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Perspective

The Potential Relationship between Biomass, Biorefineries, and Bitcoin

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Abstract: Despite advances in biofuel production and biomass processing technologies, biorefineries still experience commercialization issues. When costs exceed revenues, their long-term economic sustainability is threatened. Although integrated biorefineries have significant global potential due to process integration and product co-generation, it is crucial that they generate a positive net return, thereby incentivizing their continual operation. Nonetheless, research and development into new system designs and process integration are required to address current biorefinery inefficiencies. The integration of Bitcoin mining into biorefineries represents an innovative approach to diversify revenue streams and potentially offset costs, ensuring the economic viability and commercial success of biorefineries. When using bio-H_2, a total of 3904 sats/kg fuel can be obtained as opposed to 537 sats/kg fuel when using syngas. Bitcoin, whether produced onsite or not, is an accretive asset that can offset the sales price of other produced biochemicals and biomaterials, thereby making biorefineries more competitive at offering their products. Collaborations with policy makers and industry stakeholders will be essential to address regulatory challenges and develop supportive frameworks for widespread implementation. Over time, the integration of Bitcoin mining in biorefineries could transform the financial dynamics of the bio-based products market, making them more affordable and accessible whilst pushing towards sustainable development and energy transition.

Keywords: biofuel; biorefinery; bitcoin; bitcoin mining; cryptocurrency; value added products

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1. Introduction

Exploring the connection between biomass and Bitcoin reveals promising and exciting opportunities for enhancing profitability, innovation, and swift implementation in the biorefinery sector. As the demand for non-fossil-based chemicals increases, the possibilities for integrating Bitcoin into biorefineries, as an additional revenue stream, become more promising. If managed correctly, it has the potential of bringing biochemical prices down, making them more market competitive. Moreover, Bitcoin mining's drive for low-cost energy incentivizes the global push towards renewable energy solutions [1], potentially reinforcing the reduction in minimum sales prices of biochemicals and biomaterials through the economies of scale and technological advancements.

The field of biomass and integrated biorefineries (IBs) is well-developed [2–4]. Organic materials, known as biomass, are abundant renewable resources containing valuable chemicals that can be processed into a variety of products with significant market potential [5]. Products range from biofuels, bioplastics, biofertilizers, and other biochemicals, used in the pharmaceutical industry, as well as the agriculture, manufacturing, and energy sectors. Biofuels offer a sustainable alternative to fossil fuels and help reduce the dependency on non-renewable energy sources. Biorefinery platforms are the centerpiece, receiving biomass as inputs and transforming them into valuable products and energy.

Contrary to current public opinion, Bitcoin has the potential to positively contribute and even accelerate the United Nations Sustainable Development Goals [1,6–8]. This perspective article explores the intersection between biomass, biofuels, and biorefineries and how their potential relationship, specifically the integration of Bitcoin and other Bitcoin-related activities, could aid IBs. Bitcoin holds a role in financial portfolio diversification [9]; however, whether asset diversification also pertains to biorefineries producing real-world resources has yet to be studied. The proposed hypothesis is simple. Biorefineries generate biofuels either by utilizing waste by-products from post-processing or by directly converting biomass into biofuel and other value-added products (VAPs). Cheap or excess bioenergy can be used in Bitcoin mining, increasing revenues, and improving the biorefinery capital structure. This, in turn, could positively influence the financial aspect of biorefineries, enabling them to continue financing their operations. The proposed approach is shown in Figure 1. This symbiotic relationship not only optimizes energy use but also generates additional revenue streams, enhancing the economic viability of biorefineries. Access to reliable cheap energy, either purchased or produced onsite from biofuels, could make Bitcoin mining a highly profitable endeavor that aids in offsetting costs. Bitcoin offers a unique approach at driving much needed innovation, profitability, and sustainability in this sector by making biorefinery more profitable and thereby cheaper to operate. However, it easier said than done and requires detailed modeling and analysis of their co-integration. As Bitcoin technology continues to evolve with advancements in scalability and interoperability, more businesses will start to integrate and adopt Bitcoin as a monetary means, thereby fostering greater efficiency. Process designers and financial analysts must, on a case-by-case basis, determine whether a buy vs. make analysis of BTC is warranted or if BTC as an element of an IB balance sheet is warranted in the first place, though it has been demonstrated to be a profitable strategy to incorporate Bitcoin into an organization's long-term vision [10,11].

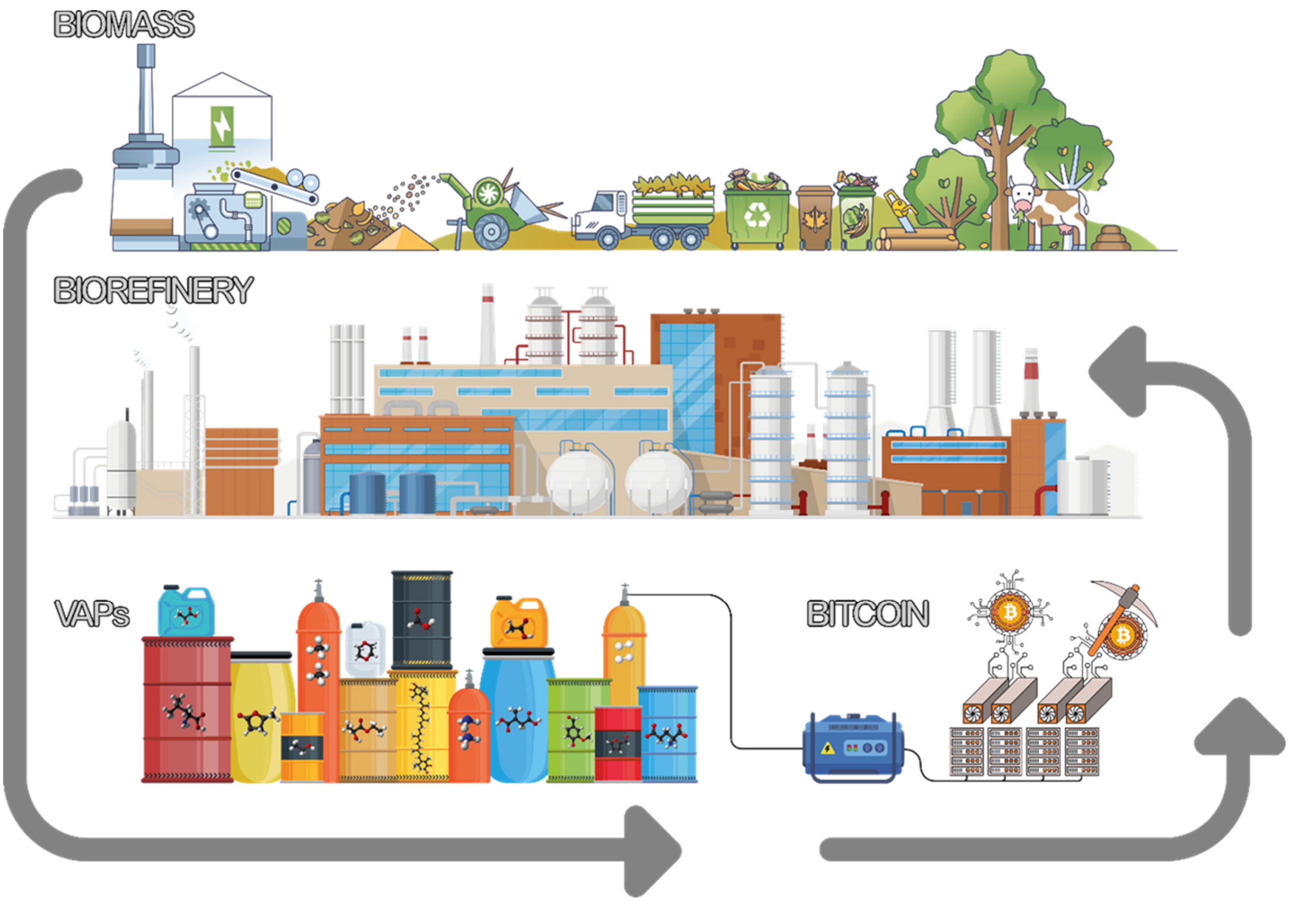

Figure 1. Overview of proposed biorefinery approach. Gray arrows indicate the flow of value through the various process stages, highlighting key interactions and transformations.

While traditional biorefinery models focus on maximizing product output and minimizing costs, the integration of Bitcoin mining introduces a novel paradigm where excess energy can be transformed into a valuable digital asset. This dual-purpose strategy not only addresses economic sustainability challenges but also enhances the environmental profile of biorefineries by reducing waste and supporting renewable energy use. This study presents the first comprehensive analysis of such an integration, demonstrating its potential to outperform current biorefinery models by providing a sustainable and profitable solution. This paper examines the innovative integration of Bitcoin mining into biorefineries to address their economic sustainability challenges. The current capabilities and future potential of biorefineries in utilizing biomass to produce bio-based products is first introduced. Thereafter, the concept of using surplus bioenergy from these processes for Bitcoin mining, presenting a dual benefit of additional revenue streams and enhanced energy utilization is assessed. Technical analysis is conducted to explore the revenue potential of using various biofuels, detailing their compatibility with different energy systems and mining machines for Bitcoin production. This illustrates how such integration could reduce costs and enhance the market competitiveness of bio-based products. Finally, potential policy frameworks and future research directions are discussed for achieving profitable and sustainable biorefinery operations.

2. Biomass, Biofuels, and Biorefineries

Biomass is a carbon-neutral renewable resource and serves as both raw material and energy in various sectors. In the energy sector, biofuels, such as biomethane and biohydrogen, enhance the sustainability and diversity of the energy mix [12]. In industrial processes, biomass-derived materials and chemicals, such as plastics and solvents, provide alternatives to fossil fuel products, for which there is clear demand. As such, utilizing and processing biomass is expected to continue expanding in meeting future global energy demands, producing specialized materials, and chemicals and transitioning to a circular economy [5]. Biomass is categorized into several types depending on their distinct source or characteristics. The main types include, but are not limited to, agricultural and forest residues, agro-industrial processing wastes [13], animal manures, macro- and microalgae [14], as well as organic wastes. For this perspective, first-generation biofuels derived from food and feed crops are not considered as it pertains to their role in global food security. Moreover, the authors do not endorse using food or feed biomass to make Bitcoin. Nonetheless, sustainable practices such as biomass replacement, biomass rotation, and waste management are crucial for ensuring stable and continuous long-term resource supply.

Lignocellulosic feedstocksare structurally comprised of cellulose (40–60%), hemicellulose (20–40%), and lignin (10–24%) [5]. Examples include woods, grasses, straws, and agricultural processing residues such as shells, pits, and husks. Lignocellulosic feedstocks are the most abundant biomass source worldwide which still remain below the optimal utilization capacity [5]. The major challenges relate to the development of effective pretreatment strategies for the separation of lignin from the holocellulosic matrix, inexpensive and regenerative enzyme mixtures, biomass logistics, and downstream processing [15].

Algal biomass is a broad and diverse group of aquatic photosynthetic organisms ranging from unicellular microalgae to multicellular macroalgae. Algal cultivation can be either in open or closed systems and necessitates precisely controlled conditions, such as light intensity, temperature, nutrients, salinity, and CO_2 levels, to optimize growth [14]. Macroalgae are mainly classified as either red, green, or brown algae and are polysaccharide-rich, both for structural integrity and energy storage. Such polysaccharides are cellulose, fucoidan, alginate, and agar, used in the food, medical, and processing industries [16]. Moreover, the breakdown of these polysaccharides yields a vast array of fermentable sugars for various value-added products. On the other hand, microalgae are rich in fatty acids and proteins, with the former being mainly used for biodiesel production [16,17]. Microalgae fix CO_2 more rapidly (i.e., they have a higher photosynthetic efficiency) than terrestrial biomass, with more rapid harvesting cycles [17]. More recently, there has been increasing interest in the nutraceutical uses of microalgae. Other than being a rich source of lipids, strains can be rich in amino acids, astaxanthin, lutein, zeaxanthin, β-carotene, and α-tocopherol [18]. However, the prohibitive costs associated with the cultivation systems, nutrient supply acquisitions (N, P, and K), and the energy-intensive processes of harvesting and downstream processing have hindered market penetration for algae. Moreover, due to their aquatic nature, algae usually suffer higher ash contents which is an added disadvantage [17].

The organic fraction of municipal solid waste (OFMSW), when properly separated from inorganics, consists mainly of food waste, yard trimmings, and paper waste. Effective separation, pretreatment, and transportation remain issues. While the conventional practice has been to landfill this type of waste, it is estimated that the EU's annual production of OFMSW was ≈140 Mt in 2021, which constitutes a significant amount that can be transformed within biorefineries [19]. OFMSW composition is extremely variable and based on spatiotemporal factors. Typically, it is rich in carbohydrates, proteins, and lipids making them ideal for fermentative processing, most notably for biogas and volatile fatty acids (VFAs) [20]. It has been shown that Black Soldier Fly larvae can effectively convert OFMSW into protein and biomethane but with poor financial performance [21]. However, the approach holds promise for future waste management solutions. Finally, although not strictly related to OFMSW, biological sewage sludge is a valuable resource with many possibilities.

While biofuels release carbon when combusted, they are generally considered carbon-neutral because the CO_2 emitted is offset by the CO_2 absorbed during biomass growth and photosynthesis. As of 2015, biofuels have reduced ≈600 Mt of CO_2 [22]. However, case-specific analyses are necessary going forward. Biofuels release a specific amount of energy and heat upon combustion, as given in Equation (1). Technological advancements in conversion efficiency and power generation are crucial. The efficient utilization of both energy and heat, such as in combined heat and power (CHP) processes, is desirable [23]. Additionally, the utilization of biofuels is technologically attractive due to the easiness of their integration into existing systems with little to no modifications needed, making them a practical and accessible option [24].

$$\mathrm{C_aH_bO_c} + \left(\mathrm{a} + \frac{\mathrm{b}}{4} - \frac{\mathrm{c}}{2}\right)\mathrm{O_2} \rightarrow \mathrm{aCO_2} + \left(\frac{\mathrm{b}}{2}\right)\mathrm{H_2O} + \mathrm{Heat}\ (\Delta\mathrm{H} < 0) \tag{1}$$

Within the next 15 years, the share of energy from renewable sources is anticipated to increase from 9% to ≈30% of the total primary energy demand [25]. Bioenergy production is expected to increase to a range between $\approx 110 \times 10^6$ and $\approx 850 \times 10^6$ Gigajoule/day in keeping with the Intergovernmental Panel on Climate Change (IPCC)-recommended target of 1.5 °C [26]. Bioethanol, biodiesel, and biogas are expected to play a critical role in the process. Bioethanol is a product of the anaerobic fermentation of sugars in a controlled environment with the use of yeasts. Second- and third-generation bioethanol has been extensively studied and generally commercialized [27]. Anaerobic digestion (AD) is a natural decomposition process occurring in the absence of O_2. It can be harnessed in a controlled environment to produce biogas, a mixture of CH_4 and CO_2. Hydrolytic microorganisms break down the biomass with the rate of hydrolysis usually being the limiting step. While carbohydrates have a higher hydrolysis rate constant ($k_h \approx 0.5$–$2\ d^{-1}$), they tend to produce less biogas [28]. Lipids and proteins are converted at a slower rate but produce more biogas per unit substrate. Biodiesel is a product of the transesterification of oil with alcohols. Recent processing advancements such as co-solvent, supercritical, plasma-assisted (PA) transesterification have further improved its efficiency [29]. Moreover, when measured on a per-hectare basis, microalgal biodiesel yields outproduced oil palm diesel by over 15-fold, all whilst relieving pressures off arable land [30]. Importantly, biodiesel suffers from oxidation, storage, and thermal stability issues [31]. Current biofuel limitations are mainly related to collection and transportation, high capital and operational expenditures

(CAPEX/OPEX), pretreatment inhibitor formation, enzyme costs, post-process separation, non-competitive sales price, positive energy balancing, and reduced yields.

Biorefineries are industrial facilities, analogous to petroleum refineries. The International Energy Agency (IEA) Bioenergy Task 42 is an international collaborative initiative focused on development and research in biorefineries. Its goal is to evaluate the potential of sustainable biomass processing guided by circular economy principles. An IB is defined as a system with multiple biomass inputs while simultaneously producing multiple outputs using a variety of processes [32]. This approach improves resource utilization, dampens dependency on biomass variability, reduces waste by-products, and adds to economic viability by catering product outputs based on market demands. The IB classification framework (i.e., feedstocks, platforms, processes, and products) and the biorefinery complexity index (BCI) were developed by Task 42 [33,34]. The main process consists of chemical, biochemical, thermochemical, and mechanical conversion with the possibility of co-integration. Final products are a mixture of fuels, chemicals, materials, food, feeds, and other products through distinct platforms.

Mercer Stendal GmbH (Germany) and Mercer Rosenthal GmbH (Germany), both subsidiaries of Mercer International Inc., process softwood biomass mixed with other forest-industrial wastes in a Kraft pulping process (NaOH + Na_2S) to remove lignin and produce paper and tissue products. Today, the former produces 740,000 tons of pulp and 148 MW of electricity, while the latter produces pulp, 5000 tons of tall oil, and over 400 GWh of electricity, used internally and to power 50,000 homes [35]. Similarly, Borregaard (Norway) uses the Kraft process to transform Norway spruce biomass into bioenergy, bioethanol, vanillin, biopolymers, and cellulosic fibrils with a 94% utilization capacity [36]. They are also the world's only producer of wood-based vanillin. Other notable biorefineries are SynataBio (USA) that produce bioethanol from syngas and Clariant (Switzerland) with their sunliquid® process that produce bioethanol without the use of added chemicals during pretreatment. Recently, St1 (Finland) and SCA (Sweden) have been set to produce a variety of fuels, including biodiesel, aviation fuel, and bionaphtha, with an annual output of ≈200,000 tons from cooking oils, animal fats, and tall oil fatty acids [37].

3. Bitcoin: What Is It?

Bitcoin was developed by an anonymous person or group of persons using the pseudonym Satoshi Nakamoto. Bitcoin is decentralized with no central party controlling the network. The white paper, published on 31 October 2008 with the title "Bitcoin: A Peer-to-Peer Electronic Cash System" [38], has gained over 33,000 citations according to Google Scholar. Bitcoin has become a hot topic of research in academia [39–43].

The genesis block was mined on 3 January 2009, which saw the creation of the first 50 BTC. Since then and until now, ≈19.72 million BTC of the intended fixed 21 million has been mined. Bitcoin has been growing both in price and popularity despite intense discussions and controversy around its energy demand and use cases. Currently, it is estimated that Bitcoin mining uses between 80 and 240 TWh of electricity annually [44]. While that number seems high, it imperative to understand it in contrast to other electricity usage. For example, domestic refrigeration, tumble dryers, video gaming, and banking use approximately 630, 108, 105, and 239 TWh/year, respectively [1,45]. In absolute terms, the Bitcoin network consumes 0.1% of global primary energy, with 39 to 73% already coming from renewables [1,45]. In 2018, it was estimated that a mere 0.06% of global CO_2 emissions are a directly result of mining, with estimates widely ranging between 0.2 and 95.4 $MtCO_2$ [45].

A growing number of private and public companies have been embracing Bitcoin. For instance, BlackRock, Fidelity, MicroStrategy, Tesla, Coinbase, Block, as well as the Norwegian Aker ASA [10,11]. Two countries, i.e., El Salvador and the Central African Republic, have adopted Bitcoin as legal tender [46]. As an open-source decentralized system, the network already has a far-reaching impact on the financial system and the broader economy and is expected to reach even further. Due to its decentralized nature, Bitcoin challenges the existing fiat system by providing a peer-to-peer system that operates without the need for intermediate third parties. This decentralization offers highly liquid capital markets, increased financial privacy, lower transaction fees, and faster cross border payments and evens out the playing field between producers and consumers.

Bitcoin mining's environmental impact and carbon emission is a hot topic in academic research. It has been shown that Bitcoin mining increases renewable energy capacity in the Texas electrical grid with cost reductions to consumers [47]. Similar positive observations have also been made [48–50]. Improving the sustainability of Bitcoin mining is imperative for mitigating its environmental impact. The utilization of renewable energy sources [51], and now biofuels, can significantly reduce carbon emissions associated with mining operations. Moreover, Bitcoin mining has the potential to contribute to heating, whether it homes in colder regions, equipment in a biorefinery, or for greenhouse farming. Encouraging miners to establish operations in areas abundant in renewable energy can facilitate this transition and make biorefineries more profitable in those areas. Leveraging advanced grid management technologies to balance supply and demand more efficiently is crucial and notable [1].

4. Bitcoin Mining: How Does It Work?

Bitcoin is the first application of blockchain. Blockchain is the underlying technology which facilitates Bitcoin, ensuring its decentralized, secure, immutable, and transparent nature. Essentially, a blockchain is a distributed ledger that keeps track of transactions across numerous nodes. Each block can be divided into a block header and block body, as shown in Figure 2. The block body contains information about the transactions. These transaction data are stored in a Merkle tree structure [52]. The Merkle root is the hash of all the hashes of all transactions inside a block. A *hash* is a fixed-length alphanumeric string generated by the Secure Hash Algorithm 256 (SHA-256) cryptographic algorithm. It uniquely represents the input data, and miners solve for a hash that meets specific criteria to validate transactions and create new blocks in the blockchain. The SHA-256 algorithm is a one-way function. Any length input will yield a fixed length output; however, one cannot compute the input from the output. Moreover, changing the input ever so slightly will change the output drastically, in a non-reversible and non-deterministic manner. Therefore, all transactions are backed up to the first block are recorded and stored in blocks [53,54]. The block header includes information about the timestamp, difficulty, nonce, Merkle root, and the previous block's hash. Thus, all blocks are linked in chronological order using cryptography and form an immutable chain.

Bitcoin utilizes a proof-of-work (PoW) mechanism to ensure network security. Bitcoin mining is an energy-intensive process that involves specialized devices known as application-specific integrated circuit (ASIC) machines to find the nonce of a block and package transactions within the Bitcoin network. Miners cannot predict the correct nonce that leads to a valid hash, which must be lower than or equal to a target value set by the network's difficulty level. Therefore, miners must iterate through various nonce values in combination with other data from the block. Miners hash the block header alongside numerous nonces using the SHA-256 algorithm iteratively attempting to discover a valid nonce. The speed at which a computer or mining rig performs these hash functions is termed as hash rate. This process is highly computationally demanding and requires substantial computational power due to the exceedingly high hash rate. Currently, the Bitcoin network operates at a hash rate of 602.4 EH/s, where EH/s denotes quintillion (10^{18}) hashes per second. To put this into perspective, the probability of solving for the successful hash is smaller than finding a single grain of sand out of all the sand on Earth (7.5×10^{17} grains), every 10 min [55]. The initial miner to identify a valid nonce meeting the difficulty criteria broadcasts it across the entire Bitcoin network. Upon validation, the miner receives newly minted Bitcoins as a reward for their work. The Bitcoin inter-block time is set to 10 min; if finding a block becomes too difficult (average higher than 10 min), then the network decreases the difficulty to bring the average back down and vice versa.

This mechanism of difficulty adjusted PoW is, on a fundamental level, the core principle behind Bitcoin, helping stabilize the network and prevent against attacks [38]. Through mining, miners produce BTC, a digital bearer asset transactable on the network. Until today, the Bitcoin network has never experienced a system breach.

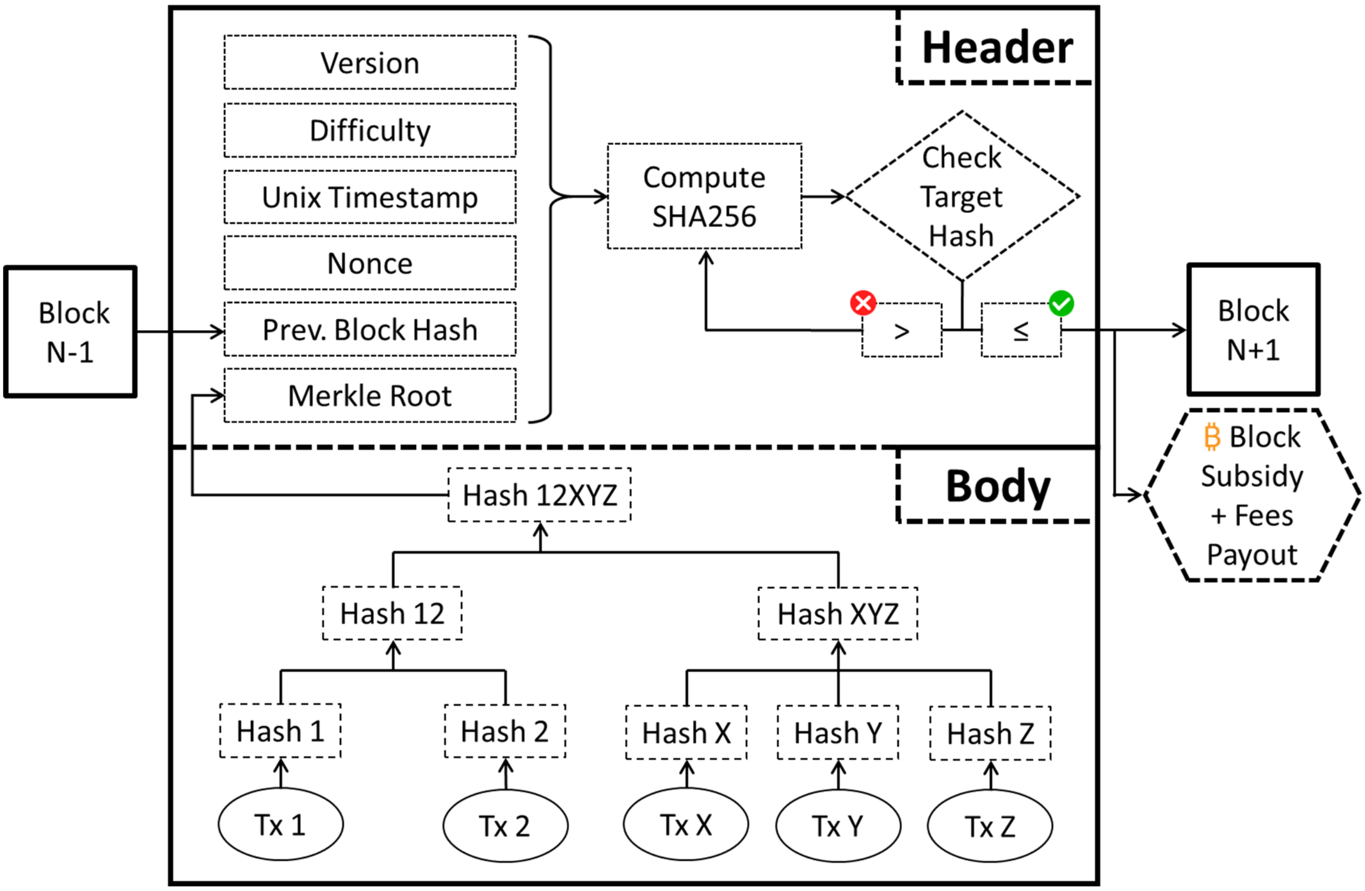

Figure 2. Bitcoin block template.

5. Connecting Bitcoin Mining to Biorefineries

The Bitcoin marginal cost of a production model [56], shows that production price substantially influences the BTC market price with significant statistical support ($p < 0.001$), which establishes the long-term value proposition of BTC. Moreover, it was shown that 81.3% of the variability in the BTC price was due to changes in its cost of production. Kristoufek [57] demonstrates how mining costs and Bitcoin price are mutually dependent on each other and approach a long-term equilibrium. Semret [58] investigates the complex dynamics of Bitcoin mining, including the impact of price changes, supply shocks, and energy costs on the feasibility and sustainability of mining operations. The feasibility of Bitcoin mining emphasizes that revenues in USD (the product of BTC mined and BTC price), exceed costs in USD, including energy and hardware depreciation [58]. Moreover, it was shown that variables such as price, ASIC efficiency, or electricity costs are intricately linked in creating this dynamically reinforced equilibrium. This aligns with the observation that the BTC price is influenced by its production cost [56]. Similarly, the marginal cost of production model is supported by identifying a long-term equilibrium trend between the BTC price and mining costs, suggesting co-adjustment over time [57]. Collectively, these studies support the value proposition of BTC as a hard money store of value [40]. Bitcoin's fixed supply and strict monetary policy enable businesses to protect and potentially increase their capital as Bitcoin captures its untapped addressable market. Therefore, it is imperative to investigate its use in IB's with the aim of making biochemical and biomaterial production cheaper by allowing the price appreciation in BTC to offset the costs of production, as an indirect method of subsidy. Equation (2) present the skeletal model for the minimum profitable price which can be used by an IB to assess Bitcoin mining as a supplementary process.

The matrix in Figure 3 evaluates the impact of Bitcoin mining and BTC returns on the production costs of VAPs and the overall economic impact on biorefineries. In scenario 1, the revenues from BTC offsets large VAP costs, leading to enhanced profitability and decreased sale prices. In scenario 2, the limited revenue from Bitcoin mining marginally reduces production costs but leads to a weak cost structure with potential economic losses with little advance warning. In scenario 3, the high energy consumption increases costs, but strong profits from Bitcoin mining result in positive economic gains, albeit less. In scenario 4, the high production costs coupled with insufficient revenue from Bitcoin mining leads to total IB failure. This matrix provides a comprehensive assessment of the possible directions when integrating Bitcoin mining into biorefineries, facilitating informed strategic decision-making. Ideally, an IB would prefer to be on the left side of the matrix rather than the right. The high variance in desirability between all quadrants indicates the riskiness of this method but a more in-depth risk assessment involving likelihoods and uncertainties is needed. Collaborative efforts among governments, industry stakeholders, and research institutions are essential for advancing the sustainability of Bitcoin mining and incorporating it into existing infrastructure is important.

$$\text{Minimum Profitable Price} = \frac{\text{Total Costs}}{\text{Total Revenues}} = \frac{\text{CAPEX} + \text{OPEX}}{\text{BTC Production}} \tag{2}$$

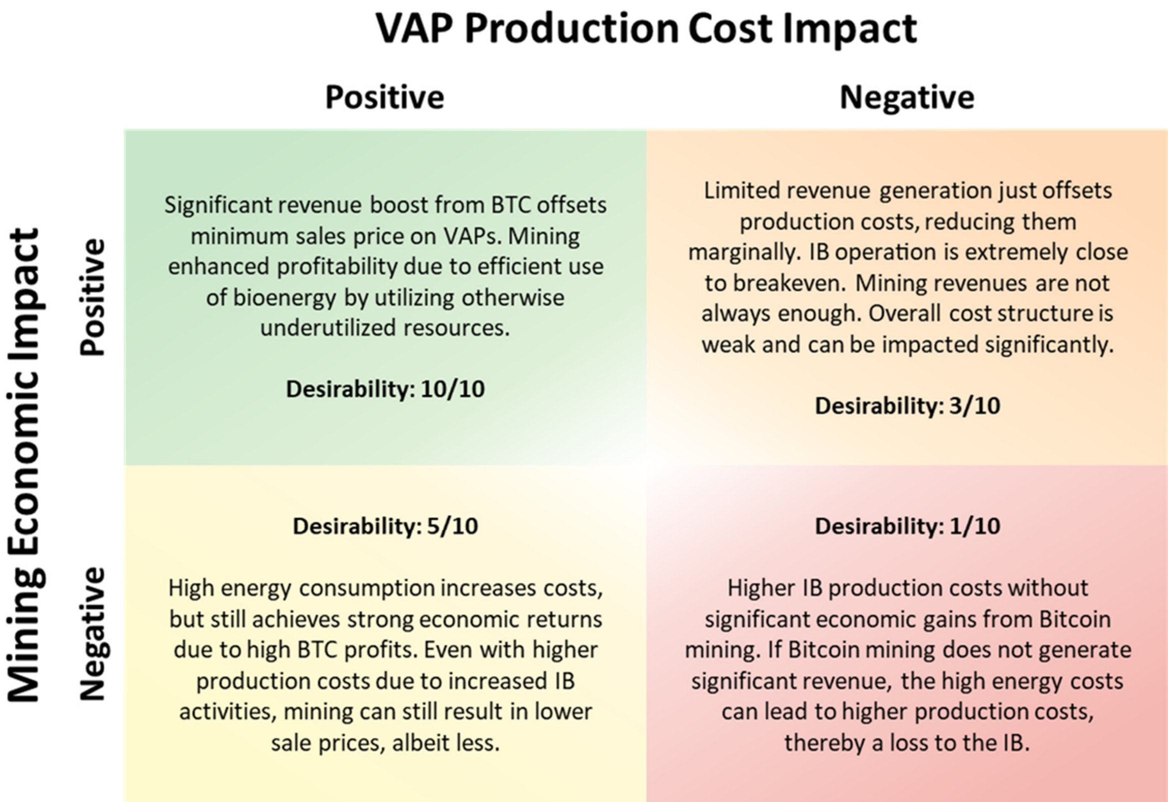

Figure 3. A 2 × 2 matrix evaluating the impacts of integrating Bitcoin mining into biorefineries. High desirability/best case scenario (green); low desirability/worst case scenario (red). The central white area signifies a passive "do nothing, gain nothing" approach.

The combustion of a biofuel with formula $C_aH_bO_c$ yields a specific amount of energy and heat, as given in Equation (1). The focus here revolves around the energy sources that could potentially be derived from biomass. The most notable biofuels alongside their main methods of production and respective energy contents are given in Table 1. Energy conversion systems likely depend on the type and quality of the biofuels as well as the scale or size of the electricity generation process. Technological maturity also plays a role.

Table 1. Bitcoin mining: fuel properties, conversion, and performance metrics.

Fuel Characteristics				**Energy Conversion System**			**Bitcoin Mining** [f,g]		
							sats [h]**/kg Biofuel**		
Name	**Process Technology**	**HHV (MJ/kg)**	**LHV (MJ/kg)**	**ICE**	**MT**	**FC**	**S21 Hydro** [i,j]	**S19XP** [i,j]	**S17** [i,j]
Biobutanol	ABE Fermentation	37.3	34.4	√	√		1119	833	398
Biodiesel	Transesterification	40.2	37.5	√	√ [e]	√ [e]	1222	909	434
Bioethanol	Fermentation	29.8	27.0	√	√		877	653	312
Biogas	Anaerobic Digestion	33.2 [a,b]	29.9 [a,b]	√ [e]	√ [e]	√ [e]	974	725	346
Biohydrogen	Gasification or Dark Fermentation	141.8 [a]	119.9 [a]		√ [e]	√	3904	2905	1388
Biomethane	Anaerobic Digestion	55.3 [a]	49.9 [a]	√ [e]	√	√	1623	1208	577
Biomethanol	Syngas Catalytic Conversion	22.9	20.1	√ [e]	√	√ [e]	654	487	233
Syngas	Gasification or Pyrolysis	19.0 [a,c] 49.9 [a,d]	16.5 [a,c] 43.0 [a,d]		√	√ [e]	537 1400	400 1042	191 498

[a]—Gasses considered at STP; 0 °C and 1 atm. $\rho(H_2)$ = 0.090 g/L; $\rho(CH_4)$ = 0.716 g/L; $\rho(CO)$ = 1.250 g/L; $\rho(CO_2)$ = 1.964 g/L; $\rho(N_2)$ = 1.250 g/L.
[b]—Biogas composition is taken to be 60% CH_4 and 40% CO_2; v/v.
[c]—Syngas composition is taken to be 20% CO, 10% H_2, 20% CO_2, 5% CH_4, and 45% N_2; v/v.
[d]—Syngas composition is taken to be 45% CO, 30% H_2, 20% CO_2, and 5% CH_4; v/v.
[e]—Aspects such as energy conversion system design as well as fuel cleaning, blending, and upgrade must be considered. In the case of FC, fuels may require conversion through reforming. The use of a methanol fuel cell (MFC) is acceptable. Solid oxide fuel cell (SOFC) permits inlet fuel flexibility.
[f]—Assuming 30% conversion efficiency of LHV to electrical power. Normalized per 1 kg biofuel.
[g]—Assuming network hash rate to be 600 EH/s, thereby taking ≈ 666,666 TH/s in 24 h to mine 1 BTC. Block reward is 6.25 BTC/block.
[h]—100,000,000 sats = 1 Bitcoin.
[i]—ASIC Miner Specifications. Bitmain Antminer S21 Hydro—335 TH/s; 5360 W; 16 J/TH. Bitmain Antminer S19 XP—140 TH/s; 3010 W; 21.5 J/TH. Bitmain Antminer S17—53 TH/s; 2385 W; 45 J/TH.
[j]—ASIC Miner Release Dates. Bitmain Antminer S21 Hydro—February 2024. Bitmain Antminer S19 XP—July 2022. Bitmain Antminer S17—April 2019.

Table 1 considers the internal combustion engine (ICE), microturbine (MT), and fuel cell (FC) for a range of biofuels. Each scenario (biofuel + power generation system) has its own limitations and must be evaluated on a case-by-case basis. A trade-off between energy density, biofuel availability, production rate and capacity, and carbon emissions must be considered and assessed. Also, these fuels are usually produced with impurities and must be purified in order to improve process utilization. The relationship between mining and energy utilization is complex and involves several corelated factors such as the cost of biomass, biofuel used, biorefinery size, process technology used, biofuel conversion efficiency, biofuel purification costs, energy generation system used, and the cost of electricity. The integration of Bitcoin mining into biorefineries requires robust power distribution systems and advanced cooling technologies to manage the high energy demands and heat generation of ASIC mining equipment. Technically, this integration demands seamless synchronization between the biorefinery's energy management systems and the mining operations, ensuring efficient energy allocation and operational stability. The high energy consumption of Bitcoin mining could strain a biorefinery's energy resources, necessitating substantial investments in energy infrastructure or leading to increased operational costs. The technological demands of integrating Bitcoin mining such as the need for uninterrupted power supply and advanced cooling systems could present significant challenges, especially in regions with underdeveloped infrastructure. Such factors must be considered in order to determine the actual cost basis one has during their mining operations. Table 1 also gives a comparison of three ASIC miners produced by Bitmain Technologies Ltd., the Antminer S21 Hydro, S19 XP, and S17. It is assumed that the conversion efficiency of the power generation system used is 30%. Miner returns increase with improved ASIC efficiency and increased biofuel capacity. For example, 1 kg of biohydrogen can produce more than double the amount of BTC when using the S19 XP as opposed to the S17. Moreover, when comparing bio-H_2 to bio-CH_4, it is shown that 1 kg of H_2 will produce nearly double the amount of BTC than 1 kg CH_4, using the same ASIC miner, due to the higher energy content of H_2 as opposed to CH_4 (119.9 vs. 49.9 MJ/kg). Table 1 also provides a detailed comparison of the energy content of various biofuels and their corresponding Bitcoin mining returns using different ASIC miners. A regression analysis between the LHV (MJ/kg) and revenues produced (sats/kg) demonstrates a strong positive correlation ($R^2 = 0.99$, $p < 0.01$), indicating that higher energy content biofuels are more efficient in Bitcoin mining. Under the conditions addressed in Table 1, the empirical model derived from regression analysis is [sats/kg] = 32.55 $\times$ [LHV]. This underscores the importance of selecting high LHV biofuels for Bitcoin mining operations to enhance profitability and efficiency. Additionally, a sensitivity analysis reveals that upgrading from an Antminer S19XP to an S21 Hydro increases mining returns by ≈34.4%. This substantial increase underscores the importance of utilizing more efficient mining hardware to maximize profitability.

The relationship between Bitcoin mining and IB profitability is complex, involving several corelated factors. Factors such as the scale of operations, VAP production and sales price, operational efficiency, heat utilization as well as BTC price, Bitcoin network difficulty, supply and demand dynamics, and ASIC hardware availability, efficiency, and costs. Power generation costs must be considered too, especially when system designs vary in terms of fuel cleaning, blending, and upgrading. For example, FCs may require conversion via reforming as opposed to direct use in MT. This inevitably adds to the total costs. Moreover, MT and ICE energy generation systems need to be supplemented with a generator, thereby adding to costs. It is identified that electrical costs, cost of ASICs, and cooling infrastructure constitute a major setback in the profitability of mining [1]. If a biorefinery has access to reliably cheap energy, either purchased or produced onsite by biofuels, then Bitcoin mining may be a highly profitable venture. Mining Bitcoin within an IB setting, and subsequently using it as a store of value, should allow for decreased production costs and pricing for other co-produced VAPs.

6. Conclusions

Biorefineries convert organic biomass into valuable bio-based products, presenting a sustainable alternative to fossil fuels. Despite advances in complete biomass utilization, reduced value-added product and biofuel costs, advanced pretreatment techniques, strain engineering, and enzymatic cocktails, biorefineries still experience commercialization issues. Bitcoin mining, which can utilize the bioenergy produced in biorefineries, provides another revenue stream that could offset these costs and ensure long-term financial sustainability. This approach can be scaled depending on energy source and region. Also, the choice of biofuel matters. Bio-H_2 can produce nearly 8-fold more BTC as opposed to syngas under the same conditions. By leveraging excess bioenergy for Bitcoin mining, this approach aims to make biorefineries economically competitive and environmentally sustainable. Future advancements could see widespread adoption of this model, leading to significant reductions in the cost of bio-based products and increased use of renewable energy in Bitcoin mining.

Merging biorefineries with Bitcoin mining suggests a cautiously optimistic outlook and represents a promising yet challenging leap towards creating cost-effective, long-term, viable, and sustainable technologies. By using biomass, the carbon footprint of Bitcoin mining operations can be reduced. Integrating mining not only provides renewable energy for mining operations but also promotes the use of residual biomass, thus enhancing the overall efficiency of biorefineries. By focusing on enhancing the conversion efficiency of biomass and optimizing the energy use in Bitcoin mining, these systems could reform our approach to integrated biorefineries. Scalable operations are crucial for achieving profitable biorefineries that adhere to environmental standards. This creates a financially appealing model where the profits generated from the sale of mined BTC provide a steady stream of revenue, offsetting production costs within biorefineries by utilizing the byproducts of biomass processing to power mining operations, reducing waste, and increasing overall energy efficiency. Such a setup not only ensures a cleaner use of resources but also introduces a new revenue stream that could potentially decrease the breakeven point for bio-based products making them more market competitive.

In an IB, generating economic value by using excessive renewable energy to mine BTC can be appealing. Since the supply of BTC is fixed at twenty-one million, any energy used by the system is inevitably stored as price value within the digital commodity itself. However, significant hurdles remain, including technological barriers, economic feasibility, and regulatory challenges that must be navigated carefully. The legal landscape for Bitcoin mining is fragmented, with significant differences across jurisdictions. Establishing a standardized regulatory framework that clarifies legal and tax obligations for biorefineries engaging in Bitcoin mining would facilitate smoother integration and compliance. With careful management and continued innovation, this approach could lead to greater adoption and decreased costs in both sectors, presenting a compelling case for the triple exploitation of biomass for bioproducts, bioenergy and Bitcoin. Finally, it is imperative to note that the above assessment pertains only to Bitcoin and does not encompass other cryptocurrencies such as Ethereum or Solana, as they do not achieve consensus through difficulty-adjusted PoW.

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