STATISTICAL ANALYSIS ON ENERGY AND DEVELOPMENT NEXUS & RIM FACILITY DESIGN AND CHARACTERIZATION

by

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Dedicated to all those that supported me on this journey and helped me complete it.

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Disclaimer of Published Work

In the following work, Chapters 2 and 3 have been recreated from papers either previously published or pending publication by the author. To avoid plagiarism, acknowledgement of these publications is presented here, and accompanying references are provided.

Chapter 2: O'Donnell J, Gutierrez W, Warsinger DM, Doosttalab A, Niyogi D, Castillo L. Promotion of socioeconomic equality through clean energy access. Journal of Renewable and Sustainable Energy. (Under Rev. 2021)

Chapter 3: Gutierrez W, O'Donnell J, Castillo L. Statistical Analysis of Causal Relations Between Energy Use and Economic Growth. Energy Policy. (Under Rev. 2021)

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NOMENCLATURE

Symbol	Description	Units
$\boldsymbol{A}$	Area	[m^2]
$\boldsymbol{A_x}$	Atkinson Index	[-]
$\boldsymbol{C_i}$	Coefficient of human inequality	[-]
$\boldsymbol{D}$	Diameter	[m]
$\boldsymbol{d_c}$	Characteristic dimension	[m]
$\boldsymbol{E}$	Fraction of energy	[-]
ECpC	Energy Consumption per Capita	[Kgoe]
EDF	Energy Diversity Factor	[-]
EI	Education Index	[-]
GDP	Gross Domestic Product	[]
GNI	Gross National Income	[PPP $]
HDI	Human Development Index	[-]
IHDI	Inequality-Adjusted HDI	[-]
LEI	Life Expectancy Index	[-]
$\boldsymbol{Q}$	Volumetric flow rate	[m3/s]
$\boldsymbol{Re_{H/2}}$	Reynolds number	[-]
Stk	Stokes number	[-]
$\boldsymbol{U}$	Velocity of the fluid	[m/s]
$\boldsymbol{\mu}$	Dynamic viscosity	[kg/m·s]
$\boldsymbol{\nu}$	Kinematic viscosity of the fluid	[m2/s]
$\boldsymbol{\rho_p}$	Density of a particle	[kg/m3]
$\boldsymbol{\rho_f}$	Density of a fluid	[kg/m3]
$\boldsymbol{\tau}$	Relaxation time of the particle	[s]

ABSTRACT

The role of energy in wealth and development is evident but the manner that a population’s access to energy effects overall growth is unclear. Understanding the role of energy in society can impact policies to push improvement in underdeveloped countries. Therefore, it is necessary to know how energy improves quality of life and what improvements need to be made to provide the necessary resources to underdeveloped populations. The first half of the thesis focuses on the role of energy use in society and its effect on human development. It is established that underdeveloped countries are in fact positively affected from increased energy access. Additionally, that the use of renewables will improve all the aspects of human development: health, wealth, and education. These results suggest that policy makers should focus on increasing clean energy in developing countries to also improve overall development. The second half shifts to the design and characterization of a water tunnel and the role it has in understanding fluid flow for near-wall visualization. Using refractive index matching (RIM) this experimental method can be used to study micro-surfaces that could improve efficiency in transportation or renewable energy. The water tunnel herein can achieve turbulent flows, unlike previous RIM designs.

1. INTRODUCTION

Clean and efficient energy supply is notably lacking in under-developed countries. The idea of equal and sufficient access to energy has been an ongoing and influential challenge for global development. Access to energy cultivates human wellbeing, economic development, and poverty. This relationship is prevalent throughout history, Smil showed associations between access to affordable modern forms of energy and higher physical quality of life in terms of health care, nutrition and sanitation and well as socio-economic stability [1]. Therefore, it is crucial to understand the nexus between increased energy consumption and how it has characterized socio-economic development, poverty alleviation and technological advancements.

In addition to determining the root causes for improving human development. It is also important to boost existing renewables and improve efficiency of transportation, all of which can affect the impact on the environment and overall human wellbeing. To explore novel solutions, there is need for experimental methods that can investigate boundary layer effects very close to the wall in high Reynolds numbers. This experimental method can demonstrate how unique surfaces can reduce drag or improve efficiency for transportation or wind turbines.

1.1 Motivation

Measurements of development have been determined through a variety of indicators such as the overall countries income or available resources. The United Nations in 2011 recognized 48 least developed countries with three criteria: per capita income, human assets, and economic vulnerability [2]. In Figure 1-1 it is seen that 33 out of the 49 countries are in Africa. The percentage of population with access to electricity within each country is shown in Figure 2-1 [3]. Like the least developed countries, majority of Africa has the lowest access to electricity.

Not only do these countries have a lack of electricity, but are also hindered by water scarcity as seen in Figure 1-3 [4]. Moreover, the least developed countries predominantly rely on fossils fuels for their energy supply. Figure 1-4 gives an example of how much water is used in the fuel cycle for energy systems [5]. Notably, coal uses a minimum of 1100 million cubic meters per year, this energy use would exacerbate the water scarcity in the areas. Whereas renewable energy would provide the necessary energy without taxing the water resources.

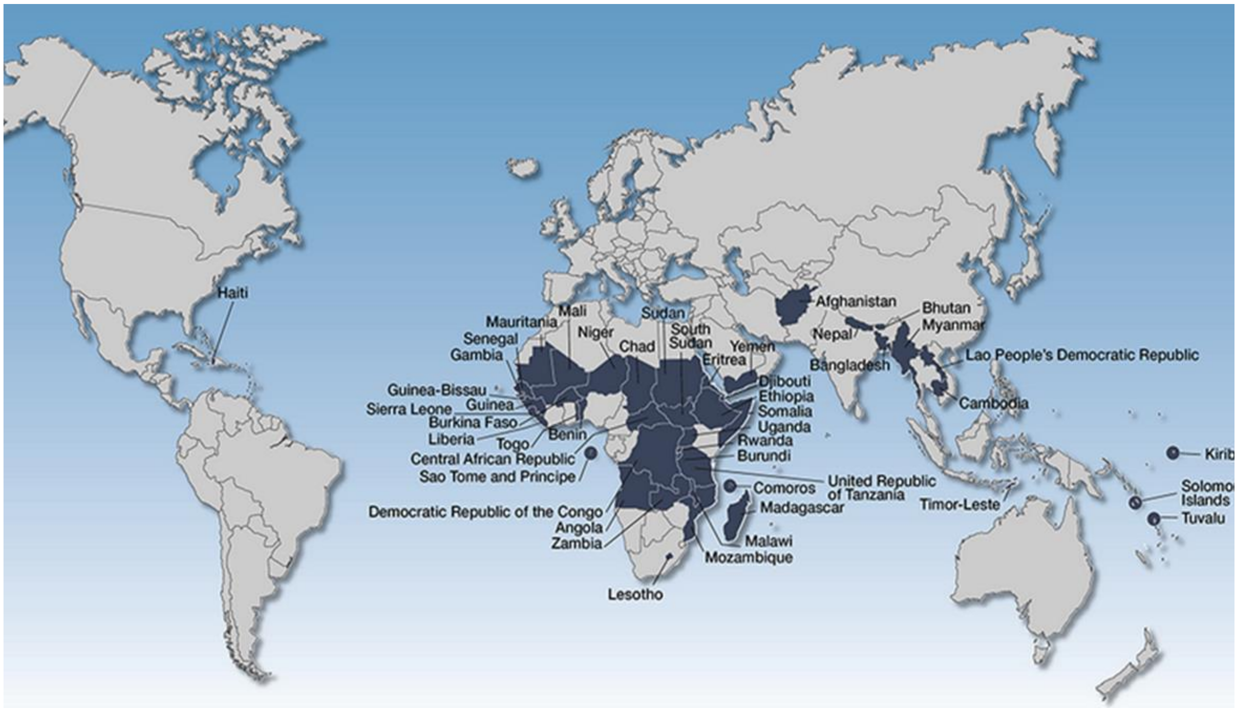

Figure 1-1 UN defined least developed countries shaded in dark blue [2] .

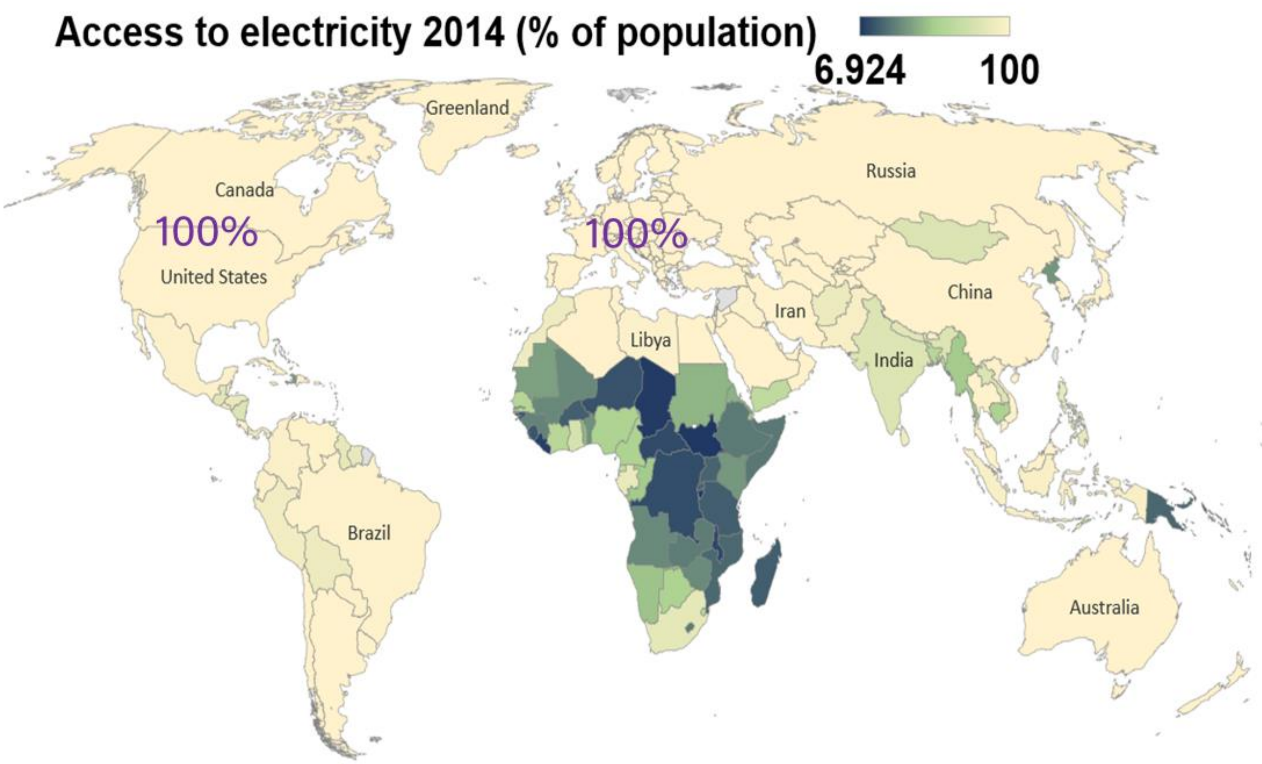

Figure 1-2 Share of the population with access to electricity in 2014, data from World Bank [3].

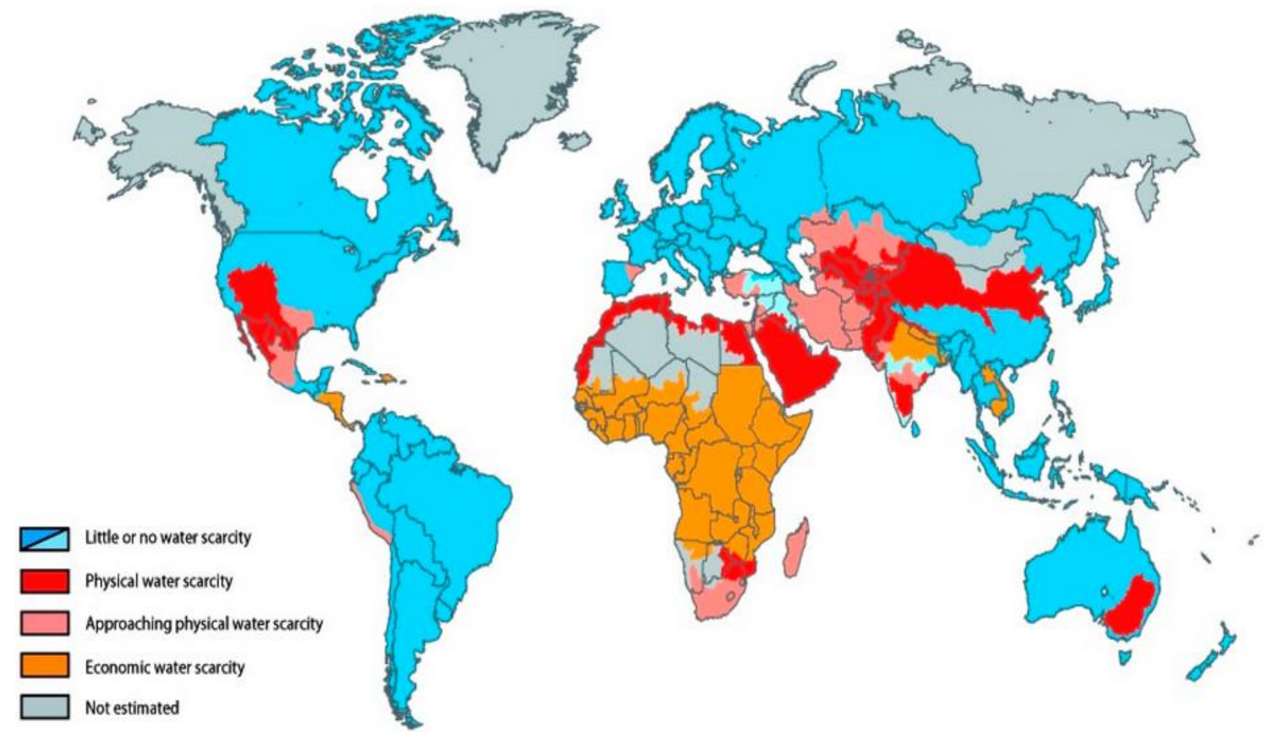

Figure 1-3 Areas of physical and economic water scarcity [4].

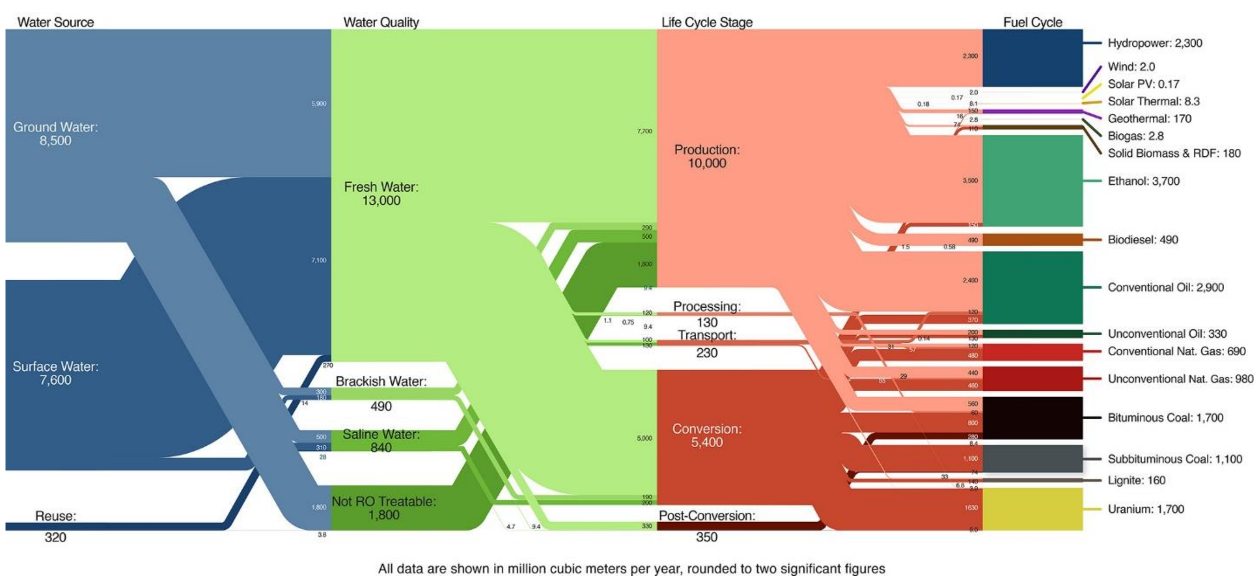

Figure 1-4 Water consumption for US energy system 2014 [5].

However, it is critical to optimize the energy sources to be the most efficient for underdeveloped countries. To innovate solutions, it is first necessary to have an experimental method to analysis the possible impact of the proposed change. This becomes particularly difficult if the modification is a surface change where the affect on the flow needs to be viewed at the viscous sublayer. Bocanegra et al tested an airfoil covered in micro-pillars inspired from the shape of shark denticles and were able to demonstrate that the pillars reduced flow separation [6]. That innovation can therefore improve the efficiency of wind energy. Though, the flow facility used to test the flow change could not achieve high speeds. For that reason, there is an interest in understanding how similar micro-surfaces would affect the flow at high Reynolds numbers.

1.2 Overview

The first chapter provides a connection for the following chapters, with general background introduced. An overview of what is included in each chapter is also given.

Chapter 2 develops the base connection between energy and human development. Specifically, energy consumption per capita and inequality-adjusted human development index (IHDI) are correlated. Additionally, by studying outliers in the data, key factors for improved development are identified.

Chapter 3 delves deeper into the causality of energy use and economic impact through a literature review. Once again energy consumption per capita is used, though here it is compared to gross domestic product (GDP) which allows for increased temporal data. The results of the previous papers are than statistically compared to determine if any policy implications can be made.

Chapter 4 than describes a novel refractive-index matching (RIM) flow facility that will be used to study methods for surface improvements. The chapter reviews design selection, preliminary testing, and establishes a calibration curve for the test section velocity. Furthermore, a bio-inspired surface is introduced that would be tested in the RIM flow facility.

2. PROMOTION OF SOCIOECONOMIC EQUALITY THROUGH CLEAN ENERGY ACCESS

2.1 Introduction

A major factor to a country's development is access to energy and the type of energy sources. Access to energy has been categorized by the delivery, the safety of use, and the level of energy consumption [3]. Of those three, energy consumption is relatively easiest to quantify and compare to human development indicators. Therefore, numerous correlation and causality studies associate energy and economic gains [7]. However, a clear direction between the two variables in developing countries has yet to be demonstrated due to contradictory results [8], [9].

The first to explore this link was Kraft and Kraft, who demonstrated that energy consumption unidirectionally causes gross national product [10]. Subsequently, the comparison of Energy Consumption (EC) and Gross National Product (GNP) for the United States (USA) with a lag of 4 for Granger causality, the unidirectional relation from EC to GNP was verified [11]. Starting in 2000 many causal analyses shifted to incorporate Gross Domestic Product (GDP) as a key comparison. An assessment of 30 OECD countries identified a diverse outcome. Of the 30 countries, 19 showed no causal link, 4 showed bidirectional relation, while 5 showed unidirectional countries from electricity consumption to GDP. Two countries even showed an opposite relation between EC and GNP [12].

Recent studies state that measures of income such as GDP fail to account for the social aspects that determine societal development, which are considered in human development indices [13]. Rather than focusing on economy indicators alone, it would be insightful to understand the relationship between access to energy and human development (e.g., quality of life in a country).

Relation between energy needs and societal development is apparent. Energy acts as a critical input for quality of life through provision of clean water, healthcare, heating, cooking, sanitation, lighting, and transport services. The International Energy Agency (IEA) states that widespread use of energy has been an ongoing and crucial challenge for global development, as energy availability cultivates human well-being, economic development, and poverty alleviation [14]. A study of 11 countries in Sub-Saharan Africa showed that only one-third of hospitals have reliable electricity access [15]. Additionally, the absence of reliable modern energy sources in healthcare facilities remains a detrimental obstacle impeding the delivery of essential health care

[16]. Thus, the underlying factors of energy access must be understood, while also considering inequality within countries.

Furthermore, rather than only comparing development to overall energy consumption, attention on the type of energy resources is necessary because they are poorly understood. For instance, an analysis of energy consumption by fuel type revealed a unidirectional short-term impact of renewable energy consumption on economic growth (i.e., GDP) for the European Union [17]. More specifically, the use of renewable energy resources was found to have a positive impact on economic growth [18]. There is a need for a broader study regarding the shift into renewable energy sources to quantify the extent of their influence on human development.

This study seeks to establish a correlation between energy consumption per capita and human development. The goal is to provide an analysis for countries that deviate from the general trend and evaluate the patterns from the median values of regions worldwide. This is undertaken by using three steps. The first employs the inequality-adjusted human development index (IHDI), which provides a better representation of a country's actual quality of life of its citizens. IHDI also allows for a comparison of the coefficient of inequality to energy access. Next, the effect of resource diversity is examined for developing and developed countries. Third, the prominent energy sources for each group are determined. Ultimately, through this synergistic analysis, the aim is to provide additional considerations for the development of energy policies across the world.

2.2 Methods and Data

Previous studies between energy and human development have largely been limited to the role of energy on the economy or the correlation with the human development index (HDI). However, the HDI does not properly account for the differences in wealth distribution within countries. Therefore, the IHDI is used as the measure to quantify the socio-economic inequality on human development versus access to energy.

The inequality-adjusted human development index is defined by the United Nationals Development Programme evaluating three major components: health care, education and income [19]. The healthcare status within a country is broadly expressed using the life expectancy index. Considering the average life expectancy within a country, inferences about the health situation such as child mortality, sanitation and access to healthcare can be drawn. The Life Expectancy Index (LEI) is determined from Equation 2-1.

$$LEI = \frac{Life\ Expectancy\ in\ a\ country - Minimum\ Life\ Expectancy}{Maximum\ Life\ Expectancy\ - Minimum\ Life\ Expectancy} \quad (2\text{-}1)$$

Education is a vital component for advancement of a country. The education quality within a country is accounted for by the Education Index (EI), with “target” mean and expected years of schooling as 15 and 18, respectively. EI is calculated with Equation 2-2 [19].

$$EI = \frac{\frac{Mean\ Years\ of\ Schooling}{15} + \frac{Expected\ Years\ of\ Schooling}{18}}{2} \quad (2\text{-}2)$$

The monetary income of the population within the country is determined by the Global National Income (GNI), with the minimum and maximum gross national income per capita provided. GNI is calculated by Equation 2-3 [19].

$$GNI = \frac{\ln(Gross\ National\ Income\ per\ capita) - \ln(100)}{\ln(75000) - \ln(100)} \quad (2\text{-}3)$$

To incorporate the inequality of resource distribution between the rich and the poor within a country, the Coefficient of Human Inequality (Ci) is used as defined in Equation 2-4. For each country, the inequality in healthcare (A_{health}), education ($A_{education}$), and income (A_{income}) are calculated and averaged to yield the coefficient that quantifies the inequality [19]; where 1 is the highest possible inequality.

$$C_i = \frac{A_{health} + A_{Education} + A_{income}}{3} \quad (2\text{-}4)$$

This coefficient is derived from the Atkinson’s inequality measure, *Ax*, given by equation 2-5; where n is the number of values in the data set, $\bar{x}$ is the average of that data, and *xi* through *xn* are the individual data values from each countries’ health, education, and income [20].

$$A_x = 1 - \frac{1}{\bar{x}} \prod_{i=1}^{n} x_i^{\left(\frac{1}{n}\right)} \quad (2\text{-}5)$$

Combining all the indexes, the Inequality-adjusted Human Development Index is given in Equation 2-6 [19].

$$IHDI = \sqrt[3]{(1 - A_{health})(1 - A_{education})(1 - A_{income})} * \sqrt[3]{LEI * EI * GNI} \quad (2\text{-}6)$$

For this study, the data on Inequality coefficient, Inequality-adjusted Human Development Index, energy production and consumption, energy resources, and population are compiled and processed from human development reports[21]–[23]. A database for this study was then created for 102 countries across the globe for the year 2014, thereby accounting for the most reliable and publicly available reported data across the various platforms. Those 102 countries were the only ones with reported data of both available energy and IHDI in 2014. After 2014, the energy data availability is too sparse. Also, IHDI began reporting values in 2010, therefore space-wise analysis was used instead of the limited time-wise data.

Metrics for studying energy diversity have been lacking. We create a metric called Energy Diversity Factor (EDF), shown in Equation 2-7. We propose this term to quantify the diverse resources used in energy production by accounting for the fraction of energy coming from each resource. It has a similar form as the development index and provides meaningful values for a wide range of energy resource compositions. This index provides a perspective of the resource available and used within the country. This is a novel index that, to the authors' knowledge, is being used for the first time.

$$Energy\ Diversity\ Factor = \left(\sum_{i=0}^{n} E_i^{\frac{1}{2}}\right)^2 \tag{2-7}$$

where *Ei* through *En* are the fraction of each energy source, calculated by dividing total consumption of one energy type by total energy consumption of the country. As expected, an EDF of 1 would mean that energy comes from only one source.

2.2.1 Regression and Correlation Tests

After the different indices were determined, three plots were created to understand the correlations: IHDI versus energy consumed per capita, inequality coefficient Ci versus energy consumed per capita, and IHDI versus energy diversity factor. To facilitate the analysis and interpretation, the data for energy consumption was transformed from linear to logarithmic scale to shrink the range. The data follows a polynomial regression power law model, used for the Ci correlation to energy, and an exponential trend, used in the comparison of IHDI to energy per capita and EDF.

Energy graphs used bubbles for data points, where the bubble size is proportional to the share of renewable consumption within the country. The renewables include solar, wind, geothermal, biomass, biodiesel, and fuel ethanol. The purpose of this delineation was to highlight the effects of renewable dominant countries on the energy consumption and inequality within the country. Since some countries have zero percent renewables, 0.1% was added to all the renewable energies to provide a bubble size and maintain the overall ratio between countries.

Correlation tests were performed to evaluate the relationship between the variables: IHDI with energy consumption, Ci with energy consumption, and IHDI with energy diversity. These calculations were done with R programming utilizing the correlation function [24], testing the null hypothesis that there is no correlation with the Pearson correlation between the variables, where perfect correlation is 1.

Significance was tested with the Welch's two sample t-test and evaluated by calculated probability (p-value; 0.001) for each relationship. The Welch's test is assumed to have unequal variance and is a two-tailed test according to Equation 2-8.

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \tag{2-8}$$

Here, $\bar{x}$ is the sample mean, *s* is the sample variance, and *1* and *2* denote the samples being tested. All calculations were done for the 102 countries.

2.3 Results and Discussion

Various bubble plots were created to show the comparison for Energy Consumption per Capita (ECpC), human development, inequality, and renewables. Each comparison looks at the 102 countries individually and as part of its geographical region in 2014. In 2.3.1 the correlation between IHDI and energy consumption per capita is demonstrated with a close inspection on any outlying countries. Then in 2.3.2 the relation between inequality and ECpC is established, and the yearly trends are identified. An innovative measure, the Energy Diversity Factor (EDF), provides a means to understand the effect of having a higher variety in energy resources. That factor is plotted in 2.3.3 compared to IHDI. Finally, the effect of renewable use is examined in 2.3.4, looking at the percentage of renewables related to a country's development. The final section analyzes the correlations for each comparison.

2.3.1 Correlation Analysis Between Energy Consumption and IHDI

Energy Consumption per Capita (ECpC) given in kilograms of oil equivalent (Kgoe) is compared to IHDI in Figure 2-1. A clear exponential behavior exists on a logarithmic axis, where the red line represents the least squares fit, thus demonstrating a positive correlation of energy with IHDI. The color coding is as follows: Africa is pink, Central and South America is green, Asia and Oceana are yellow, Middle East is orange, Eurasia is grey, Europe is dark blue, and light blue is North America. Countries are abbreviated with their three-letter country code, defined by International Organization for Standardization [25]. To avoid overcrowding in Figure 2-1A, only the countries with the maximum, minimum and median IHDI and ECpC are labeled. The bubble size represents the percent renewable energy of the corresponding country.

The fact that most countries follow this trend with IHDI shows that access to energy is indeed related to better quality of overall life. Similarly, Figure 2-1B presents the IHDI versus energy per capita in different regions of the world, showing how various continents perform and avoid crowding. Each regional bubble represents the median value of IHDI and energy per capita, with the bubble size proportional to the median renewable percentage. It can be observed that the curve fit from low to high IHDI encompasses all the regions.

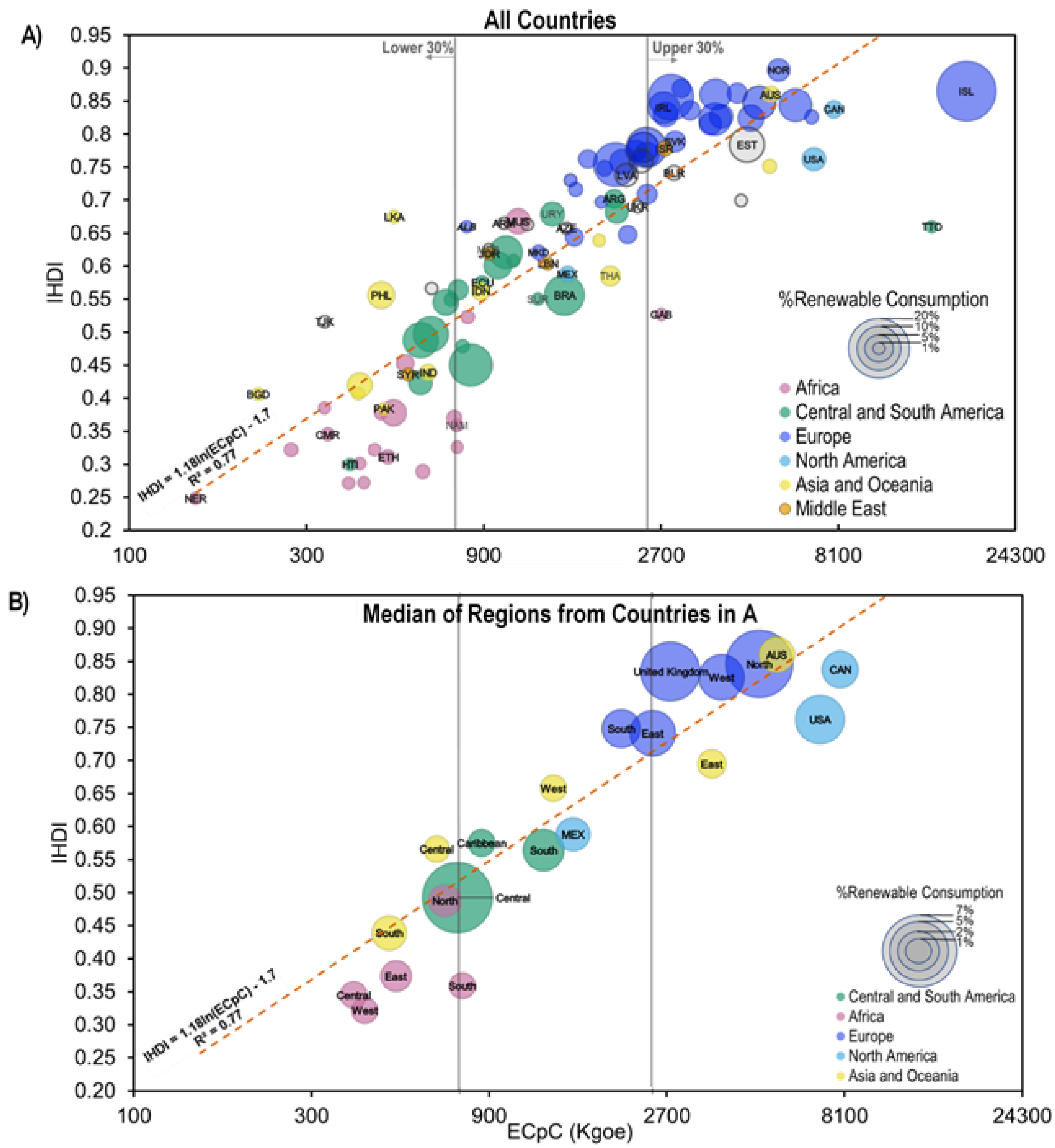

Figure 2-1 Inequality-adjusted human development index (IDHI) versus energy per capita (ECpC) in kg of oil equivalent (Kgoe) in 2014 for 102 countries (A) and selected regions (B). The bubble size indicates the share of renewable energy out of total energy sources sources used in each country. Each country is color coded by region and the data labels of the countries are shown by their ISO code (see Appendix A). A logarithmic curve shows the overall trend with equation displayed. The vertical lines represent the lower and upper 30 percentile of the energy consumption (to the left and right, respectively).

The upper right section shows that higher energy tends to lead to higher development. Figure 2-1 also demonstrates that highly developed countries associated with high IHDI are in Europe and North America, where higher energy consumption per capita clearly exists. It is interesting to observe that most countries with an IHDI greater than 0.70 also have a strong pervasion of renewables. In contrast, the bottom 30 percentile are predominantly countries located in Africa, part of South-Asia, and Haiti at the low end of Latin America, for IHDI and energy. Niger (NER), with a low energy per capita and close to no renewable sources, exhibits the lowest IHDI of the 102 countries considered from the data available in 2014.

Moreover, countries from the African continent tend to diverge from the trend compared to highly developed countries in terms of energy per capita and the IHDI—further indication that poor access to energy leads to low living standards. An exception is found in Central America (green circle in the figure), where there is a greater percentage of renewables though the quality of life is poor. For many countries in Latin America, renewables mainly consist of biodiesel, biomass, ethanol, and geothermal forms of energy. Further development in renewables for the region seems to be limited by the excessive capital needed to restructure the existing infrastructure.

Detailed View on Select Countries

Noteworthy outliers in Figure 2-1A include Haiti (HTI) and Sri Lanka (LKA). Haiti has low energy consumption and development compared to the rest of the Caribbean countries and Sri Lanka has low energy consumption but with a comparatively higher development index. While Haiti's low IHDI is the result of low life expectancy and high poverty rates; Sri Lanka invested heavily into health and education which increased literacy and life expectancy, contributing to a higher IHDI [19], [26]. Furthermore, Figure 2-1 shows some cases with large deviations from the trendline. Specifically, Trinidad and Tobago (TTO) who have disproportionally high energy consumption compared to the level of IHDI achieved. This is due to a vast indigenous oil production access, but lower development in other socio-economic factors—lower quality of life mainly due to political inequalities [27].

Countries in the upper percentile sections in general show a larger bubble size than those in the lower percentile section. Within the upper percentile, the top ranked country Iceland (ISL) has 19.9% renewables whereas a lower renewable energy share corresponds to low-income countries which also have a lower quality of life. However, it is also clear that many countries in

Central and South America with access to renewable energy fall behind in IHDI and energy consumption per capita, point in case being Brazil. Interestingly, USA, located in the upper tier in terms of energy consumption per capita, has a lower IHDI than expected. This discrepancy will be examined further in terms of the coefficient of inequality (Ci).

2.3.2 Correlation Analysis Between Energy Consumption and Inequality

To assess the relation between energy and inequality, the coefficient of inequality is depicted relative to the energy consumption per capita in Figure 2-2. This coefficient measures the inequality in three areas as given by the Atkinson inequality coefficients for health care, education, and income. The higher the value of Coefficient of inequality the greater the amount of inequality in a country; calculated by Equation 2-4 [19], [20].

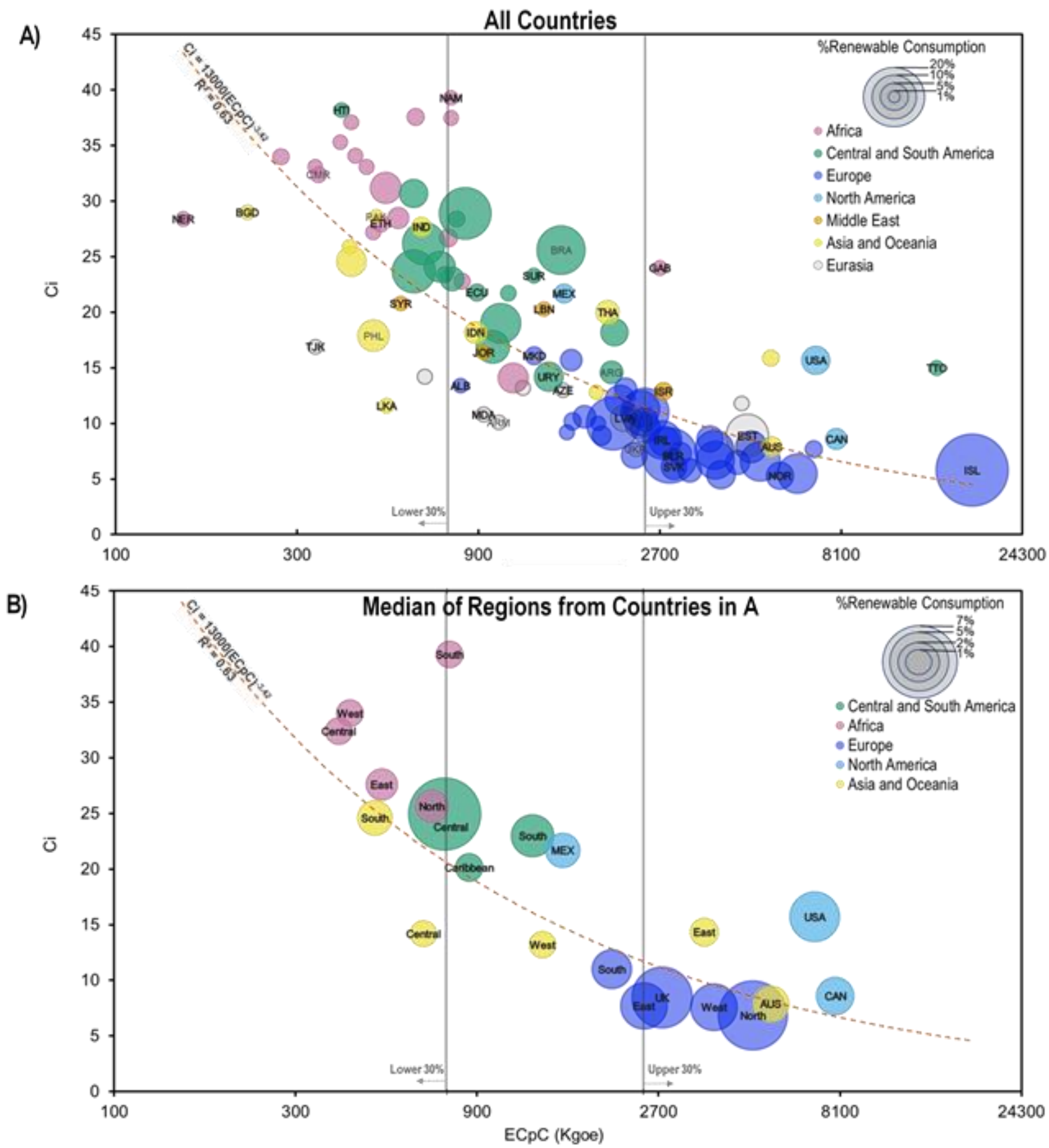

Figure 2-2 Coefficient of inequality (Ci) for human development versus energy per capita (ECpC) in Kg of oil equivalent in 102 countries (A) and the median of selected regions (B). The ratio of renewable energy consumed is represented by the size of the bubbles. The countries are distinguished by region. A power trendline is shown in red dashed line with equation displayed. The vertical lines represent the lower and upper 30th percentile of the energy consumption (left and right respectively). Low inequality correlates to high energy, with the majority also containing high renewable sources.

Inequality is seen to correlate negatively with energy per capita, thereby an increase of energy leads to a decrease in inequality. This suggests that access to energy can lead to a better quality of life, but that access needs to be enabled via policy measures and infrastructure. Iceland (ISL) has the largest penetration of renewables and enjoys the lowest Ci (about 5) of any country in the world. Also, Middle Eastern countries have high energy from oil production, but show high inequality and thus low index for quality of life.

Furthermore, the trendline shows a power scale of -3.4, the rate of this decrease is sharper in the lower percentile section, while it is slower in the upper percentile section. This is an indication that inequality decreases with energy per capita at a faster pace in countries with high inequality. In other words, the energy consumption contributes more significantly to improving equality in the countries grappling with low development. Looking at Figure 2-2B, the trend can be seen in a region-by-region basis. Countries in Africa show the highest inequality with the lowest energy per capita in the world, while European countries, North American countries, and Australia are in the side with higher energy consumption and lower inequality. Yet, one can observe that USA lags in terms of the coefficient of inequality as compared to Europe, Australia, and Canada. Reasons for this is discussed with Figure 2-3.

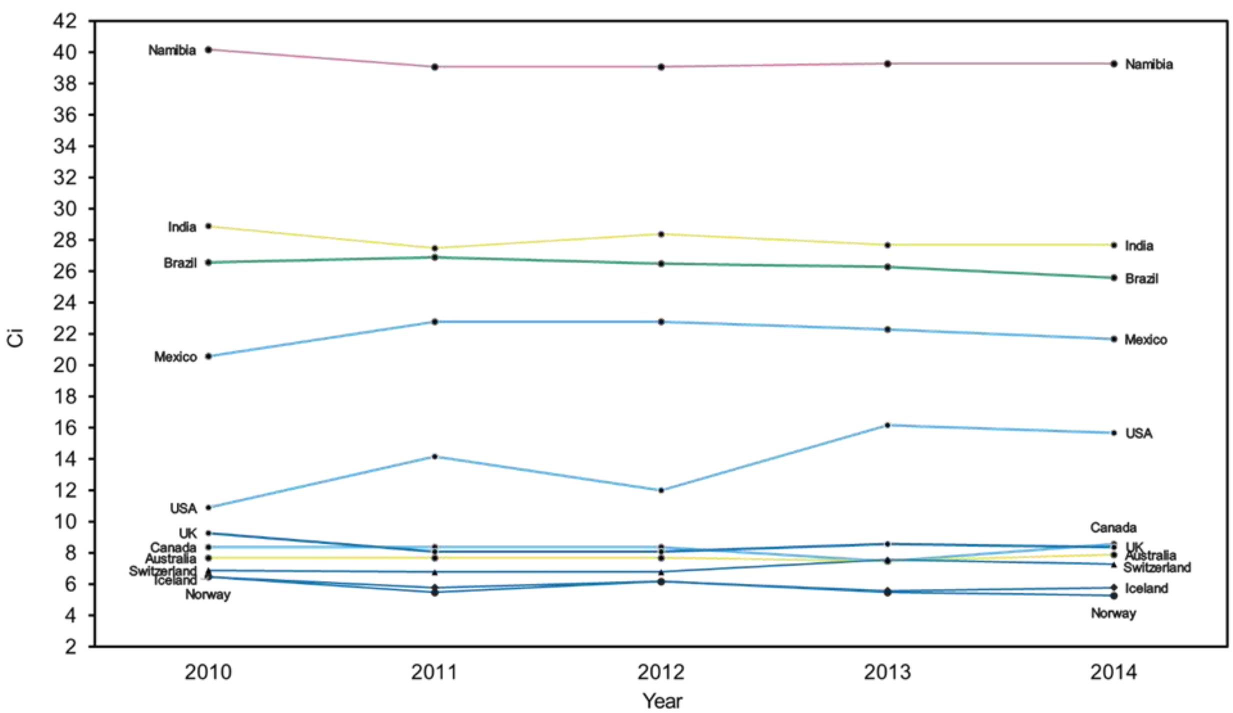

Figure 2-3 Changes in the inequality coefficient of human development versus time over five years of study. An increase over time is an increase in inequality.

High levels of inequality exist regardless of energy around a coefficient of 25, as is the case for Brazil. At the lower end, most European countries average around 9 for energy greater than 2000 Kgoe. Evidently, many European countries enjoy low levels of inequality, where education and health care are both provided and accessible to the community. Yet, USA stands out with inequality above 15. This could be a result of lack of universal health care and affordable higher education available in most European countries. Some of the issues affecting the inequality in the USA are: income disparity, high cost of housing and skewed influence from donors on legislations [28].

The USA is an exception among highly developed countries in the sense that it does not provide universal health care and has a high cost of higher education, which seems to further increase the inequality gap. Figure 2-3 depicts the variation of Ci over time in the five years of study for selected countries. A striking note is that, for most countries a flat trend is observed, but the Ci for United States has shown an increase of 44% in the lapse of four years. This observation merits a critical investigation of the origin of this trend with the goal of avoiding further detrimental causes that could lead to higher Ci.

2.3.3 Influence of Energy Diversity on IHDI

In this section, the energy diversity factor (EDF) is proposed as a metric. The EDF is a quantitative approach to examine if countries with a high variety of energy sources have positive impacts in human development. This factor calculates the norm of the proportion of energy resource contribution to the total energy consumption in a country, see Equation 2-7. Additionally, among the various existing energy sources, the role of renewable energy sources compared to other types of sources is analyzed for highly-developed (IHDI > 0.70) versus developing (IHDI < 0.55) countries, as defined in the UNDP Human Development Report [19].

Reviewing Figure 2-4A, there are two notable trends toward an IHDI of 0.80 –which has been considered as a threshold for very-highly developed countries. The best-fit curve shows that many of the Latin American countries follow that curve, although at a lower rate, but as the EDF increases their quality of life improves toward an IHDI of 0.80 (e.g., Costa Rica and Argentina). The second growth pattern shows a high rate of improvement toward IHDI of 0.80 at an EDF of about 3.25 where Israel (ISR) stands. Interestingly, some of Asian and Middle East countries follow that curve of rapid growth. Most countries in Africa fall below the lower IHDI line, with the majority at median of 0.35 for their IHDI. Evidently, access to energy is important toward a higher standard of life, but more than that is needed (examples could include policy, governmental stability, etc.). In the case of USA, despite a high energy diversity, about 84% of electricity generation comes from coal, natural gas and nuclear. Yet, those sources employ at the expenses of about 30 trillion gallons of water, mainly employed in the cooling of power plants [29].

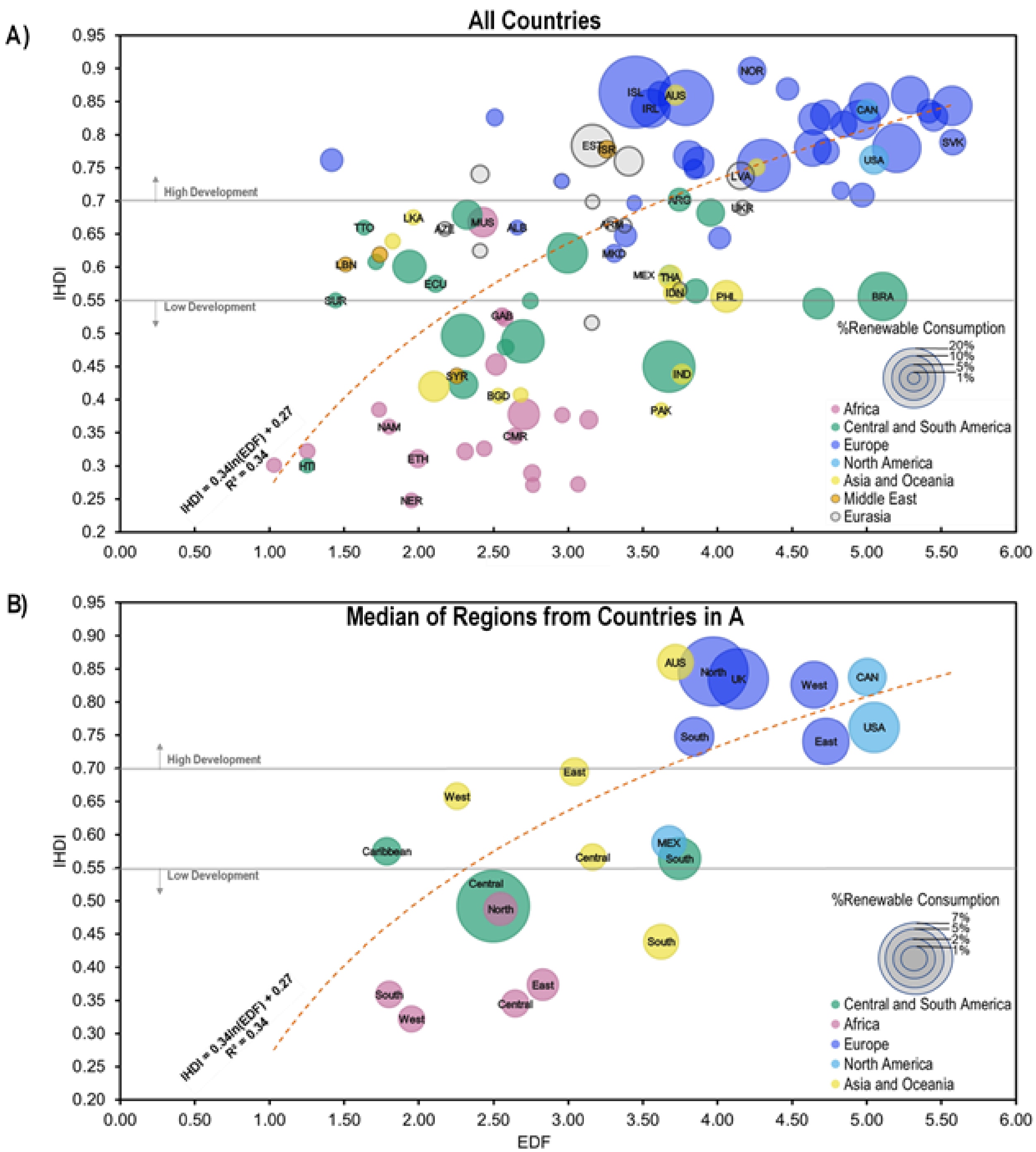

Figure 2-4 Inequality-adjusted human development index (IHDI) versus energy diversity factor (EDF) for 102 countries. The data is for calendar year 2014 (A) along with the median of each region (B). The bubble size indicates the share of renewable energy relative to the total energy sources used in each country. Each country is color coded by region and data labels of the countries are shown by their ISO code (full table in appendix). A logarithmic trendline (dashed) and best fit equation is displayed. The horizontal lines indicate the threshold for very high and low IHDI (above and below respectively).

2.3.4 Percent of Renewable Consumption

A breakdown of the renewable energies per region is shown in Figure 2-5. The renewables represented are solar, wind, geothermal, biomass, biodiesel, and fuel ethanol. These are the same energy types used in created the bubble percentages. In Figure 2-5, the specific renewable shares for each region are displayed. A large penetration of renewables is seen in European countries, and Central and South America. However, renewables here basically consist of biodiesel, biomass and waste electricity, fuel ethanol, and geothermal for electricity, with very low participation of real game changers such as wind or solar. Therefore, the choice in renewables could affect the overall human development, as Central and South America have low IHDI compared to Europe.

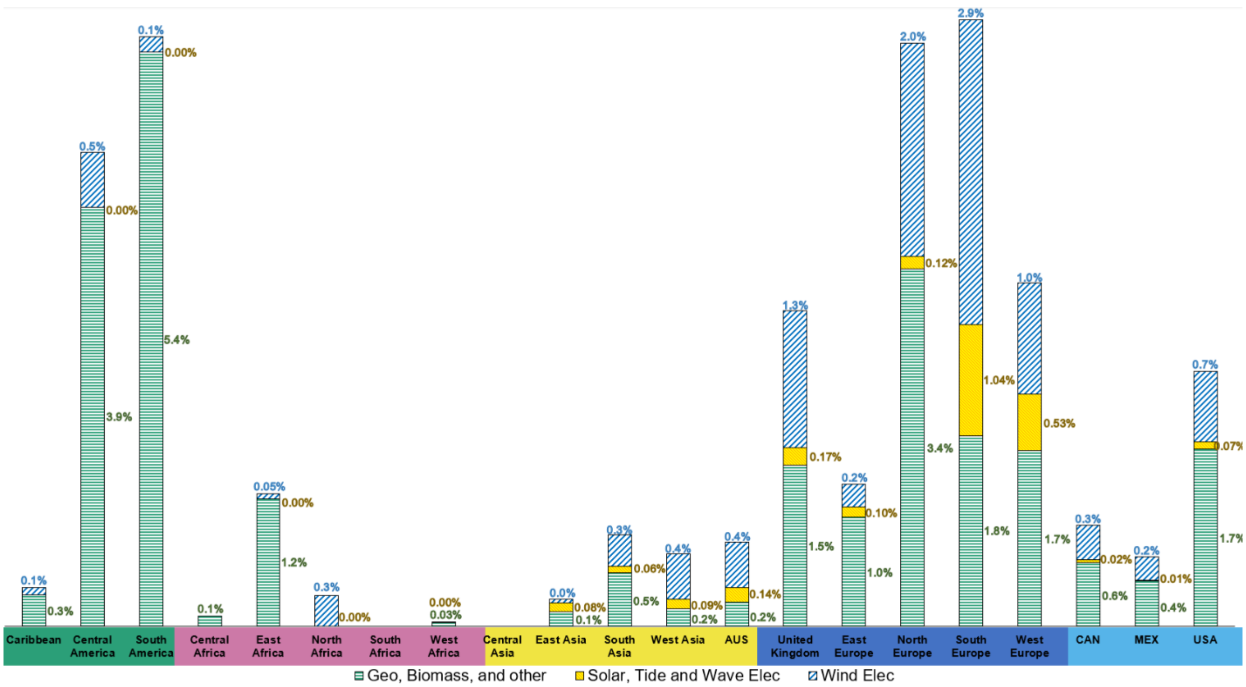

Figure 2-5 Renewable energy sources by region out of 100%. Each renewable type is divided by total energy consumption. The renewables include solar, wind, geothermal, biomass, biodiesel and fuel ethanol. Where a percentage label of 0 is less than 0.005%. These energy sources make up the bubble percentage from Figures 2-1, 2-2, and 2-4.

Figure 2-6 depicts the energy sources for very-highly developed countries (IHDI > 0.80) and developing countries (IHDI < 0.55). As defined by the human development reports: low development is below 0.550, medium is from 0.550 to 0.699, high development includes 0.70 to

0.799, and very-high development is 0.800 and above. Renewable energy sources studied include hydropower, wind, solar, geothermal, biomass, biofuels, and waste energy [22].

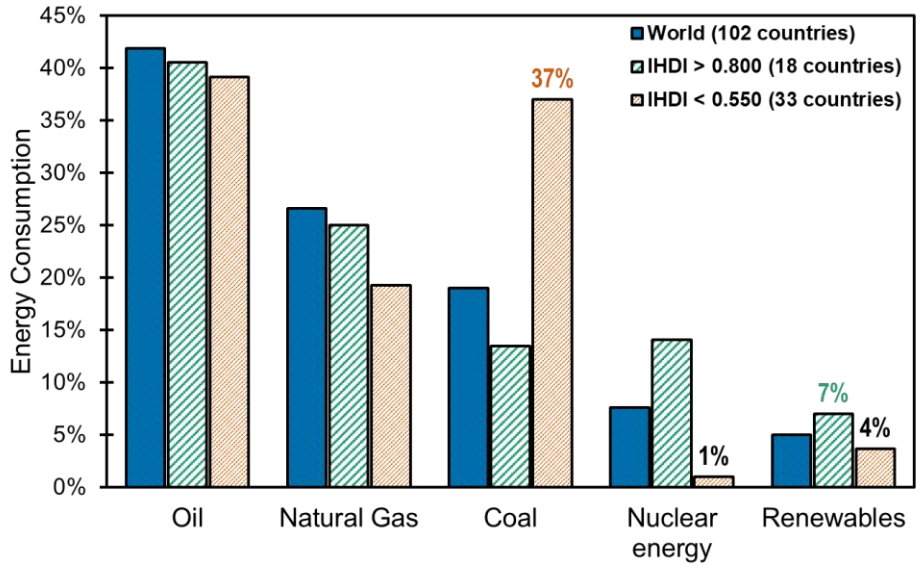

Figure 2-6 Comparison of energy sources of countries with very high human development, countries with low human development, and all countries (world). The renewables include hydroelectric, solar, wind, geothermal, biomass, biodiesel, and fuel ethanol. Values are labeled for the major contributors for each development range.

The very-highly developed countries utilize a higher share of renewable energy sources and nuclear energy compared to the average world use. By contrast, low development countries rely more on traditional fuel sources, e.g., nearly three times more for coal, accounting for 37% of their energy consumption, significantly above the 13.4% share in highly developed countries and the 19% share in all countries in the world. This high consumption of a high-emission fossil fuel also employs more water for energy than highly developed countries, which further results in an impediment to their development [29].

2.3.5 Strength of Energy Correlations

The correlations between the variables used in the three energy plots are found to be 0.77 for IHDI versus Energy per capita; 0.63 for inequality versus Energy per capita; and 0.34 for IHDI versus energy diversity. The correlations are statistically significant ($p < 0.001$). Recognizing the multitude of factors that can potentially affect the IHDI and inequality, the high correlations between the variables are notable and indicative of a strong support to the conclusions drawn from Figures 2-1, 2-2, and 2-4. Statistical analysis results are summarized in the appendix.

It is noted that the correlation in Figure 2-1 is stronger than that of Figure 2-2, as the distribution of the countries are more convergent to the central trendline, especially in the lower percentile section of energy consumption. However, Figures 2-1 and 2-2 are consistent with each other in the sense that access to energy leads to a better quality of life and as energy decreases the IHDI, as is the case for Africa. The impact of inequality is indicated by the close overall correlation coefficient of 0.77 and 0.63 in Figure 1 and 2 respectively. This suggests that inequality has more significance in the calculation of human development compared to the other factors (i.e., global national income, literacy rate, and life expectancy, see Equation 2-6).

It is also insightful to review the countries that diverge from the trendline. From this observation, in Figure 2-1, USA is shifted below the trendline, indicating that it has a lower IHDI than the trendline prediction. This factor is emphasized in terms of inequality in Figure 2-2, where USA's coefficient of inequality is displaced above the trendline—higher than European countries, Australia, and Canada. Thus, while USA is among the countries with high energy consumption per capita, its human development is still jeopardized due to lower than expected equality conditions, within the terms of health, education, and income. A major observation here is, in European countries, Australia, and Canada, college education and universal health care are both provided—and this explains in part the lower inequality index (C_i) in the figure [30]. Moreover, evaluation of the coefficient of inequality from 2010 to 2014, in Figure 2-3, shows that this index for USA continues to increase over time—a matter of concern that needs further exploration in terms of education, health, and income inequalities.

2.4 Conclusions and Policy Implications

The above analysis examines the relationship between access to energy and human development in 102 countries, applying the inequality-adjusted human development index (IHDI), energy diversity factor (EDF), and energy per capita (ECpC) metrics. Where inequality is defined by unequal access to education, health, and income. Beyond economic development, energy availability can create improvements in health and education, thereby strengthening human development factors. Availability of clean energy sources is seen as necessary since it facilitates the provision of quality health care and education.

This study provides further evidence that with increasing energy consumption and diversity, the level of inequality decreases. We came up with a comprehensive assessment of energy consumption by including the direct impact of energy diversity and introduced a key determining factor to the socio-economic equality. From this result, inequality levels can likely be effectively decreased via increased energy resources. Additionally, renewables can promote increased development and diversification in energy. This in turn can help maximize human equality – conventionally defined in terms of health care, education, and income – and could form a basis for future studies.

Increasing energy availability could be achieved by promoting infrastructure for increased energy reach. Yet, the correlation between the share of renewable energy and human development asserts an urgency to maximize accessibility of renewable energy. Given renewable energy's ability to promote a clean environment, reduce the carbon footprint, and save water for energy; with renewables countries can increase energy availability while attempt to reduce fossil fuel related liabilities.

These findings provide additional insight on energy and its relationship with inequality, which is identified as a significant factor in a country's human development. Amid the high correlation with energy factors, the findings highlight that equality is integral for human development. Subsequently, they imply the significance of policies promoting equal access to renewable energy and mitigation of systems that prevent access to education and health care. These influential aspects can serve as a basis for future research on strategies and policies to accelerate human development, in terms of access to energy.

3. STATISTICAL ANALYSIS OF CAUSAL RELATIONS BETWEEN ENERGY USE AND ECONOMIC GROWTH

3.1 Introduction of Causal Relations on Energy and Growth

Many attempts have been made to shed light on the possible causality relation between the economic size (per capita) of a country and its energy use (also per capita). Authors frequently differ in terms of which variables they will use to typify both terms. For example, the economic size is usually (but not exclusively) represented by indicators such as Gross Domestic Product (GDP), Gross National Product (GNP) or Gross National Income (GNI). On the other hand, energy use is mainly represented by indicators such as Energy Consumption (EnC), Electricity Consumption (ElC), Energy Production (EP), or Primary Energy Consumption (PEC). In turn, these indicators of energy use can be expressed as totals (or aggregated) from all energy sources, or disaggregated into specific energy sources such as energy consumption from oil, from coal, or from renewables. Henceforward in this article, whenever we need to refer to the abstract categories "economic size" and "energy use", we will use the symbolic words EcSize and EnUse, respectively, with the understanding that any given research will use two or more of the indicators to characterize both categories.

Studies about the relation between energy use and economic growth show results divided into four main theories: no relation between both (neutrality theory), EcSize preceding EnUse (conservation theory), EnUse preceding EcSize (growth theory), or bidirectional causality (feedback theory). The growth theory implies that no economic growth is possible without first ensuring an added supply of energy to sustain that development. Consequently, sudden obstructions in energy supply (e.g., due to embargos, fuel price gouging, natural disasters, etc.) can quickly lead to major recessions. On the other hand, the conservation theory suggest that economic growth stimulates further demand for energy consumptions; hence, economic downturns depress economic activity and therefore energy demand. As the name implies , the feedback theory sees both mechanisms supporting each other sequentially. Finally, the neutrality theory applies to those cases where both EnUse and EcSize seems to evolve independently from each other. Table 3-1 provides the symbolic representation that will be used in this article to illustrate each causality link scenario. This work will determine, according to literature, how often each theory has been supported by the results in previous works.

Table 3-1 Symbolic representation of possible EcSize to EnUse causality links.

Symbolic representation	**Description**	**Theories represented**
$EnUse \nleftrightarrow EcSize$	*No causal link*	Neutrality
$EnUse \longleftarrow EcSize$	*EcSize* unidirectionally precedes *EnUse*	Conservation
$EnUse \longrightarrow EcSize$	*EnUse* unidirectionally precedes *EcSize*	Growth
$EnUse \leftrightarrow EcSize$	Bidirectional link	Feedback
$EnUse \Longleftarrow EcSize$	*EcSize* precedes *EnUse*	Conservation or feedback
$EnUse \Longrightarrow EcSize$	*EnUse* precedes *EcSize*	Growth or feedback

Results from many studies tend to demonstrate that, for most countries, a clear relation exist between energy use and economic growth (section 3.2). It would be premature, however, to try to infer a general rule for the causality direction of that link, as the nature of the potential causality seems to depend, not only on the specific country studied, but also on the year span that that country has been analyzed. Some factors appear to influence the direction of that relation, including monetary policies, external variables (such as costs of capital and labor), and economic shocks within the time period studied. In some cases, the methodology used affects results, as they may consider or ignore some of the aforementioned factors.

Observing a statistical dependence between any two variables A and B is not enough to clarify whether variable A causes B, whether variable B causes A, whether there is a mutual interdependence between both variables, or whether there is a confounding variable C explaining both (i.e., a hidden variable causing both A and B) [31]. Moreover, the correlation itself may even not be true, for instance when a selection bias incurred in data acquisition led to spurious correlation. Therefore, a key fundamental question in this study is to determine, according to literature, whether a cause-effect relation prevails between energy use per capita and economic growth per capita (or at least if a sequential order can be established between both variables as is the case GDP).

The issue of determining if a causation link exists between two or more variables is difficult and, in many instances it can only be attempted by performing a controlled experiment to isolate effects by potential independent variables; all of this supported by a plausible theory to explain the probable nature of their relation [32]. This difficult setup becomes a near impossibility for countrywide socioeconomic studies where a controlled experiment is next to unattainable, as it is not realistic to lock an economic or social indicator (while letting others to fluctuate) for an entire country for the duration of the experiment (which should encompass many years for accurate results).

Fortunately, advances have been made in recent decades to solve the causation dilemma using only statistical observations, thus circumventing the need for a controlled experiment [33]. For this study, one can move beyond the correlation analysis in the spatial domain (i.e., correlating data from different countries at the same time) and attempt instead the analysis in the temporal domain to try to find whether activities in the time series of one variable were succeeded by corresponding posterior activities in the timeline of another variables. The calculation of cross correlations –also called time correlations– allows to detect whether a significant correlation maximum (or minimum) occurs when one of the series (A_t) lags the other series (B_t) by a certain amount of time (T). While the existence of that significant peak does not prove conclusively that A causes B, it nevertheless shows that activities in A tend to be followed by a corresponding reaction in B after a time delay T. Moreover, it shows that chances of A causing B are much higher than the chances of B causing A or than the chances of equally mutual causality. This can demonstrate that A is, at a very least, part of the causal mechanism leading to B, especially if a plausible theory can support results. Methods used in literature to address the problem (such as Granger causality) are usually based on some form of temporal analysis.

3.2 Literature Review of Energy Causality Links

The first ground-breaking work to study the relation between both categories using modern statistical methods was performed by John and Arthur Kraft [10]. Using postwar data of the US economy and the Sims test [34], the authors of this pioneer article evaluated whether a causality link existed between Energy Consumption (EC) and Gross National Product (GNP) in the United States. Results demonstrated that EC caused GNP, but not the other way around. As a result, the authors posited that energy conservation policies were possible in the country without harming its economic growth.

The Kraft and Kraft article was rapidly challenged by Akarca and Long, who criticized the inclusion of the exceptional period of the oil embargo of 1973-1974 into the timeframe of the analysis [35]. By just removing those two years from the study, they found that the hypothesis of causality in any direction was rejected using the same Sims test. They also warned, correctly, that the sampling frequency may also affect the results of any causality analysis. While the authors pointed out that the inclusion of periods of exceptional behavior (such as this period of oil embargo) can invalidate the results, one can argue that the inclusion of such periods (with care) can nonetheless provide useful insights into the causality relations, as such economic commotions can alter (even permanently) the policies and economic relations that countries adopt in response to such challenges.

This issue was later confirmed by Yu and Hwang, who extended the postwar period covered by the Kraft and Kraft study to update the possible causality links until 1978 [36]. No causal link was found; therefore, results seemed to support the conclusions of Akarca and Long that the inclusion of the years 1973-1974 in the Kraft and Kraft article led to probable spurious results. Moreover, they found that the addition of more "normal years" beyond that period was enough to restore the neutral relation observed in the years that preceded the oil embargo. The neutrality hypothesis was further supported by Yu and Choi, who expanded the causality analysis to five countries in different development stages, in a period from 1950 (from 1954 for South Korea) to 1976 (to 1979 for the United States). They found that neutrality was valid for the United States, the United Kingdom, and Poland, while Philippines exhibited a growth pattern and South Korea a conservation behavior [37, p. 1985].

In 1987, Erol and Yu, applied Granger causality test to several developed countries to evaluate whether countries with similar economic structures also exhibited similar causal relations between Energy Consumption (EC) and real income [38]. Results seemed to discard that notion, with neutrality pattern observed for France and United Kingdom, conservation pattern detected for Italy and West Germany, growth behavior exhibited by Canada, and feedback behavior shown for Japan. More remarkable, the authors pointed out how sensible results can be to the inclusion of abnormal years into the interval analyzed. By just removing 1950-1951 in the analysis of Japan and Italy (years in which there were outliers in the data of both countries), their patterns changed to conservation and neutrality, respectively. Even more, by shortening the upper limit to 1973 for all six countries (to eliminate the repercussions of the 1974 oil embargo), causality links disappeared for all of them except for Japan (that exhibited a conservation pattern) and the United Kingdom (that matched the growth hypothesis).

Just two years later, an unexpected turn was provided by Abosedra and Baghestani, who revisited the problem of the causal relation between Energy Consumption (EC) and Gross National Product (GNP) for the United States [11]. After using a different lag (lag=4) in their causality analysis, they obtained results that supported the original conclusion by Kraft and Kraft of a unidirectional relation running from EC to GNP. This conclusion was valid even after performing sensitivity analyses in a variety of year intervals (both including and excluding the previously conflicting years of the oil embargo).

In 1991, Hwang and Gum aimed to assess whether a causal relation existed between Energy Consumption (EC) and Gross National Product (GNP) in Taiwan, a country that depended heavily (more than 80 percent) on energy imports [39]. Granger test was preferred over Sim’s test due to the smaller loss of freedom degrees. They found a bidirectional causality link connecting both variables; hence, they concluded that energy conservation policies in Taiwan would hinder economic growth, while further economic growth would in turn create more energy demand. These conclusions would later be confirmed by Yang, who expanded the causality analysis for Taiwan to cover the period from 1954 to 1997, using Granger test with Akaike criterion for optimal lag selection [40]. Results confirmed that a feedback pattern existed between Energy Consumption (EC) and Gross Domestic Product (GDP).

A year later, Yu and Jin used cointegration tests and monthly data (instead of yearly data) to evaluate whether a long-term causality link existed between Energy Consumption (EC) and Industrial Production Index of Manufacturing (a proxy for GNP) in the United States [41]. The authors posited that short-term shocks, such as oil embargos or the Iranian Revolution, can result in short-term causality connections, but eventually the causality relation will be restored in a long-run pattern. Their results indicated that neutrality was the long-run trend during the period studied. This conclusion remained valid even after the total interval was split into two ranges: one for the years (1970s) where oil prices steadily increased and another for the years (1980s) where oil prices consistently decreased.

Departing for the trend of analyzing a single country, Masih and Masih applied Johansen's multivariate cointegration and dynamic vector error-correction model to several underdeveloped countries to evaluate the long-term causal relations between Energy Consumption (EC) and real income in countries with dissimilar energy access [42]. Results revealed neutrality patterns in the cases of Malaysia, Singapore and Philippines, conservation pattern for Indonesia, growth pattern for India, and feedback behavior for Pakistan. At the time, Malaysia and Singapore were vibrant open economies, while India and Pakistan functioned as closed economies.

In 2000, Asafu-Adjaye studied the causal relation between Energy Consumption (EC) and Gross Domestic Product (GDP) in four Asian countries in an industrialization phase [43]. A trivariate model was used, which included energy, income, and prices. Results placed India and Indonesia in a causal relation from energy to income, while the relation was bidirectional for Philippines and Thailand. A similar study was performed for Pakistan encompassing a period of 40 years; its results revealed a causal relation that ran from economic growth to energy consumption [44]. The opposite direction, running from EC to GDP, would be later found for Turkey during a period of privatizations [45].

In 2002, Ghosh analyzed the causal link between electricity consumption and GDP in India, using Granger test on logarithmic-transformed data which corresponded to a period of 46 years [46]. Results uncovered a causal link running from GDP to electricity consumption. The same year, a trivariate analysis including EC, real GDP and energy prices was performed for Greece [47]. The study found EC and GDP to be endogenous, pointing out a bidirectional causal link between both variables in the short run and in the long run.

The same year, Glasure asserted that all previous studies were probably missing causality links due to the no inclusion in their analysis of other variables to account for monetary policy and prices [48]. Consequently, he used five-variable vector error correction to assess the causality relations in Korea. Besides GDP and EC, the author also included real government expenditure, real money supply and a dummy variable to account for periods of oil price shocks. Results revealed a feedback pattern connecting EC and GDP.

The following year, Soytas and Sari analyzed the relation between EC and GDP in all members of the G-7 group and in nine of the top ten emerging markets (China was excluded for data incompleteness). Analysis was performed using cointegration and vector error correction over the natural logarithms of the variables [49]. Turkey, France, Germany, and Japan exhibited a growth pattern, while conservation was valid for Italy and Korea. Argentina was the only country in the study to show a feedback behavior. The rest of the countries in the analysis matched the neutrality hypothesis.

Due to the unique circumstances of its rapid development, China have merited several studies. In 2004, Shiu and Lam investigated the relation between electricity consumption and economic growth in China, using Granger's method and an error-correction model (ECM). Results found a unidirectional causal link running from electricity consumption to GDP; therefore, the authors recommended to accelerate the interconnection of the electric networks to accelerate the country's economic development [50]. This finding would be later supported by some studies [51] and contradicted by others [52], [53]. In particular, the Wang study used a multivariate approach (including capital and labor) to find that the economic growth was a factor in the generation of energy consumption. On the other hand, Zhang and Yang used a modified version of Granger causality test (proposed by Toda and Yamamoto) to estimate the causal relations between EC and GDP in China. They found economic growth to be driving the aggregated energy consumption.

The same year, a study showed that changes in electricity consumption in Sri Lanka generated changes in GDP [54]. By contrast, a research in the neighboring country of India, using Engle-Granger cointegration with standard Granger causality test, found a bidirectional causal relation between EC and GDP [55]. This result departed from the unidirectionality found by Ghosh barely two years before [46].

In 2005, Lee applied heterogeneous panel cointegration and panel-based error correction to evaluate the long-term and short-term causal relations between EC and GDP in 18 underdeveloped countries from different regions across the world [56]. Results showed all countries in the study matching the growth hypothesis. Based on this result, the author posited that, in underdeveloped countries, energy consumption generates economic growth; consequently, the author discourages implementing energy conservation policies in developing countries because those policies may impair economic growth.

On the other hand, an interesting question would be posed by relation between both categories in countries with a surplus of energy resources. A study targeting the members of the Gulf Cooperation Council, which are countries that possess abundant reserves of oil, pointed to a unidirectional relation running from GDP to energy consumption for all those countries (Al-Iriani 2006). More recently, Ozturk analyzed the causal relation between EC and GDP in eleven Middle East and North African countries, using the Granger causality variation by Toda and Yamamoto (Ozturk 2017). The study is significant due to the role that many countries in the area play as major oil suppliers. Results uncovered causal links running from GDP to EC in three countries (Algeria, Morocco, and Saudi Arabia), causal link running from EC to GDP in four countries (Egypt, Iran, Lebanon, and Tunisia), no relation in two countries (Bahrain and Malta), and bidirectional direction in two countries (Oman and United Arab Emirates).

The following year, a study used cointegration and Hsiao (Granger causality test coupled with Akaike FPE) methods to evaluate whether links connecting EC and GDP are stronger for developing countries than for developed countries [57]. The authors were wary about the contradictory results obtained in many previous research of causality and attributed those divergences to the different methodologies used by those studies. To achieve consistency, they devised a systematic methodology that they applied to many countries. Results confirmed that a feedback pattern existed between EC and GDP. Contrary to prior expectations, causality relations were more prevalent in OECD countries than in non-OECD countries, and were also more frequent for more developed countries. These findings were valid independently of the direction of the causal link.

Two years later, Lee and Chang also questioned the premises of previous studies [58]. They extended the analysis to two groups of countries: one encompassing 22 developed countries and the other one formed by 18 underdeveloped countries. They argued that conflicting results obtained by previous researchers were due to those studies ignoring the external shocks into their models. To address the problem, their study included the detection of structural breaks for each country. They found bidirectional links connecting EC and GDP for the group of developed countries, and unidirectional relations from GDP to EC for the group of developing countries.

To assess the causal relations in 30 OECD countries, Narayan and Prasad used bootstrap simulations with optimal lag calculated by AIC, SBC, and HQC [12]. They found unidirectional GDP to EC link in only 2 countries (Finland and Hungary), unidirectional EC to GDP link in 5 countries (Australia, Czech Republic, Italy, Portugal, and Slovak Republic), and bidirectional relation in 4 countries (Iceland, Korea, Netherlands, and United Kingdom).

No causality links were found for the rest (19 countries). Their panel approach would be later extended to the study of 93 countries, which they grouped into five regions around the world [59]. They found bidirectionality in all regions except the Middle East, where EC was found to lead GDP.

In 2010, a multivariate analysis (including energy prices and total labor force) to estimate the long-run and short run causal relations between EC and GDP was performed for New Zealand [60]. They found the economic growth to be a generator of energy consumption. The same year, Acaravci and Ozturk targeted 15 countries from East Europe after the fall of the communism system. Results did not find cointegration in the variables [61].

In 2011, Apergis and Payne used multivariate panel cointegration test for 88 countries to determine whether causal relations between electricity consumption and GDP varied with country wealth [62]. Results showed feedback relations in the short run and in the long run for both high income countries and upper-middle countries. The relations were also feedback for the group of lower-middle income countries. On the other hand, growth relations were found in the short run for this group, and in both short run and long run for the group of low-income countries.

Using cointegration and vector error correction analysis for 22 small European countries, Žiković and Vlahinic-Dizdarević evaluated the causality links between oil consumption and GDP; comparing the countries (basically from East Europe) that were transitioning from central managed economies to market economies to those countries that were already developed [63]. They found that oil consumption led GDP in only one of the developed countries (Austria), while the same situation was detected in five of the developing countries (Bosnia Herzegovina, Bulgaria, Czech Republic, Malta, and Slovakia). No bidirectional link was detected. A limitation of the study was that only 14 years were available at the time for the study of the transitioning countries.

In the Latin American scenario, Campo and Sarmiento analyzed the relation between EC and GDP in 10 South American countries. Analysis was performed using Pedroni's heterogeneous panel cointegration test and Westerlund's heterogeneous panel cointegration test with detection of structural breaks. They found that all countries analyzed exhibited a feedback behavior with notable elasticity of the variables.

In the European scenario, a research used Vector Autoregression (VAR) and Granger causality test to determine whether causal relations existed between EC and GDP in Croatia [64]. Results showed a causality link running from EC to GDP. In another study, the causal relations between EC and GDP for five emerging European countries were analyzed using Granger test in a period of 33 years [65]. Results showed that, at the 5 percent significance level, a conservation pattern was observed for Hungary and a growth pattern was exhibited by Poland, while the rest of the countries (Bulgaria, Romania, and Turkey) fitted a neutrality behavior.

Finally, a recent work studied 186 countries to assess whether the relation between energy prices, urbanization level and economic growth on one hand, and electricity consumption on the other hand varied with a country wealth [66]. Countries were divided into three groups: high income countries, upper-middle income countries, and lower-middle income countries. Results pointed to a bidirectional relation between EC and GDP for all three groups. By contrast, urbanization level and EC were connected by a feedback relation in the high-income group and in the lower-middle income group, but the relation was neutral in the upper-middle income group. Finally, energy price led EC in all three groups, but that relation was negative in the high-income group and in the lower-middle income group, and positive in the upper-middle income group. All these findings from the literature review are summarized in Table B-1.

3.3 Methods and Collected Data

The analyses in this article are based on a thoroughly bibliographic search of studies connecting countries' economic growth and energy use, from the seminal article that started the discussion until studies performed in 2019 [10]. A very detailed bibliographic summary is presented in Table B-1. In total, 37 articles with actionable information were selected, encompassing a total of 613 country-level studies (i.e., the total amount of countries analyzed at different year spans across all studies in the articles referenced). The summary in Table B-1 includes: article reference, year when article was published, region (or group of countries) targeted by the study, country name, period of years studied, result obtained (i.e., which direction is the causality link), and methodology used by authors.

The information compiled was used to perform statistical analysis, including how often each causality link theory (neutrality, conservation, growth, or feedback) has been found across all the studies analyzed, and which relation predominates according to a country level of development. As a measure of a country level of development, we use the Human Development Index (HDI), which is officially maintained by the United Nations [23]. This nondimensional index, with values ranging from 0 as the minimum development and 1 as the maximum development, accounts for a country development in three areas or dimensions: the economic dimension (represented by the Gross National Income GNI), the educational dimension (represented by a Mean Years of Schooling MYS, which in turn combines educational attainment of the adult population and expected educational attainment of the pre-adult population), and the health dimension (represented by the Life Expectancy LE).

The United Nations also keeps track of an improved version of the HDI, the inequality-adjusted Human Development Index (IHDI). As may be inferred by its name, IHDI also considers how the three index dimensions are unequally distributed across a country population. This is done by applying Atkinson coefficients to the calculation of HDI, defined by the United Nations

Development Programme (UNDP) [23]. In that sense, IHDI provides a fairer assessment of how a country development reaches all segments of the population. Unfortunately, it is very difficult to perform time-sensitive analysis of how the EcSize and EnUse causality link varied with IHDI across the studies analyzed because the inequality factor was only considered after 2010, which provides too few years to make a reliable time. One option to overcome this problem is to try to figure out values of the Atkinson corrections for precedent years, but that would introduce unnecessary complexities and estimation errors that would endanger the validity of results; therefore, we preferred to use HDI (without the inequality factor) for our analysis, as this index will suffice to capture the historical relation between the EcSize and EnUse causality link and the country development.

Historical data of HDI for the vast majority of the world countries, encompassing all the years analyzed by the bibliographic references, were obtained from Our World in Data website [67]. As each reference performed their study over a period of years, the match between a country-level study published by a reference and the country's HDI at that time was performed using the country's HDI value corresponding to the middle year of the period analyzed by the study. Following the United Nations suggested classification, levels of human development are categorized into four groups: low human development (HDI < 0.550), medium human development (0.550 ≤ HDI < 0.700), high human development (0.700 ≤ HDI < 0.800), and very high human development (HDI ≥ 0.800).

3.4 Results and Discussion

An analysis of the bibliography summarized in Table 3-2, shows that 17.00 percent (104 country-studies) fit the neutrality theory, 12.56 percent (77 country-studies) supported the conservation theory, 15.99 percent (98 country-studies) matched the growth theory, and 54.49 percent (334 country-studies) favored the feedback theory. Therefore, bidirectionality seems to be the norm, as it is present in more than half of the studies. This suggests a virtuous circle in which access to energy enables future economic growth and in turn this growth creates conditions for additional energy demand. In total, 67.05 percent (411 country-studies) showed GDP in the causal side of the relation (either in a unidirectional link to EC or in a bidirectional relation) and 70.47 percent (432 country-studies) showed EC in the causal side (either in a unidirectional link to GDP or in a bidirectional relation). Interesting conclusions can be derived from the analysis of the potential relation between the EnUse and EcSize causality link and countries' development. This relation is shown in Figure 3-1.

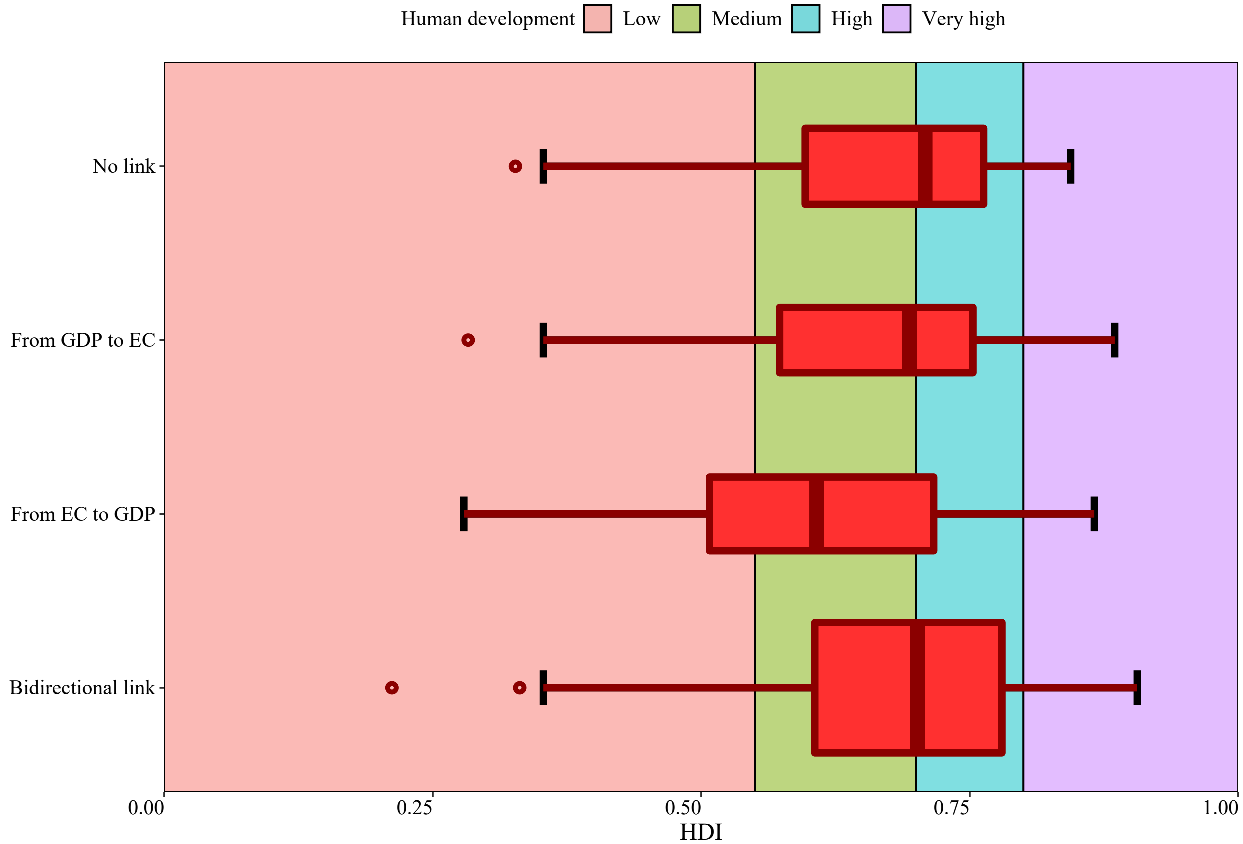

Figure 3-1 Statistical relation between the EnUse|EcSize causality link and HDI, based on 585 country-level studies in 35 articles (Table B-1). The horizontal axis represents values of the Human Development Index (HDI) for each country in the middle year of the period analyzed in their respective study. The vertical axis (categorical) groups the results of those studies into the four theories of EC-GDP links (either directly between EC and GDP, or between proxy variables). Vertical color stripes in the background are added to divide the full range of HDI values into categories of countries' human development (low, high, etc.). The width of the boxes is proportional to the number of observations that fell into each EC-GDP link. The length of the boxes delimits the range of HDI values between the 25 percentile and the 75 percentiles in each EC-GDP link. The line within each box marks the median HDI value for that particular EC-GDP link. The edges of each whisker delimit the range of HDI values between the minimum HDI and the maximum HDI for that particular EC-GDP link (with outliers removed). Outliers (values that are farther than 1.5 of the interquartile distance) are shown as individual points.

It is observed that the unidirectional causality link from EnUse to EcSize is the only one where the box enters into the range of low developed countries (the leftmost stripe), meaning that the 25-percentile limit is well within the low human development zone. While the median values for the other three links fall around the transition between medium and high human development, the median HDI value for the link from EnUse to EcSize is in the lower side of the medium category, not far from the transition to the low human development zone. This observation insinuates the important conclusion that, for many low-developed countries, the retrofit where EcSize precedes EnUse is basically absent, and that the development of those countries depends on policies destined to increase access to energy (and subsequently to foster energy consumption) to substantiate further economic growth. If those policies are implemented, the resulting economic growth will, in turn, foster future increases of their HDI, as the resulting wealth surplus can be invested in the other two dimensions of the index (education and health). Based on our analysis, we can foresee that, once those countries reach upper levels of human development, a retrofit link where EcSize precedes EnUse can appear in a substantial number of those countries, thus probably migrating to the bidirectional link group. This bidirectionality movement seems to be the trend and the development paradigm reached by the largest group of countries, with maximum value and 75 percentile value in the group being the greatest among all link groups.

In summary, Figure 3-1 supports the notion that access to energy is a requirement to the development of many countries, especially poor countries with the lowest HDI. Many of those countries tend to lack the infrastructure development to support the opposite link from EcSize to EnUse, and some others are developed but are also heavily dependent on energy consumption for that development.

The opposite link, when economic growth stimulates further energy consumption, tends to be favored by more developed countries. In fact, the situation that seems to prevail in most countries, including the ones with the highest human development, is that of mutual feedback, which leverages economic growth to stimulate energy consumption but also requires energy consumption to advance further development.

Here, we use energy use as a proxy for the phrase "access to energy". While the latest term may also include more social connotations (such as energy access fairly spread across all society sectors), the former is a parameter whose historical statistics are more readily available. Certainly, the spread of consumption will show an increase in the quantitative data of energy consumption.

3.5 Conclusions and Policy Implications

In this study, we analyzed the causality relations between energy use and economic growth through an extensive literature review, encompassing studies of many countries across the world over 50 years. It has been shown that the feedback relation (bidirectional link) has predominated in more than half of the country-level studies, with the other three theories in relatively equal proportions (conservation, growth, and no link). This identifies the bidirectional causality relation as the de-facto standard, with energy access being required for future economic growth and this economic growth setting favorable conditions for future energy demand.

An interesting observation is that the unidirectional link from energy use to economic growth appears more often, though not exclusively, when countries have a low level of development. On the other hand, when countries become more developed the opposite unidirectional link with economic growth leading future energy use tend to appear more often, but not exclusively. We may theorize that there are two stages in the timeline of a country development: an *extensive development* stage, in which improvement of all socioeconomic indicators tend to take place in connection to expanded energy use; and an *intensive development* stage, in which improvement tends to be based on better energy use rather than on expansion of energy consumption. Hence, for many countries increasing access to larger and reliable energy supply is a requirement for development and especially for many underdeveloped countries. We posit that increasing energy capacities of a country is a necessary step to develop the infrastructure needed for societal development, especially while countries are still in the *extensive development* stage. For example, reliable energy supply is needed to power other industries, which in turn will supply everything needed, both for internal consumption and to generate revenues by means of exports. Power is also needed to electrify homes, which in turn will open more communication channels for people, thus canalizing education.

These findings have major policy implications, especially for underdeveloped countries that still need to transit through both stages of development. Countries can time their investments for a planned societal development. While other variables can be added for a more detailed model (for example, to account for the development of a vial infrastructure), observations point to a clear precedence of energy infrastructure. Creating and expanding this energy infrastructure is necessary to incorporate more and more people, that were previously excluded, into the perks of society, thus increasing the tax base and the collective buying power. Benefits to people come both directly (by direct electricity supply to homes) and indirectly (by powering new industries to produce consumer goods). Social benefits, such as health benefits and education, are also outcomes since new energy infrastructure is needed to power new hospitals and educational institutions and to support hygiene in previously neglected communities.

4. DESIGN AND CHARACTERIZATION OF RIM FLOW FACILITY

4.1 Introduction on Refractive Index Matching

Many of the existing recirculating water tunnels are limited in function either in the maximum achievable speed or in the ability to fully visualize the flow. Though design solutions have been proposed for obtaining high Reynolds numbers at an affordable rate, the issue of visibility still exists [68]. On the other hand, refractive index matching (RIM) has been effectively used to allow visibility without reflections or distortion between the liquid, container, or flow model [69]. This method makes it possible to view flows inside models or very near the surface. However, current RIM facilities function at a Reynolds number just above the laminar to turbulent regimen: a value on the order of 10^3. Therefore, there is a need to resolve the flow in the viscous sub layer while achieving high Reynolds numbers.

The use of a water-glycerin-salt solution has a refractive index match with PDMS. Bocanegra and Castillo use that phenomena on a trachea model with cartilaginous rings, in this matter a flow with a Reynolds number of 2800 was visible inside the model using particle imaging velocimetry (PIV) [70]. Refractive index matching can also be used to visualize flow near the surface of a model, at a Reynolds number of 1200 with PIV a micro surface was shown to reduce recirculation regions along a surface [6]. Blois et al also used sodium iodide solution for a versatile refractive index matched flow facility with flow speeds below 1 m/s [71].

The chapter focuses on the construction of a RIM flow facility that can achieve turbulent Reynolds numbers. The design choices and required materials for building the facility to specification are discussed. Also covered is the preliminary testing for ensuring leak resistance. Finally, computational, and experimental studies were done to determine the expected flow rate in the water tunnel at any given input.

4.2 Design and Equations

The working fluid in a refractive index matching flow facility will be NaI, as this fluid is corrosive and sensitive to air many design choices were decided on to match the fluids needs. A major example of this is in choose non-corrosive components such as PVC, fiberglass, and 316 stainless steel. Other design requirements came from the need to accommodate higher test speeds and have a long enough test section to achieve a uniform flow. Figure 4-1 provides an image of the completed construction of the flow facility.

The overall circulation is mainly constructed from standard PVC straight pipe and flanges, and supported with black anodized 8020. A 6-inch diameter pipe leads up and out of the pump, followed by a contraction and test section. Immediately following a custom diffuser connects to a 6-inch pipe on the top section and then opens to 8-inch PVC which leads down the left side of the facility and back into the pump. The pump was chosen to achieve the desired flow rates; an end-suction centrifugal pump (60951 LF from Grundfos). The maximum flow rate is 12000 gpm with an 8-inch inlet and 6-inch outlet.

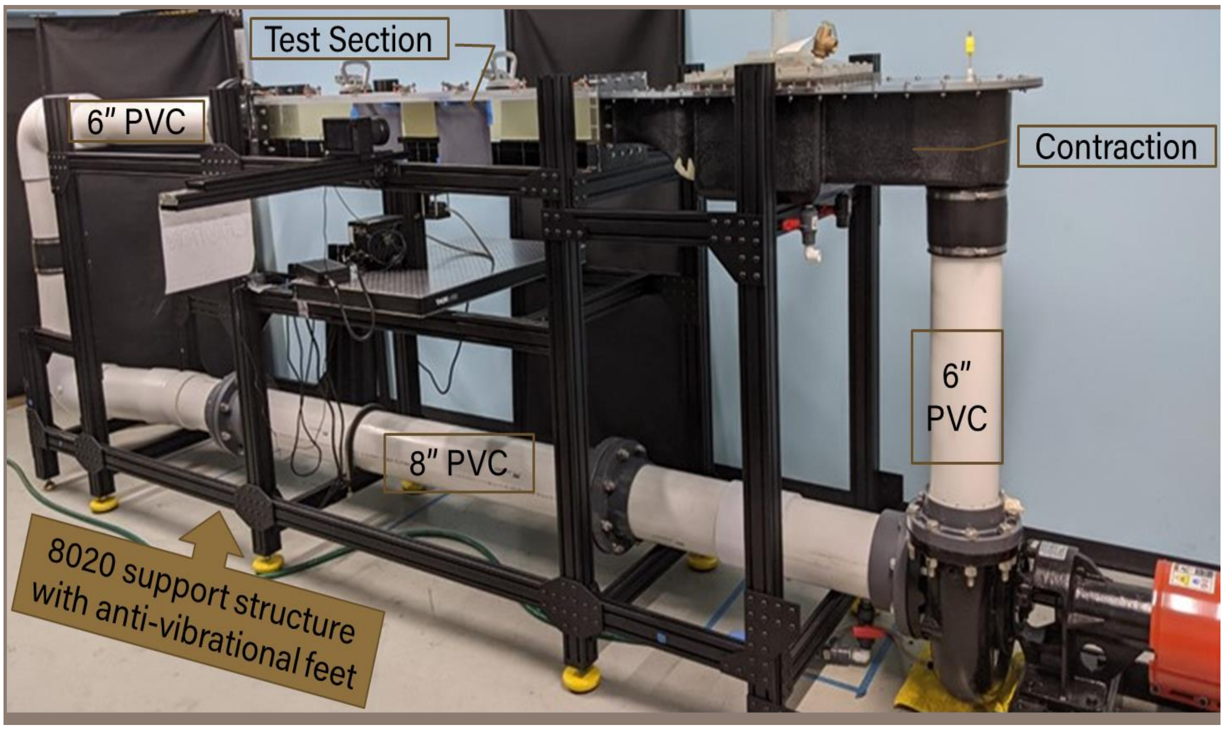

Figure 4-1 Overall construction of the refractive index matching (RIM) flow facility. The circulation mainly made of PVC pipe and is supported with an 8020 structure.

The fluid flows into a contraction above the pump outlet. This section serves to create a uniform flow by decreasing turbulence intensity, also increasing the speed of the flow. Commissioned through Engineering Laboratory Design (ELD) the contours were developed analytically to achieve the desired result with an area ratio of 4.375:1. The surfaces of the contraction are made of composite lamination of fiber glass reinforce plastic and coated with black vinyl-ester gel-coat for a smooth finish. The top of the contraction is 0.50-inch clear acrylic and sealed with marine polysulfide sealant. For draining there are two PVC ball valves on the lowest point of the contraction. A pressure relief valve and thermocouple are also included in the design.

Within the contraction there is a series of flow conditioning screens, shown in Figure 4-2. The fluid flow is initially distributed through a perforated cylinder with 9/16-inch diameter circular openings. Flowing upstream there is a 3-inch-long round cell polycarbonate plastic honeycomb followed by a 24 M Nylon screen, a 0.50-inch PVC perforated plate followed by a 34 M nylon screen, and finally a 44M nylon screen. Each of the three screen sections are capable of being taken out for easy cleaning and maintenance by removing the cupola held in place with 0.25-inch stainless steel bolts.

Figure 4-2 Flow conditioning sections. A is a PVC distribution pipe with 9/16" holes, B is the 3" long ¼" Polycarbonate honeycomb and 24 mesh nylon screen, C is the ½" PVC perforated plate followed by a 34 mesh nylon screen, and D is the 44 mesh nylon screen

Immediately following the contraction, the fluid flows into the test section. The test section is made with 0.75-inch-thick clear acrylic with a 0.50-inch thickness for the lid. The length is 1.5 meters (~59 inches) with acrylic flanges at each end of the test section. The cross-sectional area is a square with length and width equal to 11.25 cm (4.43 inches). The top of the test section is removable sealed with an EPDM gasket and secured by stainless steel horizontal hold down clamps. Therefore, there is full access to the interior of the tunnel so that flow models can be easily installed.

As the flow is between two nonmoving surfaces a Reynolds number for half of the test section height ($Re_{H/2}$) is used as shown in Equation 4-3. Where *U* is the velocity of the fluid, *H* is the height of the test section, and *v* is the kinematic viscosity of the fluid. In this case the fluid is water.

$$Re_{H/2} = \frac{UH/2}{\nu} \qquad \text{Equation 4-1}$$

To convert the expected volumetric flow rate to velocity Equation 4-2 was used. Where *Q* is the volumetric flow rate and *A* is the cross-sectional area of the pump outlet.

$$V = \frac{Q}{A} \qquad \text{Equation 4-2}$$

For the particle image velocimetry (PIV) experimental setup an iLA 5150 LED pulsing system (LPS 3 unit) is used to create a light sheet. The camera used to capture the images is a Chronos 1.4 with Nikon 24mm F1.4 AS IF UMC lens. To obtain the desired image quality the camera is set at a resolution of 1280 by 1024 pixels and 1069 fps at a focal length of 0.5m and the aperture at the lowest setting. Finally, the light is scattered using 9-13µm glass spheres from Sigma Aldrich.

The ability for the spheres to follow the fluid flow was checked using stokes number (*Stk*), Equation 4-3. Where τ is relaxation time of the particle, *U* is the velocity of the fluid, and d_c is the characteristic dimension which for this instance is *H* the height of the test section.

$$Stk = \frac{\tau U}{d_C} \qquad \text{Equation 4-3}$$

Relaxation time for the particle is obtained from Equation 4-4, where the subscript designates particle (*p*) or fluid (*f*), ρ is density, *D* is diameter, and μ is dynamic viscosity.

$$\tau = \frac{(\rho_p - \rho_f) D_p^2}{18\mu_f} \qquad \text{Equation 4-4}$$

4.3 Simulations

Preliminary analysis on the flow rate in the test section was done on ANSYS Fluent. Only the first section of the circulation was used for the model: the 6-inch outlet from the pump, to the contraction, into the test section. The flow straighteners were excluded from the model, thus resulting in a less streamline flow. Table 4-1 relates the rated pump flow to an initial velocity using Equation 4-1.

Table 4-1 The relation between percent output to the expected initial velocity. Where the output is designated by the user on the VFD and initial velocity is from the 6" pump outlet.

Output [%]	**Q [gpm]**	**Velocity [m/s]**
100%	1200	3.4040
90%	1080	3.0636
80%	960	2.7232
70%	840	2.3828
60%	720	2.0424
50%	600	1.7020
40%	480	1.3616
30%	360	1.0212
20%	240	0.6808
10%	120	0.3404
5%	60	0.1702
1%	12	0.0340
0%	0	0.0000

Computational models are then created on ANYSYS Fluent based on the initial expected velocity from the pump into the test section. A course mesh was used with a total of 45000 elements, this mesh was small enough to resolve any errors withing the model. Figure 4-3 displays the results in Fluent for the maximum initial velocity.

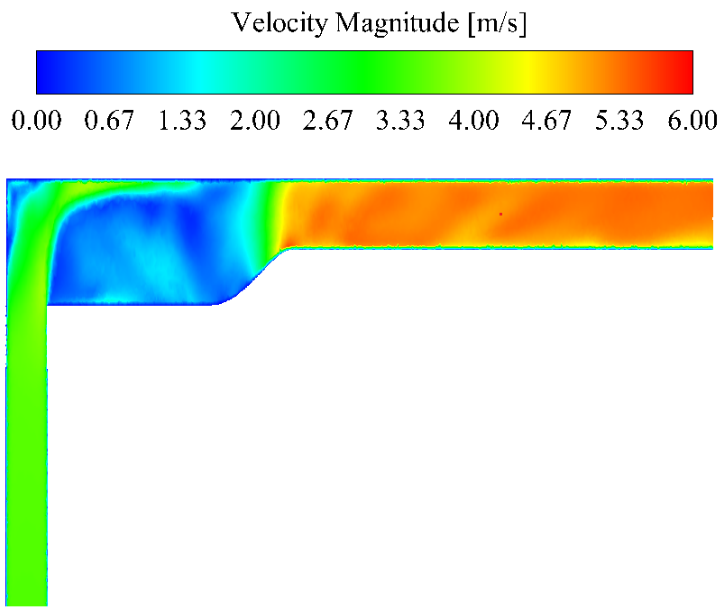

Figure 4-3 Computational result of the test section velocity with maximum possible pump output.

The maximum velocity found with the simulation for the test section is 5.57 m/s. This velocity would relate to an $Re_{H/2}$ of 3.12E05. Looking specifically at the very center of the test section, 0.75m in from the end of the contraction and 0.05625m from the test section wall, a velocity was obtained to be compared to the experimental results.

4.4 Experimental Results

Particle image velocimetry (PIV) is set up to capture the fluid flow in the test section experimentally. An iLA 5150 LED pulsing system is used to create a light sheet at the center of the test section with the camera set up to capture a window illuminated by the light sheet. Figure 4-4 shows the PIV set up with the window of interested block off with black paper. The field of view (FOV) for the camera images is just over half the test section with the following dimensions: 0.160 m long and 0.074 m wide, portrayed in Figure 4-5. Therefore, the flow is captured from the bottom to slightly above the centerline of the test section.

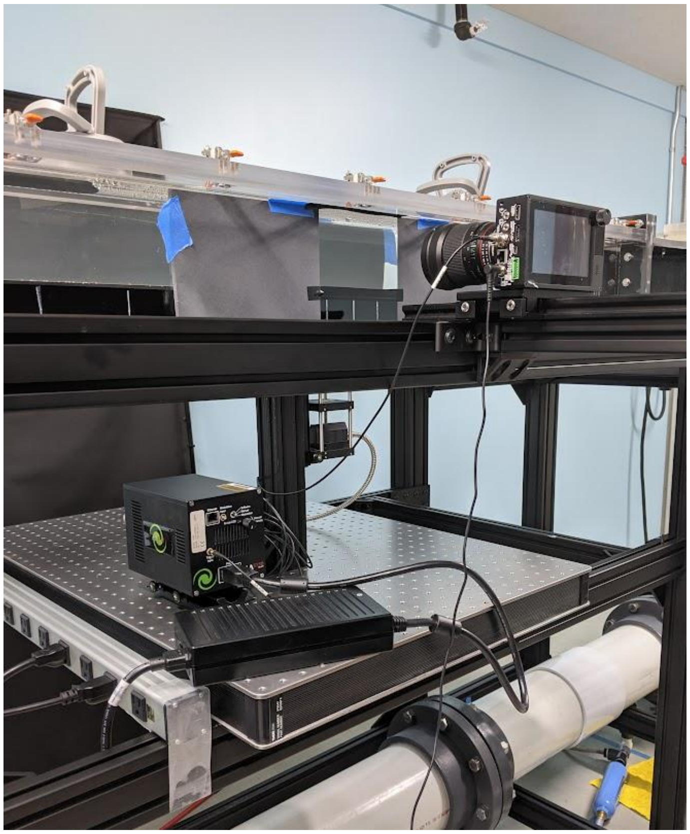

Figure 4-4 PIV setup of a chronos camera and iLA5150 LED Pulsing System and viewing window on test section blocked off.

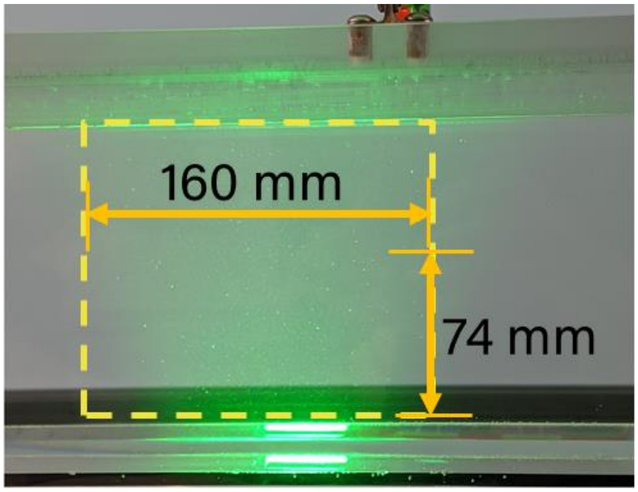

Figure 4-5 Test section is marked by the dotted lines and the dimensions for the field are view are given, at a length of 160 mm and a width of 74mm.

There were a few limitations in testing various outputs for the test section velocity. First, the variable-frequency drive (VFD), used to control the pump motor speed, was set up such that the input could not exceed 30 percent of the max output. Secondly, due to the system sitting inactive with water the pump oxidized resulting in unwanted particles in the system.

These existing particles interfere with the quality of the images above an initial flow speed from the pump at 1 m/s. Therefore, the integration window used to analysis those frames were 128 px by 128 px with 50 percent overlap. Standard cross-correlation methods were used in PIVTEC program. For a motor speed of 1 percent, the interrogation used was 128 px by 128 px with a 16 by 16 step size. For each output a total of 500 images were analyzed, with each mean velocity recorded to be compared to the computational test section velocities.

Figure 4-6 shows the results for three of the five velocity tests, each labeled by the percent used on the VFD corresponding to the expected velocity out of the pump. The contour graphs have a uniform velocity throughout the FOV and the local velocity line graphs, taken from the center of the view, reinforce that uniformity as the range is at most 0.05. For this reason, the mean velocities can be used in creating a calibration curve to relate the user VFD input to the expected fully developed flow velocity in the test section.

The VFD percent output was then compared to both the measured velocities and the computational results. Figure 4-7 compares the curves of the both the PIV and Fluent results to obtain a calibration curve to be used for future operation. The experimental model does not have any resistance as the motor speed is increased and the velocity steadily increases. On the other hand, the experimental results have a smaller slope with the consideration of the return to the pump and the additionally elbows the flow encounters prior. Looking at the graph, it is seen that 1 m/s can be expected at a VFD value of 18. Using the linear curve fit the expected maximum velocity for the experimental results is about 5 m/s in the test section. This maximum value corresponds to a Reynolds number around 3E5.

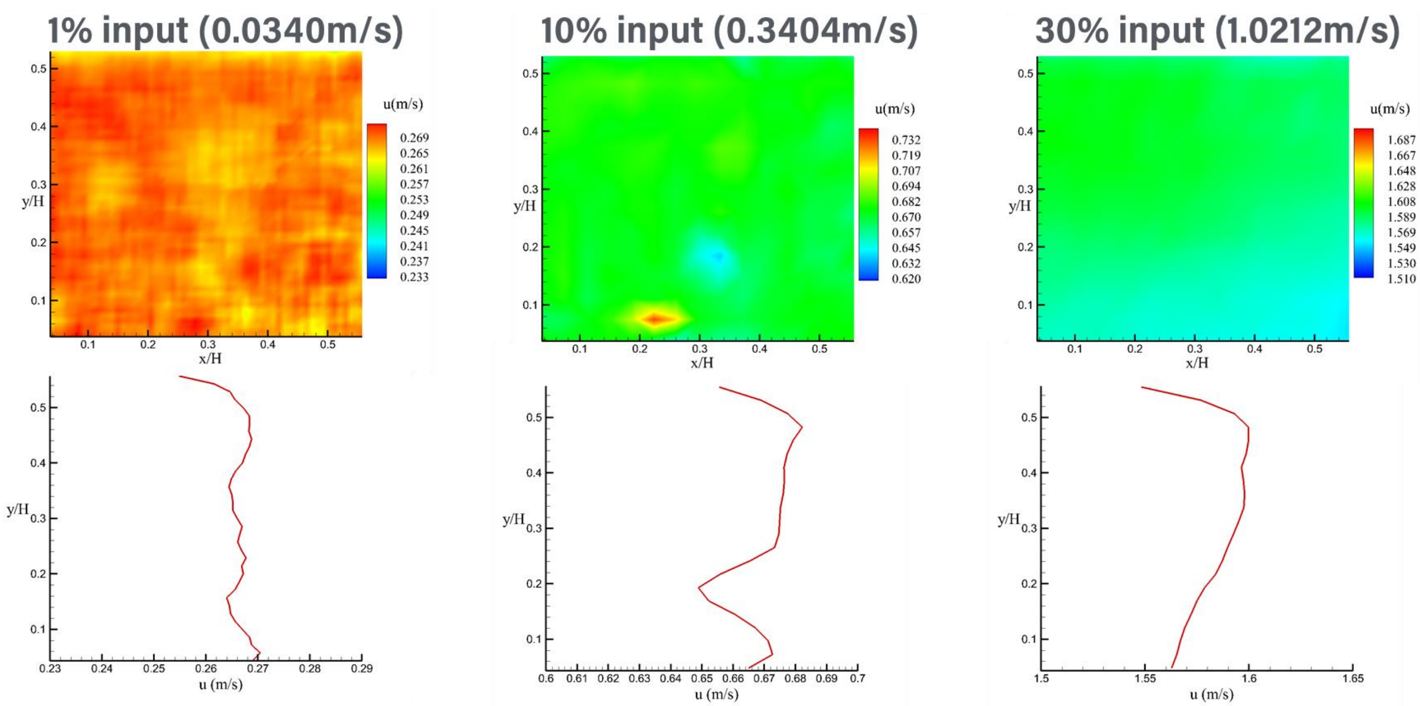

Figure 4-6 PIV contours and local velocity at center of view, there is minimal variance throughout the velocity vectors showing a uniform flow.

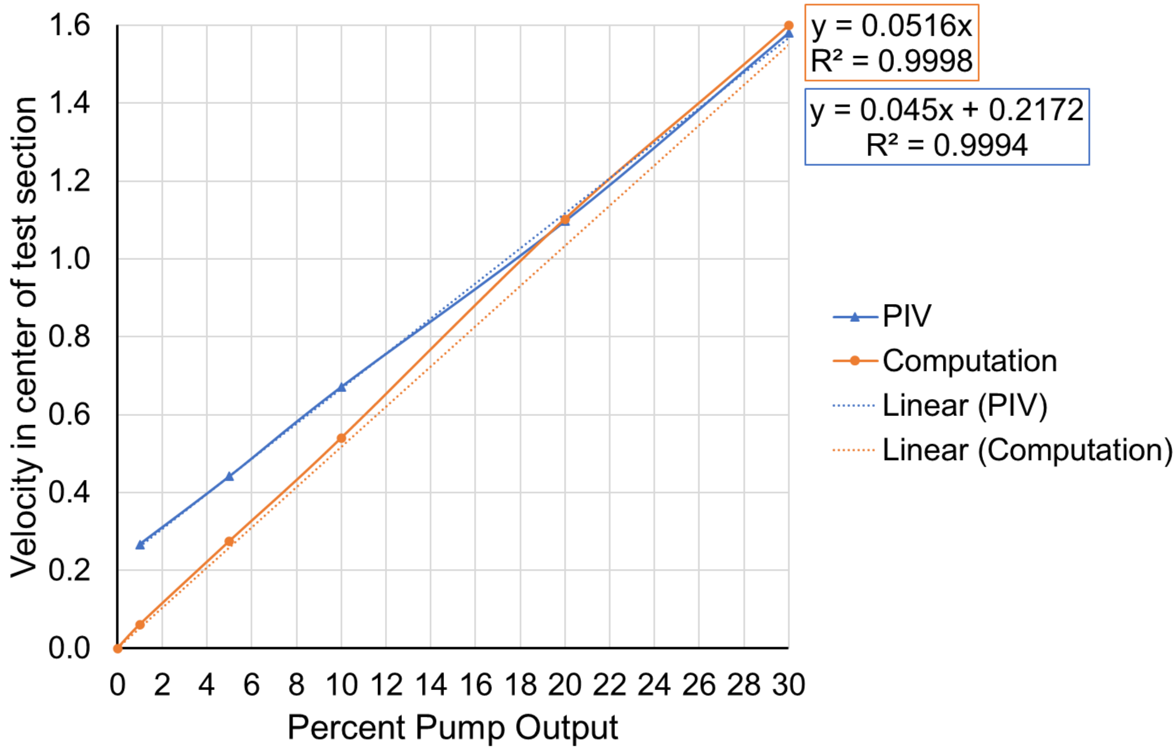

Figure 4-7 Calibration curve relating percent input to velocity in the center of the test section.

4.5 Conclusion on RIM Facility

A refractive index matching flow facility was designed and constructed that will be able to achieve Reynolds numbers on the order of 10^5. Thorough testing has been done to ensure the facility is leak proof and capable of withstanding the loads placed on the system. The ANSYS model and experimental model are in good agreement and show a generally linear trend between the motor speed and the velocity experienced in the test section.

Future users will be able to relate the percent input on the VFD to the expected flow within the test section with the establish calibration curve. It is seen that around 20 percent of the motor speed the velocity in the test section is expected to be at 1 m/s. Additionally, that at the center of the test section the flow is uniform at all the tested velocities. Currently, only water has been used for the testing and therefore some additional setup will be required for the addition of the sodium iodine solution.

To fully achieve the refractive index matching potential, certain design changes are recommended. First and foremost, the pump will need to be replaced or coated with a non-corrosive material. The current use of tap water has already caused significant corrosion in which rust particles are consistently present in the overall flow. Secondly, as the highest point in the circulation is in the opposite side of the pump it is recommended that an additional valve be added to that side for even filling or emptying. Lastly, nitrogen will be required to protect the sensitive sodium iodine solution during filling and emptying of the system.

5. CONCLUSION

Energy and human development have a clear link, however the exact causality between base indicators is inconclusive. It is evident that lower developed countries have a lack of renewable sources and would benefit from policies that provide energy for the entire population. Policy makers can focus on the direct effects of infrastructure with clean energy resources, the population would have decreased greenhouse gas which in turn provided cleaner air for all., Also medical and educational buildings could have more utility through increase energy and thus improve health and education metrics. Ultimately access to energy effects all aspects of human development.

It is farther proven that statistically countries with low human development would benefit most from a growth theory. Specifically, access to energy is a requirement for development in low HDI countries. Though developed countries are seen to predominantly exhibit a feedback behavior between energy and economic growth, it is still evident that energy consumption is required to advance further development.

Additionally, improvements need to be made to aid in energy expenditure. Possible methods include reducing the separation point on wind turbine airfoils to increase its efficiency, providing a self-cleaning surface on the airfoils or on solar panels, reduce drag on trucks and improve transportation efficiency. The construction of the flow facility and understanding its capabilities will allow future user to make informed decisions for experimental testing. Therefore, the RIM facility will allow studies to be done on novel surfaces focusing on the near wall effect and how those changes create significant improvements in large scale applications.

The understanding on how energy and specifically clean renewable energy can benefit populations is necessary to promote policies within countries. Then increased efficiency of existing technology allows increased energy to all areas in the world. It is also significant to create these energy solutions to be accessible such that the countries in most need can benefit from them.

APPENDIX A. COUNTRY CODES AND REGION

Table A-1 List of countries and 3 letter ISO code by region

AFRICA	MIDDLE EAST
CENTRAL AND SOUTH AMERICA	EURASIA
	EUROPE
ASIA & OCEANIA	NORTH AMERICA

Caribbean	Dominican Republic	DOM
Caribbean	Haiti	HTI
Caribbean	Jamaica	JAM
Caribbean	Trinidad and Tobago	TTO
Central	Costa Rica	CRI
Central	El Salvador	SLV
Central	Guatemala	GTM
Central	Honduras	HND
Central	Nicaragua	NIC
Central	Panama	PAN
South	Argentina	ARG
South	Bolivia	BOL
South	Brazil	BRA
South	Chile	CHL
South	Colombia	COL
South	Ecuador	ECU
South	Peru	PER
South	Suriname	SUR
South	Uruguay	URY
Central	Cameroon	CMR
Central	Democratic Republic of the Congo	COD
Central	Gabon	GAB
East	Ethiopia	ETH
East	Kenya	KEN
East	Mauritius	MUS
East	Mozambique	MOZ
East	United Republic of Tanzania	TZA
East	Zimbabwe	ZWE
North	Egypt	EGY
North	Morocco	MAR
South	Namibia	NAM
West	Benin	BEN
West	Côte d'Ivoire	CIV
West	Ghana	GHA
West	Niger	NER
West	Nigeria	NGA
West	Senegal	SEN
West	Togo	TGO
East	Mongolia	MNG
East	Republic of Korea	KOR
South	Bangladesh	BGD
South	India	IND
South	Nepal	NPL
South	Pakistan	PAK
South	Sri Lanka	LKA
South	Cambodia	KHM
South	Indonesia	IDN
South	Philippines	PHL
South	Thailand	THA
	Australia	AUS

Central	Kazakhstan	KAZ
Central	Kyrgyzstan	KGZ
Central	Tajikistan	TJK
West	Armenia	ARM
West	Azerbaijan	AZE
West	Georgia	GEO
West	Israel	ISR
West	Jordan	JOR
West	Lebanon	LBN
West	Syrian Arab Republic	SYR
West	Cyprus	CYP
West	Turkey	TUR
East	Bulgaria	BGR
East	Czech Republic	CZE
East	Hungary	HUN
East	Poland	POL
East	Romania	ROU
East	Slovakia	SVK
East	Belarus	BLR
East	Moldova	MDA
East	Ukraine	UKR
North	Estonia	EST
North	Latvia	LVA
North	Lithuania	LTU
North	Denmark	DNK
North	Finland	FIN
North	Iceland	ISL
North	Norway	NOR
North	Sweden	SWE
South	Albania	ALB
South	Bosnia and Herzegovina	BIH
South	Croatia	HRV
South	Greece	GRC
South	Italy	ITA
South	Macedonia	MKD
South	Montenegro	MNE
South	Portugal	PRT
South	Serbia	SRB
South	Slovenia	SVN
South	Spain	ESP
West	Austria	AUT
West	Belgium	BEL
West	France	FRA
West	Germany	DEU
West	Luxembourg	LUX
West	Netherlands	NLD
West	Switzerland	CHE
Bristish Isles	Ireland	IRL
Bristish Isles	United Kingdom	GBR

APPENDIX B. BIBLIOGRAPHIC SUMMARY OF CAUSALITY LINKS

STUDY		TARGET		Years			HYPOTHESIS				METHODOLOGY
REFERENCE	YEAR	REGION / GROUP	COUNTRY	From	To	Diff.	NEUTRALITY (NO LINK)	CONSERVATION $EC \longleftarrow GDP$	GROWTH $EC \longrightarrow GDP$	FEEDBACK $EC \rightleftarrows GDP$	
(Kraft and Kraft 1978)	1978		United States	1947	1974	27		x			Sim's test
(Akarca and Long 1980)	1980		United States	1947	1972	25	x				Sim's test
(Yu and Hwang 1984)	1984		United States	1947	1979	32	x				Sim's test
(Yu and Choi, The Causal Relationship Between Energy and GNP: An International Comparison 1985)	1985	Five countries in heterogeneous states of development	United States	1947	1979	32	x				Sim's test and Granger test
			United Kingdom	1950	1976	26	x				
			Poland				x				
			Philippines						x		
			South Korea	1954	1976	22		x			
(Erol and Yu 1987)	1987	Six major industrialized countries	Japan	1950	1982	32				x	Granger test
			Italy					x			
			West Germany					x			
			France				x				
			United Kingdom				x				
			Canada						x		
			Japan	1952	1982	30		x			
			Italy				x				
			Japan	1950	1973	23		x			
			Italy				X				
			West Germany				X				
			France				X				
			United Kingdom						x		
			Canada				x				
(Abosedra and Baghestani 1989)	1989		United States	1947	1972	25		x			Granger test

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \longleftarrow GDP$	Growth $EC \longrightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
				1947	1974	27		X			
				1947	1979	32		X			
				1947	1987	40		x			
(Hwang and Gum 1991)	1991		Taiwan							x	Granger test with Akaike criteria
(Yu and Jin, Cointegration Tests of Energy Consumption, Income, and Employment 1992)	1992		United States	1974	1990	16	x				Cointegration test with monthly data
				1974	1981	7	x				
				1981	1990	9	x				
(Masih and Masih 1996)	1996	Six Asian countries	India	1955	1990	35			x		Johansen's multivariate cointegration and dynamic vector error-correction model
			Pakistan	1955	1990	35				x	
			Indonesia	1960	1990	30		x			
			Malaysia	1955	1990	35	x				
			Singapore	1960	1990	30	x				
			Philippines	1955	1991	36	x				
(Yang 2000)	2000		Taiwan	1954	1997	43				x	Granger test with Akaike criterion
(Asafu-Adjaye 2000)	2000	Asian developing countries	India	1973	1995	22			x		Cointegration and vector error correction analysis
			Indonesia	1973	1995	22			x		
			Philippines	1971	1995	24				X	
			Thailand	1971	1995	24				x	
(Soytas, Sari and Ozdemir 2001)	2001		Turkey	1960	1995	35			x		Cointegration and vector error correction analysis
(Aqeel and Butt 2001)	2001		Pakistan	1956	1996	40		x			Cointegration and Hsiao's Granger causality
(Ghosh 2002)	2002		India	1951	1997	46		x			Granger test with logarithmic transformation of the data
(Hondroyiannis, Lolos and Papapetrou 2002)	2002		Greece	1960	1996	36				x	Trivariate with vector error-correction model
(Glasure 2002)	2002		Korea	1961	1990	29				x	Five-variable vector error correction
	2003		Turkey	1950	1992	42			x		

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \leftarrow GDP$	Growth $EC \rightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
(Soytas and Sari, Energy consumption and GDP: causality relationship in G-7 countries and emerging markets 2003)		G-7 and 9 of the top ten emerging markets	France	1950	1992	42			x		Cointegration and vector error correction with natural logarithms of the variables
			Germany	1950	1992	42			x		
			Japan	1950	1992	42			x		
			Italy	1950	1992	42		x			
			Korea	1953	1991	38		x			
			Argentina	1950	1990	40				x	
			Canada	1950	1992	42	x				
			United Kingdom	1950	1992	42	x				
			United States	1950	1992	42	x				
			Brazil	1950	1992	42	x				
			India	1950	1992	42	x				
			Indonesia	1960	1992	32	x				
			Mexico	1950	1992	42	x				
			Poland	1965	1994	29	x				
			South Africa	1950	1992	42	x				
(Shiu and Lam 2004)	2004		China	1971	2000	29			x		Granger's method (1988) and an error-correction model (ECM)
(Morimoto and Hope 2004)	2004		Sri Lanka	1960	1998	38			x		Granger test
(Paul and Bhattacharya 2004)	2004		India	1950	1996	46				x	Engle-Granger cointegration with standard Granger causality test
(Al-Iriani 2006)	2005	Gulf Cooperation Council	Kuwait	1971	2002	31		x			Panel cointegration and dynamic panel causality
			Oman	1971	2002	31		x			
			Saudi Arabia	1971	2002	31		x			
			Bahrain	1971	2002	31		x			
			United Arab Emirates	1971	2002	31		x			
			Qatar	1971	2002	31		x			
(Lee 2005)	2005	East Asia	South Korea	1975	2001	26			x		

Study		**Target**		Years			**Hypothesis**				**Methodology**
Reference	**Year**	**Region / Group**	**Country**	From	To	Diff.	**Neutrality (no link)**	**Conservation** $EC \longleftarrow GDP$	**Growth** $EC \longrightarrow GDP$	**Feedback** $EC \rightleftarrows GDP$	
			Singapore	1975	2001	26			x		
		East Europe and Central Asia	Hungary	1975	2001	26			x		
			Argentina	1975	2001	26			x		
			Chile	1975	2001	26			x		
		Latin America	Colombia	1975	2001	26			x		
			Mexico	1975	2001	26			x		
			Peru	1975	2001	26			x		
			Venezuela	1975	2001	26			x		Heterogeneous panel cointegration and panel-based error correction
			Indonesia	1975	2001	26			x		
		Southeast Asia	Malaysia	1975	2001	26			x		
			Philippines	1975	2001	26			x		
			Thailand	1975	2001	26			x		
			India	1975	2001	26			x		
		South Asia	Pakistan	1975	2001	26			x		
			Sri Lanka	1975	2001	26			x		
		Sub-Saharan Africa	Ghana	1975	2001	26			x		
			Kenya	1975	2001	26			x		
			Australia	1960	2000	40		x			
			Austria	1960	2000	40			x		
			Belgium	1960	2000	40			x		
			Canada	1960	2000	40		x			
(Chontanawat, Hunt and Pierse 2006)	2006	30 OECD countries	Czech Republic	1971	2000	29			x		Cointegration and Hsiao (Granger coupled with Akaike FPE)
			Denmark	1960	2000	40			x		
			Finland	1960	2000	40		x			
			France	1960	2000	40				x	
			Germany	1960	2000	40				x	

Study		**Target**		Years			**Hypothesis**				**Methodology**
Reference	**Year**	**Region / Group**	**Country**	From	To	Diff.	**Neutrality (no link)**	**Conservation** $EC \longleftarrow GDP$	**Growth** $EC \longrightarrow GDP$	**Feedback** $EC \rightleftarrows GDP$	
			Greece	1960	2000	40				x	
			Hungary	1965	2000	35				x	
			Iceland	1965	2000	35				x	
			Ireland	1960	2000	40			x		
			Italy	1960	2000	40				x	
			Japan	1960	2000	40				x	
			Korea	1971	2000	29			x		
			Luxembourg	1960	2000	40	x				
			Mexico	1971	2000	29			x		
			Netherlands	1960	2000	40			x		
			New Zealand	1960	2000	40				x	
			Norway	1960	2000	40				x	
			Poland	1960	2000	40			x		
			Portugal	1960	2000	40				x	
			Slovakia	1971	2000	29				x	
			Spain	1960	2000	40		x			
			Sweden	1960	2000	40		x			
			Switzerland	1960	2000	40				x	
			Turkey	1960	2000	40	x				
			United Kingdom	1960	2000	40	x				
			United States	1960	2000	40	x				
			Albania	1971	2000	29		x			
			Algeria	1971	2000	29		x			
		78 non-OECD countries	Angola	1971	2000	29				x	
			Argentina	1971	2000	29				x	
			Bahrain	1971	2000	29	x				
			Bangladesh	1971	2000	29			x		

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \longleftarrow GDP$	Growth $EC \longrightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			Benin	1971	2000	29	x				
			Bolivia	1971	2000	29		x			
			Brazil	1971	2000	29				x	
			Brunei	1971	2000	29				x	
			Bulgaria	1971	2000	29		x			
			Cameroon	1971	2000	29	x				
			Chile	1971	2000	29			x		
			China	1971	2000	29	x				
			Colombia	1971	2000	29			x		
			Congo	1971	2000	29	x				
			Congo Republic	1971	2000	29			x		
			Costa Rica	1971	2000	29		x			
			Cote d'Ivoire	1971	2000	29	x				
			Cuba	1971	2000	29		x			
			Cyprus	1971	2000	29			x		
			Dominican Republic	1971	2000	29			x		
			Ecuador	1971	2000	29	x				
			Egypt	1971	2000	29			x		
			El Salvador	1971	2000	29		x			
			Ethiopia	1971	2000	29		x			
			Gabon	1971	2000	29	x				
			Ghana	1971	2000	29				x	
			Gibraltar	1971	2000	29				x	
			Guatemala	1971	2000	29				x	
			Haiti	1971	2000	29	x				
			Honduras	1971	2000	29	x				
			Hong Kong	1971	2000	29	x				

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \longleftarrow GDP$	Growth $EC \longrightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			India	1971	2000	29	x				
			Indonesia	1971	2000	29	x				
			Iran	1971	2000	29				x	
			Iraq	1971	2000	29	x				
			Israel	1971	2000	29			x		
			Jamaica	1971	2000	29	x				
			Jordan	1971	2000	29				x	
			Kenya	1971	2000	29			x		
			Kuwait	1971	2000	29				x	
			Lebanon	1971	2000	29				x	
			Libya	1971	2000	29	x				
			Malaysia	1971	2000	29	x				
			Malta	1971	2000	29	x				
			Morocco	1971	2000	29				x	
			Mozambique	1971	2000	29				x	
			Myanmar	1971	2000	29				x	
			Nepal	1971	2000	29			x		
			Nicaragua	1971	2000	29	x				
			Nigeria	1971	2000	29	x				
			Oman	1971	2000	29			x		
			Pakistan	1971	2000	29	x				
			Panama	1971	2000	29		x			
			Paraguay	1971	2000	29		x			
			Peru	1971	2000	29		x			
			Philippines	1971	2000	29			x		
			Qatar	1971	2000	29				x	
			Romania	1971	2000	29				x	

Study		**Target**		Years			**Hypothesis**				**Methodology**
Reference	**Year**	**Region / Group**	**Country**	From	To	Diff.	**Neutrality** (no link)	**Conservation** $EC \longleftarrow GDP$	**Growth** $EC \longrightarrow GDP$	**Feedback** $EC \rightleftarrows GDP$	
			Saudi Arabia	1971	2000	29		x			
			Senegal	1971	2000	29	x				
			Singapore	1971	2000	29	x				
			Sri Lanka	1971	2000	29	x				
			Sudan	1971	2000	29				x	
			Taiwan	1971	2000	29				x	
			Tanzania	1971	2000	29	x				
			Thailand	1971	2000	29		x			
			Togo	1971	2000	29	x				
			Trinidad Tobago	1971	2000	29				x	
			Tunisia	1971	2000	29				x	
			United Arab Emirates	1971	2000	29				x	
			Uruguay	1971	2000	29			x		
			Venezuela	1971	2000	29		x			
			Vietnam	1971	2000	29			x		
			Yemen	1971	2000	29				x	
			Zambia	1971	2000	29	x				
			Zimbabwe	1971	2000	29		x			
(Lee and Chang, Energy consumption and GDP revisited: A panel analysis of developed and developing countries 2007)	2007	22 developed countries	Australia	1965	2002	37				x	Structural breaks, panel VARs and GMM
			Austria								
			Belgium								
			Canada								
			Denmark								
			Finland								
			France								
			Germany								
			Iceland								

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \longleftarrow GDP$	Growth $EC \longrightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			Ireland								
			Italy								
			Japan								
			Luxembourg								
			Netherlands								
			New Zealand								
			Norway								
			Portugal								
			Spain								
			Sweden								
			Switzerland								
			United Kingdom								
			United States								
		18 developing countries	Argentina	1971	2002	31		x			
			Chile								
			Colombia								
			Ghana								
			India								
			Indonesia								
			Kenya								
			Malaysia								
			Mexico								
			Nigeria								
			Pakistan								
			Peru								
			Philippines								
			Singapore								

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \longleftarrow GDP$	Growth $EC \longrightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			Sri Lanka								
			Thailand								
			Turkey								
			Venezuela								
(Yuan, et al. 2007)	2007		China	1978	2004	26			x		Cointegration theory
(Narayan and Prasad 2008)	2008	30 OECD countries	Australia	1960	2002	42			x		Bootstrap simulations with optimal lag by AIC, SBC, and HQC
			Austria	1960	2002	42	x				
			Belgium	1960	2002	42	x				
			Canada	1960	2002	42	x				
			Czech Republic	1960	2002	42			x		
			Denmark	1960	2002	42	x				
			Finland	1960	2002	42		x			
			France	1960	2002	42	x				
			Germany	1960	2002	42	x				
			Greece	1960	2002	42	x				
			Hungary	1965	2002	37		x			
			Iceland	1960	2002	42				x	
			Ireland	1960	2002	42	x				
			Italy	1960	2002	42			x		
			Japan	1960	2002	42	x				
			Korea	1971	2002	31				x	
			Luxembourg	1960	2002	42	x				
			Mexico	1971	2002	31	x				
			Netherlands	1960	2002	42				x	
			New Zealand	1960	2002	42	x				
			Norway	1960	2002	42	x				
			Poland	1960	2002	42	x				

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \leftarrow GDP$	Growth $EC \rightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			Portugal	1960	2002	42			x		
			Slovak Republic	1971	2002	31			x		
			Spain	1960	2002	42	x				
			Sweden	1960	2002	42	x				
			Switzerland	1960	2002	42	x				
			Turkey	1960	2002	42	x				
			United Kingdom	1960	2002	42				x	
			United States	1970	2002	32	x				
(Bartleet and Gounder 2010)	2010		New Zealand	1960	2004	44		x			Trivariate demand-side and multivariate production models
(Narayan, Narayan and Popp, Does electricity consumption panel Granger cause GDP? A new global evidence 2010)	2010	Asia	17 countries	1980	2006	26				x	Unit root tests and the cointegration test of Pedroni
		Latin America	17 countries	1980	2006	26				x	
		Middle East	12 countries	1980	2006	26		x			
		Africa	25 countries	1980	2006	26				x	
		G6	6 countries	1980	2006	26				x	
		World	93 countries	1980	2006	26				x	
(Acaravci and Ozturk 2010)	2010	15 East Europe transition countries	Albania Belarus Bulgaria Czech Republic Estonia Latvia Lithuania Macedonia Moldova Poland Romania Russian Federation	1990	2006	16	x				Panel cointegration and dynamic panel causality

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \leftarrow GDP$	Growth $EC \rightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			Serbia Slovak Republic Ukraine								
(Apergis and Payne 2011)	2011	29 high income countries	Australia Austria Belgium Brunei Darussalam Canada Czech Republic Denmark Finland France Germany Greece Hong Kong Hungary Iceland Ireland Italy Japan Korea Luxembourg Netherlands New Zealand Norway Portugal Slovenia Spain Sweden Switzerland	1990	2006	16				x	Multivariate panel cointegration test (short and long run)

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \leftarrow GDP$	Growth $EC \rightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			United Kingdom United States								
		23 upper-middle income countries	Algeria Argentina Belarus Brazil Bulgaria Chile Costa Rica Dominican Republic Gabon Kazakhstan Latvia Macedonia Malaysia Mexico Panama Peru Poland Romania Russia South Africa Turkey Uruguay Venezuela							x	Multivariate panel cointegration test (short and long run)
		25 lower-middle income countries	Armenia Azerbaijan Bolivia Cameron	1990	2006	16			x		Multivariate panel cointegration test (short run)

STUDY		TARGET		Years			HYPOTHESIS				METHODOLOGY
REFERENCE	YEAR	REGION / GROUP	COUNTRY	From	To	Diff.	NEUTRALITY (NO LINK)	CONSERVATION $EC \leftarrow GDP$	GROWTH $EC \rightarrow GDP$	FEEDBACK $EC \rightleftarrows GDP$	
			China Ecuador Egypt El Salvador Georgia Guatemala Honduras India Indonesia Iran Jordan Morocco Nicaragua Pakistan Paraguay Philippines Sudan Syria Thailand Tunisia Ukraine	1990	2006	16				x	Multivariate panel cointegration test (long run)
		11 low-income countries	Bangladesh Ethiopia Ghana Kenya Kyrgyz Republic Mozambique Senegal Tajikistan Tanzania	1990	2006	16			x		Multivariate panel cointegration test (short and long run)

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \leftarrow GDP$	Growth $EC \rightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			Uzbekistan Zambia								
(Žiković and Vlahinic-Dizdarević 2011)	2011	8 small European developed countries	Austria	1980	2007	27			x		Phillips-Perron test or Augmented Dickey-Fuller test, Granger test
			Belgium	1980	2007	27		x			
			Denmark	1980	2007	27		x			
			Finland	1980	2007	27	x				
			Ireland	1980	2007	27		x			
			Norway	1980	2007	27		x			
			Sweden	1980	2007	27		x			
			Switzerland	1980	2007	27	x				
		14 small European developing countries	Albania	1993	2007	14	x				
			Bosnia and Herzegovina	1993	2007	14			x		
			Bulgaria	1993	2007	14			x		
			Croatia	1993	2007	14		x			
			Cyprus	1993	2007	14	x				
			Czech Republic	1993	2007	14			x		
			Estonia	1993	2007	14	x				
			Latvia	1993	2007	14		x			
			Lithuania	1993	2007	14		x			
			Macedonia	1993	2007	14	x				
			Malta	1993	2007	14			x		
			Moldova	1993	2007	14		x			
			Slovakia	1993	2007	14			x		
			Slovenia	1993	2007	14		x			
(Georgantopoulos and Tsamis 2012)	2011	Balkan countries	Greece	1980	2009	29		x			
			Bulgaria	1980	2009	29			x		

Study		**Target**		Years			**Hypothesis**				**Methodology**
Reference	**Year**	**Region / Group**	**Country**	From	To	Diff.	**Neutrality** (**no link**)	**Conservation** $EC \longleftarrow GDP$	**Growth** $EC \longrightarrow GDP$	**Feedback** $EC \rightleftarrows GDP$	
			Romania	1980	2009	29			x		Granger Causality test, Vector Auto Regression (VAR), Error Correction Model
			Albania	1980	2009	29	x				
(Wang, et al. 2011)	2011		China	1972	2006	34			x		Neo-classical aggregated production model
(Zhang and Yang 2013)	2013		China	1978	2009	31			x		Modified version of Granger test proposed by Toda and Yamamoto
(Campo and Sarmiento 2013)	2013	South American countries	Argentina	1971	2007	36				x	Pedroni heterogeneous panel cointegration test and Westerlund heterogeneous panel cointegration test with multiple structural breaks
			Bolivia	1971	2007	36				x	
			Brazil	1971	2007	36				x	
			Chile	1971	2007	36				x	
			Colombia	1971	2007	36				x	
			Ecuador	1971	2007	36				x	
			Paraguay	1971	2007	36				x	
			Peru	1971	2007	36				x	
			Uruguay	1971	2007	36				x	
			Venezuela	1971	2007	36				x	
(Borozan 2013)	2013		Croatia	1992	2010	18			x		Vector Autoregression (VAR) and Granger causality test
(Caraiani, Lungu and Dascălu 2015)	2015	Emerging European countries	Bulgaria	1980	2013	33	X				Stationarity, cointegration and Granger causality tests (at 5% significance level)
			Hungary	1980	2013	33		X			
			Poland	1980	2013	33			X		
			Romania	1980	2013	33	X				
			Turkey	1980	2013	33	X				
(Ozturk 2017)	2017		Algeria	1971	2011	40		x			Granger causality methodology developed by Toda and Yamamoto
			Bahrain	1971	2011	40	x				

STUDY		TARGET		Years			HYPOTHESIS				METHODOLOGY
REFERENCE	YEAR	REGION / GROUP	COUNTRY	From	To	Diff.	NEUTRALITY (NO LINK)	CONSERVATION $EC \longleftarrow GDP$	GROWTH $EC \longrightarrow GDP$	FEEDBACK $EC \rightleftarrows GDP$	
		11 Middle East and North African countries	Egypt	1971	2011	40			x		
			Iran	1971	2011	40			x		
			Lebanon	1971	2011	40			x		
			Malta	1971	2011	40	x				
			Morocco	1971	2011	40		x			
			Oman	1971	2011	40				x	
			Saudi Arabia	1971	2011	40		x			
			Tunisia	1971	2011	40			x		
			United Arab Emirates	1971	2011	40				x	
(Wang, et al. 2019)	2019	77 high income countries	Andorra Antigua and Barbuda Aruba Australia Austria Bahamas Bahrain Barbados Belgium Bermuda British Virgin Islands Brunei Darussalam Canada Cayman Islands Channel Islands Chile Curacao Cyprus Czech Republic Denmark	1980	2015	35				x	Unit root tests, Johansen co-integration test, Granger causality test, the impulse response function (IRF) analysis and the variance decomposition (VD) technique

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \longleftarrow GDP$	Growth $EC \longrightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			Estonia								
			Faroe Islands								
			Finland								
			France								
			French Polynesia								
			Germany								
			Gibraltar								
			Greece								
			Greenland								
			Guam								
			Hong Kong								
			Hungary								
			Iceland								
			Ireland								
			Isle of Man								
			Israel								
			Italy								
			Japan								
			Korea								
			Kuwait								
			Latvia								
			Liechtenstein								
			Lithuania								
			Luxembourg								
			Macao								
			Malta								
			Monaco								
			Netherlands								
			New Caledonia								
			New Zealand								

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \longleftarrow GDP$	Growth $EC \longrightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			Northern Mariana Islands								
			Norway								
			Oman								
			Palau								
			Poland								
			Portugal								
			Puerto Rico								
			Qatar								
			San Marino								
			Saudi Arabia								
			Seychelles								
			Singapore								
			Sint Maarten (Dutch part)								
			Slovak Republic								
			Slovenia								
			Spain								
			St. Kitts and Nevis								
			St. Martin (French part)								
			Sweden								
			Switzerland								
			Trinidad and Tobago								
			Turks and Caicos Islands								
			United Arab Emirates								
			United Kingdom								
			United States								
			Uruguay								
			Virgin Islands (U.S.)								

Study		**Target**		Years			**Hypothesis**				**Methodology**
Reference	**Year**	**Region / Group**	**Country**	From	To	Diff.	**Neutrality** (no link)	**Conservation** $EC \leftarrow GDP$	**Growth** $EC \rightarrow GDP$	**Feedback** $EC \rightleftarrows GDP$	
		56 upper-middle income countries	Albania Algeria American Samoa Argentina Azerbaijan Belarus Belize Bosnia and Herzegovina Botswana Brazil Bulgaria China Colombia Costa Rica Croatia Cuba Dominica Dominican Republic Ecuador Equatorial Guinea Fiji Gabon Grenada Guyana Iran Iraq Jamaica Kazakhstan Lebanon	1980	2015	35				x	

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \longleftarrow GDP$	Growth $EC \longrightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			Libya								
			Macedonia								
			Malaysia								
			Maldives								
			Marshall Islands								
			Mauritius								
			Mexico								
			Montenegro								
			Namibia								
			Nauru								
			Panama								
			Paraguay								
			Peru								
			Romania								
			Russian Federation								
			Samoa								
			Serbia								
			South Africa								
			St. Lucia								
			St. Vincent and the Grenadines								
			Suriname								
			Thailand								
			Tonga								
			Turkey								
			Turkmenistan								
			Tuvalu								
			Venezuela								
		53 lower-middle income countries	Angola	1980	2015	35				x	
			Armenia								

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \longleftarrow GDP$	Growth $EC \longrightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			Bangladesh								
			Bhutan								
			Bolivia								
			Cabo Verde								
			Cameroon								
			Cambodia								
			Congo								
			Cote d'Ivoire								
			Djibouti								
			Egypt								
			El Salvador								
			Georgia								
			Ghana								
			Guatemala								
			Honduras								
			India								
			Indonesia								
			Jordan								
			Kenya								
			Kiribati								
			Kosovo								
			Kyrgyz Republic								
			Lao								
			Lesotho								
			Mauritania								
			Micronesia								
			Moldova								
			Mongolia								
			Morocco								
			Myanmar								

Study		Target		Years			Hypothesis				Methodology
Reference	Year	Region / Group	Country	From	To	Diff.	Neutrality (no link)	Conservation $EC \longleftarrow GDP$	Growth $EC \longrightarrow GDP$	Feedback $EC \rightleftarrows GDP$	
			Nicaragua								
			Nigeria								
			Pakistan								
			Papua New Guinea								
			Philippines								
			Sao Tome and Principe								
			Solomon Islands								
			Sri Lanka								
			Sudan								
			Swaziland								
			Syrian Arab Republic								
			Tajikistan								
			Timor-Leste								
			Tunisia								
			Ukraine								
			Uzbekistan								
			Vanuatu								
			Vietnam								
			West Bank and Gaza								
			Yemen								
			Zambia								

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