energy sources such as onshore wind and solar PV could generate approx. one-quarter of the electricity in 2030 without compromising grid stability. Particularly during the rainy season that runs from May to October, when the wind speeds are low and the sun does not shine as often, dispatchable renewable energy sources such as geothermal and hydro are capable of meeting the demand with only a small contribution from thermal power plants during peak time. This situation is depicted graphically in Figure 6.2(a). During the dry season, renewable energy sources can meet the entire electricity demand at all times without affecting the balance between supply and demand as seen in Figure 6.2(b). In this case, an excess of electricity is generated; however, it can be exported to the Central American Regional Electricity Market.



(a) 2 days (So + Mo), October



(b) 2 days (Fr + Sa), January

Figure 6.2: Sample hourly electricity mix in the EXP and BIO scenarios in 2030 during (a) rainy and (b) dry season

Source: Vanegas Cantarero [2018]

This transformation of the Nicaraguan electricity mix could bring the country closer to the decarbonisation of the power sector, especially when the expansion strategies are coupled with energy efficiency measures. The results from the BIO scenario[1] developed in Paper 1 indicate that small changes such as the introduction of a biofuel mandate promoting the use of blends of up to 10% of indigenously-produced ethanol

[1]Refer to Vanegas Cantarero [2018] for a detailed description of the scenarios explored.

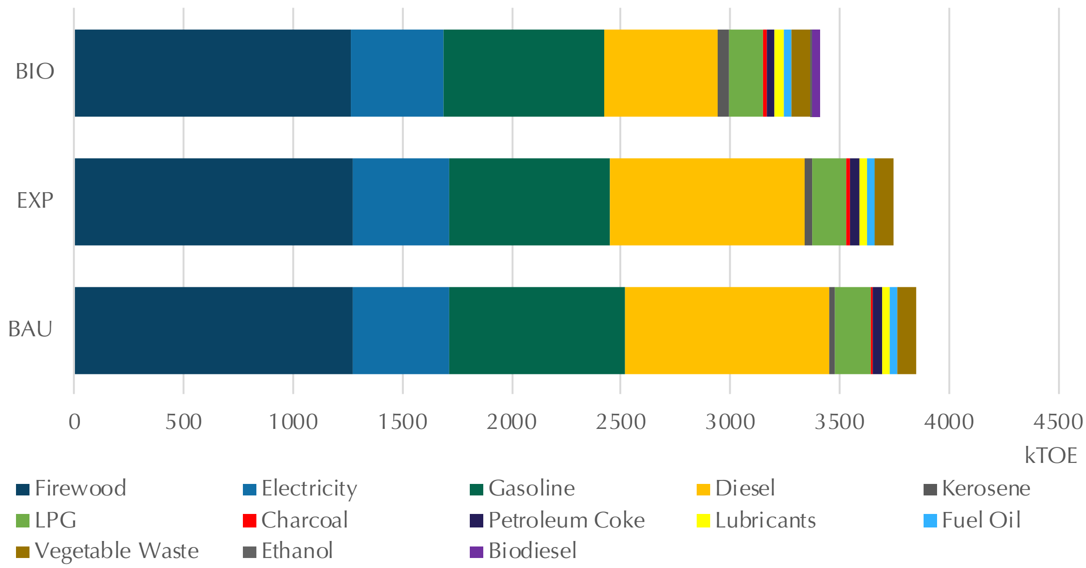


Figure 6.3: Secondary energy consumption in 2030 per scenario explored in Paper 1

Source: Vanegas Cantarero [2018]

and biodiesel in the Nicaraguan transport sector or the replacement of incandescent lamps with compact fluorescent lamps (CFLs) in Nicaraguan households could lead to a reduction of 18.5% in greenhouse gas (GHG) emissions in 2030 relative to business-as-usual conditions.

Despite these benefits, the single sector approach adopted by the Nicaraguan central government is unlikely to have a significant impact on the final energy mix. This is because the two largest energy-consuming sectors are virtually neglected in the country's energy strategies. Figure 6.3 shows that, despite the significant reduction in the use of fossil fuels for electricity generation, the Nicaraguan final energy mix remains predominantly reliant on traditional firewood (used for cooking in the residential sector) and gasoline and diesel (both used mainly in the transport sector). Electricity represents a modest 12% of the total final energy consumed in 2030 in all the scenarios explored by Vanegas Cantarero [2018]. Hence, the results suggest that efforts should be redirected towards the transformation of the entire Nicaraguan energy system and not solely of the power sector.

Reflecting on the trends found in the literature in Chapter 2, cross-sectoral synergies within the Nicaraguan energy system may be an alternative worth exploring to aid the transition to a low-carbon energy system and tackle sustainable development challenges. Journal Paper 2 [Vanegas Cantarero, 2019] explored potential synergies between the Nicaraguan power and transport sectors. As Managua, Nicaragua's capital, plans and prepares a restructuration of the public transport system, the country is presented with the opportunity to stabilize transport demand and decrease the carbon footprint of the sector. Coupling a decarbonised power system with a modern and more efficient transport sector can significantly reduce GHG emissions, improve the living conditions of the Nicaraguan society and promote economic growth.

Four pathways[2] were proposed for a decarbonised Nicaraguan transport system in 2030: i) a mass public transport system with a Bus Rapid Transit (BRT) system and an Automated Guideway Transit (AGT) system for the Nicaraguan capital by 2030; ii) the electrification of the national vehicle fleet by replacing conventional internal combustion engine vehicles with commercially-available electric vehicles; iii) the local production of electrofuels to power heavy-duty vehicles and airplanes; and iv) a combination of all the previous alternatives.

Key features of sustainable energy systems are high efficiency, cost-effectiveness and low-carbon intensity. These three characteristics are achieved in the final pathway explored in Journal Paper 2 by combining all the decarbonisation strategies. The results, presented in Figure 6.4, show that a mass public transport system is likely to have a significantly higher abatement cost than any of the other alternatives. This is due to the relatively high annual costs of a transport system with an electrified mass public transport system yet with a high share of private internal combustion engine vehicles on the roads relying entirely on oil derivatives. A mass public transport system would, nonetheless, aid in stabilizing the demand for private and individual transport in the Nicaraguan capital. Currently, the vehicle fleet is growing at an unsustainable rate and regulations and reforms are necessary. The proposed system would bring additional benefits, for instance, enhanced communication and integration in the city as well as the creation of jobs and economic development that is socially inclusive.

[2] Refer to Vanegas Cantarero [2019] for a detailed description of the scenarios explored.

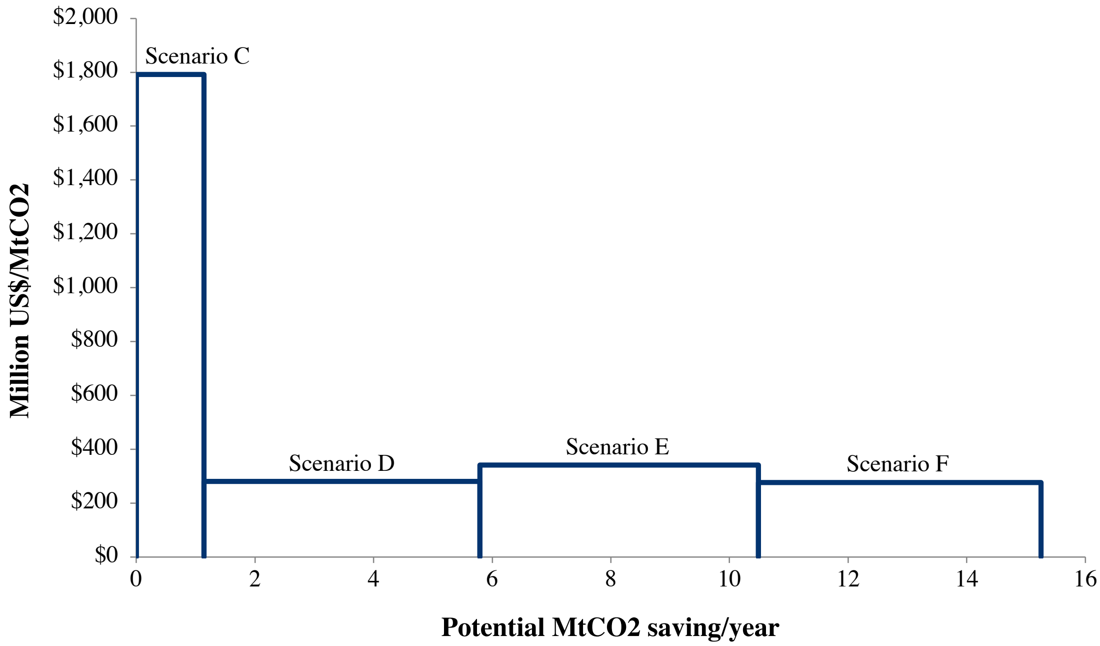


Figure 6.4: Abatement cost per scenario

Source: Vanegas Cantarero [2019]

Arguments for and against the electrification of light-duty vehicles were presented as well. On one hand, this alternative would require significant additional installed capacity to meet the new electricity demand. Ideally, the additional electricity generation should come from renewable energy sources not to offset the benefits of the lower carbon footprint that electric vehicles have with a higher demand for electricity generated from fossil fuels. This implies significant investment costs. Additionally, a market and infrastructure must be created for new vehicles. This includes a regulatory framework, a charging network and the skills and training required to operate and maintain these new technologies in the country. On the other hand, such a transition would reduce the levels of air and noise pollution in the Nicaraguan capital particularly, where approx. 50% of the country's vehicle fleet operates. Additionally, users would perceive an economic incentive given the lower fuel costs of electric vehicles relative to conventional internal combustion engine vehicles[3] and the fact that

[3]On average, driving 100 km with an electric vehicle would have cost approx. 60% less than with an internal combustion engine vehicle considering the average fuel prices in September 2018 in Nicaragua and average fuel economies of 5.5 km/kWh and 10.2 km/lt respectively (see Vanegas Cantarero [2019] for further details.)

electric vehicles are expected to reach cost parity between 2024 and 2029. Moreover, when the use of electric vehicles is coupled with smart charging and vehicle-to-grid (V2G) capabilities, the security of supply and the stability of the grid (i.e., the balance between supply and demand) can be improved, thereby reducing the consumption of fossil fuels for electricity generation and the levels of CO_2 emissions.

A similar case is presented for the production of electrofuels in Nicaragua. Electrofuels are expected to begin a gradual introduction into the marketplace in the medium term as the required technologies reach higher levels of technology readiness. At the moment, electrofuels are not commercially available and, thus, are more expensive than oil derivatives. Investment costs for these technologies are rather high and their future is uncertain. Prices are expected to decrease as processes are optimised and production increased; however, policy and regulatory intervention will be required to ensure adoption and deployment. Furthermore, renewable electricity is necessary to produce low-carbon hydrogen and this implies additional renewable installed capacity. The resulting abatement cost for this pathway is thus higher than for the previously described electrification of the light-duty vehicles, as seen in Figure 6.4. Notwithstanding this, electrofuels are a feasible alternative to replace oil derivatives with low-carbon fuels in heavy-duty vehicles, marine transport and aviation. Moreover, electrofuels would enable the storage of excess electricity from fluctuating renewable sources such as wind and solar PV in the form of liquid fuels, thereby increasing the flexibility of the Nicaraguan energy system. Finally, since a supply chain must be established and developed, jobs will be created and economic development fostered.

Ultimately, the most sustainable and cost-effective pathway is a combination of all these alternatives. In such an energy strategy, not only is the electricity demand lower than in the previous two pathways, but more renewable energy is integrated into the Nicaraguan power system, the annual costs are approx. half of business-as-usual conditions and both the power and transport sectors are decarbonised. Nicaragua would experience socio-economic and environmental benefits[4] including those described in the individual pathways; however, this is only one example of the type of synergies that could be created between the Nicaraguan power sector and other energy sectors leading to a smart energy system.

[4] The socio-economic and environmental benefits of the individual pathways require further investigation via, e.g., a macro-level study or a cost-benefit analysis.

6.2 Renewable Energy for Sustainable Development

Papers 1 and 2 show how a transition to a sustainable and renewable energy system in Nicaragua may contribute to tackling sustainable development challenges. However, it remains yet to be assessed if and how has renewable energy contributed until now.

Fast-growing economies such as the Nicaraguan economy run the risk of following the resource-intensive path that developed nations have followed. Close attention must be paid to the sustainability of economic growth in such nations. Vanegas Cantarero and Movsessian [2018] reviewed the role that renewable energy has played in Nicaragua's recent economic development and the country's environmental condition. Initially, the authors explored the (linear) correlations between the following economic indicators: ecological footprint, gross domestic product per capita, the share of alternative energy in total energy use, agricultural production index and urban population growth.

The results are presented graphically in Figure 6.5 and show that both income and the use of renewable energy are negatively correlated with the ecological footprint suggesting that income and the use of renewable energy increase as environmental damage decreases. Conversely, the positive correlation between agricultural production and urbanization rate and the ecological footprint suggests that crop production and migration to cities increase as environmental damage increases. Furthermore, the results show that both renewable energy use and agricultural production are positively correlated with economic development. However, agricultural production and urbanization are negatively correlated with the use of renewable energy. These results suggest that the nexus between economic growth and environmental damage in Nicaragua between 1971 and 2013 may have been affected by the integration of clean-energy technologies into the energy system.

These results hint to the validity of the EKC hypothesis in the country. Vanegas Cantarero and Movsessian [2018] studied further the energy - environment - economic growth nexus. Their econometric analysis found that, between 1971 and 2013, the country had a performance that resembled the EKC hypothesis: the income elasticity of environmental degradation is larger in the short-term than in the long-term, i.e., the responsiveness of environmental degradation to a change in income levels is

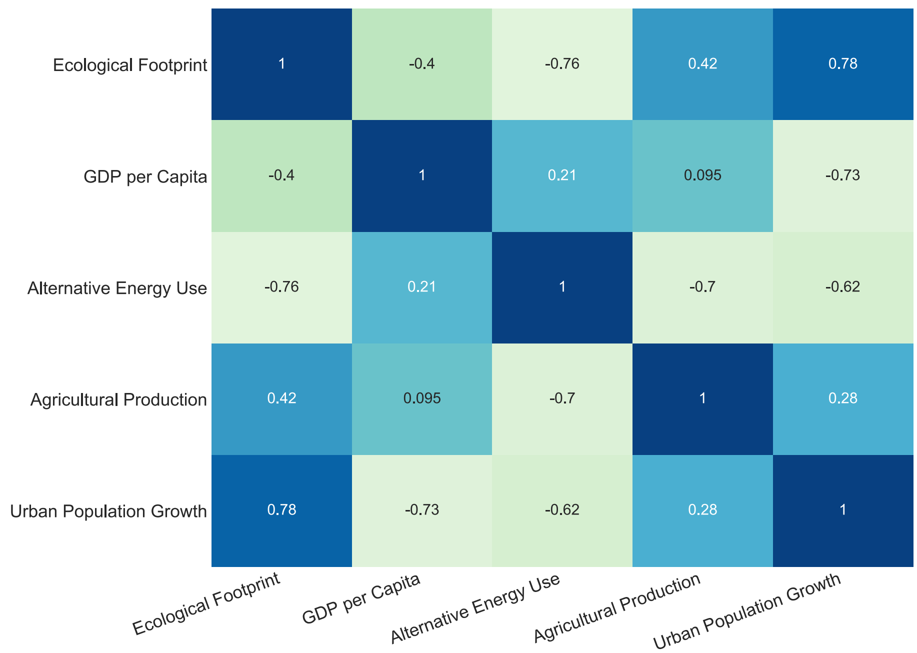


Figure 6.5: Pearson correlations between selected economic indicators in Nicaragua between 1971 and 2013

Source: Author based on Vanegas Cantarero and Movsessian [2018]

curbed in the long-run relative to the short-run. The results from Vanegas Cantarero and Movsessian [2018] shown in Table 6.1 indicate that, in the short-run, a 1% increase in GDP per capita increases the ecological footprint by 0.27% whilst, in the long run, a 1% increase in GDP per capita increases the ecological footprint by 0.22%.

Furthermore, the environmental benefits of renewable energy were confirmed both in the short- and long-run; however, the marginal effect is higher in the long-run where a 1% increase in the renewable share of total energy use decreases the ecological footprint by 0.22% (as opposed to 0.09% in the short-run). In the short-run, only the integration of renewable energy into the Nicaraguan energy system contributes to alleviate environmental degradation, yet the contribution is rather modest. This is in line with the results from Vanegas Cantarero [2018] where the sole focus on the integration of higher shares of renewable energy in the Nicaraguan electricity mix do not significantly impact neither the final energy mix nor the level of greenhouse gas (GHG) emissions.

Table 6.1
ARDL model long and short run parameter estimations

ARDL (1,3,4,4,4)					
Dependent variable: ln(EF) Conditional error correction regression			Dependent variable: Δ ln(EF) Error correction regression		
Variable	Coefficient	t-Statistic	Variable	Coefficient	t-Statistic
ln(GDPpc)	0.224	6.172***	Δ ln(GDPpc)	0.271	8.322***
ln(RE)	-0.209	-6.304***	Δ ln(RE)	-0.086	-4.651***
ln(AGRO)	-0.603	-5.801***	Δ ln(AGRO)	-0.123	-1.634
ln(URB)	0.038	0.162	Δ ln(URB)	4.317	3.535***
Trend	-0.004	-0.596	Δ dummy78	-0.168	-5.090***
dummy78	-0.168	-2.921**	Δ dummy93	-0.187	-6.087***
dummy93	-0.187	-3.601*	CointEq(-1)	-1.328	-10.481***

*Denotes significance at 10% level; **Denotes significance at 5% level; ***Denotes significance at 1% level

Source: Vanegas Cantarero and Movsessian [2018]

Table 6.2
Toda-Yamamoto Granger non-causality test results

T-Y Granger Causality test, 3 lags (SC and HQ), 1 additional lag as exogenous variable								
Dependent variable: ln(EF)			**Dependent variable: ln(GDPpc)**			**Dependent variable: ln(RE)**		
	Chi-square	p-value		Chi-square	p-value		Chi-square	p-value
ln(GDPpc)	5.872	0.118	**ln(EF)**	16.117	0.001	**ln(EF)**	6.145	0.105
ln(RE)	5.815	0.121	**ln(RE)**	16.736	0.001	**ln(GDPpc)**	4.815	0.186
ln(AGRO)	6.570	0.087	**ln(AGRO)**	15.155	0.002	**ln(AGRO)**	1.884	0.597
ln(URB)	12.281	0.007	**ln(URB)**	1.645	0.649	**ln(URB)**	1.518	0.678
All	30.576	0.002	**All**	44.40598	0	**All**	26.131	0.010
Dependent variable: ln(AGRO)			**Dependent variable: ln(URB)**					
	Chi-square	p-value		Chi-square	p-value			
ln(EF)	6.508	0.089	**ln(EF)**	57.904	0.000			
ln(GDPpc)	3.207	0.361	**ln(GDPpc)**	23.060	0.000			
ln(RE)	3.377	0.337	**ln(RE)**	0.313	0.958			
ln(URB)	1.958	0.581	**ln(AGRO)**	24.330	0.000			
All	31.683	0.002	**All**	84.667	0.000			

Source: Vanegas Cantarero and Movsessian [2018]

The results from the causality tests performed by Vanegas Cantarero and Movsessian [2018] and presented in Table 6.2 indicate that the use of renewable energy does not only affect the ecological footprint of the country but also income per capita, thereby confirming the growth hypothesis described in Chapter 3 and suggesting that these energy sources can be a motor powering sustainable development in the long-run. In the period 1971 - 2013, renewable energy has been an important source of input for the country's development processes. Overall, the results indicate that Nicaragua is tackling development and environmental challenges with clean energy as part of its portfolio of strategies. Nonetheless, a broader portfolio of mitigation options must be agreed on and implemented for the country to direct its development processes towards sustainability. The alternative pathway presented in Vanegas Cantarero [2019] could contribute to tackling some development challenges such as poverty, social exclusion, access to health and education, among others, while accelerating the transition to renewable energy systems. Further opportunities for synergies across the energy and economic sectors as well as for innovation and sustainability should be researched and encouraged.

6.3 Society and Politics in the energy transition

The energy transition is a socio-technical process. The transformation of the energy systems cannot be achieved without the participation of society and, simultaneously, society will be undoubtedly affected by the changes taking place in the energy systems. Similarly, the energy transition involves political changes. Since the industrial revolution, we have witnessed that energy transitions are accompanied by a reshaping of the institutions and policies involved in the management or establishment of energy systems, among other changes. These two dimensions of the energy transition are as important as the technological dimension for a progression towards sustainability. However, addressing these two dimensions and including them in energy decision-making is not straightforward, especially at the stage in which Nicaragua is in terms of its transition. In that sense, detailed descriptive research such as the one outlined in Chapter 4 and performed in Journal Paper 3 [Vanegas Cantarero, 2020] may shed light onto the integration of society and politics into the energy transition in Nicaragua through the identification of potential inter-linkages between the three dimensions (i.e., technology, society and politics) and across different energy sectors.

Journal Paper 3 [Vanegas Cantarero, 2020] highlights the co-produced nature of the energy transition where changes in technologies, society and policies and institutions occur in parallel and reshape energy systems. The findings suggest that the notion of a *just energy transition* is a relevant alternative to deal with the multi-dimensionality of this transformative process. Justice in the energy transition - particularly in developing countries, where this process encompasses expectations of energy affordability, efficiency, security and sustainability - can be achieved by a combination of the technological, societal and political alternatives suggested in Figure 6.6.

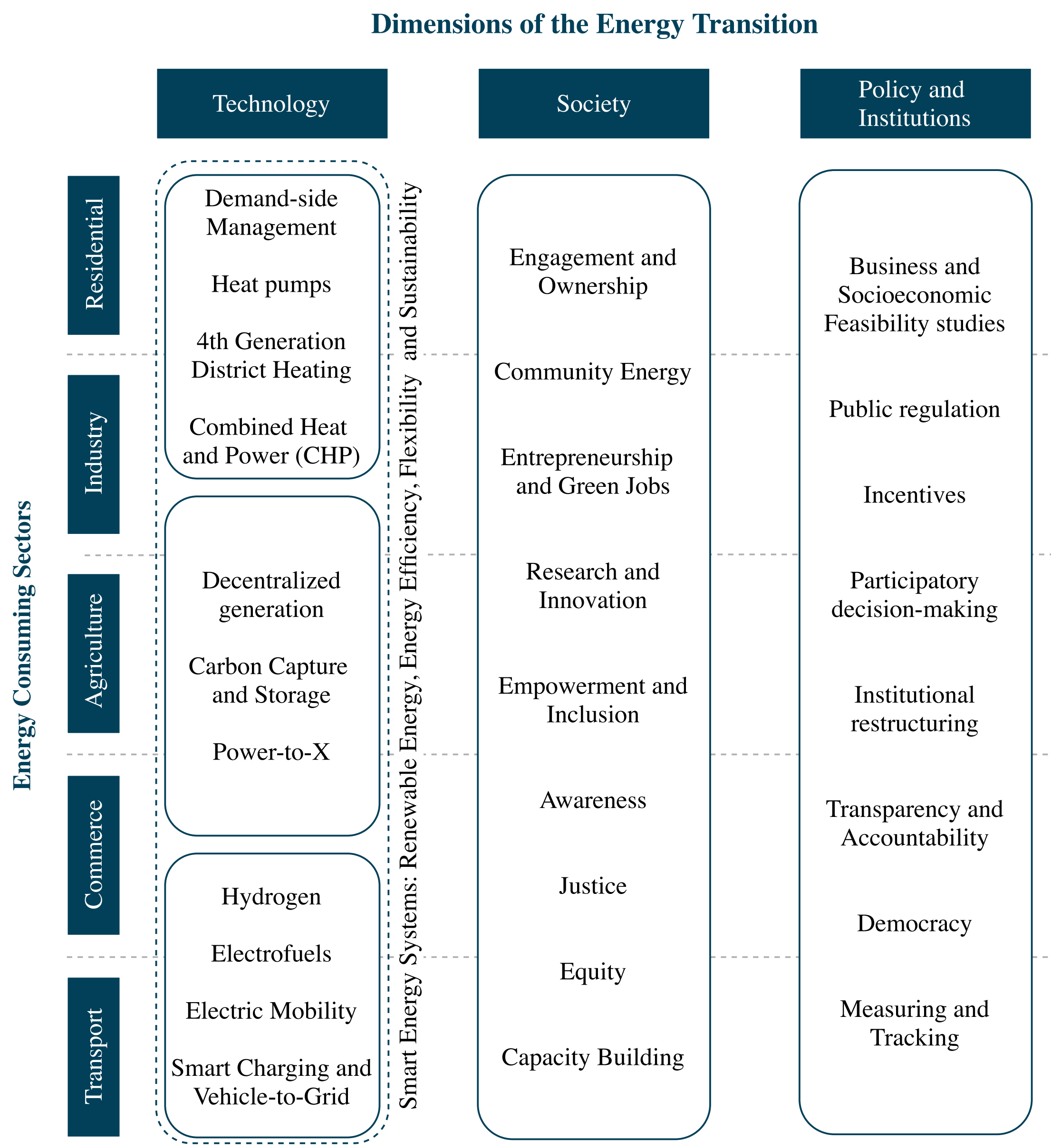


Figure 6.6: Roadmap of technological, societal and political alternatives to accelerate the energy transition

Source: Vanegas Cantarero [2020]

Nicaragua has made progress in the integration of renewable energy into the country's power system with plans for the expansion of the renewable installed capacity in the coming years and a decrease of the sector's carbon footprint. Nonetheless, the uptake of renewable energy in the remaining energy sectors could be increased by using technologies such as power-to-X, hydrogen, electric mobility, demand-side management, decentralized generation, among others also mentioned in the "Technology" dimension in Figure 6.6. These technologies would not only reduce the carbon footprint of the energy sector overall but improve the efficiency and affordability of the energy services. Vanegas Cantarero [2019] described technological alternatives to decarbonise the Nicaraguan transport sector. The result was a significant reduction in CO_2 emissions that require lower costs relative to 2015. However, it must be considered that such radical changes will affect the Nicaraguan society and that appropriate regulations and support schemes are necessary for their implementation. It is important, thus, to further examine these other dimensions of the Nicaraguan energy transition.

To date, decentralized generation has been the most widely adopted technological alternative in Nicaragua for the energy transition and it has been an effective solution to provide access to clean and modern energy services in remote and rural areas [Madriz-Vargas et al., 2018]. The National Programme for Sustainable Electrification and Renewable Energy (PNESER) and the Off-grid Rural Electrification Project (PERZA) have contributed to increasing the share of the population with access to electricity from 54% in 2006 to 97.6% in Q12020 [MEM, 2020b]. Nonetheless, despite this success, the programmes struggled with loan repayment at the local level and skills training [Colbert, 2017]. These circumstances weakened the sense of ownership among the community members and limited their level of engagement. Moreover, many systems experienced failures and were not promptly repaired due to a lack of local skilled labour. This situation highlights the strong interlinkages between technology, society and policy-making for the energy transition.

The current single-sector approach envisioned by the Nicaraguan central government does not enable the integration of society and politics into the energy transition. Furthermore, this approach does not facilitate a swift transformation or ease the adoption of the Sustainable Development Goals (SDGs). As thoroughly described in Chapter 5, the Nicaraguan energy system and its transition are managed under a top-bottom approach to energy planning and society has very limited participation.

Additionally, the legal framework has been largely shaped to accommodate the interests of oil incumbents in the country. Small and rural communities in Nicaragua have taken a different approach to the energy transition: *energy democracy*. Due to their scale, these communities and their energy strategies are not prominent players in the Nicaraguan energy system at the moment. However, they have shown significant progress and, thus, are worth reviewing in detail to identify key lessons learned that could be extrapolated to the national transformation of the energy system.

The PNESER and PERZA programmes contributed to increasing the level of awareness and social acceptance of renewable energy technologies in the country [Multiconsult y CIA. LTDA., 2015]. In 2010, various civil society actors such as technology developers, business owners, communities, volunteers, donors and not-for-profit organisations came together and formed the Nicaraguan Association for Renewable Energy (RENOVABLES), the first national non-governmental institution devoted to the promotion of renewable energy. Some well-established associations within RENOVABLES include Fénix Association (AsoFenix) [2020], the Association of Rural Development Workers – Benjamin Linder (ATDER-BL) [2008] and blueEnergy [2019]. These associations promote the use of decentralized renewable energy systems for electrification with support from international organisations such as the United Nations Development Program (UNDP), the Dutch non-governmental organisation (NGO) Hivos and other Nicaraguan stakeholders. Furthermore, these associations have a gender-equity and communal focus and attend to the local needs of the members of a community. The not-for-profits and communities in Nicaragua are using the energy transition as a platform to actively participate in local decision-making and change the social structure.

The energy projects carried out by some of the aforementioned associations in Nicaragua have been identified as drivers for energy autonomy and security, the development of social capital, environmental awareness and sustainable development. Their work could be a benchmark for other regions. Vanegas Cantarero [2020] highlights the case of the municipality of El Cuá in the highlands of Jinotega, Nicaragua. ATDER-BL contributed to the construction of a 235 kW micro-hydro power plant in 1994 for the community of San José de Bocay (see Figure 6.7(a)), approx. 33 km northeast of El Cuá [ATDER-BL, 2008]. The Pelton turbine was locally built by machinists trained by ATDER-BL while villagers and contract workers built the concrete dam and pipeline shown in Figure 6.7(b). ATDER-BL coordinated the design

(a) Entrance to hydroelectric power plant

(b) Hydroelectric dam

(c) Small business in El Cuá

(d) Typical households in the city of El Cuá

Figure 6.7: Views of the hydroelectric power plant "El Bote" and the municipality of El Cuá, Jinotega, Nicaragua in 2020

and construction of the electrical lines and the training of linesmen and plant operators. Furthermore, ATDER-BL aided the local Bocay Electrical Service Development Association (APRODELBO) to assume the operation and ownership of the Bocay micro-hydro power plant [ATDER-BL, 2008].

In the early 2000s, ATDER-BL constructed and commissioned a 930 kW hydropower plant in the basin of the El Bote river in El Cuá, Jinotega. This ambitious project included the construction of 65 km of transmission power lines and is now connected to the national grid. ATDER-BL and the El Bote power plant have enabled APRODELBO to become a distributor for the national grid as well. Both organisations have been selling electricity to the national grid for virtually a decade now at competitive prices, as can be seen in Table 6.3.

Table 6.3
Annual average electricity prices in Nicaragua in selected years (C$/kWh)

Distribution System	2010	2015	2018
APRODELBO	3.9985	6.0988	6.9373
ATDER-BL	4.2279	4.0922	5.5134
DISNORTE	4.2448	5.6042	6.5664
DISSUR	4.1771	5.5853	6.5013
National Average	4.2014	5.5793	6.5237

Source: Author based on official statistics from INE [2019c]

With the revenues from the sale of electricity to the national grid and with a donation of US$ 25,000 from the UNDP Small Donations Program, since 2010 ATDER-BL has installed solar PV panels for the families in the community as well [SE4All, 2013].

The electrification of San José de Bocay and El Cuá in Jinotega, Nicaragua has facilitated progress in these once small towns. As of December 2018, both associations were supplying electricity to nearly 10,000 customers [INE, 2019b]. The grinding of corn and the hulling of rice are among the main uses of electricity in these towns. These activities used to be performed manually by local women. Therefore, electricity has enabled female empowerment and strengthen economic activity in San José de Bocay and El Cuá. Micro and small businesses such as barbers and internet cafes as well as carpentry, welding and car repair shops are now available (see Figure 6.7(c) and 6.7(d)). Furthermore, access to electricity has enabled an increase in the years of schooling, which have gone from four to seven [World Bank, 2018]. Additional benefits include access to drinking water in the communities, improved health facilities and services and capacity building and employment [Colbert, 2017].

These energy community projects differ from the top-down model of development envisioned by the Nicaraguan central government. Organizations such as ATDER-BL and APRODELBO can play a key role in shaping the energy future. Their *modus operandi* suggests that democratic principles such as citizen engagement, justice, accountability and transparency are drivers of positive change. These projects are run by a committee generally comprised by six members: president, operator, fund manager or treasurer, record keeper or secretary, a person responsible for assembly organisation and a person in charge of communication [ATDER-BL, 2008]. The members of the committee are selected by consensus and voting and participation is open to all the members of the community. This small gesture reinforces the trust and the relationships between the community and the project developers. Furthermore, citizen participation is encouraged from an early stage with the community being in charge of building the turbine, dam and transmission lines. At the end of the project, the community owns the power plant. For operation and maintenance, the members of the community contribute to a common fund that is managed by the committee. The same fund can be used for general re-investment and upgrades. The payment frequency and methods are agreed in advance between a community member and the committee: either annually or in monthly instalments [Colbert, 2017]. This type of arrangements has avoided issues of electricity theft and losses. The community feels responsible for the supply of electricity and, therefore, takes part actively in the overall management of the system.

By coupling the technological and social dimensions of the energy transitions, community energy projects such as those in San José de Bocay and El Cuá are simultaneously shaping the political dimension. The success of associations like ATDER-BL and APRODELBO are inspiring even for the central government. The Nicaraguan government has employed ATDER-BL for several pre-feasibility and feasibility studies in the northern highlands of Nicaragua. In the last decades, ATDER-BL has organised the construction and commissioning of over 30 projects in the region. Remarkably, most of these projects have responded to the interest of the communities that identify a resource potential and seek to exploit it with the aid from ATDER-BL [Laursen, 2015].

The increasing popularity of community energy projects in Nicaragua and the active role of civil society organisations can open an alternative energy pathway to shape the country's energy future. However, recent policy changes have diminished the impact of such projects at the national level and associations such as ATDER-BL and APRODELBO have perceived some pressure to pass their community energy projects to private distribution companies [Madriz-Vargas et al., 2018].

Community energy projects have had little legislative support. RENOVABLES has drafted a bill to enable the development of off-grid small and micro-hydroelectric projects that has been under review and consideration since 2015 [Zúñiga, 2015]. The topic has been discussed extensively yet no decision has been reached. The influence of incumbent energy actors, particularly oil corporations, has hampered the expansion of initiatives such as community energy projects that could rapidly increase the uptake of renewable energy in Nicaragua [Vanegas Cantarero, 2020].

The country has certainly made significant progress in both the technological and societal dimensions of the energy transition (refer to Fig. 6.6); however, the dimension that refers to policy and institutions requires further work. In a country with a deteriorating democracy, there has not been much room for participatory decision-making, transparency and accountability, or institutional restructuring. These principles of democracy are fundamental for a just energy transition.

Modern energy, society and political power are expected to co-evolve during this transformative process. Nicaragua's future should embody a new, equitable, social and economic order based on democratic principles and an energy system that seeks to replace the incumbent oil corporations with alternative institutions. The voices of those communities that have been marginalized until now and those providing sustainable development solutions for those communities must be represented in the new institutions to guarantee the preservation of the multi-dimensional and cross-sectoral nature of a just energy transition.

6.4 Tracking the Nicaraguan energy transition

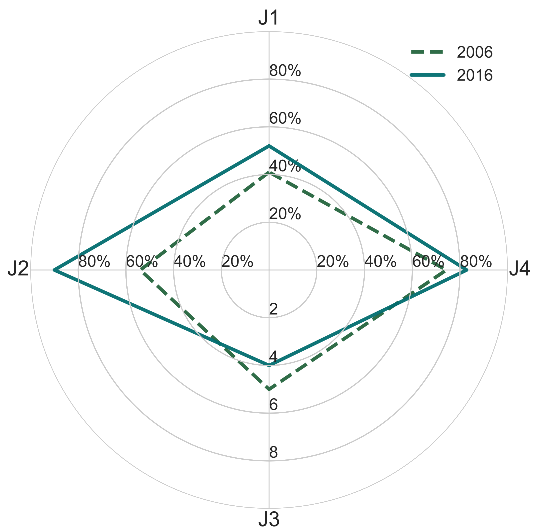
It is this multi-dimensional and cross-sectoral nature that makes keeping track and measuring progress in the energy transition such a challenging endeavour. Journal Paper 3 [Vanegas Cantarero, 2020] proposed a framework to track the advance of the energy transition, facilitate the decision-making processes, aid policy formulation and evaluation and bring attention to the areas that require more effort. The framework seeks to monitor the progress in four key areas, namely justice (J), democracy and citizenship (D), energy security (ES) and environmental sustainability (ENV). These four areas are considered crucial for a just energy transition and address the three dimensions reviewed previously, namely technology, society and policy and institutions. Based on this framework, 14 indicators have been selected to note the progress (or lack thereof) in the aforementioned key areas related to the energy transition. The framework has been implemented for the case of Nicaragua. The indicators are described in Table 6.4 and the corresponding scores for two selected years are compared and depicted in Figure 6.8. It is worth noting that additional or proxy indicators can be selected to measure each area. The decision depends on data availability, as this remains a challenge in developing countries.

On one hand, most of the progress made in recent years corresponds to access to modern fuels for cooking (indicator J1) and electricity (indicator J2), the number of green jobs in the country (indicator D2) and the number of support schemes for renewable energy (indicator D3). On the other hand, indicators such as the average price of electricity (indicator ES3), net imports of energy (indicator ES4) and the carbon intensity of the Nicaraguan economy (indicator ENV2) have worsened. Meanwhile, the ecological footprint per capita (indicator ENV3), the energy intensity of the Nicaraguan economy (indicator ES1) and the carbon emissions per capita (indicator ENV1) have remained virtually stationary between 2006 and 2016. Relative to the growth of the renewable installed capacity in the last decade in Nicaragua (refer to Figure 5.3), the indicators shown in Figure 6.8 depict more moderate progress. The framework provides a more holistic overview of the current transition and, despite a lack of easily available data for many indicators, it brings attention to areas other than technology that are equally important for an equitable energy future in Nicaragua.

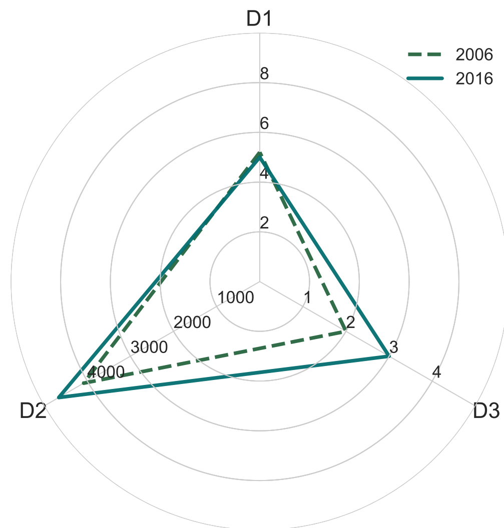
Integrating the analyses and results from the research, important findings can be highlighted including:

- There is significant merit in decarbonising the power system. However, creating inter-linkages between this sector and other energy sectors expands the range of benefits and provides opportunities to reach marginalized sectors while increasing the efficiency of the overall energy system and tackling issues such as affordability and reliability.

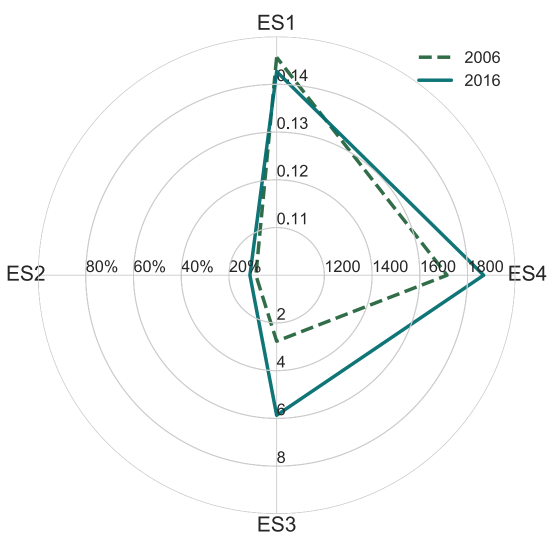
- Coupling the energy transition with other sustainable development challenges such as green mobility, urban planning, gender equality, clean water and sanitation, quality education, justice and economic development increases the chances of success and has a larger positive impact on society, the environment and the economy. Such a strategy could accelerate the acceptance of technological changes and increase the attractiveness of renewable energy in the eyes of society and governments.



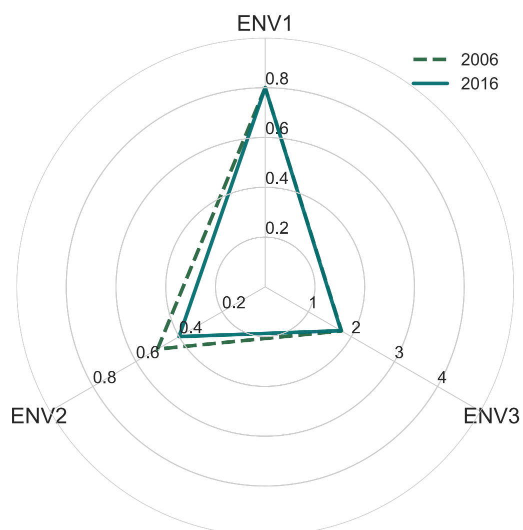
(a) Justice



(b) Democracy and citizenship



(c) Energy security



(d) Environmental sustainability

Figure 6.8: Monitoring the progress in different dimensions of the Nicaraguan energy transition

See Table 6.4 for a detailed description of the indicators.

Table 6.4
Indicators and sources referenced in Figure 6.8

	Indicators	Unit of measure	Source
1	**J1**: Share of population with access to modern fuels for cooking	Percentage (%)	IEA [2019]
2	**J2**: Share of population with access to electricity	Percentage (%)	IEA [2019]
3	**J3**: Rule of Law measured on a 1 - 10 scale as per the Bertelsmann Transformation Index - Democracy Status	Dimensionless	Stiftung Bertelsmann [2019]
4	**J4**: Share of female enrolment in secondary school	Percentage (%)	World Bank Group [2020]
5	**D1**: Consensus Building measured on a 1 - 10 scale as per the Bertelsmann Transformation Index - Governance Index	Dimensionless	Stiftung Bertelsmann [2019]
6	**D2**: Number of green jobs	Dimensionless	IRENA [2017, 2013]
7	**D3**: Number of active support schemes for renewable energy	Dimensionless	Bloomberg New Energy Finance and UKAid [2014; 2019]
8	**ES1**: Energy intensity	toe per 1000 USD (2010 PPP) of GDP	IEA [2019]
9	**ES2**: Share of modern renewable energy in final energy consumption	Percentage (%)	IEA [2019]
10	**ES3**: Average price of electricity	C$/kWh	BCN [2018]
11	**ES4**: Net energy imports	ktoe	IEA [2020b]
12	**ENV1**: CO_2 emissions from combustion per capita	tCO_2/capita	IEA [2020a]
13	**ENV2**: Carbon intensity	kg CO_2 per unit of GDP (2010 USD)	IEA [2020a]
14	**ENV3**: Ecological footprint per capita	gha per person	Global Footprint Network [2019]

- The energy transition does not imply solely a technological transformation. Instead, the energy transition is a co-produced transformation in the technological, societal and political dimensions. The new technologies adopted to increase the uptake of renewable energy and replace conventional energy sources tend to redefine the role of citizens, turning them into prosumers and active agents of the energy systems. Furthermore, these changes increase societal awareness of environmental and energy issues and lead to higher levels of engagement in both decision and policy-making. In this sense, the energy transition becomes a driver for democratic institutions and political systems founded in the values of justice, transparency and participation.

- The technological changes required for such a transformation are commercially available. The sizes of the energy systems in the Global South are a valuable opportunity to make swift changes. In the case of developing countries such as Nicaragua, progressing in the energy transition is a matter of political will and societal engagement as well as technical know-how or technological alternatives. The energy transition requires parallel actions in these three dimensions.

- Community energy projects such as those being carried out by civil society organizations in Nicaragua have been successfully coupling the technological and social dimension of the energy transition. Nonetheless, policies and institutions require adaptation and re-structuring to enable and incorporate the new technologies and provide room for the new stakeholders. Such changes will enable democracy and equity in the energy transition.

Chapter 7

Conclusions and Recommendations

Nicaragua is a developing country in the heart of Central America. It is one of the smallest economies in the western hemisphere and, historically, it has relied on imported fossil fuels to meet its energy needs. Despite efforts to drive an energy transition in the country, progress has stalled. The main aim of this dissertation was to identify energy pathways and strategies to accelerate the transition to a sustainable and renewable energy system in this country while tackling sustainable development challenges such as poverty and environmental degradation. The case of Nicaragua resembles the situation of many small economies that are oil-dependent despite having varied and abundant domestic renewable energy resources to meet their energy needs. In this sense, the findings derived from this research can be valuable not only for Nicaragua but for other developing countries with similar conditions. This chapter compiles the conclusions drawn from this research project and outlines recommendations to strive for a just and sustainable energy transition in Nicaragua as well as the contributions of this dissertation to the field of energy planning and policy.

7.1 Concluding Remarks

In recent decades, economic growth in Nicaragua has coincided with high levels of fossil fuel consumption, overuse of natural resources and environmental degradation.

The Nicaraguan energy system and its regulatory framework had favoured the consumption of oil derivatives such as diesel, gasoline and fuel oil. These fuels have been mainly used for electricity generation and transportation. Given that Nicaragua does not have oil reserves, this fossil fuel and its derivatives are imported and, therefore, the country has been exposed to the volatility of the international oil price. Furthermore, traditional biomass such as firewood and charcoal has played a predominant role in Nicaragua's primary energy mix. Firewood has been mainly used for cooking in the Nicaraguan residential sector; however, in rural areas, this fuel meets all energy needs. These energy consumption trends have resulted in high carbon intensity, environmental issues such as deforestation and high levels of indoor pollution. In that sense, and answering the first research question presented in Chapter 1, the transformation of the Nicaraguan energy system is being driven by the need to address issues that include energy security, affordability, sustainability and equity.

Regarding research question 2, the Nicaraguan central government has approved an ambitious plan to generate 90% of Nicaragua's electricity from renewable energy by 2027. This plan seeks to seize the country's renewable energy potential, mainly through hydro, wind and geothermal resources. Solar energy and biomass (i.e., vegetable waste) are also part of the envisioned Nicaraguan energy system. It is important to highlight that the current policies and strategies shaping the Nicaraguan energy system aim to increase the uptake of renewable energy in the power sector solely. The results of the research show that, with this single-sector approach, renewable energy is not expected to account for a significant share of the country's final energy unless radical changes are implemented. This is because electricity accounted for approximately one-sixth of the energy consumed in Nicaragua in 2015 and this is likely to remain the case in 2030. The decarbonisation of the power system must be accompanied by electrification of the energy system, i.e., electricity should replace conventional fuels in the energy system for this strategy to have a more significant impact.

In terms of the contribution of the envisioned energy transition to sustainable development in Nicaragua (i.e., research questions 3), the research performed shows that the single-sector approach adopted currently has moderately contributed to curbing the levels of environmental degradation in the country. Although this contribution is unable at the moment to counteract the environmental impact of, e.g., economic growth or rapid urbanisation, this research found that the potential to curb environmental degradation via renewable energy increases in the long-run. Moreover, the results show that the promotion of renewable energy in Nicaragua has contributed to boost economic growth and, therefore, may potentially become a motor to power sustainable development in the long-run.

Nonetheless, this centralised strategy to the energy transition has had only a small impact on the carbon footprint of the Nicaraguan energy system and is not expected to enable the country to actively tackle climate change and meet the Sustainable Development Goals. The current top-bottom strategy seems somewhat inconsistent with the decentralized nature of renewable energy systems. Marginalized, rural communities are scarcely favoured by such an approach and, ultimately, the rural-urban divide is stretched. Moreover, the current single-sector approach neglects the two most energy-consuming sectors, namely residential and transport. These two energy sectors have a notable impact on social and environmental well-being and, thus, should be included in strategies for both the energy transition and sustainable development. At the moment, Nicaragua lacks decarbonisation strategies for these and other remaining energy sectors.

Answering research question 4, Nicaragua faces the challenges of enabling the participation of society and new stakeholders (e.g., new energy generators, development agencies, academia) in the decision-making of the energy transition, extending the benefits of the transition to marginalized sectors and communities and making radical changes in a short time frame given the current climate and financial crisis. It can be said that the main challenge is guaranteeing a democratic and sustainable transformation of the Nicaraguan energy system.

To address research question 5, the thorough literature review performed sheds light on the most promising approaches to deal with those challenges, namely smart energy systems and energy democracy. These two approaches have been previously explored in the context of developed nations leading the global energy transition such as Denmark, Germany and the United Kingdom. They remain strikingly understudied in the Global South. Nonetheless, they provide a holistic framework to address the transformation of the energy systems by merging the technological energy transition with a strengthening of the values of societal participation, justice, democracy, efficiency and adaptability.

Furthermore, Nicaragua has had experience using the decentralised nature of renewable energy technologies to tackle the issues of energy access and poverty. Two rural electrification programs funded by multi-lateral organisations and the Nicaraguan government have significantly increased the share of Nicaraguans with access to electricity. However, community energy projects using local renewable energy resources have successfully contributed to raising social awareness on environmental issues and climate change, aided economic development and improved access to health services and education.

Bearing in mind the aforementioned challenges but also lessons learned from previous experiences and seeking to design alternative energy pathways for Nicaragua (thereby answering research question 6), this dissertation examined the decarbonisation of the Nicaraguan power system, synergies between energy sectors such as electricity and transport, community energy projects and the concept of energy democracy. These alternatives have important impacts on both the level of social awareness and engagement and the speed of decarbonisation as illustrated in Figure 7.1.

Finally, regarding research question 7, this research shows that the smart energy systems approach can be a techno-economically feasible alternative for the country's energy transition. The results from this research show that combining the decentralised nature of renewable energy with a smart energy systems approach and the principles of energy justice and democracy can have positive effects, e.g., enabling economic growth, modernisation of energy services, local job creation, social inclusion, poverty reduction and a significant reduction in the levels of greenhouse gas emissions.

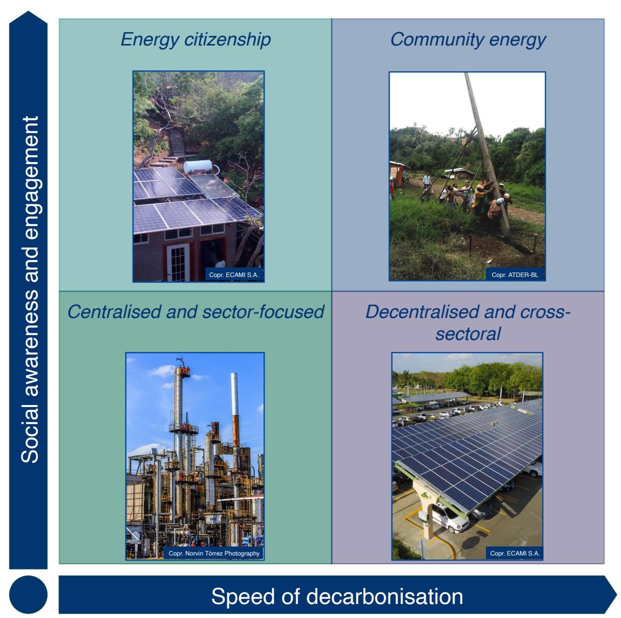


Figure 7.1: Pathways to accelerate the energy transition in Nicaragua

Furthermore, this research found evidence that such strategy tackles the reliance on imported oil, increases energy security and represents a techno-economically feasible alternative for the

Nicaraguan energy system. The promotion of renewable energy tends to decrease the unit-cost of electricity, eventually leading to lower electricity prices. This situation could incentivise utilities to increase their cost-competitiveness relative to variable renewable generation while creating potential business opportunities for companies providing services or products that could provide flexibility to the power system against the fluctuations of variable renewable energy. Additionally, lower electricity prices could lead to lower production and operation costs for Nicaraguan industries and services, making the Nicaraguan economy more competitive. Moreover, synergies between energy sectors such as the one studied in this dissertation between the power and transport sectors improve the efficiency of the overall energy system, reduce CO_2 emission levels and provide social and economic benefits, thereby improving the living conditions of the Nicaraguan society.

Furthermore, the high levels of societal engagement witnessed in community energy projects in Nicaragua can be exploited in combination with the smart energy systems approach to rapidly increase the uptake of modern and renewable energy, foster institutional and political restructuring, improve transparency and accountability, create opportunities for economic development and entrepreneurship and tackle the issues of energy poverty and injustice.

7.2 Recommendations

Based on the findings of this research, to accelerate the transition to a sustainable and renewable energy system in Nicaragua it is advisable to:

- Establish energy plans and policies as part of a politically agnostic development agenda for the country;
- Allow citizen participation in the formulation and evaluation of energy and development strategies and foster participatory decision-making;
- Provide reliable and accurate data and information to the general public as a means to increase social awareness and enable citizens' engagement as well as to enhance transparency and accountability in the energy system;

- Secure objective and apolitical techno-economic and environmental assessments of the alternative energy pathways being considered;
- Establish a regulatory and legal framework that incentivises communal and citizen engagement and ownership;
- Include considerations of energy efficiency as first-stage in the energy plans and policies to achieve demand stabilisation before the implementation of radical technological changes;
- Adopt and adapt modern technologies to increase the uptake of renewable energy in the energy system such as power-to-X, electric mobility, electrolysers for hydrogen production and demand-side management;
- Prompt follow-up strategies to decarbonise the Nicaraguan power sector through the sustainable exploitation of domestic renewable energy resources;
- Couple this decarbonisation with a smart energy systems approach for the energy transition, i.e., enable synergies between energy sectors to add flexibility in the energy system when integrating higher shares of variable renewable energy and extend the benefits of the transition to all socio-economic sectors of the Nicaraguan economy;
- Measure and track the implementation of these recommendations in a multi-dimensional framework to secure progress and development not only in the technological facet of the energy transition but also in the social, political, economic and environmental sides. This can be done, e.g., in liaison with the tracking and monitoring intended for the implementation of the Sustainable Development Goals framework.

7.3 Contribution of the Research

This research shows that the energy transition is a multi-dimensional process. Future energy plans and strategies must take into account the technological, economic, social and political implications of the changes in the energy system. This dissertation provides an overview of state-of-the-art technical and planning solutions to transform current energy systems into sustainable and renewable energy systems based primarily on the smart energy systems approach and the principles of justice and democracy. The case of Nicaragua exemplifies how renewable energy can play a key role in sustainable development strategies providing opportunities for economic growth, social inclusion and development and environmental management.

Furthermore, clean and renewable energy is crucial for developing economies to leapfrog the energy-intensive development paths that their developed counterparts have followed. Renewable energy and smart energy systems can increase the security of supply, tackle the reliance on imported fossil fuels and enable sustainable development opportunities. Nonetheless, the case of Nicaragua shows that energy citizens, i.e., an engaged and aware society, are fundamental to reshape current energy systems and the political and institutional frameworks required for sustainable and renewable energy systems.

Finally, this research integrates the fields of economic development, energy planning and policy and, to some extent, the social sciences to understand the co-produce nature of the energy transition with an emphasis on developing countries. As such, the analyses included in this dissertation sought to expand the energy alternatives explored until now in the Global South and couple the potential energy pathways with development strategies and social practices to achieve a just and democratic energy system. The recommendations derived from the results of this research extend over the dimensions of technology, society and policy. Commonly, developing countries battle between tackling sustainable development challenges or climate change through the implementation of adaptation and mitigation strategies. However, these two agendas are interlinked and require multi-disciplinary, mixed-method and holistic but locally adapted research. The relevance of this dissertation becomes apparent in the need for this type of research.

This dissertation contributed to the aforementioned fields of study and the multi-disciplinary and mixed-method research with the publications listed below and attached in the Appendices:

1. "Reviewing the Nicaraguan transition to a renewable energy system: Why is 'business-as-usual' no longer an option?" published in volume 120 of the journal *Energy Policy* in 2018.

2. "Decarbonizing the transport sector: The Promethean responsibility of Nicaragua" published in volume 245 of the *Journal of Environmental Management* in 2019.
3. "Of Renewable Energy, Energy Democracy and Sustainable Development: A Roadmap to Accelerate the Energy Transition in Developing Countries" published in volume 70 of the *Energy Research & Social Sciences* journal in 2020.

7.4 Limitations and Further Work

The ambitious endeavour of carrying out multi-disciplinary research is a time- and data-intensive process. Unfortunately, data availability is limited in the Global South and represented an important limitation to this dissertation. This research could have explored synergies between the power and industry sectors or, more relevant to the Nicaraguan context, decarbonisation strategies in the residential sector. However, data describing these sectors is rather scarce and outdated. Moreover, the need for system boundaries in the energy models to represent pragmatically the scenarios considered in this dissertation disregards other parts of society and limits the comprehensiveness of the analyses. Further work should focus on exploring these issues to enhance the holistic approach here implemented to explore pathways to accelerate the Nicaraguan energy transition.

Furthermore, some issues need further consideration in this type of research including competition for land resources, the need for effective institutions, regulations and market mechanisms capable of dealing with the new inter-dependencies that will arise from a higher integration of variable renewable energy in the Nicaraguan energy system, among others. These issues were not thoroughly addressed in this dissertation due to a lack of time and resources. Nonetheless, they are integral elements of a transition to a sustainable and renewable energy system.

Finally, the type of research performed, which is predominantly desk-oriented, lacks the feedback or responses that can be obtained when performing, e.g., field research. This dissertation is a critical first step to understand the Nicaraguan energy transition. The knowledge gained through this research could serve as a foundation for further, more in-depth and applied research.

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Appendices

Appendix A: Interview Questions and Interviewees

Preguntas de Entrevistas

"Seeking a more environmentally sound Nicaragua by 2035: promoting the use of Renewable Energies and assessing their contribution towards Sustainable Development in the country"

Maria Mercedes Vanegas

Preguntas Generales

- ¿El Sistema de energía de Nicaragua (no sólo el sistema eléctrico) es sostenible para usted?
- ¿Qué necesita este sistema para ser sostenible?
- ¿Cuáles son los mayores desafíos para que Nicaragua tenga un sistema energético sostenible?
- ¿Cuáles son las ventajas que posee Nicaragua para llegar a tener un sistema energético sostenible?
- ¿Considera usted que la sociedad nicaragüense entiende y acoge el cambio tecnológico que implica hacer una transición hacia las energías limpias?
- ¿Cree usted que los nicaragüenses cuentan con información suficiente respecto a energías renovables?
- Desde su punto de vista, ¿quiénes deberían proveer esta información a los nicaragüenses?
- ¿Cuál considera usted es el papel de las energías renovables en Nicaragua?
- ¿Cómo puede beneficiarse la economía nicaragüense de este tipo de tecnologías?
- ¿Cuál es su posición ante los subsidios existentes a los combustibles fósiles?
- ¿Considera usted que el marco regulatorio legal existente es efectivo para la promoción de las energías renovables en el país?
- El rol protagónico en nuestra matriz primaria de energía lo tiene la biomasa, en específico la leña cuya producción ha demostrado no ser sostenible (debido a la deforestación) y su uso, dañino para la salud. ¿Qué alternativas se pueden presentar o implementar?

Preguntas específicas a la Institución

- ¿Tiene GIZ/ SNV/ Blue Energy un programa o proyecto en este sentido? (Continuación a la pregunta anterior)
- ¿Cuál es la función y los objetivos de su institución?
- ¿Cómo se financian los proyectos?
- ¿Qué deben hacer las comunidades para participar de los proyectos?
- ¿Ha realizado GIZ/ SNV/ MEM una evaluación del potencial existente en Nicaragua para la generación de electricidad a partir de fuentes renovables (especialmente solar)?
- Desde su experiencia, ¿cuál es el impacto que tiene los proyectos de energía renovable desarrollador por su institución en la calidad de vida de las personas?
- ¿Se realizan monitoreo o evaluaciones de impacto posterior a la implementación de los proyectos?
  - ¿De qué manera se realizan estas evaluaciones?
  - ¿Qué se evalúa?
- ¿Se aborda el tema de eficiencia energética en los proyectos?

Preguntas de Entrevistas

"Seeking a more environmentally sound Nicaragua by 2035: promoting the use of Renewable Energies and assessing their contribution towards Sustainable Development in the country"

Maria Mercedes Vanegas

General Questions

- Is the Nicaraguan energy system (not just the power system) sustainable for you?
- What does this system need to be sustainable?
- What are the biggest challenges for Nicaragua to have a sustainable energy system?
- What are the advantages that Nicaragua has in order to have a sustainable energy system?
- Do you think that the Nicaraguan society understands and welcomes the technological change involved in making a transition to clean energy?
- Do you think Nicaraguans have enough information about renewable energy?
- In your opinion, who should provide this information to Nicaraguans?
- What do you consider to be the role of renewable energy in Nicaragua?
- How can the Nicaraguan economy benefit from this type of technologies?
- What is your position regarding existing fossil fuel subsidies?
- Do you consider that the existing legal regulatory framework is effective for the promotion of renewable energy in the country?
- The main source of primary energy is biomass, specifically firewood whose production has proven to be unsustainable (due to deforestation) and its use harmful to health. What alternatives can be presented or implemented?

Specific Questions to the Institution

- Does GIZ/ SNV/ BlueEnergy have a program or project in this regard? (Continued from previous question)
- What is the role and objectives of your institution?
- How are projects financed?
- What must communities do to participate in the projects?
- Has GIZ/ SNV/ MEM carried out an evaluation of the existing potential in Nicaragua for the generation of electricity from renewable sources (especially solar)?
- Based on your experience, what is the impact that renewable energy projects developed by your institution have on the quality of life of the people?
- Are monitoring or impact evaluations carried out after the implementation of the projects?
    - How are these evaluations conducted?
    - What is evaluated?
- Do projects address the issue of energy efficiency?

Evidence of Interview

"Seeking a more environmentally sound Nicaragua by 2035: promoting Renewable Energies and assessing their contribution towards Sustainable Development"

Doctoral Thesis by Maria Mercedes Vanegas

Date:	06 July, 2015
Place:	Managua, Nic
Interviewee:	Lizeth Zúniga
Company/ Institution:	Asociación Renovables
Job Position:	Directora Ejecutiva.

Hereby I certify that I participated in an interview held at the time and place detailed above and conducted by Maria Mercedes Vanegas. I also acknowledge that the information provided during this interview will be used by Ms. Vanegas during her Doctoral Thesis regarding Renewable Energies and Sustainable Development in Nicaragua. Thus this information is accurate and reliable.

Signatures

MVanegas

Interviewer

Lizeth Zúniga.

Interviewee

Europa-Universität Flensburg
Internationales Institut für Management und ökonomische Bildung

Evidence of Interview

"Seeking a more environmentally sound Nicaragua by 2035: promoting Renewable Energies and assessing their contribution towards Sustainable Development"

Doctoral Thesis by Maria Mercedes Vanegas

Date: 07/06/15

Place: Casa Hivos

Interviewee: Sonia I. Wheelock Díaz

Company/ Institution: Hivos

Job Position: Coordinadora Proyecto SE4ALL

Hereby I certify that I participated in an interview held at the time and place detailed above and conducted by Maria Mercedes Vanegas. I also acknowledge that the information provided during this interview will be used by Ms. Vanegas during her Doctoral Thesis regarding Renewable Energies and Sustainable Development in Nicaragua. Thus this information is accurate and reliable.

Signatures

MVanegas

Interviewer

Interviewee

Europa-Universität Flensburg
Internationales Institut für Management und ökonomische Bildung

Evidence of Interview

"Seeking a more environmentally sound Nicaragua by 2035: promoting Renewable Energies and assessing their contribution towards Sustainable Development"

Doctoral Thesis by Maria Mercedes Vanegas

Date: June 26, 2015

Place: Managua

Interviewee: Jean-Baptiste Boudot

Company/ Institution: BlueEnergy

Job Position: Director

Hereby I certify that I participated in an interview held at the time and place detailed above and conducted by Maria Mercedes Vanegas. I also acknowledge that the information provided during this interview will be used by Ms. Vanegas during her Doctoral Thesis regarding Renewable Energies and Sustainable Development in Nicaragua. Thus this information is accurate and reliable.

Signatures

MVanegas

Interviewer

JB Boudot

Interviewee

Europa-Universität Flensburg
Internationales Institut für Management und ökonomische Bildung

Evidence of Interview

"Seeking a more environmentally sound Nicaragua by 2035: promoting Renewable Energies and assessing their contribution towards Sustainable Development"

Doctoral Thesis by Maria Mercedes Vanegas

Date:	26.06.15
Place:	GIZ Managua
Interviewee:	Javier Cabrera Flores
Company/ Institution:	EnDev GIZ.
Job Position:	Asesor Tecnico

Hereby I certify that I participated in an interview held at the time and place detailed above and conducted by Maria Mercedes Vanegas. I also acknowledge that the information provided during this interview will be used by Ms. Vanegas during her Doctoral Thesis regarding Renewable Energies and Sustainable Development in Nicaragua. Thus this information is accurate and reliable.

Signatures

MVanegas

Interviewer

Interviewee

Europa-Universität Flensburg
Internationales Institut für Management und ökonomische Bildung