Impact of Solar Power Consumption on GDP and Human Development Index: A Cross-Country Analysis

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Abstract—***This research is conducted to determine a relational impact of solar energy consumption on GDP and HDI of two developed and two developing countries from the year 2016 to 2019 to avoid disturbances and discrepancies in the dataset due to covid 19. This research will provide evidence of the comparison by applying data analysis and data mining techniques on the publicly available datasets. It intends to evaluate the tasks as described in Goal 7 of the UN's Envision 2030. This research focuses on deciding countries using machine learning algorithms. As a result of this research, a relation between Solar energy consumption, GDP and HDI of the given countries will be established through visual analysis along with its effects and help government agencies and policy makers to decide upon the implementation and usage of a clean source of energy.***

Keywords—Solar Energy, Renewable Energy, Energy Policy, Regression, Machine Learning, GDP, Analysis, HDI.

I. Introduction

This study focuses on the potential of solar energy as the world's largest domestic renewable energy source [15]. By examining the economic impact and benefits of solar energy adoption, the research aims to provide insights to individuals, businesses, governments, and investors. It is anticipated that these insights will facilitate a broader understanding of solar energy's advantages and contribute to its increased adoption as a sustainable and economically viable energy source.

A. Problem Description

Significant obstacles still stand in the way of the broad adoption of solar energy as a critical component of the worldwide effort to guarantee everyone has access to inexpensive, dependable, ecological, and contemporary energy.

The UN has acknowledged the significance of expanding the proportion of renewable energy sources in the world's energy mix [12]. Significant investments in renewable energy technology and infrastructure are required for achieving this goal. It is critical to acquire funds and increase awareness among many stakeholders, including governments, users, investors, and entrepreneurs, to solve this situation successfully [13]. These stakeholders may be extremely helpful in supporting and promoting efforts involving renewable energy by raising money and encouraging the spread of knowledge. The adoption of various renewable energy sources and the advantages they provide for stakeholders globally depend on well-informed decision-making Jacobsson, S., & Bergek, A. [14]. By conducting comprehensive studies, valuable insights can be gained into the potential of renewable energy sources, their environmental impacts, and their socioeconomic implications. Such research is essential for guiding policy formulation, investment decisions, and the development of sustainable energy solutions.

B. Motivation

With the increase in depletion of natural resources for energy or electric power generation it is one of the major concerns to get enough energy produced by the renewable energy sources to serve the globe to its energy needs. Also, as per the Goal 7: Affordable and Clean Energy of Envision2030 by UN it is the field to be explored [9]. Solar Energy, being one of the largest renewable energy producers which makes us more inclined towards the research about Solar Energy A. Qazi et al. [10]. Other renewable energy sources such as wind, hydro etc. involve large scale infrastructure and area to get deployed to produce energy and are difficult to install. Whereas solar panels can be installed anywhere like rooftops of buildings, large vacant land etc. The major challenge for the Solar Power generation is the need of sunlight for majority of the time.

The government of lot of countries provide subsidies for the installation of solar panels. Which makes it more

interesting to know whether there is any economic factor or not related to this.

If there is any relation which we will establish from our research, it will be beneficial for investors, traders, government agencies and scientists for better decision making, related to solar energy.

C. Uniqueness

This paper pays specific attention on deciding the countries for analysis as, it is important to have a fair comparison. The analysis will be done on the data from 2016-2019, keeping instability caused due to covid in mind. Linear Regression technique will be applied for analysis of the countries and correlation plot will be analyzed to get the relationship between different attributes.

II. Literature Review

This section examines the literature study in terms of many areas, including the potential for solar energy and machine learning methods.

A. Solar Energy Potential

Solar energy possesses significant potential as a renewable energy source due to its vast availability and environmental benefits. The sun continually emits an enormous amount of energy, with an estimated solar irradiance of 1,368 Watts per square meter (W/m^2) at the Earth's outer atmosphere. By harnessing solar power through various technologies such as photovoltaics (PV) and concentrated solar power (CSP). According to the National Renewable Energy Laboratory (NREL), the technical potential for solar photovoltaic installations in the United States alone is estimated to be 1,118,800 gigawatts (GW), highlighting the immense capacity for solar energy utilization [1].

The main advantage of using solar energy is its renewable nature, as sunlight is an abundant and inexhaustible source of energy, reducing dependence on finite fossil fuels and mitigating climate change [2]. Hence, Solar energy offers a reliable and sustainable source of electrical power generation, making it an asset. Furthermore, solar-based technologies not only benefit the environment but also have a positive impact on the economy of any nation.

Several factors play a crucial role in determining the solar energy potential of a particular region. Firstly, the number of sunlight hours is essential, as regions with longer and more intense periods of sunlight have higher solar energy potential. Secondly, the total area available for solar installations influences the capacity for harnessing solar energy. Additionally, the level of development in a region can impact its solar energy potential, with more developed areas having better infrastructure and resources to support solar energy systems [3].

B. Relationship between energy consumption and economic parameters

The relationship between energy consumption and the increase in output in recent years has been demonstrated in numerous studies in literature. Due to rapid growth in population and advancements in technology, the need for sustainable energy is experiencing a substantial growth. The solar industry at a global scale is continuously growing, propelled by the rising energy demand, limited reserves of fossil fuels, and the heightened costs associated with alternative energy alternatives. Solar energy has transformed into an asset for enhancing the economies of both developing and developed nations, ensuring the well-being of people.

Numerous econometric time series models, such as the Granger causality test, Engle-Granger cointegration, and Johnsen's multivariate cointegration technique, were used to examine the Indian setting between 1950 and 1996 S. Ghosh [4]. The outcomes of Engle-Granger and Johnsen's models showed that an economic recovery eventually results in higher energy usage. Furthermore, the conventional Granger causality test demonstrated that an economic boom is the direct result of increasing energy consumption, ultimately resulting in economic expansion. These results corroborated the unidirectional association between economic recovery and energy consumption and were compatible with the conclusions drawn from Johnsen's error correction model.

The findings of the empirical analysis indicated a modest yet positive influence of renewable energy consumption on economic growth G. Soava, et al. [5]. Moreover, causalities were observed between the two key macroeconomic indicators, with some European Union countries exhibiting bidirectional causality and others demonstrating unidirectional Granger causality within the panel.

The effect of solar energy consumption and overall renewable energy consumption on the GDP of the USA is being investigated in yet another study employing an empirical approach B. Umit and N. Apergis B. Umit and

N. Apergis [6]. Cobb-Douglas production functions were used for the analysis, which covered the years 1984 through 2018.

In the wind and solar energy sectors in emerging economies, there are a total of 24 potential determinants that could have an impact on foreign direct investment (FDI). These criteria were subsequently validated and improved based on feedback from subject-matter specialists, yielding a final set of 18 factors A.R. Keeley and K. Matsumoto [7]. The detected variables were divided into four categories: institutional context, macroeconomic context, environmental factors, and renewable energy policies. Considering earlier research and the expert opinions acquired through semi-structured interviews, the significance of each aspect was examined.

By examining developing and developed economies, another study determined the effect of energy consumption on the HDI, both in terms of quantity and quality A. Yumashev et al. [8]. The study focused on investigating the relationship between energy use, HDI, and environmental variables, notably CO2 emissions. The study's findings suggest that several variables, such as the rate of urbanization growth, the GDP and GNI per capita, the share of "clean" energy consumption in total energy consumption by the population and businesses, the degree of socioeconomic development, and Research & Development expenditures, affect the size and ranking of the HDI.

As a result, the literature amplifies the growing need for sustainable energy solutions by offering convincing proof of the link between energy consumption and economic parameters. Due to its availability and abundance, solar energy is emerging as a promising alternative, and the global solar business is still growing. The development of renewable energy sources benefits both developed and developing nations by fostering economic prosperity.

C. Data Analysis Techniques

The data analysis techniques contain a set of computational algorithms. Mohanty et al [34] provide insights to improve the accuracy of short-term solar power prediction. By developing and comparing different models, researchers can determine which model performs better in predicting solar power based on the given input parameters (hourly solar radiation, historical transmissivity, sky cover, relative humidity, and wind speed). The goal is to find the most accurate and reliable model for short-term solar power prediction. Paper develops a radial basis function (RBF) neural network-based model and compared its performance with two linear regression models: an autoregressive (AR) model and a local linear regression (LLR) model.

However, this model may not be applicable in situations where accurate historical transmissivity data or the required meteorological variables are not available. Additionally, the developed models may have limitations in regions with significantly different climatic conditions or locations outside the defined climatic zone.

Another technique used is the Granger causality test, to examine the presence and direction of causality between variables. It determines whether the past values of one variable can help predict another variable, indicating a causal relationship G. Soava, et al. [5]. It is mainly being used to identify unidirectional or bidirectional causalities between real GDP and renewable energy consumption. By analyzing the historical data, the test determines whether changes in renewable energy consumption can predict future changes in real GDP of European Union Countries.

Understanding the direction of causality is crucial for policymakers and researchers to make informed decisions regarding renewable energy policies and their potential impact on economic development.

Despite that, it doesn't establish a clear cause-and-effect relationship. It just looks for statistical relationships between variables. The test also assumes that there are no measurement mistakes or missing factors that could skew the results.

D. Datasets

In this study, annual data covering the period 2016–2019 were used. Independent data has been used for the GDP, HDI and Solar energy consumption. Data for GDP is obtained from the database of World Bank [26]. Whereas, for HDI the data from the database of Our World in Data publication is used [28]. And for the Solar energy consumption data from Wikipedia is used which refers to nearly 170 research to account that data [27]. Also, few other datasets, sunlight hours Shetty et al [19], land area [30], developed and developing countries [29].

Below is the table that justifies the dataset used in this paper.

Table 1: Research using the datasets.

Variable	Research using the dataset

Gross Domestic Product (GDP)	Zubair et al [23], Mukhtar et al [24], Tu et al [25]
Human Development Index (HDI)	Yumashev et al [20], Kpolovie [21], Y.Liu [22]
Solar Energy Consumption	Babu et al [17], Jayapradha et al [18], Shetty et al [19]
Sunshine Hours	Mehl-Madrona et al [31]
Land Area	Berisha et al [32]
Development status	D. Protic et al [33]

III. Methodology

A. Factors under consideration

This subsection briefly describes the rationale for shortlisting the factors mentioned above.

i. **Factors for deciding countries**

1. Total Sunlight Hours: Sunlight hours that a country gets all year round pose a significant impact on the usage of solar power energy by that country. The hours of sunlight and solar energy consumption for a specific country have a relationship, which is observed to have a significant correlation when considered over the long period of time.

2. Country Area: The surface area of a country holds a crucial value when considering solar power energy as a resource. In technicality, this would be the core basis of the number of solar panels to be installed for a specific region with respect to the total sunlight hours it gets.

3. Development Status: Another key factor to be considered is the development status of the nation, this would mean whether the country come under the category of developed or developing nation, and should be considered before even designing the project of solar power energy.

4. Total Solar Energy Consumption: Energy is the building block for the development of any country. The most abundant form of energy that some countries have is solar power energy which is a potential gold mine and might result in a complete stop for the remaining renewable resources.

ii. Factors for Analysis

1. GDP per capita: Gross Domestic Product (GDP) serves as a key indicator of a country's economic performance, reflecting the total value of goods and services produced within its borders. It provides insights into economic growth, productivity, and living standards, influencing investment, employment, government policies, and international trade.

2. HDI: The Human Development Index (HDI) is a comprehensive statistic that analyses a country's overall progress by considering parameters such as life expectancy, education, and income. It also provides significant insights into a country's progress and highlights the well-being of its people. For starters, it provides a standard for comparing and rating countries in terms of progress. It enables policymakers, scholars, and international organizations to detect cross-national patterns, trends, and areas for improvement. From the perspective of this paper, it goes beyond economic indicators by giving a holistic view of development, creating a more thorough knowledge of a country's total well-being.

3. Solar Energy consumption: Solar energy consumption can positively impact a country's economy by reducing reliance on fossil fuels, promoting energy independence, creating jobs in the renewable energy sector, and reducing greenhouse gas emissions, leading to environmental and economic benefits.

B. Regression

A statistical method known as regression is used to measure the degree of connection between a series of already existing independent and dependent variables. Regression models are primarily divided into three categories: polynomial, multiple, and linear.

To determine the nature of the relationship between variables, linear regression is performed. The dependent variable will vary consistently as the independent variable changes by a unit. The linear regression form is represented by equation (1)

$$Y = \mathrm{c} + \mathrm{m}x \qquad (1)$$

In case of prediction Equation (1) helps the researcher to predict what the dependent variable's actual value will be.

But in the case of analysis, it can also be used to get the correlation between two variables.

When there are more than 1 variables Multiple regression is used, where the Equation (1) is stretched to include the additional varying attributes. Equation (2) shows a multiple linear regression form.

$$Y = \mathrm{c} + \mathrm{m}1x1 + \mathrm{m}2x2 + \mathrm{m}3x3 + \cdots + \mathrm{m}k\ xk \qquad (2)$$

Where, c is Y-intercept; xj is an independent variable; mj is the net change in Y for a unit change in xj, j=1, 2, …k.

In polynomial regression, the correlation between the independent and dependent variables is remodeled as an nth-degree polynomial.

The above-mentioned techniques will be used in this paper to determine a correlation between HDI, GDP and solar energy consumption over the period of 2016-2019.

C. Analysis Model

1. Data Collection: The initial step of the model involves the collection of data for the following indicators: Human Development Index (HDI), Gross Domestic Product (GDP), solar power consumption, sunlight hours, and land area of different countries. Data collection for these indicators is important for understanding and analyzing various aspects of a developed and developing country's development and characteristics.

2. Data Preprocessing: The second step of the model, the collected data from the first step undergoes preprocessing. The collected datasets for the different indicators will be merged into a one comprehensive dataset. Subsequently, a filtering process takes place to remove data entries for countries that have null values in any of the indicator datasets for the years 2016-2019. This step ensures that the final dataset used for analysis and modelling only includes countries with complete and reliable data for the specified time period.

3. Deciding Countries:

i. **Categorizing countries based on development status:** Categorizing countries into developed and developing groups relies on assessing their Gross Domestic Product (GDP) and Human Development Index (HDI). GDP indicates a country's economic prowess, while HDI reflects its overall state of development and welfare. By carefully comparing these indicators, countries can be sorted into developed nations, often characterized by elevated GDP and HDI values, and developing nations, which typically display lower levels of GDP and HDI. This systematic analysis allows for a clear distinction between countries based on their economic strength and overall progress.

ii. **Selecting 2 comparable countries for each category**: To analyze and compare countries, it is important to ensure a fair comparison by selecting countries with similar characteristics. In this step, two countries are chosen from each category, developed and developing, based on their sunlight hours and land area and solar energy consumption. By selecting countries with similar numbers of sunlight hours, we can account for their potential solar energy utilization and climate conditions. Additionally, considering countries with comparable land areas allows for a balanced comparison of their territorial extent.

4. Analysis: In this step, the 4 selected countries will be analyzed individually based on GDP, HDI and Solar Power Energy Consumption.

The data for particular country will be retrieved from the comprehensive dataset for each indicator. The data points will be plotted for Solar Energy Consumption, HDI and GDP from the year 2016-2019, respectively. Then Linear Regression will be applied, and the line will be plotted on the same graph. At the end, there will be 3 regression lines on a single graph, analysis based on these three lines will be done to see the relation between these three attributes. This will be repeated for all the 4 countries.

D. System Definition

This paper will use Python as the language for analyzing the data. Where different libraries will be involved, such as Pandas, for data manipulation and filtering, Matplotlib for plotting graphs, and Sklearn for linear regression.

This paper will decide countries based on the parameters mentioned above. And then with those data values graphs will be plotted and also linear regression will be applied, and regression line will be plotted. At the end, there will be 4 plots for each country individually and there will be 3 regression lines on each graph. A correlation plot will be plotted to get more insights on the relation between the parameters. These plots will be analyzed and from that analysis conclusion will be drawn.

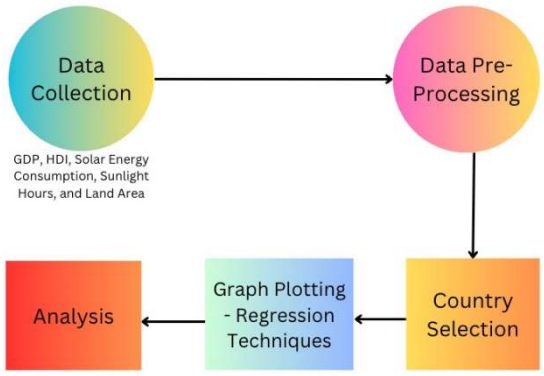

Figure 1: Flow of process

IV. Algorithms

A. Algorithm for deciding countries:

Step 1: Combine 4 dataset to generate 1 combined dataset. The 4 datasets used are Average of Sunlight Hours, Land Area of Countries, Gross Domestic Product, Development Status for year 2019.

Step 2: Generate product of Average of Sunlight Hours data and Land Area of Countries data and normalize GDP dataset along with the product dataset between 0 - 1.

Step 3: Plot the graph with normalized GDP on x-axis and the normalized product of avg. sunlight Hours and land area on y-axis.

Step 4: Filter data points from the dense area on the graph by visualizing i.e. on x-axis data is filtered between 0 - 0.25, and on y-axis data is filtered between 0 - 0.4.

Step 5: Apply K-means clustering on filtered data generated in Step 4.

Step 5.1: Try out k-means clustering with number of clusters ranging between 3-10, until we get the most efficient plot for analysis.

Step 6: Plot the clusters with country names, where data points are between 0.05 - 0.10 on x-axis and data points are between 0 - 0.10 on y-axis based on the visual analysis.

Step 7: After following these steps, decide 4 countries, 2 developed and 2 developing countries based on the graph plotted, on which the analysis is to be done.

B. Algorithm of Analyzing:

Step 1: Obtain the normalized values (from 0-1) of HDI, GDP, and solar energy consumption.

Step 2: Plot the normalized values on the y-axis, and time in years on the x-axis.

Step 3: Through the Linear Regression algorithm, plot the regression line of each of the given parameters (HDI, GDP, and solar energy consumption).

Step 4: Visually analyze the growth of the parameters on each other.

Step 5: Repeat this process from steps 1-4 for all the 4 countries decided (2 developed & 2 developing).

V. Results

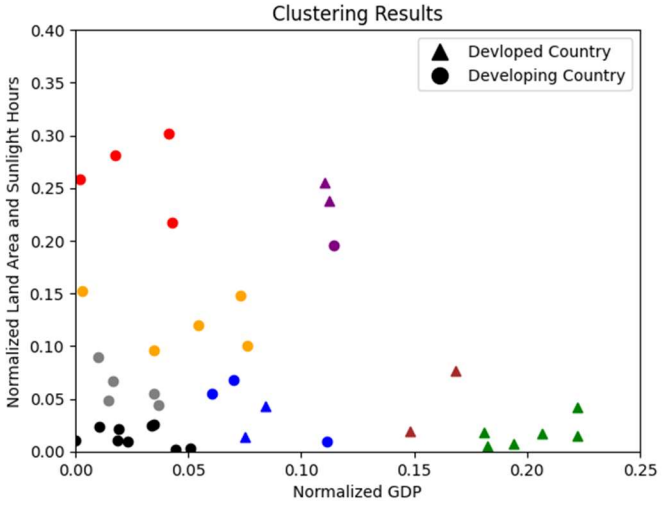

Figure 2: Results of k-means clustering

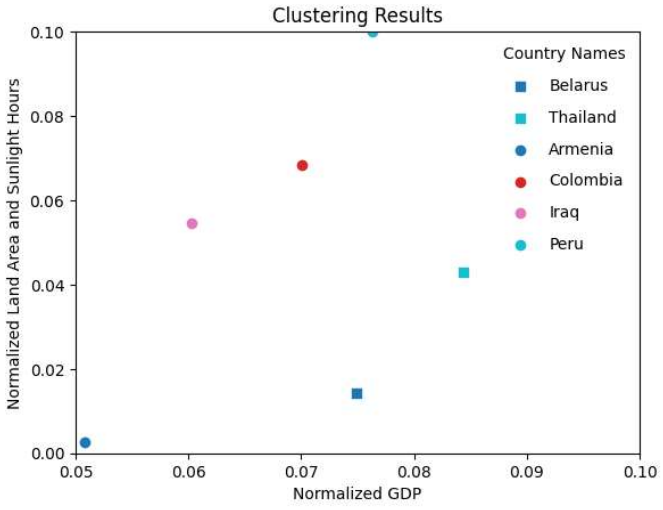

Figure 3: Results after segregating countries based on their development status

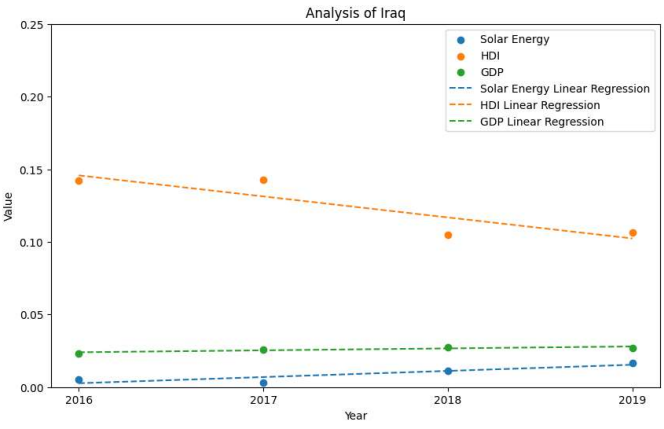

Figure 4: Regression & Scatter Plot for Iraq

By analyzing the plot, the slopes of these linear regression lines reveal growth of both Solar Energy and GDP and decline of HDI. However, the absolute value of slope of HDI is much higher than that of Solar energy and GDP and so, the decline of HDI is more than the growth of Solar energy and GDP.

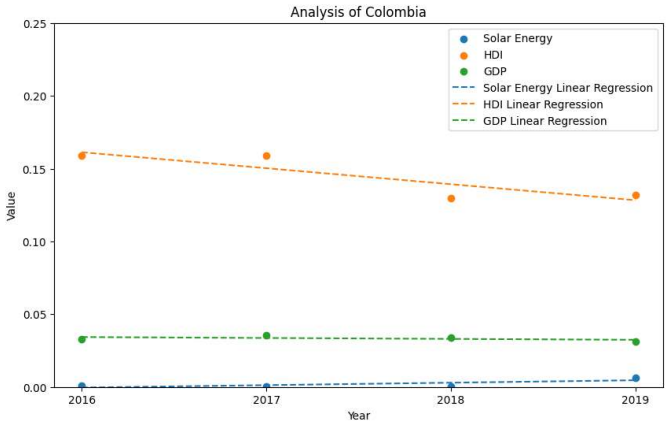

Figure 5: Regression & Scatter Plot for Columbia

From the plot we can see that the slopes of these linear regression lines reveal that the growth of both Solar Energy and GDP is very negligible. However, there was a significant decline in HDI over the span of 2016 to 2019.

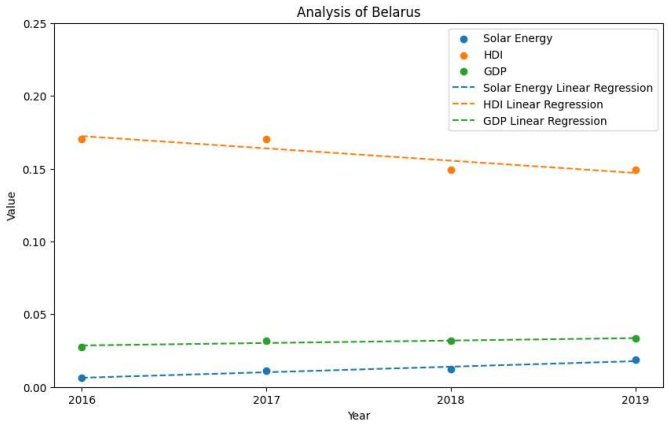

Figure 6: Regression & Scatter Plot for Belarus

From the plot, we can observe the trends and correlations between these variables over time. By analyzing the plot, the slopes of these linear regression lines reveal that the growth of both Solar Energy and GDP remains constant and Over the Span of 2016 to 2019, there was a significant decline in HDI of Belarus.

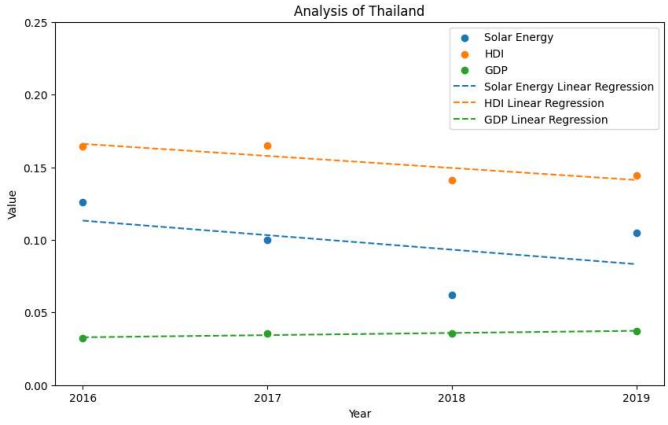

Figure 7: Regression & Scatter Plot for Thailand

By analyzing the plot, the slopes of these linear regression lines reveal growth of GDP and decline in HDI and Solar Energy. However, the absolute value of decline in Solar Energy is much higher than that of HDI. Although the solar energy consumption regression line is negative, its trend is positive, as we can see it bounced back to the 2017 data point by 2019.

Table 2: Each Country's Slopes of Linear Regression

	Solar Energy	HDI	GDP
Iraq	0.00423	-0.01447	0.00133
Columbia	0.00168	-0.01098	-0.00063
Belarus	0.0038	-0.00843	0.00168
Thailand	-0.00999	-0.00829	0.00149

VI. Limitations or Challenges

1. The dataset utilized for the analytical study is for the years 2016 to 2019 and comprises of Gross Domestic Product, Human Development Index, Average Sunlight Hours, and Land Area for various countries. The data beyond 2019 is not accurate due to unforeseen disruptions and alterations in the economic and developmental landscape worldwide due to Covid-19 pandemic.

2. Development status is ambiguous primarily due to the use of different variables and parameters by various organizations in their data collection processes. Consequently, the absence of a standardized framework for assessing development often leads to discrepancies and variations in the classification of development status across different analyses and reports. As a result, interpreting and comparing development indicators from different sources necessitates careful consideration of the specific

criteria employed by each organization, ensuring a comprehensive understanding of the nuances underlying their respective assessments.

3. Encountering challenges in obtaining data predating the year 2016 is a prevailing concern. The scarcity of pre-2016 data may arise from various factors, including limited availability, data storage constraints, and changes in data collection methodologies over time.

4. The graph plotting reveals densely clustered points, presenting a challenge in effectively performing data clustering. The high density of points makes it harder to discern clear boundaries or patterns, potentially hindering the accurate identification of distinct clusters within the dataset. The intricacy arising from the densely packed points requires employing sophisticated clustering algorithms and visualization techniques to uncover meaningful insights and structure hidden within the data points.

5. The linear regression line's accuracy is negatively impacted by the small dataset size. With a limited number of data points, the model may struggle to capture the full complexity of the underlying relationship, leading to less reliable predictions and a decreased level of confidence in the regression line's fit to the data.

6. Another alternative for analysis is multiple regression, which allows for the incorporation of multiple independent variables to predict a dependent variable. However, a drawback of multiple regression is that it generates a plot in four dimensions (4D), making it challenging to analyze directly on a conventional computer screen. The visualization of data in 4D involves complexities that can overwhelm the ability to perceive patterns and relationships intuitively.

VII. Conclusion & Future Work

A. Conclusion

As per the goal #7 affordable and clean energy of UN Envision 2030 this paper offers insights on impact of solar energy consumption on HDI and GDP of developed and developing nations.

In this study, clustering analysis is performed using machine learning techniques to decide two developed and two developing countries for fair analysis. Further, on each country regression analysis is performed on total solar energy consumption, HDI, and GDP. This analysis has been done using python programming environment with Google Colab interface.

Based on the factors and analysis, four countries were decided namely, Iraq, Columbia, Belarus, and Thailand. And each country is analyzed based on the HDI, solar energy consumption and GDP from the year 2016 to 2019.

In a nutshell, we can conclude that with a rise in solar energy consumption, there is an increase in GDP and a decrease in HDI of both developed and developing countries.

In other words, with the increase in solar power consumption, there is a downfall in HDI. However, this could also be a result of other factors, such as geographic location, natural resources, energy infrastructure, and technological developments. Regardless of GDP or HDI, countries with a lot of sunshine and a commitment to renewable energy legislation typically have higher solar energy usage.

B. Future Work

1. The criteria utilized to categorize and select countries for analysis may differ from those employed in our specific method or approach. The variance in parameter selection can lead to variations in the composition of the chosen countries, potentially impacting the outcomes and conclusions of the analysis. As such, it is essential to be aware of these discrepancies when comparing results between different studies or when interpreting the findings of our own analysis. Careful consideration of the specific parameters used in each case is necessary to ensure accurate and meaningful interpretations of the data.

2. With access to a diverse range of data encompassing various parameters, we have the potential to perform predictions and forecasting for solar energy. By leveraging advanced analytical techniques and machine learning algorithms, we can establish correlations and patterns between solar energy generation and the numerous factors that influence it, such as average sunlight hours, geographical location, climate conditions, and more. Utilizing this comprehensive dataset, we can develop accurate predictive models that forecast solar energy production, aiding in optimizing renewable energy

utilization and facilitating effective energy planning and management strategies. The integration of multiple parameters into our forecasting methodology empowers us to make more reliable and data-driven predictions, contributing to the advancement and widespread adoption of solar energy solutions.

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