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Can Climate Change Mitigation be Catalyzed through Green Hydrogen Coupled with Crypto's Resurgence?

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Climate change continues to be a major global challenge, largely due to substantial emissions from fossil fuels. Although countries are pushing for global decarbonization through green hydrogen, the increasing use of crypto operations like Bitcoin mining has worsened the climate crisis. This work examines the potential of combining Bitcoin mining operations with green hydrogen technology to support climate mitigation strategies. Findings suggest that integrating Bitcoin mining with green hydrogen infrastructure can drive the expansion of solar and wind power capacities, thus strengthening conventional mitigation frameworks. Moreover, incentives for green hydrogen power can boost the capacity for negative emission technologies, enabling states to mine Bitcoins with the economic potential to capture at least 7.4 tCO_2-eq per Bitcoin. Therefore, the proposed technological frameworks, which merge green hydrogen and Bitcoin mining with suitable policy measures, can significantly enhance clean energy production and carbon capture capabilities, contributing to climate sustainability.

1. Introduction

Climate change is largely driven by the rise in greenhouse gas (GHG) emissions resulting from both human activities and natural processes (Klemeš et al., 2023). Escalating emissions from energy production continue exacerbating the global carbon footprint (Miyazaki and Bowman, 2023), with fossil fuels remaining the dominant energy source (Brockway et al., 2019). To reduce GHG emissions from fossil energy sources, deploying renewable power installations is essential, forming a key part of traditional mitigation strategies that facilitate the energy transition (Fawzy et al., 2020). Expanding on these strategies, many countries are also looking to use energy carriers to enhance the utilization of clean energy (Chatterjee et al., 2021). Green hydrogen is anticipated to be instrumental in addressing climate change by providing renewable energy (Kazi et al., 2021). Nonetheless, the production of conventional energy carriers often leads to energy inefficiencies, losses, and direct emissions based on the fuel used for transportation (Al-Breiki and Bicer, 2021). Despite these limitations, green hydrogen can enhance renewable installations and meet the increasing demand for hydrogen derived from clean energy sources (Hassan et al., 2023). The transition from a fossil-fuel-based economy to one driven by hydrogen is expected to receive significant regulatory support for decarbonization efforts (Lal et al. 2023). However, the past decade has seen a notable rise in the energy costs associated with blockchain-based applications (Kohler and Pizzol, 2019). The reliance on grid-powered mining in the cryptocurrency sector has contributed significantly to the growing carbon debt (Lal et al., 2023), which continues to increase steadily (Zhao et al., 2024). Shifting the energy source for cryptocurrencies to support the deployment of renewable infrastructure can create a vital connection for clean energy penetration (Lal et al., 2024). In addition, negative emissions technologies provide a favorable approach to decarbonizing various sectors, thus enhancing traditional climate strategies. By adopting these measures, cryptocurrency mining could potentially operate with net-zero GHG emissions (Niaz et al., 2022), leveraging its economic potential to support climate change mitigation efforts.

This work explores the strategic integration of green hydrogen production and Bitcoin mining to significantly boost the adoption of clean energy installations and enhance carbon capture measures in the energy sector (Lal and You, 2024). To test this hypothesis, we explore a multi-faceted strategy across US states. This strategy involves using clean energy installations for crypto mining and green hydrogen production. Additionally, we

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analyze scenarios where crypto operations are operated using grid power supplemented with green hydrogen under net-zero conditions across various US states to strengthen the negative mitigation framework.

2. Methodology

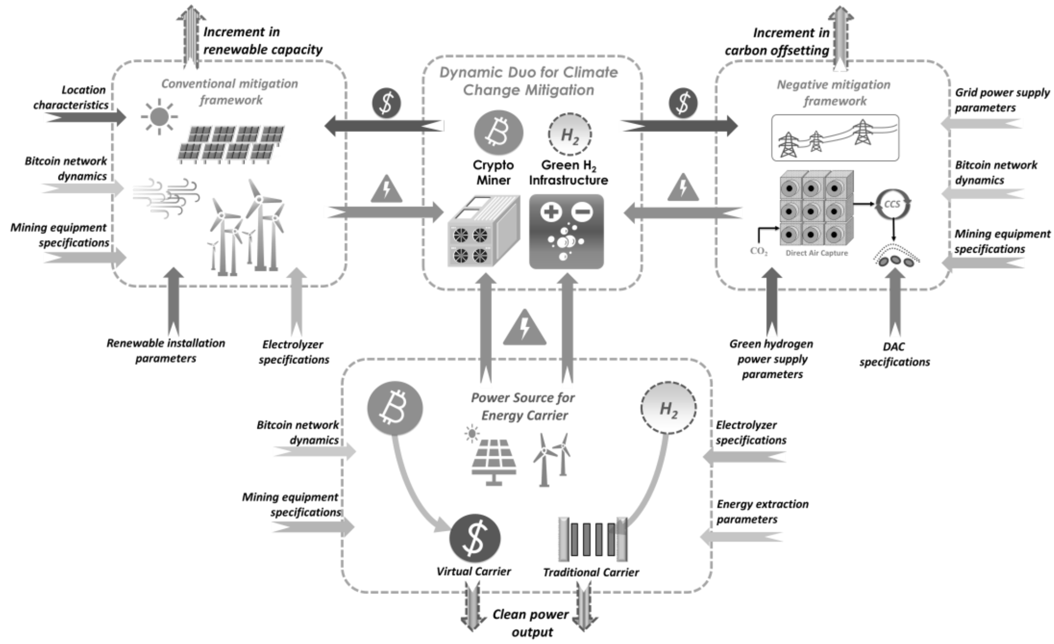

Figure 1: Schematic representation for analyzing the potential of green hydrogen and Bitcoin as a combined solution to enhance conventional and negative mitigation strategies

This study investigates the expected role of cryptocurrency operations and green hydrogen production to aid in energy transition and decarbonization, as depicted in Figure 1. The conventional mitigation framework utilizes a clean power supply instead of a fossil-dominant supply for Bitcoin mining and green hydrogen production to enhance investment in renewable infrastructure. Specifically, we investigate the conventional mitigation framework based on the development of wind and solar power facilities in different US states to mine Bitcoin and produce green hydrogen, utilizing their economic potential to increase renewable energy capacity. For the negative mitigation strategy, this work explores the combination of cryptocurrency operations with green hydrogen power generation to enhance carbon offsetting capacity. This approach involves using grid electricity alongside green hydrogen power for crypto mining, directing the economic potential toward improving carbon offsetting capabilities through technologies such as Direct Air Capture (DAC). Considering the recent trends for increasing developments in various technological fields, such as artificial intelligence, the potential stimulating effect of these technologies can also be assessed as part of future work. The general systems optimization framework used in the study for the proposed technological solutions and respective constraints is presented in Eq(1).

$$max\ NPV\ of\ proposed\ technological\ solutions \tag{1}$$

s.t. Load balance constraints
Operational constraints
Economic evaluation constraints

The load balance constraints utilize the data for wind speed and solar irradiation for the different states installing a renewable power generation facility with a fixed capacity. The calculated wind or solar power values indicate the total available power distributed among the utilized and surplus power at different time intervals (Balaji and You, 2024). However, these constraints vary in the negative mitigation framework. The total available power represents the power imported from the respective state electricity grids and power generation using green hydrogen. The operational constraints in the optimization framework govern the equipment performance. For example, the operation of mining equipment leads to the generation of heat, which must be removed using heat pumps. The power consumption in the heat pumps can be estimated using the specified coefficient of performance. These constraints include the CO_2 capture quantities from DAC units, which are calculated based on equipment efficiencies. Correspondingly, these also specify the maximum limit on the power dedicated to different equipment based on the number of units utilized and the individual capacities. The economic evaluation in the study estimates the total revenue for the project based on the summation of the income for different time intervals, including the revenue generated for mining bitcoin and green hydrogen production for the respective scenarios. The income generated from the crypto mining process depends on the price of the currency, the number of coins rewarded for adding a new block, the power dedicated to mining equipment, and the network difficulty. The capital expenditure for the different process components is computed using unit capital cost and the number of units utilized. The operating cost for the process components is estimated by summing the operational and maintenance cost units in different time intervals or as the percentage of the capital cost for each year of operation. Some components in the total operating cost are the storage and transportation costs for the captured CO_2. Based on the considered project life, we utilize the double-depreciation method to calculate the corresponding salvage values for the equipment used. This analysis utilizes the historical data corresponding to the network parameters to get the range of energy demand for the crypto-mining process. The expansion potential is quantified based on the NPV for the proposed technological solutions and the cost parameters for renewable energy technologies and carbon offsetting capacities. Moreover, in this work, we conduct sensitivity analysis to investigate the impact of equipment specifications on the efficiency of the proposed technological solutions. Specifically, this work considers the influence of mining equipment hash rate and the electrolyzer efficiency on the conventional mitigation framework.

The key input data in this study include:

(1) the wind speed and solar irradiation data for variable renewable power supply across different US states;

(2) the performance metrics of renewable power facilities including characteristics such as cut-in and cut-out speeds for wind turbines and solar panel efficiency;

(3) the network dynamics for the Bitcoin mining operations, such as the Bitcoin prices and the network difficulties, along with the geographical distribution of mining computational power;

(4) the equipment specifications for the process sections in the considered technological solutions, including the mining equipment, heat pumps, electrolyzer, and DAC;

(5) economic parameters used in the optimization modeling framework, such as the unit capital costs and operational and maintenance costs; the emission factors in the considered technological solutions, such as the grid power supply for crypto mining operations and conventional pathways for hydrogen production.

The model outputs include:

(1) the economic potential that can be generated based on the implementation of the considered technological solutions;

(2) the total deployment of renewable infrastructure, which can be attained based on the conventional mitigation framework incorporating bitcoin mining operations and green hydrogen production;

(3) The total deployment of carbon capture capacity can be attained based on the negative mitigation framework incorporating bitcoin mining operations and green hydrogen power supply.

The major decision variables include:

(1) the load balance between power utilized for Bitcoin mining and green hydrogen production and the surplus power generation in the conventional mitigation framework, considering the equipment capacities and constraints;

(2) the load balance between grid power supply in various states and green hydrogen-based power generation utilized for crypto operations in the negative mitigation framework, considering the equipment capacities and constraints;

(3) the economic implications of the considered technological solutions, such as the revenue generation from Bitcoin mining and green hydrogen production, capital and operational expenditure for other process sections such as renewable power infrastructure electrolyzer, and DAC;

(4) the total avoided emissions that can be attained based on the implementation of the considered technological solutions, considering the emission abatement from grid-powered crypto operations and fossil-based conventional pathways for hydrogen production.

3. Results and Discussion

Chapter 2 The findings presented in Figure 2a reveal that New Mexico exhibits the greatest potential for increasing solar power capacity based on initial investment potential. Additionally, California, Arizona, Hawaii, and Nevada also show strong performance in this strategy. In a similar analysis, Figure 2b assesses the viability of wind energy systems in supporting traditional mitigation efforts through Bitcoin and green hydrogen. The analysis identifies Wyoming, South Dakota, and Oklahoma as having considerable potential for wind energy expansion. In contrast, states such as Arkansas and Arizona are not suitable for promoting traditional mitigation through Bitcoin and green hydrogen due to insufficient wind energy potential. The proposed strategy utilizes a solar or wind power facility to quench the demand for Bitcoin, thereby avoiding substantial carbon emissions

(Krause and Tolaymat, 2018). This also applies to hydrogen production, where most of the demand is currently fulfilled through fossil-heavy production processes such as steam methane reforming and coal gasification (Zhang et al., 2023). The investigated framework can also be used to evaluate the future economic potential for expanding renewable capacity, considering the increasing cost-effectiveness of renewable power generation (Lu et al., 2020). In order to assess the impact of equipment specifications on the effectiveness of technological frameworks, Figure 2c shows that under the minimum hash rate for the Bitcoin mining equipment, states such as New Mexico maintain a capacity increment potential close to the base case evaluation, indicating considerable resilience to less efficient mining operations.

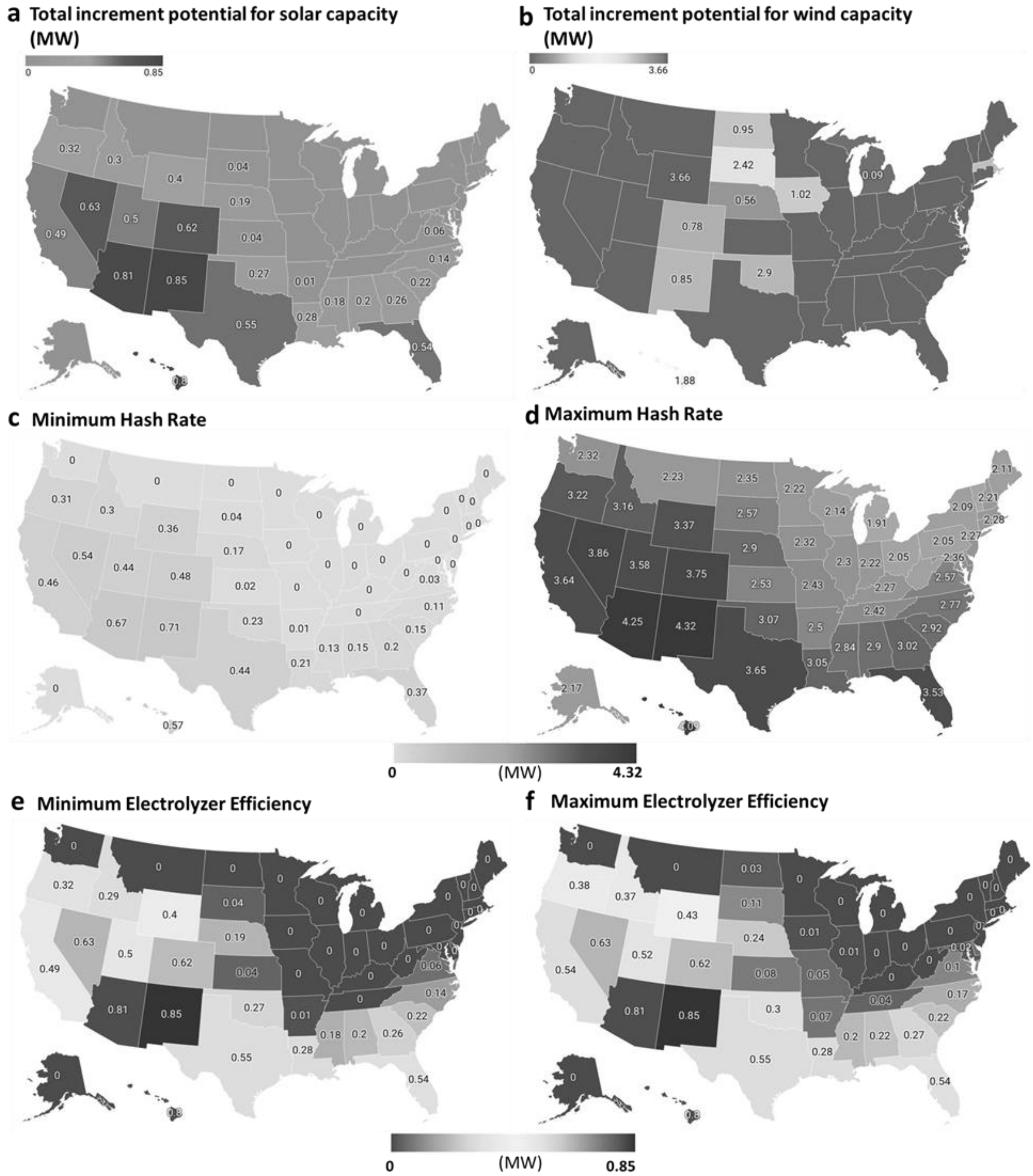

Figure 2: (a) Expansion in solar capacity (MW) in various US states driven by economic potential from cryptocurrencies and green hydrogen. (b) Expansion in wind capacity (MW) in various US states driven by economic potential from cryptocurrencies and green hydrogen. (c) Total increment potential for solar capacity (MW) in different US states based on minimum mining equipment hash rate. (d) Total increment potential for solar capacity (MW) in different US states based on maximum mining equipment hash rate. (e) Total increment potential for solar capacity (MW) in different US states based on minimum electrolyzer efficiency. (f) Total increment potential for solar capacity (MW) in different US states based on maximum electrolyzer efficiency.

On the other hand, states like Arizona, California, Hawaii, etc., can utilize solar energy resources to enhance the increment potential by more than 100 % in case of maximum mining equipment hash rates. In the case of electrolyzer efficiency, the solar capacity increment potential was reduced by 3.4 % and 11.9 % in Idaho and South Dakota, respectively. However, many states indicated a relatively smaller effect on the increment potential due to electrolyzer efficiency. Therefore, the impact on the solar capacity increment potential due to electrolyzer efficiency is less significant than the mining equipment hash rate, which can be attributed to the load balance. The cryptocurrency industry's heavy dependence on grid electricity results in a significant carbon footprint (Jiang et al., 2021). While technologies like DAC can mitigate this impact, their high costs pose a challenge (Lackner and Azarabadi, 2021). As an alternative, this study explores combining cryptocurrency operations with green hydrogen power generation to enhance carbon offsetting capabilities and support negative mitigation strategies. Initially, the economic potential of mining Bitcoin in various US states is assessed for CO_2 capture using the levelized cost of carbon capture technologies, as depicted in Figure 3a. The analysis reveals that states like Idaho can effectively mine Bitcoin and achieve substantial carbon offsetting due to their high share of renewable energy in the grid and favorable electricity prices. Conversely, other states are less feasible for enhancing negative mitigation potential through crypto operations due to high operational costs, significant investment requirements for DAC technologies, and the expenses associated with green hydrogen power generation. Notably, the framework indicates that Idaho does not rely on green hydrogen power, while some states supplement grid supply with green hydrogen. Figure 3b illustrates the economic potential of Bitcoin mined under carbon-neutral conditions across various US states, utilizing both grid power and incentivized green hydrogen power generation. States with a greener electricity mix do not show a change in their potential for enhancing negative mitigation capacity. Yet, some states significantly improve their potential through incentivized green hydrogen power generation.

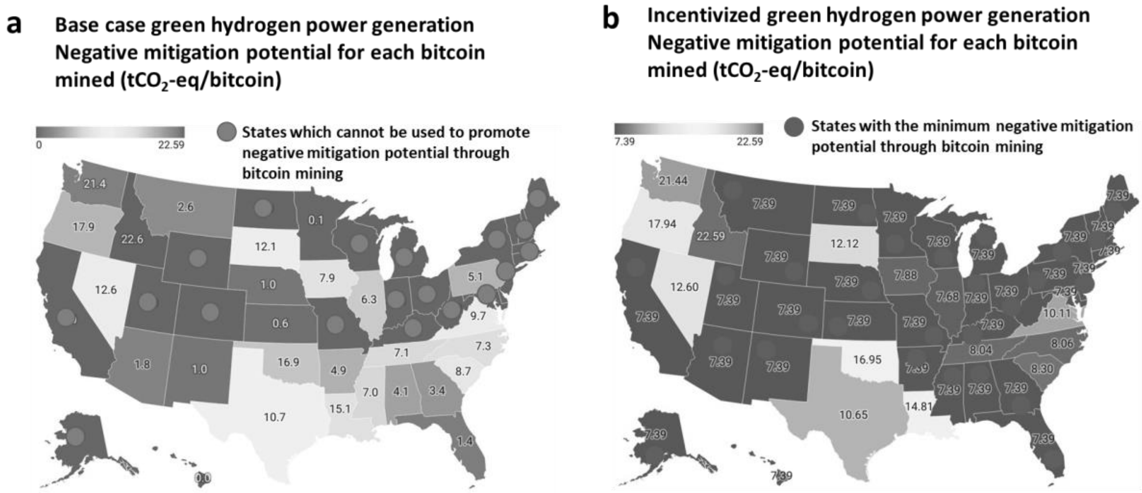

Figure 3: (a) Negative emissions capacity per Bitcoin mined in different states using the base case for green hydrogen power generation. (b) Negative emissions capacity per Bitcoin mined in different states using the incentivized case for green hydrogen power generation

4. Conclusions

This work investigated integrating cryptocurrency operations with green hydrogen production to bolster climate mitigation efforts by enhancing renewable infrastructure deployment and improving carbon offsetting mechanisms. The comprehensive strategy explored the potential of combining Bitcoin mining with green hydrogen infrastructure and solar and wind power installations to advance conventional climate change mitigation methods. Results showed significant differences in the effectiveness of these technological solutions across various US states, reflecting the diverse renewable energy potentials. These findings highlighted the need for a tailored approach in applying the conventional mitigation framework. Strategic decision-making took into account state-specific renewable energy potential, economic viability, and environmental impacts. The analysis went beyond traditional climate mitigation by evaluating the economic potential of Bitcoin mining to support carbon capture using grid power and green hydrogen generation. Due to substantial renewable energy contributions to grid power supply, some states showed considerable capacity for Bitcoin-enabled CO_2 capture within the proposed negative mitigation framework. In contrast, other states faced challenges due to higher operational costs and dependency on fossil fuels. The efficiency of this framework varied based on the proportion of green hydrogen power in the total energy supply, underscoring the importance of region-specific strategies and robust policy measures to optimize the negative mitigation potential of crypto operations. Thus, the proposed technological solutions offer a pathway to enhance climate change mitigation efforts by leveraging the economic benefits of crypto operations and green hydrogen while considering their environmental impacts.

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