



The aggregated leapfrogging estimate: a novel approach to defining energy leapfrogging

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Abstract. Energy leapfrogging (i.e., skipping non-renewable grid infrastructures to micro-grid renewable sources) has been promoted by researchers and politicians as a solution in fighting against climate change and for access to electricity in less developed countries. Despite research on its potential, quantitative measurement of leapfrogging is still required to determine those nations who have utilized energy leapfrogging's promise. In this study, we present a quantitative analysis using World Bank Open Database data from 2000 to 2015, creating an aggregated leapfrogging estimate (ALE) through renewable energy consumption (i.e., percentage of total energy consumption) and access to electricity (i.e., percent of total population with access). We defined the ALE by subtracting (renewable consumption % in 2000 / access to electricity % in 2015) from (renewable consumption % in 2015 / access to electricity in 2000). We included only countries whose renewable energy consumption increased during the study interval. Low-income countries collectively leapfrogged more than other income groups. Somalia (48.11), Togo (3.05), Eswatini (2.76), and Timor-Leste (1.04) all had ALE values greater than 1 (range: 1.7×10^{-5} –48.11). We then conducted a policy analysis of these countries, confirming that all four had implemented renewable energy policies to create access to electricity. Our ALE accurately determined countries with energy leapfrogging, uniquely incorporating access to electricity, consistent with the fundamental purpose of leapfrogging as a strategy to increase access. Future studies are needed to understand why low-income countries with low ALEs and access to electricity failed to leapfrog in the past. Future studies are also required to design prospective quantitative statistical models predicting the outcomes of leapfrogging strategies.

Keywords: Energy leapfrogging / renewable micro-grids / access to electricity

1 Introduction

Traditional economic development is commonly associated with carbon dioxide and greenhouse gas production. As a result, both developed countries, who largely rely on fossil fuel grid infrastructures, and developing countries, many of whom are working to create their own non-renewable grid infrastructures, face the looming threat of climate change and its consequences. Furthermore, climate change is associated with an increased sea surface temperature and rising probability of extreme weather disasters, resulting in health consequences such as waterborne diseases,

complications due to exposure to environmental toxins, increasing trends of cardiopulmonary diseases [16], and mental illnesses [21].

Renewable energy consumption (REC) has been shown to considerably decrease carbon emissions [14]. As such, international organizations have encouraged countries to replace non-renewable energy, such as fossil fuels, with renewable energy in their economies [6]. However, transforming and replacing existing carbon-intensive grid infrastructures into a new sustainable renewable economy takes time and effort. One such solution for electrification that circumvents the slow progress of transforming grid infrastructures while also increasing renewable energy consumption is energy leapfrogging. Here we use the United Nation's definition of leapfrogging: "bypassing intermediate stages of technology through which countries have historically passed during the development process" [26].

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Past instances of leapfrogging technology have been particularly successful, for example, with the introduction of mobile phones in the early 2000s. There, countries in the Global South who initially had no landline infrastructures leapfrogged past this traditional method of communication to mobile phones. Eventually, countries that initially had no phone service ended with higher mobile subscriptions than the global average [26]. Energy leapfrogging presents a similar method of providing increased energy access through bypassing slow and expensive traditional non-renewable infrastructures by establishing modern renewable energy microgrids. These renewable microgrids act as independent renewable energy sources for local communities without relying on slowly creating expensive energy grids [26]. Thus, energy leapfrogging provides renewable energy directly to communities, addressing the need for renewable energy and energy accessibility. For effective and expedient energy accessibility in Sub-Saharan Africa, for example, previous investigations have concluded that energy leapfrogging may be one of the only realistic solutions, as centralized grids are not feasible in the short term [23]. Despite its theoretical potential, the current literature is markedly influenced by the lack of numerical tools identifying countries who have leapfrogged.

Although leapfrogging is pivotally defined by an increase in accessibility through modern technology, many leapfrogging studies often do not incorporate access to electricity alongside renewable consumption [15]. Furthermore, prior investigations of energy leapfrogging have been substantially affected by geographical restriction, with many focusing on the potential for energy leapfrogging in specific countries or regions [9,19,22]. Moreover, local data on renewable energy consumption may not be systematically or consistently collected, particularly in the Global South, resulting in insufficient study periods [23]. Therefore, prior study results are frequently associated with poor external validity affecting the extrapolation of study findings.

To address these issues, we designed a global-scale study using the World Bank Open Database over an extensive study period (i.e., 15 yr) with steady data across nearly all countries. Thus, we set out to address this gap by determining whether existing data in renewable consumption and access to electricity can be used to develop a comprehensive and accurate quantitative measure of energy leapfrogging.

2 Methodology

This study aims to identify a method of quantitatively representing energy leapfrogging around the world. Using World Bank Open Database [24] data from 251 countries from 2000 to 2015, we created an aggregated leapfrogging estimate (ALE) including renewable energy consumption (as a % of total energy consumption) and access to electricity (% of total population with access) as a way of quantitatively measuring between the aforementioned

years. We defined the ALE through:

$$ALE = \frac{REC_{2015}}{Access_{2000}} - \frac{REC_{2000}}{Access_{2015}}.$$

Countries that had leapfrogged, with higher REC and access to electricity in 2015, would therefore be propelled to have higher ALEs than all other scenarios of the two variables. 2000 and 2015 were chosen as the respectively earliest and latest years for which the variables of REC and access to electricity were available for nearly every country.

In addition, analyses relating to different global income groups, the Organisation for Economic Co-operation and Development (OECD) countries [20], and countries that were included under the International Bank for Reconstruction and Development (IBRD) [11], and International Development Association (IDA) [11], were compared to a myriad of renewable and non-renewable energy variables. More specifically, the following variables were included in the analysis: country name and categorization as OECD, IBRD, or IDA, country income group, geographical region, Gross Domestic Product (GDP), access to electricity (% of total population with access) REC (% of total consumption), electricity production from renewable sources (% of total), electricity production from oil, gas, and coal sources (% of total).

3 Results

3.1 Electricity production from renewable sources

While energy leapfrogging relates primarily to renewable energy consumption, understanding the evolution of renewable production aids in interpreting and providing a wholistic view of renewable implementation and integration. In different geographical regions, it appears that the mean electricity production from renewable sources increased in different geographical regions. Increasing trends were more noticeable in 57 countries in the Europe & Central Asia region (10.6% increase), while 20 countries in Middle East & Northern Africa had the smallest increase (1.159%). These trends were found to be statistically significant in multivariate analysis (i.e., Wilks' Lambda test), including percentage mean renewable energy sources out of total energy sources in 1990, 1995, 2000, 2005, 2010, and 2015, and different geographical regions ($p=0.006$). Figure 1 demonstrates the global and regional trends of the estimated marginal means of the percentage of renewable energy sources in 1990, 1995, 2000, 2005, 2010, and 2015.

In the same interval, trends of electricity production from oil, gas, and coal sources (% of total production) changed across different regions (Fig. 2). However, this association was not found to be statistically significant ($p=0.067$).

Cumulatively, Table 1 provides mean percent renewable energy sources, percent REC, and percent non-renewable electricity production throughout different global regions.

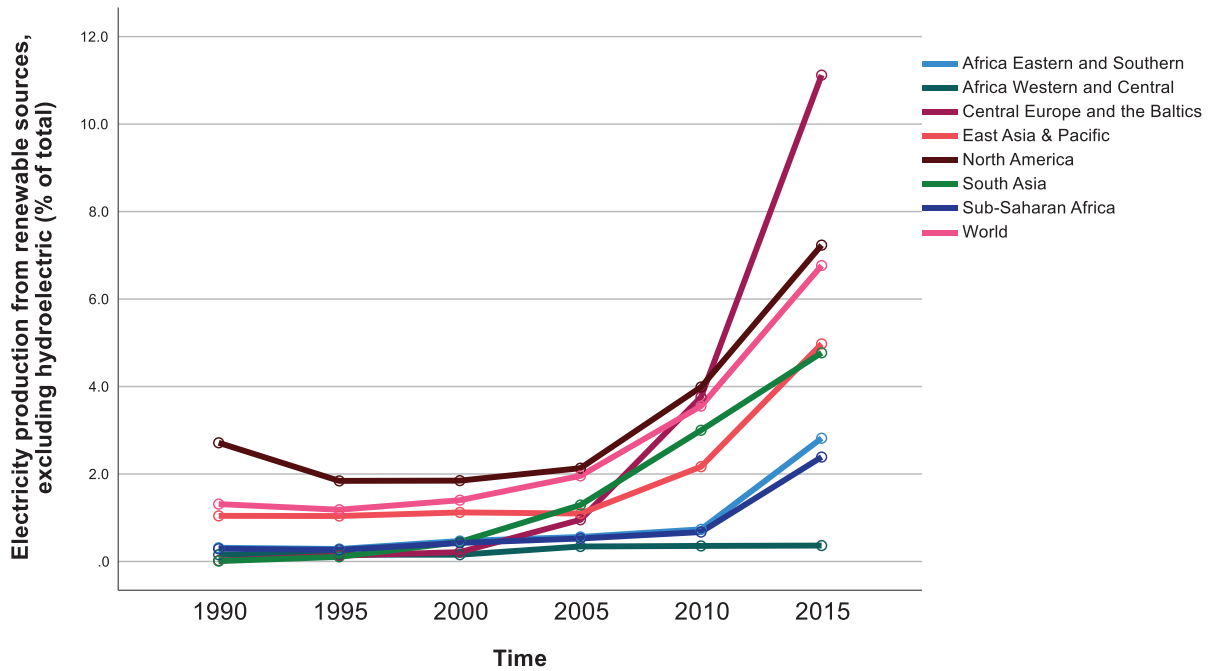


Fig. 1. Regional relative frequency of electricity production from renewable sources (1990–2015).

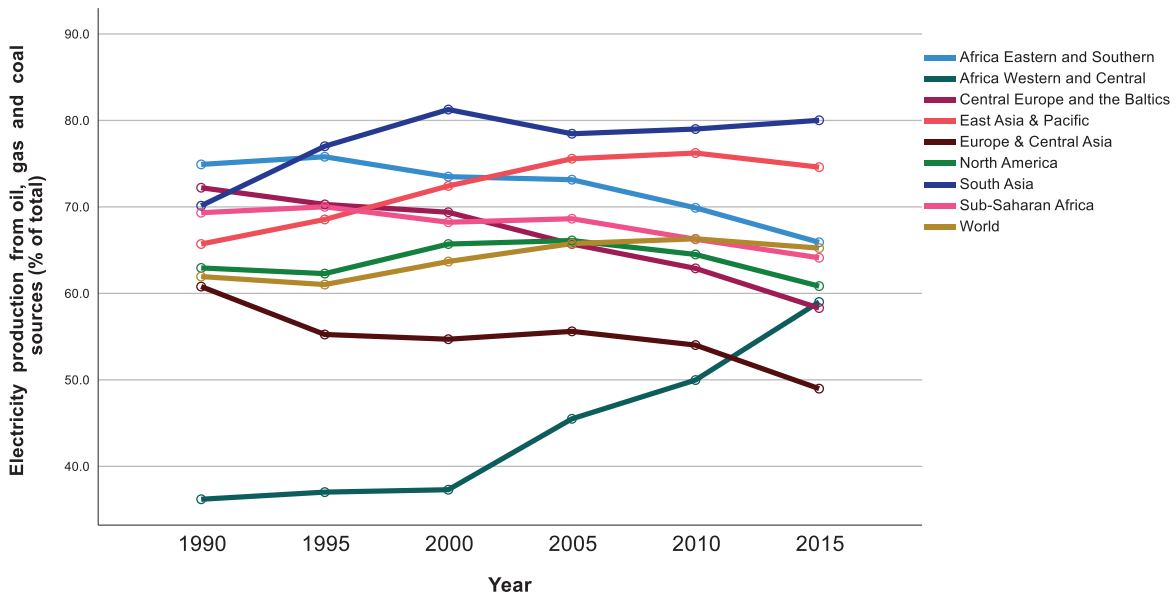


Fig. 2. Regional relative frequency of electricity production from non-renewable (oil, gas, and coal) sources (1990–2015).

The summation of these statistics appears to indicate a gradual increase in renewable energy consumption and decrease in non-renewable production in relatively further developed regions, such as North America and Europe & Central Asia. In contrast, Sub-Saharan Africa, South Asia, and Latin America & Caribbean, comparatively less developed regions, show larger increases in non-renewable production and lower renewable consumption.

3.2 Renewable energy consumption (REC)

Fundamentally, energy leapfrogging is defined by the increased consumption of renewable energy as a way to increase access to electricity. In the REC analysis, we examined how the percentage of REC changed in global regions during the study interval (1990–2015). Percent REC most considerably dropped (i.e., by -14.57%) in 8 countries classified as South Asian: Afghanistan,

Table 1. Regional percent renewable energy sources, renewable energy consumption, and non-renewable energy production change between 1990–2015.

Regions, N (%)	Mean renewable energy sources (% of total energy source)			Renewable energy consumption (% of total final energy consumption)			Electricity production from oil, gas and coal sources (% of total)		
	1990	2015	Change	1990	2015	Change	1990	2015	Change
	East Asia & Pacific, N = 37 (17.2)	2.27	4.91	+2.64	25.04	19.51	-5.53	70.37	74.85
Europe & Central Asia, N = 57 (26.5)	0.68	11.28	+10.6	10.22	20.47	+10.25	60.53	48.50	-12.03
Latin America & Caribbean, N = 42 (19.5)	4.60	10.76	+6.16	28.22	20.27	-7.95	36.11	51.18	+15.07
Middle East & North Africa, N = 20 (9.3)	0.001	1.16	+1.159	5.80	4.42	-1.38	92.47	93.31	+0.84
North America, N = 3 (1.4)	1.91	6.82	+4.91	8.73	10.72	+1.99	45.76	44.07	-1.69
South Asia, N = 8 (3.7)	0.002	1.95	+1.948	59.66	45.09	-14.57	43.30	59.05	+15.75
Sub-Saharan Africa, N = 48 (22.3)	1.97	4.31	+2.34	74.65	64.53	-10.12	37.85	48.54	+10.69

Bangladesh, Bhutan, India, Sri Lanka, Maldives, Nepal, and Pakistan. Substantial changes ($> +20\%$ increase and $< -20\%$ decrease) are shown in [Table 2](#).

[Figure 3](#) further represents regional percent REC consumption between 1990 and 2015.

This analysis appears to provide more context for the previously noted gradual increases in Europe & Central Asia, and North America. Indeed, while less developed regions, such as Sub-Saharan Africa and South Asia experienced decreases in REC, these regions still hold a substantially higher reliance upon REC than all other global regions. The stark decreases in REC in some less electrified countries appears to correspond with larger efforts to pursue non-renewable grid infrastructures. These results in combination with those presented in [Figure 2](#) demonstrate an overall trend in the Global South to shift toward non-renewables, not renewable micro-grids.

3.3 The aggregated leapfrogging estimate (ALE)

With evidence that renewable energy production and consumption both increased most in the more developed Europe & Central Asia, and North America regions, and that countries in the Global South overall follow a trend towards non-renewable grid energy, we next set out to understand whether energy leapfrogging was occurring. That is, if less electrified countries were using renewable energy micro-grids to increase access to electricity. We restricted analysis of leapfrogging to countries with a positive trend of REC from 2000 to 2015 ($n=98$). Of all countries, Somalia (48.11), Togo (3.05), Eswatini (1.04), and Timor-Leste (1.04) had the highest ALE scores. The results of this analysis indicate that Somalia, Togo, Eswatini, and Timor-Leste are model examples of energy leapfrogging's potential for implementation in lesser developed countries and regions. All countries with an ALE greater than 0.10 are further represented in [Figure 4](#). A break has been included to account for Somalia's comparatively high ALE.

4 Discussion

Energy leapfrogging has been touted by professionals and politicians alike as a potential major solution in the efforts for both increasing renewable energy consumption and access to electricity in developing countries. Globally, gradual withdrawals from fossil fuels and non-renewable sources for transitions to new renewable grid infrastructures are expected at best in the 2030s and 2040s [\[4\]](#), as renewable integration strategies to REC remain challenging due to financial, political, economic, and social barriers [\[18\]](#). Our analysis indicated that globally, countries in the Global North continue to have steady increases in the production of their renewable energy infrastructure resulting from their already established grids. Meanwhile, as an overall trend, developing regions of the world slowly attempt to develop their renewable infrastructures alongside their non-renewable grid infrastructures. Regions in the Global South appear to have more significant increases in percent non-renewable

Table 2. Countries with considerable changes ($> +20\%$ increase and $< -20\%$ decrease) in renewable energy consumption (% of total final energy consumption) from 1990 to 2015.

Country name	Renewable energy consumption (REC) changes	
	Highest increase in REC changes (i.e., $> +20$)	Highest decrease in REC changes (i.e., > -20)
Angola	–	✓
Bangladesh	–	✓
Benin	–	✓
Bolivia	–	✓
Burkina Faso	–	✓
China	–	✓
Cuba	–	✓
Denmark	✓	–
El Salvador	–	✓
Equatorial Guinea	–	✓
Estonia	✓	–
Fiji	–	✓
Ghana	–	✓
Iceland	✓	–
India	–	✓
Indonesia	–	✓
Kiribati	✓	–
Lao PDR	–	✓
Latvia	✓	–
Lithuania	✓	–
Mauritius	–	✓
Moldova	✓	–
Myanmar	–	✓
North Macedonia	✓	–
Panama	–	✓
Papua New Guinea	–	✓
Philippines	–	✓
Romania	✓	–
Sri Lanka	–	✓
St. Kitts and Nevis	–	✓
Vietnam	–	✓

production, mainly in Western and Central Africa, with an increasing trend from below 40% to nearly 60% between 2000 and 2015. The only other region with an increasing trend towards 2015 was South Asia, a rapidly developing region, reflecting an overall tendency in emergent countries to invest in non-renewable development.

Theoretically, through leapfrogging, countries can use more modern renewable technologies in micro-grids to ‘leapfrog’ past slow, traditional grids [2]. However, previous investigations of energy leapfrogging have not identified any quantitative measure of energy leapfrogging to provide evidence of its past usage, potentially contributing to a hesitation in investment into renewable technologies reflected in developing nations’ trend to

increase non-renewable production. Using open data from the World Bank, this study attempted to amalgamate statistics of percent REC and percent access to electricity to create the first comprehensive quantitative measure of energy leapfrogging, a first step towards providing a greater understanding for the place of energy leapfrogging in electrification and renewable efforts.

Prior investigations into energy leapfrogging are considerably affected by numerous key limitations. First, the lack of incorporation of access to electricity in quantitative measures of leapfrogging, which is often replaced by economic variables [15]. Furthermore, feasibility or data availability concerns frequently cause geographic limitations in leapfrogging studies, creating

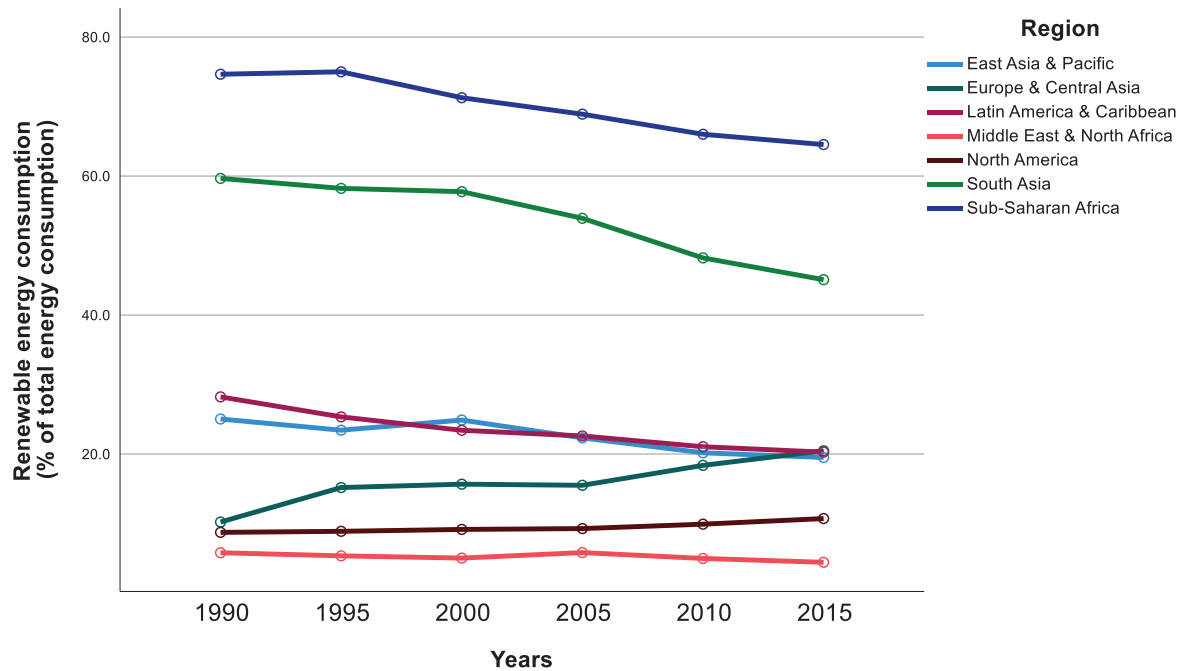


Fig. 3. Regional relative frequency of renewable energy consumption as a percentage of total energy usage (1990–2015).

analyses focused on just one country or region (e.g., Philippines [19], Serbia [9], and China [22]). Lack of data, particularly in the Global South, provides an additional barrier, often resulting in studies with insufficient periods of investigation, such as Szabó et al., which studied energy leapfrogging in Sub-Saharan Africa over four years from 2008–2012 [23]. Our results indicate that three countries in Sub-Saharan Africa (Somalia, Togo, Eswatini) and one country in East Asia & Pacific (Timor-Leste) were the most prominent practitioners of energy leapfrogging between 2000 and 2015. In 2022, the renewable installed capacity in Somalia was 51 MW, Togo was 124 MW, Timor-Leste was 1 MW, and Eswatini 179 MW [13]. Furthermore, the 2022 electricity demand of these respective countries was 0.4 TWh, 1.4 TWh, 0.5 TWh, and 1.7 TWh [17]. With this analysis, we lastly conducted a policy review of these four nations to identify if a higher ALE indeed corresponds with a history of policy aimed at increasing access to electricity through renewable energy micro-grids. We found that each of these four countries had evidence of the utilization of renewable micro-grid infrastructures for the explicit purpose of broader electrification.

A 2015 report on energy investments in Somalia by the African Development Bank Group found hybrid infrastructures almost entirely privately owned, with the aid of government subsidies for renewable energy [1]. Somalian urban developments (with the exception of the major cities Mogadishu, Hargeisa, and Kismayo which have grid infrastructures) appear to be powered by hybrids of both non-renewable grid infrastructures and renewable micro-grids [1]. Furthermore, rural electrification projects appear to be led through independent low voltage solar mini-grids [1], showing a large-scale push towards renewable electrification.

Next, in 2014, the Togolese Republic Ministry of Economy and Finance submitted an expression of interest and application [25] for the Scaling up Renewable Energy Program (SREP) in Low Income Countries created by the Strategic Climate Fund of the Climate Investment Funds [5]. This report highlights the already existing role of renewable (specifically, solar) energy in rural areas, starting with major policy decisions and changes in 2003. First, the 2003 “Code Bénino-Togolais de l’électricité” or Benino-Togolese Electricity Code [3] began allowing and encouraging independent energy producers to begin introducing renewable micro-grids in areas without traditional grid infrastructures found in larger cities [25]. Furthermore, programs developed in rural municipalities sponsored by the United Nations Development Programme also began encouraging the implementation of solar equipment in 2003 [25].

Third, a 2014 report by the International Renewable Energy Agency (IRENA) on Eswatini (then Swaziland) renewable integration highlighted the ongoing usage of off-grid solar infrastructures for rural electrification brought on by the 2009 National Energy Policy [12]. It was noted that Eswatini’s major energy investments for rural electrification have still been in non-renewable grid expansion, but the report did reiterate the apparent success of decentralized solar micro-grids [12]. Furthermore, Eswatini’s 2007 Electricity Act was highlighted for its place in encouraging private entities to create rural electrification projects and initiatives through renewable micro-grids ([12], similar to the privately subsidized renewable projects of Somalia).

Lastly, our policy review investigated Timor-Leste, the only non-Sub-Saharan African nation that was found to have a comparatively high ALE. We found that with the introduction of the IV Constitutional Government of

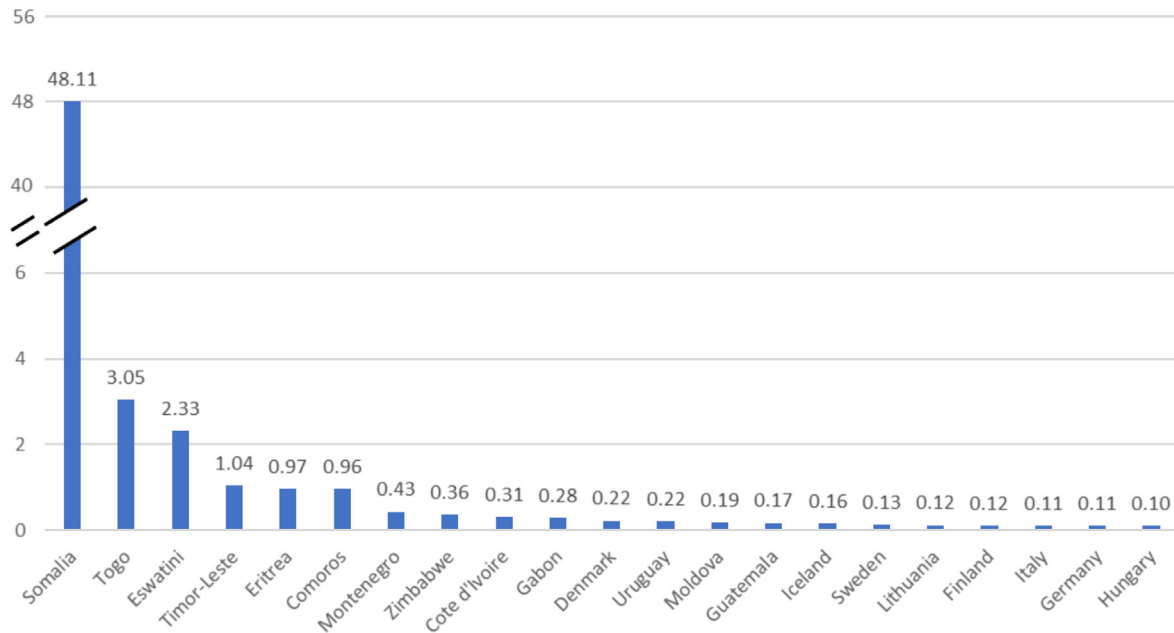


Fig. 4. ALE scores of all countries with ALE greater than 0.1 (break to account for distinctly high Somalian score).

Timor-Leste, large efforts to decrease Timor-Leste's import-dependent energy through establishing renewable infrastructures were created [7,8]. The government of Timor-Leste, more specifically the Secretariat of State for Energy Policy, also sponsored national studies of the potential for renewable infrastructures to become the central focus of Timor-Leste's electrification strategies. The Timor-Leste Secretary of State for Energy Policy would later state on this study, "the study shows that Timor-Leste possesses a strong potential in the renewable energies area. If these are well explored, altogether, they can produce an installed capacity of 451 megawatts, or in other words, enough energy to supply the whole country, thus constituting, our energy matrix" [7,8]. Interestingly, the government of Timor-Leste's investments in renewable energy infrastructure, including rural micro-grid infrastructure, were centered on wind and hydroelectric power, instead of the solar power that Somalia, Togo, and Eswatini prioritize [7,8].

The first of its kind, the ALE developed in this study appears to show four countries (Somalia, Togo, Eswatini, and Timor-Leste), who have successfully taken advantage of energy leapfrogging's promise and utilized it to rapidly electrify their respective nations. Moreover, each of these countries have specifically pursued successful large-scale national renewable electrification in all of solar, wind, and hydroelectric power sources. Energy development is crucial for economic growth. For infrastructure that can remain effective towards the future, it is essential that developing nations look to develop renewable infrastructures (micro-grids or grid) for fast and effective electrification. However, creating infrastructure for renewable energy resources does not necessarily guarantee the REC leapfrogging, which requires the successful integration of

renewable resources in the energy economy. The strategies employed by the countries identified by the ALE appear to be applicable on a broader scale. Still, our results beg the question of why many other developing nations have not yet applied the promise leapfrogging holds.

Our analysis and modelling of REC showed that more developed regions (such as Europe & Central Asia and, North America) have had steady increases in REC from 1990 to 2015. On the other hand, some developing regions, such as Sub-Saharan Africa and South Asia, despite starting with a high percent REC, had a decreasing trend over time. Other regions, such as Middle East & North Africa, consistently had low percent REC, likely due to the high production of non-renewable energy resources and an overall reliance upon non-renewable energy in the economic sector. Furthermore, Latin America, Caribbean, East Asia & Pacific had a percent REC above 20% at the beginning of the study period but consistently decreased over the next 25 yr. These results show that overall, those regions likely extended the reach of the traditional non-renewable grids that are commonly found in urban areas. While our study showed that energy leapfrogging has been successfully executed in the past, further studies are required to relate different REC trends to leapfrogging's potential for implementation and success. Moreover, additional investigation with comprehensive designs may help further research to understand energy leapfrogging's viability in regions that are not currently using it, and particularly, the potential for the strategies outlined by Somalia, Togo, Eswatini, and Timor-Leste in these regions.

Conflict of interest

The authors have no conflict of interest to declare.

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Author contribution statement

S.H-M, B.G., H.C., T.L. contributed to study design, S.H-M, B.G. collaborated on data collection and data analysis, S.H-M wrote and revised the manuscript, every author provided comments on the manuscript.

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