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Global potential for carbon reduction via renewable energy and negative emission technologies

Lanyu Li[1,3], Jun Jie Yeoh[2], Xiaonan Wang[1,3] *

[1] Department of Chemical and Biomolecular Engineering, National University of Singapore, Singapore
[2] Engineering Science Program, National University of Singapore, Singapore
[3] Energy and Environmental Sustainability Solutions for Megacities (E2S2), CREATE, Singapore

ABSTRACT

Combining renewable energy, waste-to-energy (WtE), and negative emission technologies could provide efficient solutions to mitigate emission or even achieve negative emissions. However, there is a lack of understanding of the global potential of such systems considering countries or regions with varying resource portfolios. In this article, we quantify the potential role of such combination in climate change mitigation around the world and recommend the top places for technology implementation. A mixed-integer linear programming (MILP) optimization was used to select the specific technologies for 20 countries. The result showed that 17 countries were decided to be profitable locations for the proposed system when net present value was maximized. Negative emission was possible to be achieved in 16 countries if greenhouse gas emission was minimized, but it may result in a dramatic increase in cost compared to the optimal NPV scenario.

Keywords: hybrid renewable energy system, negative emission technologies, greenhouse gas emission, economic assessment, optimization.

1. INTRODUCTION

Due to the delayed action in the mitigation of greenhouse gas emissions (GHGe), we need to multiply our efforts in the next decade to avoid the growing threat of abrupt and irreversible climate change [1]. The widespread COVID-19 has taught us to plan for the worst. An effective greenhouse gas mitigation strategy is necessary in case immediate actions are needed in the future. The practical implementation requires us to know where resources are located and how to plan the utilization of resources. Renewable energies (RE) are critical alternatives to fossil fuels for emission mitigation, and negative emission technologies (NET) are promising candidates to mitigate emissions by removing CO_2 from the atmosphere. As the intersection of both, bioenergy with carbon capture and storage (BECCS) and biochar (BC) are two key NETs based on the thermal conversion of biomass. While RE mitigate emissions, NETs hold great potential to offset the harder-to-abate emissions in other sectors and facilitate "net-zero" climate goals [2].

However, the amount of these resources is usually constrained by geographical boundaries. Just like oil and gas, the exploitation of renewable energy requires us to have a good understanding of the location of renewable sources and its constraints of exploitation, energy transmission and storage. Previous research has been limited to assessing the emission reduction potential of implementing specific renewable or carbon capture technologies at individual sites or countries. There is a lack of geographical survey on the carbon mitigation and reduction potential that could be synthetically achieved by RE, BECCS, and BC in different regions around the world.

Therefore, this article aims to provide an initiative global assessment of renewable energy and mitigation technologies using publicly available data. Solar, onshore wind, bioenergy (pyrolysis, gasification, combustion for inorganic waste, and anaerobic digestion for organic waste), and biochar are potential renewable, waste-to-energy, and negative emission technologies considered in this study. Here, we present an evaluation of economic and emissions mitigation potential by using a proposed integrated assessment model and publicly available datasets covering 20 countries around the world, selected based on their high biomass energy generation potential [3] and their dominant contribution (around 68.81% in 2018) in global carbon emission [4].

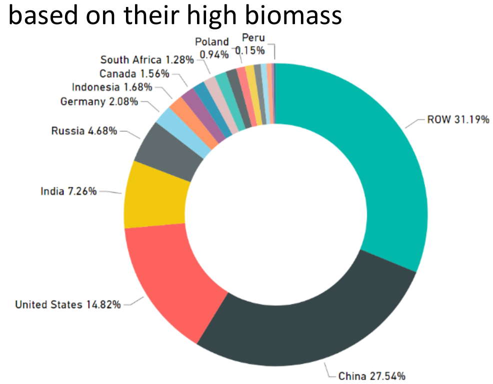

Figure 1. Annual ton-CO_2 emission in 2018 (ROW represents Rest of World).

2. METHODOLOGY

A snapshot of the current waste, emission, and policy information in different countries around the world was first obtained according to real-world data sources. The Negative Emission Hybrid Renewable Energy System (NEHRES) assessment and optimization tool developed in our previous work [5], containing the conversion models for the RE technologies and NETs as well as the economic and emission assessment models, was modified and applied to analyze the optimal energy mix in different regions. While the previous work proposed the novel framework, this study provides further insight into the geographical variation. To adapt to this research objective, the formulation of the economic evaluation has been improved on top of the previously developed framework. The process of data collection and the improvement of the modeling framework are detailed in the following subsections.

2.1. Data collection and analysis

The inputs for the optimization model are the meteorological, biomass, land area, economic and social data for each of the 20 featured countries. The solar irradiance and wind speed data are attained from NASA POWER data access viewer [6] on a global grid with a spatial resolution of 0.5° latitude by 0.5° longitude. The operational hours for the wind turbines and bioenergy components are assumed to be 24 hours a day, while the operational hours for the solar panels are in accordance with the averaged sunshine hour duration for each country [7]. The mass of agricultural, horticultural, and food waste are collected for the biomass conversion model inputs. The annual mass of agricultural crop residue and the annual volume of horticultural forestry residue for 2018 in the 20 target countries are collected from FAOSTAT [8]. To improve the accuracy of agricultural crop residue production, appropriate monthly seasonality is introduced using FAO's country briefs which presents the crop calendar for several major food crops [9].

2.2. Economic indicator

To account for the regional difference of the economic environment, the modeling of the discount rate for different countries is introduced. Following the previous development, the financial profitability of the system is determined using the net present value (NPV), a widely recognized variable in renewable energy project financing modeling. The NPV reflects the net returns of the energy project from an investment point of view, and is expressed as follows:

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{\mathrm{NCF}}{(1+\mathrm{DR})^{t}} - \mathrm{CAPEX} \quad (1)$$

where NCF is the monthly net cash flow, T is the lifetime of the system assumed to be 20 years, DR is the discount rate unique to each country, and FC is the capital investment for the system.

Here, the discount rate is estimated using the weighted average cost of capital (WACC), expressed in the following:

$$\mathrm{WACC} = w_d \times K_d + w_e \times K_e \quad (2)$$

where w_d and w_e are the share of debt and equity financing respectively, K_d and K_e are the cost of debt and equity respectively. The capital structure is assumed to have a 70% debt and 30% equity form of financing, in line with industry averages [10]. The after-tax cost of debt is derived as follows:

$$K_d = i \times (1 - t) \quad (3)$$

where i is the lending interest rate of national banks obtained from the World Bank [11] and t is the corporate tax rate for 2020 obtained from KPMG [12]. The cost of equity is derived as follows:

$$K_e = r_f + \beta \times (r_m - r_f) \quad (4)$$

where r_f is the risk-free rate, β is the renewable energy industry average beta which gives a measure of its market risk, and r_m is the market return. The risk-free rate and market risk premium (r_m - r_f) for each country are obtained from a market survey conducted in 2020 [13]. The industry average values for levered betain different regions are obtained from compilations by A. Damodaran [14].

2.3. Carbon emission indicator

The greenhouse gas emission (GHGe) for the system was derived from the product of simulated annual energy output and the emissions factor, with reference to the average kg-$CO_{2\text{-eq}}$/kWh for each technology from an IPCC report [15]. The stable carbon percentage for the mass of carbon absorption per mass of biochar is referenced from a prior study on biochar stability [16].

2.4. Constraints

The land area of each country is obtained from the World Bank [17]. The land area used for the system is constrained to within 0.1% of the total land area of each country, a more conservative restriction than the EU Science Hub's stance [18] that converting 1% of land to renewable energy production will be sufficient to provide EU's electricity consumption.

3. RESULTS AND DISCUSSION

With the updated method, the global analysis on the profitability and greenhouse gas absorption potential of the 20 countries was carried out.

3.1. Maximizing NPV

To begin with, the scenario that the NPV is maximized is calculated. The result indicates that 17 of the 20 countries analyzed were decided to be profitable locations for the NEHRES system when maximizing NPV. Figure 2 shows the optimal breakdown of electricity supply by technology for different countries returned by the optimization, and Figure 3 provides the geographical variation of renewable generation by region. The non-profitability of Argentina, Mozambique and Zambia may be attributed to their relatively higher cost of capital due to their high investment risk. Figure 4 depicts the potential of NEHRES in fulfilling each country's annual electricity demand, with a profitable electricity supply for Australia and Spain capable of exceeding 100%.

The blue bars in Figure 5 shows the result of NPV (4a) and GHGe (4b) by region of the maximum NPV scenario. As shown in Figure 3 and 5a, China has the highest financial potential from solar energy, with an NPV 701% greater than the next highest potential region. Solar energy was selected as the most profitable technology for 10 countries. Australia has the highest financial potential from wind energy, followed by Canada, South Africa and Ukraine. Wind energy was selected as the most profitable technology in 12 countries. A mixture of solar and wind energy was deemed to be most profitable for Colombia, Indonesia, Mexico, Peru, and Spain, given the land constraints. India was found to have the highest financial potential from combustion, followed by China and Brazil. Fourteen countries were deemed to be profitable in biomass combustion. Eleven countries were deemed to be profitable in AD. Brazil was found to have the highest financial potential from AD, followed by the United States, Mexico, Germany and France. However, negative emission cannot be achieved when we aim to maximize profit as indicated in Figure 5b.

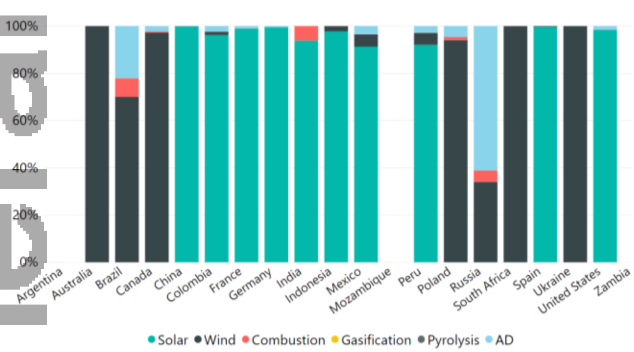

Figure 2. Optimal breakdown of electricity supply by technology for different countries.

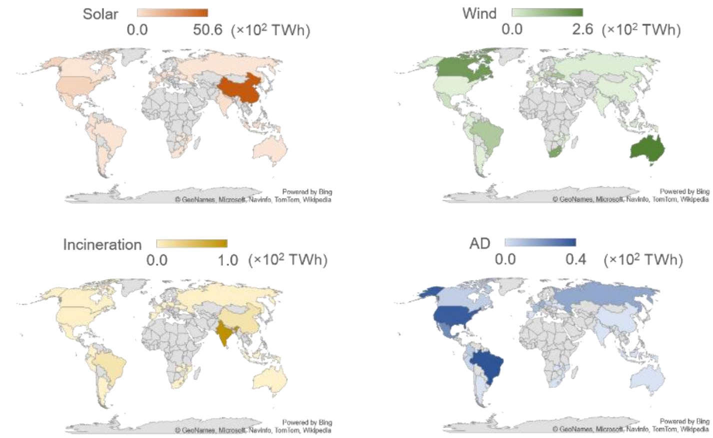

Figure 3. Optimal renewable generation by region.

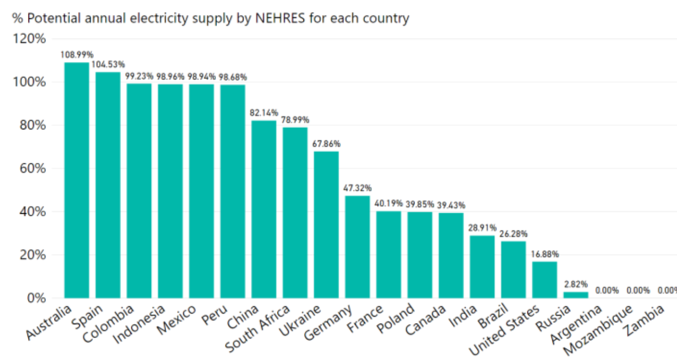

Figure 4. Potential annual electricity supply as % of electricity demand for each country.

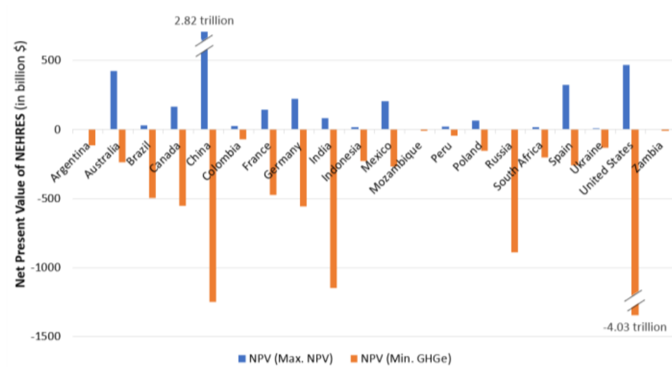

Figure 5a. NPV results of two different objective functions.

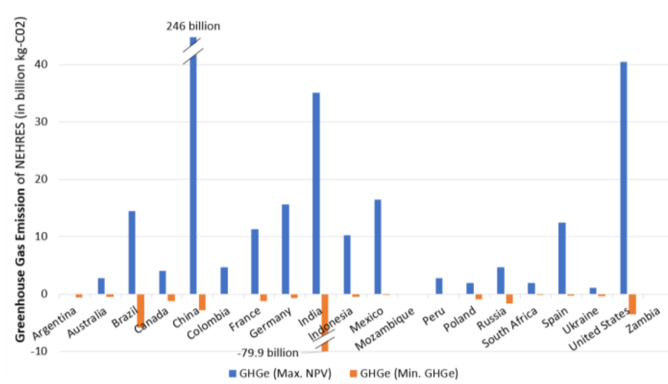

Figure 5b. GHGe results of two different objective functions.

3.2. Minimizing GHGe

In addition to the maximization of the net present value, the case where the greenhouse gas emission is minimized was also investigated. The result of this scenario is indicated by the orange bars in Figure 5a and 5b. Results show that the largest negative emission could be achieved in China with a sequestration of 13.9 Mt CO_2 per year. A closer examination of the capital efficiency in terms of kg-CO_2 saved per unit of investment is shown in Figure 6. It reveals that India, Mozambique, and Brazil could potentially have the highest positive environmental impact per unit of investment required when GHGe is minimized.

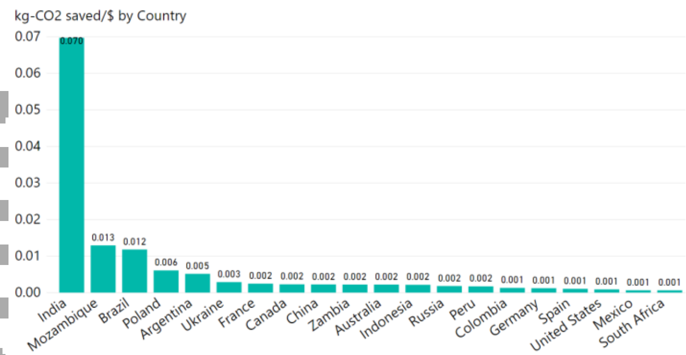

Figure 4. Capital efficiency in terms of kg-CO_2 saved per unit of investment

As a measure of the effectiveness of the optimized systems in carbon abatement, the annual tonne-CO_2 expected to be absorbed is compared against the annual tonne-CO2 produced in 2018 for each country as shown in Figure 7. The results showed that the potential carbon absorption by the NEHRES is not significant as a share of actual annual emissions, especially in the largest emitters (China, India, and the U.S.). The countries with the highest percentage of current annual emission potentially being absorbed by the NEHRES are low emission countries, with the largest difference in Mozambique at 42.9%.

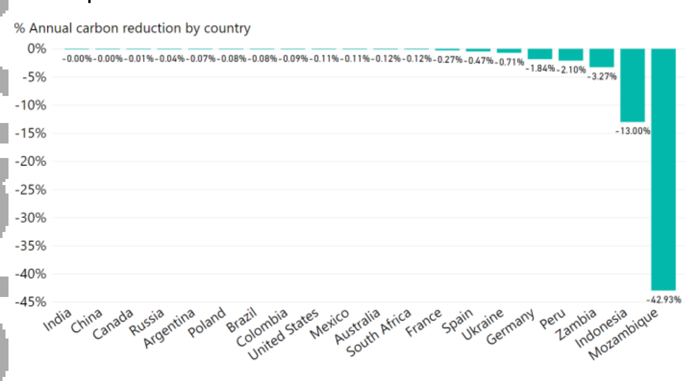

Figure 5. Potential percentage reduction in annual carbon emission with the adoption of NEHRES.

These results indicate that merely minimizing the GHGe could lead to great economic burden and may not be an economically attractive option when using this as the design objective.

4. CONCLUSION AND FUTURE WORK

This work presents the economic assessment and the potential for carbon reduction via renewable energy and negative emission technologies for 20 countries around the world. The result shows that 17 countries were decided to be profitable locations for the proposed system when net present value is maximized. Negative emission was possible to be achieved in 16 out of 20 countries if greenhouse gas emission was minimized, but it may lead to a dramatic increase in cost compared to the optimal NPV scenario. The geographically heterogeneous diversification of renewable resources and system design was observed in the local and global analysis. The methodology framework was demonstrated to be versatile and conveniently applicable to study the feasibility of the proposed NEHRES system in multiple regions. In future studies, the impact of grid integration of renewables, a higher-precision analysis accounting for the temporal-spatial variation of various factors can be carried out to provide more insights.

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