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The Environmental Stake of Bitcoin Mining: Present and Future Challenges

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Abstract: The environmental impact of Bitcoin mining has raised severe concerns considering the expected growth of 30% by 2030. This study aimed to develop a Life Cycle Assessment model to determine the carbon dioxide equivalent emissions associated with Bitcoin mining, considering material requirements and energy demand. By applying the impact assessment method IPCC 2021 GWP (100 years), the GHG emissions associated with electricity consumption were estimated at 51.7 Mt CO_2 eq/year in 2022 and calculated by modelling real national mixes referring to the geographical area where mining takes place, allowing for the determination of the environmental impacts in a site-specific way. The estimated impacts were then adjusted to future energy projections (2030 and 2050), by modelling electricity mixes coherently with the spatial distribution of mining activities, the related national targeted goals, the increasing demand for electricity for hashrate and the capability of the systems to recover the heat generated in the mining phase. Further projections for 2030, based on two extrapolated energy consumption models, were also determined. The outcomes reveal that, in relation to the considered scenarios and their associated assumptions, breakeven points where the increase in energy consumption associated with mining nullifies the increase in the renewable energy share within the energy mix exist. The amount of amine-based sorbents hypothetically needed to capture the total CO_2 equivalent emitted directly and indirectly for Bitcoin mining reaches up to almost 12 Bt. Further developments of the present work would rely on more reliable data related to future energy projections and the geographical distribution of miners, as well as an extension of the environmental categories analyzed. The Life Cycle Assessment methodology represents a valid tool to support policies and decision makers.

Keywords: life cycle assessment; cryptocurrencies sustainability; bitcoin; low-carbon electricity; net-zero greenhouse gas emissions; energy transition

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1. Introduction

1.1. Climate Change and Cryptocurrencies

Climate change is one of the biggest concerns of the modern era, due to the proven impacts on human health [1–3] and ecosystems [4–6]. An increasing awareness of the influence of human activities on climate change has captured the attention of both politics and society [7] and pushed the research towards reaching a net-zero greenhouse gas (GHG) emission goal [8,9] by taking actions to boost the implementation of sustainable processes and technologies [10–13].

A worldwide picture of the cumulative CO_2 emissions from 1750 to 2022 is reported in Figure 1, representing the amount already emitted into the atmosphere. Although the global CO_2 emissions are "only" slightly increased in 2023 compared to 2022 [14], the concentration of CO_2 in the atmosphere reached 427 ppm (June 2024) [15], stressing the need for proper and timely mitigation actions.

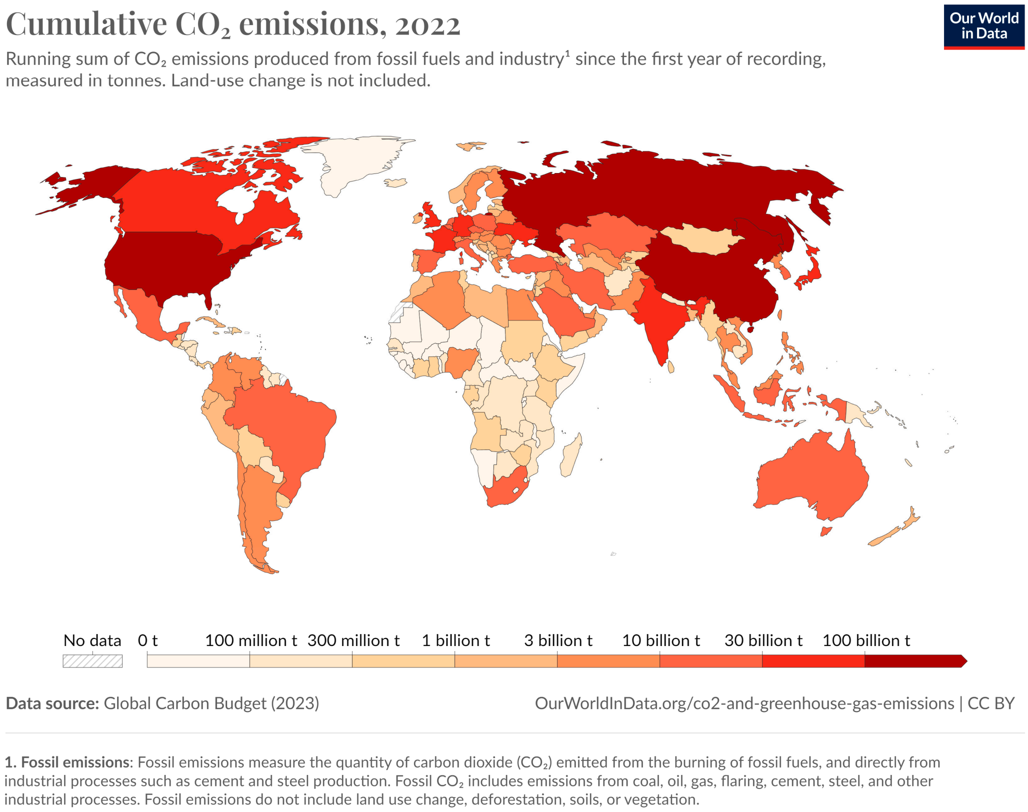

Figure 1. Cumulative CO_2 emissions from 1750 until 2022 [16].

To tackle the issue of present and future emissions, beyond the transition to low-carbon technologies and universal efforts towards greener industrial systems, it is essential to identify the major sources of GHG emissions. Historically, transportation, building, and industry have covered most of the GHG emissions, mainly due to energy requirements. However, today, new sectors are growing, the impact of which remains little investigated, if at all. Of relevance here, in a world increasingly oriented towards digitalization, cryptocurrencies have been widely discussed in recent years, because of their potential implications on the monetary system [17–21], by removing the middlemen and establishing trust between unknown parties [22].

Cryptocurrencies have also been placed under investigation due to several environmental implications [23]. Here, the Bitcoin mining activity is particularly noteworthy, reporting that in 2021, the mining network globally consumed 89.00 TWh of electricity [24], which represents about 0.3% of the total electricity consumed worldwide [25]. Qin and colleagues (2023) recognized the significance of the impactful energy consumption and consequent carbon intensity of the cryptocurrency system. They also reported the existence of several implications that may affect both energy consumption and emission trends, such as, for instance, the price of Bitcoin [26], whose relationship with the total energy consumption is suggested to be "chaotic" and "nonlinear" [27].

The close link between CO_2 emissions relative to the use of Bitcoin was also confirmed by Polemis and Tsionas [28] by means of a Bayesian analysis and quantile cointegrated vector autoregression investigation, which corroborates a Bitcoin use/carbon emissions "causal effect" existing between them. In particular, the contribution of Bitcoin mining to the total global carbon emissions in 2016 was estimated to be around 0.19% [29], a value which is highly dependent on different factors, especially the electricity mix employed.

In recent years, researchers have attempted to assess the environmental impact of cryptocurrencies [22,23,30–33]. However, to the best of our knowledge, there is a lack of adequate discussion on how this market fits into the pathway toward carbon neutrality predicted for the coming decades. In fact, Kohler et al. (2019) [22] and Chamanara et al. (2023) [23] presented a comprehensive model that included the evaluation of spatial variability by detailing all the countries involved, but they did not project GHG emissions for the coming years. Liu et al. [32] accounted for the positive implications of mining alongside its effects on climate change. However, in this study as well, the impacts were neither assessed based on future projections nor was spatial variability considered.

Stoll et al. [34] provide a methodology to obtain precise estimates, as of November 2018, of carbon emissions (22.0–22.9 Mt CO_2) and annual electricity consumption 45.8 TWh, by considering IPO filings of mining hardware, mining facility operations, pool composition, and geographic footprint. Their understanding of the impact of Bitcoin mining leaves room to define possible future carbon emission scenarios as well as the evaluation of the impact of power recovery in mining operations.

According to one (logistic model) of the two models described by Shi et al. [35], estimated carbon emissions of the Proof-of-Work-based Bitcoin will be in the 117.03–331.90 Mt CO_2 range in 2030, increasing by about two orders of magnitude in 2050.

Roeck et al. [36] introduced the application of LCA as an innovation to a behind-the-meter Bitcoin mining system, taking into account future energy projections in the discussion. However, in this case, the study is limited to a single facility and does not provide results on a global scale. To fill this gap, our study aims to calculate the GHG emissions associated with the Bitcoin mining phase, striving to accurately represent the electricity mixes of the involved states and considering potential future variations in both the electricity mixes (in relation to projections aimed at reducing GHG emissions) and the electricity for hashrate (EfH). These estimates will enable us to understand the role and potential future responsibilities of Bitcoin in a world that must mitigate the impacts of climate change. In particular, this study primarily aims to address the following two hypotheses: (i) The increase in EfH could, at some point, nullify efforts made to reduce the carbon intensity of energy mixes. This assertion is partially in contrast to what has been stated by Lal et al. [37] and Bruno et al. [38], who understandably argue that the increase in EfH could drive the energy transition; however, if this low-carbon energy is then consumed for mining activities, other sectors may not benefit from it. (ii) Energy mixes will reduce their carbon intensity, but if energy demand proves to be particularly high, it will be necessary to rely on fossil resources to meet the share that cannot be obtained from renewable sources.

1.2. Reaching Net Zero and Carbon Capturing

There is an international scientific consensus that, to prevent the worst climate damage, global net human-caused carbon dioxide emissions need to be reduced by about 45% from the 2010 levels by 2030, reaching net zero in 2050 [39]. This goal suggests that the various sectors should proportionally contribute to the reduction. Such a vertical approach relates to the concept of absolute sustainability, whose assessments have been developed to quantitatively determine if the environmental impact of an activity [40], e.g., Bitcoin mining, can be considered sustainable when inserted in the global context. This approach is also useful for determining the global contribution of a sector or activity to total global emissions, allowing for the assignment of a specific role to it and potentially identifying it as a hotspot that requires targeted intervention.

CO_2 capture from the atmosphere, combined with its utilization and/or storage, is one of the proposed strategies to mitigate climate change [41] In particular, carbon capture from industrial chimneys is considered among the most promising strategies aimed at limiting the rise in the overall concentration of CO_2 [42]. In this context, several technologies have been developed in the last few decades to directly reduce the CO_2 released during industrial activities or remove CO_2 from the atmosphere to balance emissions [43–45].

Scientific research is facing numerous challenges to enhance the performance of both liquid and solid sorbent materials, and IEA consistently provides a prediction about the percentage of CO_2 trapped by CCUS technologies [46]. For this reason, the following sections consider the potential of CCUS technologies to mitigate CO_2 emissions from Bitcoin mining activities to be of particular interest.

The authors believe that raising awareness regarding the sectors with the greatest impact on global GHG emissions, as well as the underlying causes of these impacts, would support decision makers in developing policies and recommendations aimed at advancing progress towards achieving net zero.

2. Materials and Methods

LCA is a methodology that consists of the evaluation of the environmental performances of a system or a product in all the phases of its life cycle and is standardized by ISO 14040:2006 [47] and ISO 14044:2006 [48], and it is structured into four fundamental phases: (i) goal and scope definition; (ii) Life Cycle Inventory (LCI); (iii) Life Cycle Impact Assessment (LCIA); and (iv) interpretation.

2.1. Goal and Scope Definition

The main goals of this study are to (i) estimate the carbon emissions (mass of carbon dioxide equivalent) associated with the life cycle of Bitcoin in 2022 (baseline Scenario) according to a site-specific LCA model; (ii) predict the carbon emissions associated with 2030 and 2050, by assuming a reduction in the carbon fraction of the electricity mix; (iii) investigate five additional scenarios considering the reduction or increase in the EfH; (iv) elaborate four different hypotheses related to the capability of the electricity mix to supply low-carbon electricity (LCE), in relation to higher electricity demands.

The analysis is focused on Bitcoin, considered the cryptocurrency with the largest market capitalization (≈80% of the total cryptocurrencies) [30]. The selected functional unit is “1 year” of mining. The system boundaries include the extraction of raw materials and the consumption of resources involved in electricity production, including related infrastructure burdens, electricity generation at the plant, transmission losses and burdens, and consumption during the mining phase, following a cradle-to-gate approach. A cut-off was applied to the infrastructure (including informatic equipment) of the mining phase, as it was considered out of scope. To avoid allocation, consistently with ISO 14044 [48], the heat produced and recovered during the mining phase was included in the assessment by expanding the system and following the ‘avoided product’ criterion, thereby crediting a gain to the model (see Section 2.2.4). This strategy allowed for the avoidance of the employment of allocations.

2.2. Life Cycle Inventory

The proposed study is structured around two main categories of data: (i) geographical and flow information related to Bitcoin mining and cryptocurrency transactions, and (ii) data about energy mixes.

2.2.1. Cryptocurrencies

The selected data source for Bitcoin mining is the Cambridge Bitcoin Electricity Consumption Index (CBECI) website [24], whose “hybrid top-down approach” is suggested to best account, among 22 blockchain energy investigations, for the proposed “best practices for direct energy use analysis” [49]. The total amount of energy consumed for Bitcoin mining in 2022 is estimated at 95.53 TWh. The website displays a mining map, allowing one to determine the percentage of Bitcoin mined per country involved. The reported percentages for Bitcoin mining distribution in January 2022 are as follows: USA (38%), China (21%), Kazakhstan (13%), Canada (6%), Russia (5%), Germany (3%), Malaysia (3%), Ireland (2%), and other (9%) (See Table S1 and caption).

2.2.2. Electricity

The carbon intensity (i.e., kgCO_2 eq/kWh) of electricity principally depends on the energy sources and process technology employed in power generation [50–52]. In order to simplify the description of the results, electricity will be divided into two macro-categories according to its derivation, i.e., high-carbon electricity (HCE), constituted by oil, coal and natural gas sources; and LCE, constituted by the electricity generated by nuclear and renewable resources. The electricity mixes, specific to each country involved in the mining, were accurately modelled in the SimaPro software (v. 9.6). In the case of the baseline scenario (i.e., 2022), electricity mixes were modelled by referring to the most updated information reported in IEA (2022) [53], while the environmental information associated with the electricity production and supply was drawn by the ecoinvent database [54]. The use of the ecoinvent database and the SimaPro software allows for the estimation of GHGs by considering all phases of the life cycle of the electricity consumed during the mining phase. This includes the impacts associated with the extraction and procurement of raw materials needed for electricity production, the infrastructure burdens, whether at the level of the production plant or the electricity distribution network, the electricity grid losses, as well as emissions during the production phase at the plant (e.g., combustion gas emissions in the case of thermoelectric power plants). When ecoinvent contained multiple technologies for producing electricity from the same source, the production from that source was distributed among the available technologies according to the proportions indicated in the ecoinvent proxy [54]. For instance, if in the United States, nuclear energy production accounted for 6.4% of the country's power generation in 2022 [54], and both boiling water reactor (32%) and pressurized water reactor (68%) technologies were operating in the US, it was assumed, for that country, that 2.0% of the nuclear power generation is produced using the boiling water reactor technology and 4.4% by using the pressurized water reactor technology.

According to Section 2.2.1, 'Other' countries accounted for 9% of the Bitcoin mining and, to simplify the calculation, by limiting the number of countries and their data, the corresponding electricity mix was not modelled, and the 91% covered by the eight states mentioned above was proportionally scaled to 100%.

Future projections associated with country energy mixes are reported in Table S2 and were drawn by different resources, often specific to the analyzed country. The first projection scenario is modelled by referring to the best available data (BAD) found in the literature and on the web for each involved country. Two more scenarios were created according to different estimations provided by, respectively, the International Renewable Energy Agency (IRENA) [55] and EMBER [56], which report percentages of LCE shares referring to global averages. More details and references about the BAD, IRENA, and EMBER scenarios are reported in Table S3 of the ESI. The authors are aware that future projections are not absolute predictions, so the explored shares may not be easily achievable for all the involved countries. Conversely, for some countries (e.g., Canada and Germany), these objectives have already been met. Nevertheless, it was decided to maintain the BAD as a reference scenario and to provide these two alternative perspectives to understand how the conversion of energy mixes could impact the carbon intensity of Bitcoin mining. In the cases where the set objectives had already been achieved, a stationary evolution to the future was assumed (e.g., Canada had already achieved a percentage of 82.5% by 2022, while the IRENA scenario indicates a global percentage of 40% by 2030, so that, for 2030, it was decided to maintain the 82.5% for Canada, and so on).

2.2.3. Electricity for Hashrate

Hashrate refers to the computational power (in terms of speed and efficiency) of a mining device to process transactions. The EfH consumed in 2022, reported by the CBECI (2022) [24], was equivalent to 95.53 TWh. Because increasing the hashrate corresponds to improving the ability to solve the complex algorithms required to validate transactions, making the network more secure and efficient, an increase in time of the overall EfH is expected. However, due to the high variability of Bitcoin values and the unpredictability of the market, it is not easy to predict EfH consistently with reliable future projections. To enhance the robustness of our estimates relating to possible EfH fluctuations in the future, five more EfH scenarios (EfH-Sc) were modelled, covering different decrease or increase pathways in hashrate (i.e., −10%EfH; +10% EfH; +20% EfH; +50% EfH; +100% EfH with respect to 2022). Two further estimates of CO_2 emissions for 2030 are also provided by extrapolating the EfH data available in ref. [24] considering either (i) the yearly available data (2010–2023) modelling with a quadratic regression model or (ii) a linear regression taking into account the 2016–2023 data, which results in the highest R-squared value (0.985) whether consecutive years of the available data are considered (see plots in Figure 2). The predicted values (and intervals) are equal to 232 TWh ± 25 (two-tailed, α = 0.05) and 334 ± 19 (two-tailed, α = 0.05), therefore about +143% and +250% with respect to the 95.53 TWh of 2022.

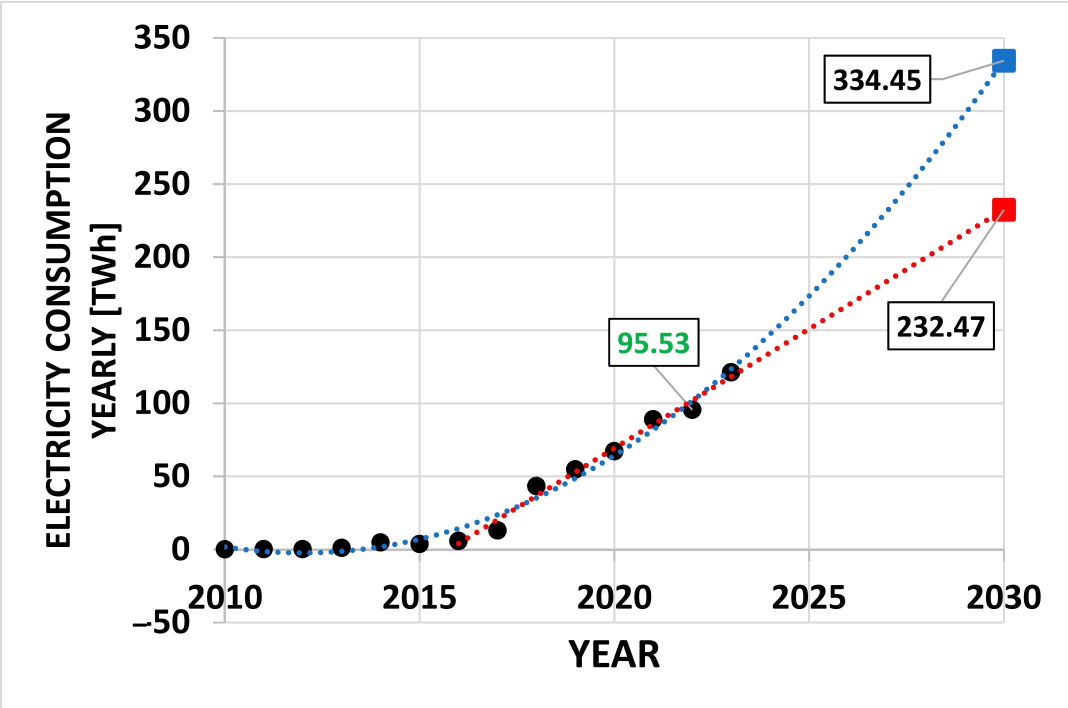

Figure 2. Plots of the linear (dashed red dots) and nonlinear regression (dashed blue dots) models and the corresponding extrapolated predictions for 2030 (red and blue squares). Energy consumption data are taken from ref. [24]. The 2022 value of 95.53 TWh is also highlighted. Data and models are reported as Table S12.

2.2.4. Heat Recovered from Mining

Mining activity generates substantial amounts of heat from the hardware involved in the process [37,57]. Although several private companies involved in Bitcoin mining have already been set up to recover a portion of this heat, the actual amount potentially recoverable from the mining process has not been quantified yet. To provide reliable estimates, primary information shared by the company Mining Farm Italia [58] was used, which reported heat generation of approximately 0.95 kWht per each kWhe of electricity consumed. Based on the expertise of the company, up to 70–80% of the heat could be recovered in a well-designed system. However, it has been conservatively assumed that only 50% of this heat will be recovered. This assumption aligns with findings from other mining machines [59]. The heat produced is assumed to be employed for district heating and credited in the LCA model for avoiding the generation of an equivalent amount of heat from natural gas combustion, by referring to the ecoinvent record "Heat, central or small-scale, natural gas {GLO}| market group for heat, central or small-scale, natural gas |

APOS, U" [54]. This assumption implies the presence of inhabited areas or, more in general, locations where there is a demand for heat.

2.2.5. CO_2 Sorbents

Beyond the main goals described in Section 2.1, a quantification of the adsorbing materials hypothetically needed to sequestrate the amount of CO_2 equivalent to compensate the GHG emitted into the atmosphere from the baseline scenario was determined.

In the framework of the carbon capture technologies, we focused on the largely employed amine-based sorbents [60–66]. To this aim, we referred to the work published by Leonzio et al. (2022) [45], which reports the adsorption capacity values (expressed in mol CO_2/kg of sorbent) of Class I, II and III amine-functionalized sorbents.

It is worth mentioning that all these data were used, including the adsorption capacities of the same sorbent in different conditions/CO_2 concentrations. Since for 3-aminopropyltriethoxysilane (APS), an adsorption efficiency range was reported, the average value of 0.45 mol CO_2 eq/kg of sorbent was considered. The model to estimate the amount of sorbents hypothetically employed to capture the quantity of CO_2 necessary to mitigate the GHG emitted in the mining phase does not consider the possibility of regenerating the materials. Consistently, it also excludes energy and additional materials to allow for such regeneration.

2.3. Life Cycle Impact Assessment

In the LCIA phase, material and energy flows identified and quantified in LCI (e.g., direct and indirect emissions, energy and resource consumptions) are converted into potential environmental impacts using well-established cause–effect models. In our analysis, according to the purposes of this study, the IPCC 2021 GWP (100 years) is adopted as the LCIA method.

Breakeven Electricity

As highlighted above, the results were calculated based on the electricity mixes modelled for the baseline and future scenarios, considering a set of hypothetical energy requirements that vary depending on the EfH, which reflects the Bitcoin market trends. In our analysis, the global warming potential (GWP) value calculated for the baseline scenario is set as the reference GWP for estimating the 'breakeven electricity' (BEE). The BEE represents the amount of electricity that can be required in each scenario to equal the GWP of the baseline scenario in 2022, in relation to the mixes modelled for 2030 and 2050. We believe that this normalization can emphasize that an excessive increase in future electricity consumption for Bitcoin mining could trade off the beneficial effect of reducing the carbon intensity of the electricity mix. Since the BEE is dependent on the mix employed to generate electricity and the mix reflects the capacity of the country to satisfy the electricity demand, four hypotheses are provided: (H1) it is assumed that countries will be able to meet the increasing demand while maintaining a constant fraction of LCE in the mix (see Section Hypothesis 1 (H1)); (H2) it is assumed that the electricity equivalent to that consumed in the year 2022 (i.e., 95.5 TWh) will be produced according to the mix related to the 2030 and 2050 scenarios but that the excess of electricity required to reach the total emission of the baseline scenario in 2022 will be produced entirely from HCE sources (see Section Hypothesis 2 (H2)); (H3) it reflects the same assumption of (H1), but it includes the contribution of the avoided GWP emissions associated with heat recovery (see Section Hypothesis 3 (H3)); (H4) it is based on the same assumptions of (H2), but it includes the contribution of the avoided GWP emissions associated with heat recovery (see Section Hypothesis 4 (H4)). A summary of the assumptions applied in the four hypotheses is reported in Table 1.

Table 1. Summary of the 4 hypotheses.

Hypotheses	Description
H1	Countries will be able to meet the increasing EfH maintaining a constant fraction of LCE in the mix.
H2	The electricity mix of the scenario is maintained constant until the electricity consumption of 2022 is reached. Then the excess of electricity will be produced entirely from HCE sources.
H3	Same as H1, but it includes the credit associated with the heat recovery.
H4	Same as H2, but it includes the credit associated with the heat recovery.

Hypothesis 1 (H1)

In H1, the BEE is computed by assuming that, in each scenario, the electricity consumed by Bitcoin mining is generated from the same electricity mix modelled for that scenario, independently of the absolute power consumed. $BEE_{Scenario}$ represents the BEE estimated for each future scenario (i.e., BAD 2030, IRENA 2030, EMBER 2030, BAD 2050 and IRENA and EMBER 2050).

Accordingly, the BEE of H1 ($BEE_{Cmix,Scenario}$) is computed as reported in Equation (1), where GWP_{tot} is the GWP estimated for the baseline scenario; $C\%_{LC,Scenario}$ is the percentage contribution of LCE in the mix; $C\%_{HC,Scenario}$ is the percentage contribution of HCE in the mix; and $GWP_{LC,TWh}$ and $GWP_{HC,TWh}$ are the GWP referring to the consumption of 1 TWh produced by LCE and HCE, respectively (Equation (1)). The complete sequence which generates Equation (1) is reported in the Supplementary Material (Section titled "Equation (S1)").

$$BEE_{Cmix,Scenario} = \frac{GWP_{tot} * C\%_{LC,Scenario}}{GWP_{LC,TWh}} + \frac{GWP_{tot} * C\%_{HC,Scenario}}{GWP_{HC,TWh}} \tag{1}$$

Hypothesis 2 (H2)

In H2, the BEE ($BEE_{HCex,Scenario}$) is computed assuming that the electricity equivalent to that consumed in 2022 (i.e., 95.5 TWh) will be produced by the electricity mix modeled as for the future scenarios, but the excess of electricity required to reach the GWP_{tot} of the baseline scenario will be produced entirely from HCE sources. As depicted in Equation (2), $BEE_{HCex,Scenario}$ is equal to the sum of GWP associated with the high-carbon fraction of the mix ($GWP_{HC,Scenario}$) and the GWP associated with the low-carbon fraction of the mix ($GWP_{LC,Scenario}$), both consistent with the considered scenario of the reference. In H2, both GWP_{tot} and $GWP_{LC,Scenario}$ are constant, while $GWP_{HC,Scenario}$ is dependent on $BEE_{HC,Scenario}$. The complete sequence which generates Equation (2) is reported in the Supplementary Material (Section titled "Equation (S2)").

$$BEE_{HCex,Scenario} = \frac{GWP_{LC,HCex}}{GWP_{LC,TWh}} + \frac{GWP_{tot} - GWP_{LC,HCex}}{GWP_{HC,TWh}} \tag{2}$$

Hypothesis 3 (H3)

The equations reported above pertain to scenarios where no energy recovery is expected during the mining phase. In H3, Equation (3) is instead applied. Similarly to Equation (1) (H1, Section Hypothesis 1 (H1)), H3 fixes the GWP to that estimated for the baseline scenario (GWP_{tot}) but also includes the contribution of the avoided GWP emissions associated with heat recovery. The amount of heat assumed to be recovered is 0.475 kWht/kWhe (GWP_{TWht}), according to the section. In H3, $BEE_{Cmix,HR,Scenario}$ is the the breakeven electricity estimated for each scenario; $BEE_{LC,Cmix,Scenario}$ is the breakeven LCE estimated per scenario; $GWP_{LC,HCex}$ represents the GWP associated with the LCE amount consumed in each specific future scenario, when the electricity consumed is fixed at the amount consumed in 2022 (95.5 TWh [24]); $GWP_{HC,HCex}$ represents the GWP associated with the HCE consumed to reach the difference between GWP_{tot} and $GWP_{LC,HCex}$; $GWP_{LC,TWh}$ and $GWP_{HC,TWh}$ are the GWP referring to the consumption of 1 TWh produced by LCE and HCE, respectively; and GWP_{TWht} represents the GWP assigned to 1 TWh of heat consumed. The complete sequence which generates Equation (3), is reported in the Supplementary Material (Section titled "Equation (S3)").

$$BEE_{Cmix,HR,Scenario} = BEE_{LC,Cmix,Scenario} + \frac{GWP_{tot} - GWP_{LC,Cmix} * (GWP_{LC,TWh} - GWP_{TWht})}{(GWP_{HC,TWh} - GWP_{TWht})} \quad (3)$$

Hypothesis 4 (H4)

Equation (4) defines how to estimate $BEE_{Scenario}$ in H4, if the excess of electricity required to reach the total emission of the baseline scenario is produced entirely from HCE sources but including the credit associated with the heat recovery ($BEE_{HCex,HR,Scenario}$). Equation (2) is, therefore, modified to include the contribution of heat recovery, where GWP_{tot} is again the GWP estimated for the baseline scenario (Equation (4)); $BEE_{LC,HCex,Scenario}$ represents the breakeven electricity produced by LCE sources for each specific scenario; $GWP_{LC,HCex}$ represents the GWP associated with the LCE amount consumed in each specific future scenario, if the electricity consumed equals the amount consumed in 2022 (95.5 TWh [24]); $GWP_{HC,HCex}$ represents the GWP associated with the HCE consumed to reach the difference between GWP_{tot} and $GWP_{LC,HCex}$; $GWP_{LC,TWh}$ and $GWP_{HC,TWh}$ are the GWP referring to the consumption of 1 TWh produced by LCE and HCE, respectively; and GWP_{TWht} represents the GWP assigned to 1 TWh of heat consumed. The complete sequence which generates Equation (3) is reported in the Supplementary Material (Section titled "Equation (S4)").

$$BEE_{HCex,HR,Scenario} = BEE_{LC,HCex,Scenario} + \frac{GWP_{tot} - GWP_{LC,Cmix} * (GWP_{LC,TWh} - GWP_{TWht})}{(GWP_{HC,TWh} - GWP_{TWht})} \quad (4)$$

3. Results and Discussion

3.1. Carbon Emission Estimations

The GWP estimated for the baseline scenario is 51.7 Mt CO_2 eq/year, an amount like the 2022 total carbon emissions of Singapore (53.25 Mt CO_2 eq) [67]. The values were derived as 98% from the USA (35.8%) and China (37.4%), which overcomes the USA despite the lower EfH, and Kazakhstan (24.8%). The estimated GWP emission can be compared with some important industrial chemical productions such as those for ammonia and methanol. By taking as a reference the GWP estimated for the baseline scenario 2022 (51.7 Mt CO_2 eq/year) and the carbon emissions of 1 kg of ammonia (Ammonia, anhydrous, liquid {RER}| market for ammonia, anhydrous, liquid | APOS, U, 2.87 kg CO_2 eq/kg) and methanol (Methanol {RER}| market for methanol | APOS, U, 0.96 kg CO_2 eq/kg) reported in the ecoinvent database [54], it is possible to estimate that, in 2022, the carbon emission predicted corresponds to the production of about 18 Mt of ammonia or 54 Mt of methanol, corresponding to the 12% and 49% of the worldwide production for 2022 of such chemicals, respectively [68,69].

Concerning the electricity mix projected variations, assuming that in 2030 and 2050, the EfH of Bitcoin mining would remain the same as in 2022 (i.e., 95.53 TWh), GWP is estimated to reduce as follows: −17.5% (2030 BAD), −11.9% (2030 IRENA), −37.6% (2030 EMBER), −54.5% (2050 BAD) and −72.3% (2050 IRENA and EMBER).

Figure 3a displays the GWP values (y axis) estimated according to future projections (x axis) and changes in EfH (z axis). Figure 3b depicts pie charts containing the same values presented in the histograms of Figure 3a but including the contribution of each country in the estimated values. The contribution of the country reflects both the amount of EfH consumed in the country and the electricity mix. Kazakhstan, the United States, and China emerge as the main GWP hotspots, contributing 24.8%, 35.8%, and 37.4% of the GWP_{tot} in 2022, respectively. These countries were also characterized by the highest EfH scores.

Moreover, according to our estimates, China and Kazakhstan were also characterized by the highest carbon intensities of national electricity, with 0.88 kg CO_2 eq/kWh and 0.93 kg CO_2 eq/kWh, respectively. By assuming that the EfH sharing will remain constant in the next few decades, the cumulative contribution of the remaining countries (i.e., Canada, Russia, Germany, Malaysia and Ireland) is expected to be <2% of GWP_{tot}. Assuming maintenance of the same electricity mix, the GWP ranges from a minimum of 36.6 Mt CO_2 eq (−10% EfH) to a maximum of 127.2 Mt CO_2 eq (+100% EfH). In the 2030 BAD Scenario, the GWP ranges from a minimum of 24.7 Mt CO_2 eq (−10% EfH) to a maximum of 120.0 Mt CO_2 eq (+100% EfH) while, in the 2050 BAD scenario, the GWP ranges from a minimum of 12.4 Mt CO_2 eq (−10% EfH) to a maximum of 66.2 kg CO_2 eq (+100% EfH). The results are reported in Tables S4–S10 with a higher level of detail.

On the other hand, considering the two estimated EfH values obtained by extrapolating the CBECI data to 2030 according to the two proposed models (linear model: 232 ± 25 TWh; quadratic model: 334 ± 19 TWh) described in Section 2.2.3, the BAD, IRENA, and EMBER scenarios for 2030 in terms of carbon emissions can be determined. Accounting for the increased values of EfH starting from 2022, the determined linear regression models within each of these scenarios are shown in Figure 4 (see Table S13 for the corresponding linear regression models). Their values range (predicted intervals) from 143 ± 2 TWh and 226 ± 3 TWh for the 2030 EMBER scenario to 154 ± 1 and 234 ± 1 TWh for 2030 IRENA, and this latter almost overlapped with the results for the BAD scenario (153 ± 1 TWh and 236 ± 2 TWh).

These findings allow us to make some considerations:

(1) The GWP estimated for the baseline scenario of 51.7 Mt CO_2 eq for 2022 is more than double with respect to the predictions as of November 2018 (22.0–22.9 Mt CO_2) by Stoll et al. [34], in agreement with the increase in the yearly electricity consumption, which moves from 45.8 TWh [34] to 95.5 TWh in 2022 (from ref. [24]) considered in this study.

(2) While the carbon emission projections to 2030, extrapolating values of EfH (see Figure 4), are estimated within the range 117.03–331.90 Mt CO_2 provided by Shi et al. [35] in their PoW carbon projection logistic model, only values of the 2030 BAD and 2030 IRENA scenarios for an EfH value increased by +100% (120.0 Mt CO_2 and 121.0 Mt CO_2, respectively, see Figure 3), remain within such a range.

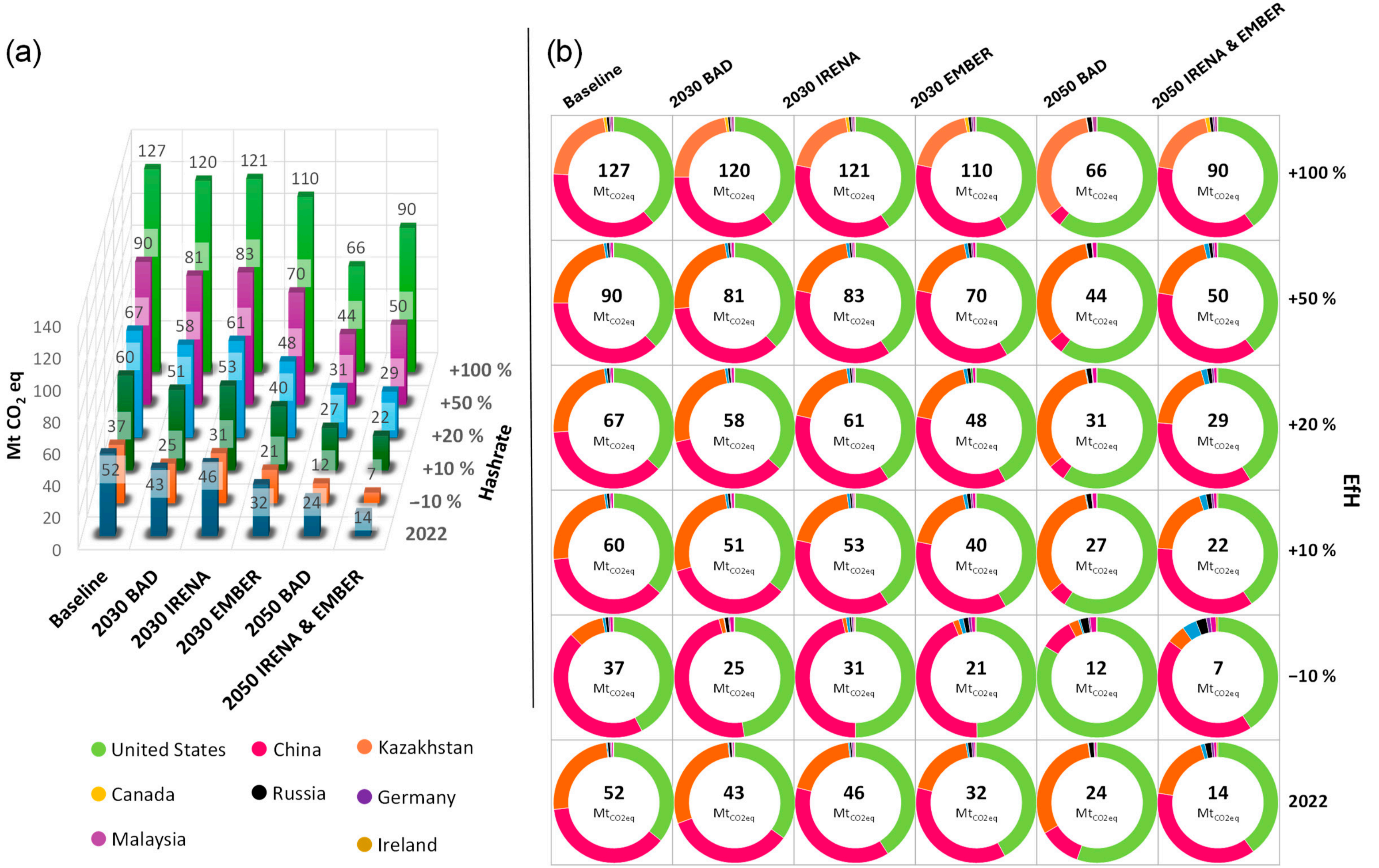

Figure 3. (**a**) carbon emissions (y axis) associated with future scenarios (x axis) and EfH changes (z axis); (**b**) the pie charts depict the absolute value corresponding to the bars of the histogram, displaying the emission value within them and showing the contribution of each state to the overall impact value in the pie chart. Legend is referred to figure "(**b**)". Values (see Table S10 for the listed data) have been rounded to the unit.

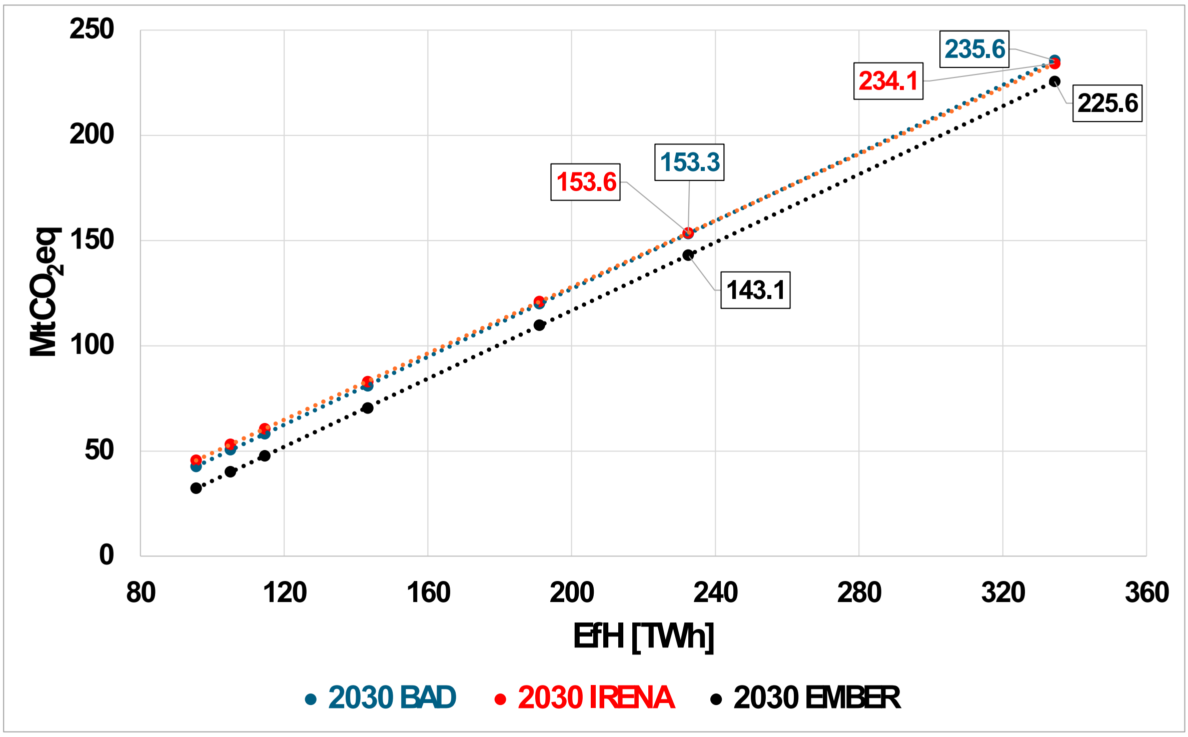

Figure 4. Carbon emissions (in Mt CO_2) estimated for 2030 BAD, 2030 IRENA and 2030 EMBER scenarios at the two extrapolated EfH values (see Figure 2), highlighted in green and blue, respectively (see Table S13 for models).

3.2. CO_2 Sorbents

Figure 5 reports the amount of amine-functionalized sorbent materials needed to capture the CO_2 emitted to generate the electricity employed in the mining phase of the baseline scenario in 2022. The results are presented in the form of the three-class division as reported by Leonzio and colleagues [45]. The same results are reported in Table S11.

According to the findings, if it is assumed to capture the total CO_2 eq emitted directly and indirectly in the mining phase for 1 year (i.e., again 51.7 Mt CO_2 eq), an amount of sorbent ranging from a minimum of 302 Mt for Hydrazine (N_2H_4) in Mg_2(4,4′-dioxidobiphenyl-3,3′-dicarboxylate) sorbent to a maximum of 11754 Mt for NH3 in SBA-15 would be required. According to literature estimations, only 0.01 Mt CO_2/year [70] can be captured from the 27 worldwide commissioned plants, thus requiring more than 5000 years to completely remove 1 year of Bitcoin-derived CO_2 eq emissions. However, a remarkable reduction of 2 orders of magnitude in time could be potentially achieved in the next few years, with the two largest plants under construction designed to capture more than 1 Mt CO_2/year [70–72].

If all the 130 new facilities projected by IEA [70] are built and activated in the coming years, the capturing of 65 Mt CO_2/year should be reached, enabling the mitigation of the 51.7 Mt CO_2 eq/year emitted during Bitcoin mining (baseline scenario).

In addition, it is specified that the proposed estimation includes only the GHG emissions occurring in the mining phase, while this discussion can be potentially extended to all systems on which information systems, including artificial intelligence, are built.

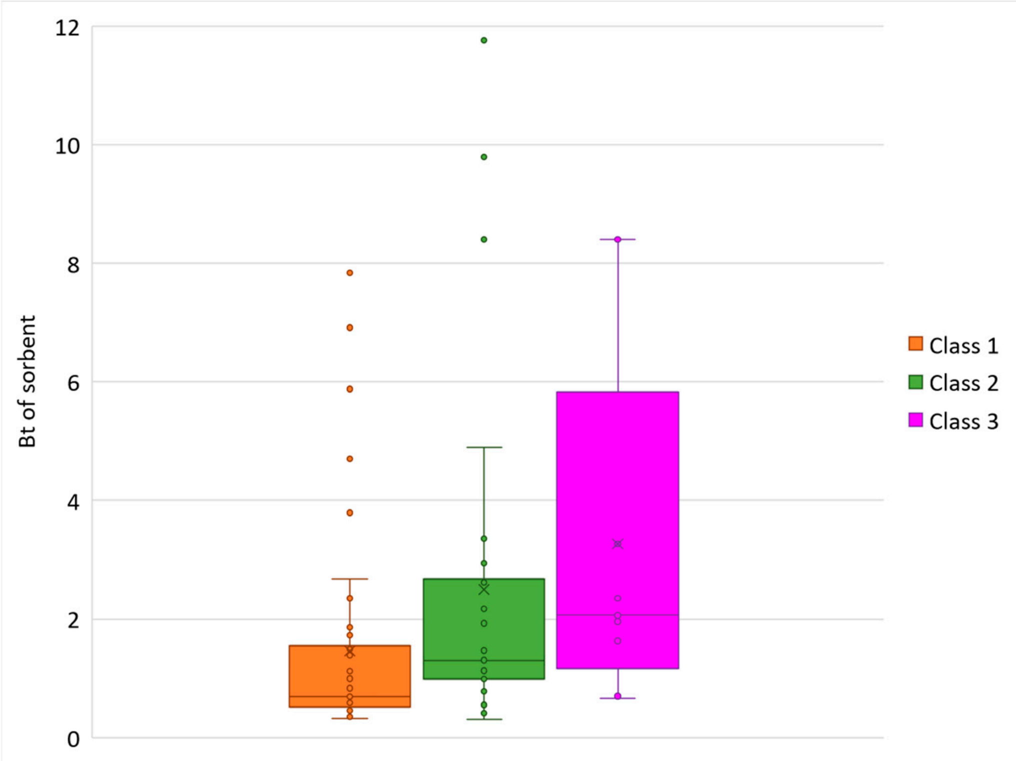

Figure 5. Amounts of sorbent necessary to capture the amount of CO_2 emitted to generate the electricity needed in the mining phase of the Baseline Scenario in 2022 (i.e., 51.7 Mt CO_2 eq/year).

3.3. Breakeven Electricity

According to Equations (1)–(4), the BEE electricity associated with the four hypotheses (i.e., H1–H4) is depicted in Figure 6. The calculation of the BEE allowed for the estimation of the limit values of electricity consumption for which the reduction in the carbon intensity of the energy mix of the involved nations would be a trade-off. In Figure 6, the black solid-fill bars indicate the electrical consumption achievable, assuming that the percentages of LCE and HCE remain constant for each specific scenario (H1). In contrast, the green solid-fill bars show the electrical consumption achievable, assuming that the excess electricity is entirely derived from HCE (H2). The dashed bars indicate the two already shown hypotheses (H1 and H2) but with additional electrical consumption achievable by introducing the credit associated with the recovered heat into the model (black and green dashed bars H3 and H4). The consumption limit observed for the H1 and H2 hypotheses grows, driven by increasing LCE percentages in the mixes; for this reason, an increase in the limit is observed over time. According to Figure 6, the window of 2030 ranges from 117.9 TWh to 130.6 TWh in the BAD scenario, from 117.3 TWh to 124.8 TWh in the IRENA scenario and from 135.2 TWh to 178.1 TWh in the EMBER scenario. Regarding 2050, the limits range from 146.3 TWh to 235.1 TWh in the BAD scenario and from 172.9 TWh to 442.4 TWh in the IRENA and EMBER scenario. The BEE calculated assumed to recover the heat generated during the mining processes (Sections Hypothesis 3 (H3) and Hypothesis 4 (H4)) extends the ranges between 175.3 and 194.1 TWh in the 2030 BAD scenario, 179.1 and 190.7 TWh in the 2030 IRENA scenario, 211.1 and 278.0 TWh in the 2030 EMBER scenario, 246.1 and 395.5 TWh in the BAD 2050 scenario, and 284.4 and 727.4 TWh in the 2050 IRENA and EMBER scenario.

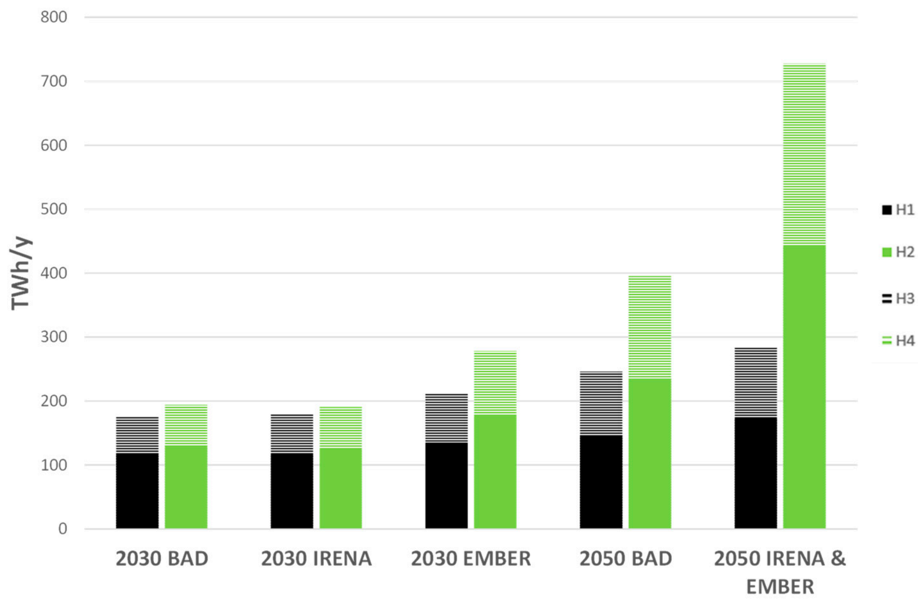

Figure 6. Electricity consumption associated with the five future scenarios that would imply reaching a GWP value of 51.7 Mt CO_2 eq/y.

3.4. Limits of the Study

This study is structured on reliable data provided by CBECI [24] and information derived from the IEA [53], and the two mentioned sources allowed for a reliable estimation of the GHG emissions of the baseline scenario. However, as highlighted by the results and discussed in the Introduction, it is complex to define the actual impacts of Bitcoin mining processes on GWP in future, as they depend on a series of unpredictable factors, such as the energy mixes used, the geographical areas where mining will occur, and the EfH, which, in turn, depends on uncertain economic dynamics. Regarding future projections related to the electricity mixes, although nations have set targets for reducing the carbon intensity, geopolitical situations and, consequently, energy market instability could alter the predicted scenarios. Similarly, it is challenging to accurately predict how mining percentages might be distributed across different countries. To address these issues, this study presents different projections (different EfH), scenarios (from baseline to 2050 IRENA and EMBER), and assumptions (related to the capacity of LCE sources to support high consumption values) to provide a broad spectrum of possibilities. Furthermore, the data related to heat recovery were not directly measured but based on a survey with experts in the field [58]. Despite these limitations, our results are consistent with previous findings in the literature [59]. It should be noted that the aim of this study is not to provide an exact value of GWP associated with Bitcoin mining but to understand the role and potential future responsibilities in a world that must mitigate the impacts of climate change. Finally, this study did not evaluate the positive effects of a transition toward greater adoption of cryptocurrencies. However, such benefits depend on market dynamics that are not easily predictable, encompassing social and economic aspects in addition to environmental ones, which fall outside the scope of this study.

4. Conclusions and Future Perspectives

In this study, LCA was applied to estimate the current (2022) and expected GHG emissions associated with Bitcoin mining. The analysis covered the development of several modelled scenarios: (i) future variations in the energy mix at constant EfH; (ii) increased electricity consumption during the mining phase for a given country at different energy mix projections; (iii) the energy mix ability to maintain a constant percentage of LCE production despite a significant increase in electricity demand. The results indicate that uncontrolled growth in energy demand associated with mining could be a significant limiting factor in the reduction in GHG emissions within the energy sector. The relevance of emissions associated with mining was also illustrated by estimating the hypothetical amount of CO_2 sorbents required to capture the equivalent of the CO_2 eq emissions resulting from the mining process, highlighting values in the range of about 300–12,000 Mt. Considering uncertainty associated with the decarbonization roadmap of the national energy mix and fluctuations in the Bitcoin market, our results are intended as preliminary estimates, to be periodically updated by refining the LCA model created to show temporal-specific information and representative data.

The approach adopted by the authors could be extended to a broader spectrum of environmental categories since consequences associated with the employment of different energy sources cannot be collected into one single category. For instance, nuclear energy is known to affect ionizing radiation [73], biomass-sourced energy significantly contributes to land occupation [74,75], thermoelectric plants, especially if carbon sources, emit consistent amounts of particulate matter [76], and so on. Annual bitcoin water footprint may have reached 2237·GL in 2023 [77],with land footprint and annual e-waste production of 1869.69 km^2 in 2020–2021 [23], and about 31 kt as of May 2021 [78], respectively. In addition, the nexus between resources with a focus on water and energy (i.e., the water-energy nexus) [79–81] and land and mineral exploitation [82] related to Bitcoin mining can be outlined for future works.

Regardless of the estimated impacts, the significant EfH is certainly recognizable, which cannot be excluded from debates on sustainability at a time when environmental protection is paramount. The global effort to convert energy mixes risks being rendered futile if these devices require higher energy flows than renewable-based systems can support. It is, therefore, necessary to precisely define which functions of these devices are essential for the evolution of a sustainable market—economically, socially, and environmentally—and which are not.

This study could benefit academic research by stimulating new studies in the field that take inspiration from the proposed approach, which extends reasoning to future scenarios, whether they derive from economic aspects (e.g., increases and decreases in EfH), energy-related (e.g., evolutions in national energy mixes), or geographical-related (e.g., countries where mining occurs). Decision makers could be the most interested stakeholders, finding, in this study, evidence of the role that Bitcoin may play in hindering the energy transition. Lastly, citizens might also be interested in better understanding the implications associated with the employment of the currency. In conclusion, LCA is confirmed to be a versatile and reliable tool to support strategic planning and policies engaged with the sustainability challenge.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14209597/s1.

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Abbreviations

BAD	Best Available Data	HCE	High Carbon Electricity
BEE	Breakeven Electricity	IRENA	International Renewable Energy Agency
EfH	Electricity for Hashrate	LCE	Low Carbon Electricity
GHG	Green House Gas	LCI	Life Cycle Inventory
GWP	Global Warming Potential	LCIA	Life Cycle Impact Assessment

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