Bitcoin mining as a flexible load for feed-in congestion management in the electricity grid

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Abstract

The increasing amount of renewable energy generation sources (RES) via photovoltaic (PV) generation introduces problems of feed-in congestion in the electricity grid. One way to reduce the overproduction penetration into the grid is by curtailing RES production, which means foregoing clean energy without benefit. Adding additional flexible loads is also possible, such as electric vehicle (EV) charging stations, but this often requires expensive infrastructure such as the charging station itself, making it less financially attractive to build them. Bitcoin mining is proposed as a flexible load to use the excess renewable energy. Bitcoin mining makes effective use of this renewable energy, and avoids high excess power penetration into the grid, while also avoiding the need for renewable energy generation curtailment. Different scenarios including one where the grid is congested due to excess of RES generation are simulated using a 33-node distribution system and the potential of Bitcoin miners to reduce feed-in congestion is assessed. Concerns and ethical aspects of the choice of Bitcoin mining are also discussed and explained. The results show that when a dynamic algorithm is used to determine the amount of Bitcoin miners per node, and Bitcoin miners can be turned on and off based on excess PV generation, Bitcoin mining can function as a flexible load to completely alleviate feed-in grid congestion. The paper indicates that Bitcoin mining can offer an alternative to RES curtailment and serve as a flexible load.

I. Introduction

With European Union regulations in place that aim for CO2 neutrality by 2050, a reduction of CO2 emissions is necessary [1]. This includes producing energy without the need for fossil fuels. A large part of the solution lies in renewable energy sources (RES) in the form of photovoltaic (PV) panels and wind energy generation. The energy carrier for this power is electricity. This introduces two problems. Energy storage and scalability. This paper will focus on the scalability aspect of electricity.

A. Electricity grid

The electricity grid in the Netherlands currently experiences overloads, both by excess production and excess consumption. This paper focuses on the excess production problem. PV panels produce most power during the midday, which is also the time when the consumption is low. This causes excess power to enter the grid, with feed-in capacity queues of up to 311 MW [2]. In the Netherlands, the total PV generation produced up to a peak of 4.66 GW in 2024 [3]. Excess power creates problems like overvoltage and overcurrent, which can damage appliances, and degrade cables and transformers [4]. Distribution system operators (DSOs) in the Netherlands adopted a day-ahead tariff scheme that allows for dynamic pricing of electricity based on the predicted production and consumption levels. This helps shift the consumption load but does not lead to a full production match. Electricity prices sometimes become negative, as no consumer is willing to use the electricity, even for free. This introduces the question: what can this electricity be used for? DSOs such as Enexis in the Netherlands have called for turning on appliances and charging electric vehicles (EVs) during the midday [5], but EV charging introduces new problems like an increase in peak load during low electricity price time intervals as discussed in section III. These methods also include RES curtailment, thereby reducing RES usage, resulting in negative economic consequences as free energy is forgone for paid energy. Flexible loads that dynamically match generation using a demand response algorithm can be seen as a solution here.

B. Economic aspects

Another concurrent problem in the world is the widespread usage of fiat money. Fiat money is government-issued money. Its value depends on the supply and demand of the market and is not backed by anything, other than the stability of the government. Take the United States dollar (USD) as an example. The USD experiences problems of higher than desired inflation, which causes instability and destruction of value over the longer term and promotes short-term thinking [6]. Moreover, government control over a currency limits the market function of goods and services and thus causes poorer quality goods and services to sell for higher prices. Bitcoin has a low and predictable inflation rate, and it is not controllable by any government. Adoption of Bitcoin as money would result in a more financially stable and future-oriented economy, incentivizing more future-oriented investments, such as investing in RES, and implementing long-term solutions for energy grid congestion.

Historically, people tend to find and use new forms of money if the previous one is inadequate. Gold is an example of this. Gold is better money for storing value, as it is more scarce, but it is harder to transport compared to the USD, as gold cannot be digitally transported. Bitcoin combines the desirable properties of gold and the USD in that it is more limited in supply than gold and thus a good store of value while being digitally transportable like the USD. It is possible to self-custody Bitcoin on a digitally encrypted device, and there is no government or third-party control over it, thus making it safer to hold than gold or the USD.

Production of Bitcoin is done in a process called Bitcoin mining, or the Proof of Work protocol (PoW), and is energy intensive. This can be considered a negative, and alternatives such as Proof of Stake (PoS) have been suggested for securing the Bitcoin network, but PoW is necessary for the superior safety of the Bitcoin network compared to PoS. The key insight is that the Bitcoin network requires a large amount of energy, which is location-independent, meaning any electricity can be used to secure the Bitcoin network. Another important point is that Bitcoin has value and can be traded for USD on the market. If there is overproduction of RES, Bitcoin miners can use the excess RES energy yielding a financial reward without electricity costs. This research intends to answer the question: How can Bitcoin mining be used by distribution system operators as a flexible load to reduce feed-in electricity grid congestion and avoid RES curtailment?

II. Literature review

This section will discuss relevant literature concerning the Bitcoin network and what problems it solves, the electricity grid in the Netherlands and the problems it experiences, and the solutions currently used in electricity grids.

A. Bitcoin

As discussed in The Bitcoin Standard by Saifedean Ammous, money has to have three functions to be money [7]. It must be a medium of exchange, a store of value, and a unit of account. The fiat standards currently present in most countries worldwide, function as a medium of exchange and a unit of account, but not as a proper store of value, as they are subject to high inflation. Ammous argues that if not addressed, the value of fiat currencies will leak into more scarce money. In 2008, Satoshi Nakamoto proposed a peer-to-peer, decentralized electronic cash system: the Bitcoin network [8]. The Bitcoin network is an online ledger that allows for the creation of a finite amount of coins, provides a final settlement within an hour to anywhere in the world, and is divisible in large or small quantities, all without the need for a trusted third party and solving the double spending problem that previous electronic cash systems had.

B. Algorithm and profitability

Hossein Yaghmaee discusses the profitability of Bitcoin mining and provides an incentive-based demand response program for a blockchain network [9]. In this article, he proposes an algorithm that turns a miner on or off based on the price of energy and the price of Bitcoin. For this, a Bitcoin miner is considered as a flexible curtailable load, showing that Bitcoin miners can indeed be modeled as a flexible load. Hossein Yaghmaee also indicates that an individual Bitcoin miner can reach up to 1700 USD in net profit over its lifetime. De Vries discusses the rising energy consumption of Bitcoin [10]. He also points out that up to 70% of the cost of a Bitcoin miner stems from its electricity costs, meaning that if electricity costs can be excluded in the case of RES overproduction, the profitability can increase by a large margin.

C. Current grid congestion solutions and problems

Most efforts for reducing grid congestion come from different power demand balancing schemes. One scheme to avoid congestion is to allow the DSO to have full control over the consumer's flexible loads against a reduced network charge. This comes at the cost of limited freedom in energy usage. Static capacity subscriptions are sometimes employed by DSOs, but this leaves limited flexibility for the consumer. DSOs commonly employ a day-ahead tariff scheme, meaning the cost of energy changes based on the availability of energy. This has the downside of being inaccurate due to unpredictable weather or power demands, and often leads to restrictions on power consumption, but is less restrictive on the consumer [11]. Verzijlberg et. al. discuss the implications of day-ahead tariffs [12]. They find that fixed ex-ante tariffs are burdened by cost-minimizing EVs. The EVs cause a high peak in demand, thereby weakening the correlation between price and network demand. If left unaddressed, the authors find that this worsens the problem compared to flat tariffs.

The organization of this paper is as follows. In the next section, problems and their possible solution will be formulated. In section IV the methods and simulation processes of the proposed solutions are given. Section V shows and explains the results of section IV and section VI discusses the results and remaining questions. Finally, the conclusion is given in VII.

III. Problem statement

A. Bitcoin mining

Since Bitcoin miners will be used as flexible loads, it is important to understand and include the load characterization of the miners. Bitcoin mining is the process of finding a solution for the next block in the blockchain, which is done using the SHA256 algorithm. Finding a solution for the next block involves finding a correct hash that allows the blockchain to advance the next block, and thereby processing transactions on the Bitcoin blockchain. Hashing is a function that converts a string of characters into another string of characters. A string that comes out of this function, a 'hash', can not be reverse-engineered and thus has to be guessed. The string must be below a threshold to be accepted as a solution. On average, it takes a large number of hashes, currently $320 \cdot 10^{21}$ hashes to guess a correct value [13]. This means that on average the blockchain advances by 1 block every 10 minutes. Bitcoin miners are application-specific integrated circuits (ASICs) that are designed to guess as many hashes per second as possible. These ASICs consist of many smaller circuits that can be activated individually. For this paper, the ASICs will be considered curtailable flexible loads that can be turned on or off. The Bitcoin miner model called 'ANTMINER Bitcoin Miner S21 Pro' hashes an expected $234 \cdot 10^{12}$ per second

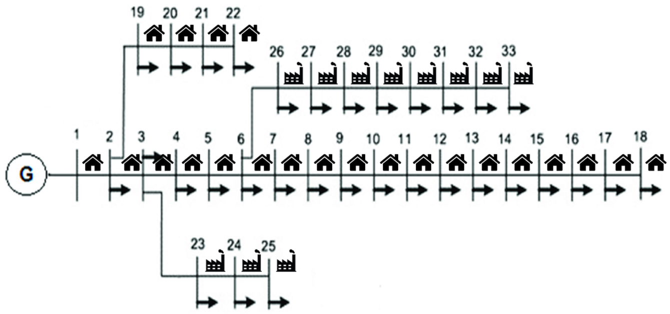


Fig. 1. Modified IEEE 33-node system with realistic load profiles

while consuming 3.51 kW according to seller BITMAIN [14]. Bitcoin mining will be modeled as a large number of these Bitcoin miners that consume 3.51 kW each. Each miner can be turned on or off separately, making the load profile of these Bitcoin miners completely controllable.

B. Modelling of the grid and grid congestion

1) Grid: The grid used for the simulations is a modified version of the Baran and Wu medium voltage (MV) IEEE 33-node system as shown in figure 1, which is used to represent a 33-node MV distribution grid of 12.66kV [15]. The distribution system considers node 1 to be the substation or grid transformer node. Nodes 2 to 22 are residential loads, and 23 to 33 are industrial loads. The grid simulations are run and analyzed using pandapower [16], a power systems simulation tool for Python.

2) Input data: To get a more detailed depiction of a populated area's power consumption, load profiles of a residential and an industrial area are used [17]. The addressed problem in this paper is one of overproduction during the daytime by PV production. A production profile of a high PV production day in the Netherlands is used to simulate this[3].

C. Congestion reduction

After the feed-in congestion is modeled, an architecture to reduce the congestion has to be found. Bitcoin miners can be placed at any of the nodes. To assess if an algorithm is needed to determine miner placements. First, a simulation will be run to see the impact of adding a set number of Bitcoin miners to voltage-congested nodes. Then, if that does not prove effective, a more advanced miner placement algorithm can be used.

The advanced miner placement algorithm must address both voltage congestion and current congestion. The grid transformer regulates voltage and not current, while PV panels can generate higher voltages, but not current. This means the current and voltage congestion do not necessarily happen at the same locations in the grid. A possible algorithm can first target the voltage congestion and then the current congestion. If both are addressed properly, the grid transformer can not be congested, as it is designed to handle the maximum line current capacity at its regulated voltage level.

If all miners that are placed with the advanced algorithm have no activation control, the increased total load per node during low PV production intervals will cause overconsumption congestion. Therefore, a control mechanism based on PV overproduction and power consumption must be designed.

IV. Methodology

This section explains the simulation process and how the grid will be analyzed. Feed-in congestion is a voltage at a node or current in a power line above the grid limit. Congestion will thus be measured in both voltage at nodes, and current in distribution lines. This will be done using several case studies addressing the problems and discussed in section III:

- Realistic Load Case
- PV Congestion case
- Bitcoin Miner Flat Addition Case
- Bitcoin Miner Dynamic Control Case

The progression of these cases can be seen in figure 2. The aim is to see if Bitcoin miners can be deployed to reduce the congestion created in the PV Congestion Case.

The IEEE 33-node system is based on a nominal voltage of 12.66 kV. The law in the Netherlands dictates that for low-voltage grids the grid limits are 0.9 and 1.1 times the nominal voltage. This same standard will be applied to this MV system.

Different distribution lines have different maximum currents. 'Netten voor distributie van elektriciteit' [18] mentions that most MV grids in the Netherlands have distribution lines that are made of aluminium. R/X value of the lines in the IEEE 33-node system mostly have values of higher than 2, which 'Netten voor distributie van elektriciteit' indicates has a cross-section of less than or equal to $150mm^2$. Another table in the same book links this to a maximum current of 265 A, which will be used as a maximum line current for this paper. The figures will refer to the maximum current as a percentage of this value. Any current value above 100% will be considered as congestion.

The external grid transformer in the original IEEE 33-node system has a maximum power delivery capacity of 10 MW and 0 MW export capacity. For this paper, the grid is set to be bidirectional and to have an export capacity of up to 10 MW. If the import or export of power exceeds 10 MW, the grid transformer is considered congested.

A. Realistic Load Case

For the realistic load case, an industrial and a residential load profile are used [17]. The profiles are scaled to a value between 0 and 1 while keeping the shape of the load profiles. The residential profile shape seen in figure 3(a) is applied to nodes 2-22 to emulate residential neighborhoods, and the industrial profile shape seen in figure 3(b) is applied to nodes 23-33 to emulate industrial complexes.

In this case, the aim is to see how the voltage behaves over the different nodes.

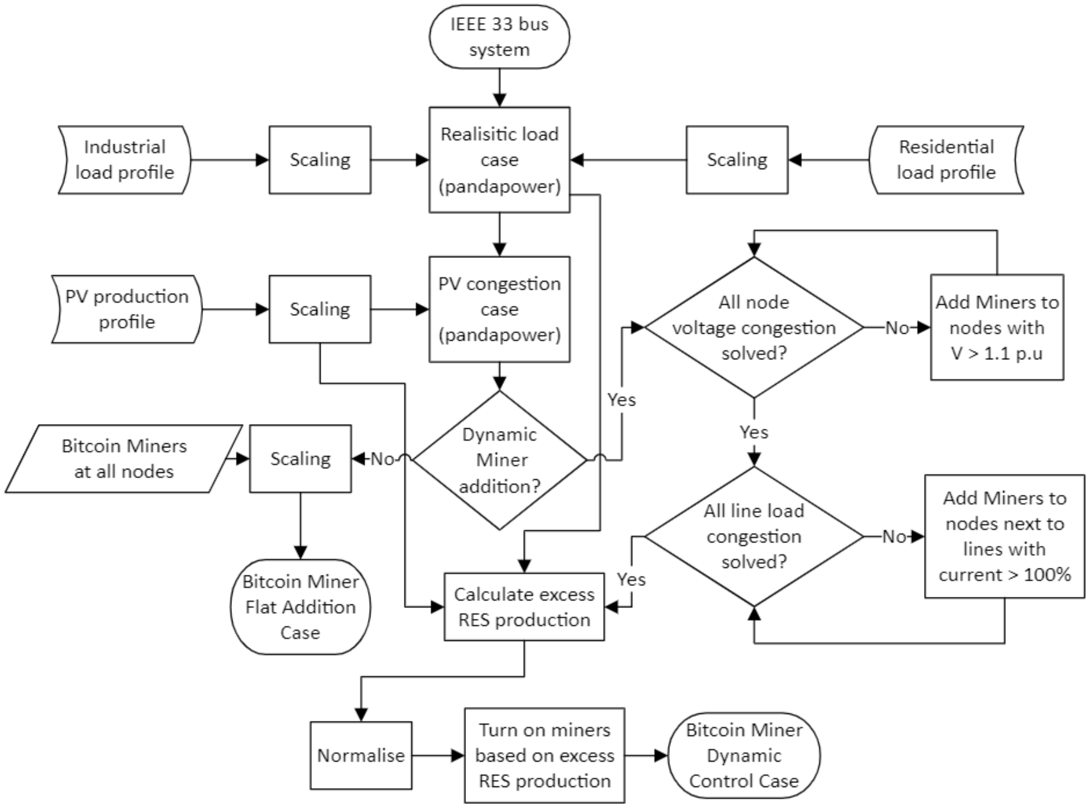
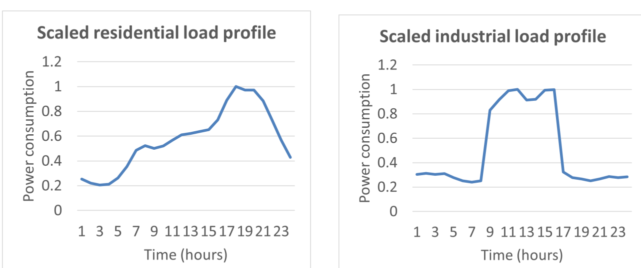


Fig. 2. A flowchart of the progression of how input data is used and processed in different cases. The final result is an algorithmically determined number of Bitcoin miners that can be controlled based on PV energy production and grid power consumption.



(a) The scaled residential load profile. (b) The scaled industrial load profile.

Fig. 3. Consumption profiles used for the Realistic Load Case.

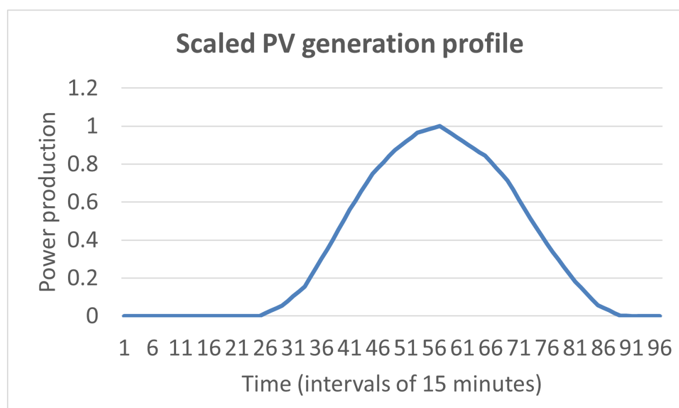


Fig. 4. The scaled PV production profile.

B. PV Congestion Case

To create feed-in congestion in the Realistic Load Case, a PV production profile of a sunny day is added to each node, scaled to a value between 0 and 1, and proportionally multiplied to each load [3]. The production profiles are then multiplied by a number to achieve current congestion in lines; voltage congestion in nodes; and power congestion in the grid transformer. The PV profile used for this is shown in figure 4.

C. Bitcoin Miner Flat Addition Case

In this case, building on top of the PV Congestion Case, Bitcoin miners are added to each node in the grid with a voltage of more than 1.1 p.u. 30 miners are added to all voltage-congested nodes to assess the impact these miners have without optimized placement or control.

D. Bitcoin Miner Dynamic Control Case

To address the voltage feed-in congestion, an algorithm is set up to identify all nodes with a voltage above 1.1 p.u at the time interval when the collective voltage in all nodes is the highest and to add 10 miners at each node. All remaining congested nodes are identified, and this process is repeated until no nodes have a voltage of more than 1.1 p.u., after which the voltage congestion on the upper limit side is considered solved.

Then a similar algorithm is used for line currents. All congested lines are identified, and 10 miners are added to

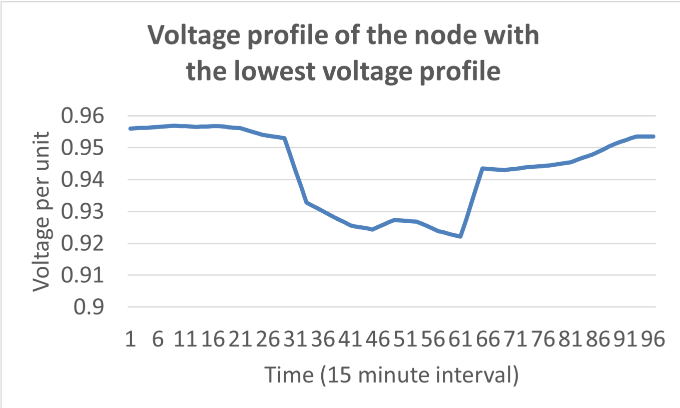


Fig. 5. The voltage profile of node 33 over 24 hours in intervals of 15 minutes. The maximum voltage is 0.957 p.u. and the minimum is 0.922 p.u.

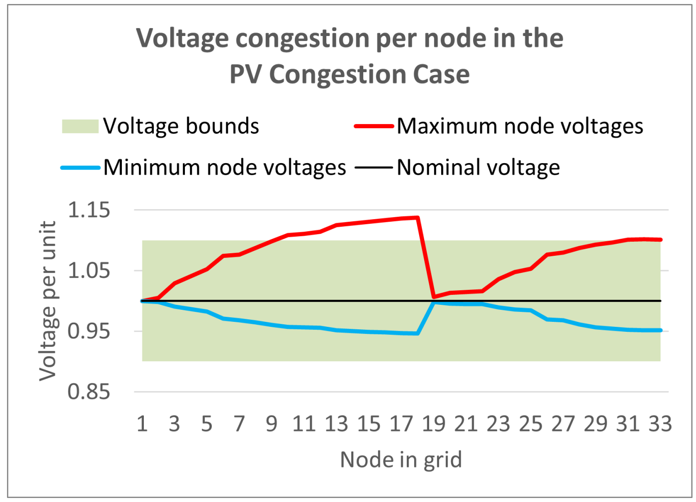


Fig. 6. The voltage at each node in the PV congestion case. The maximum voltage is 1.137 p.u. and the minimum is 0.946 p.u.

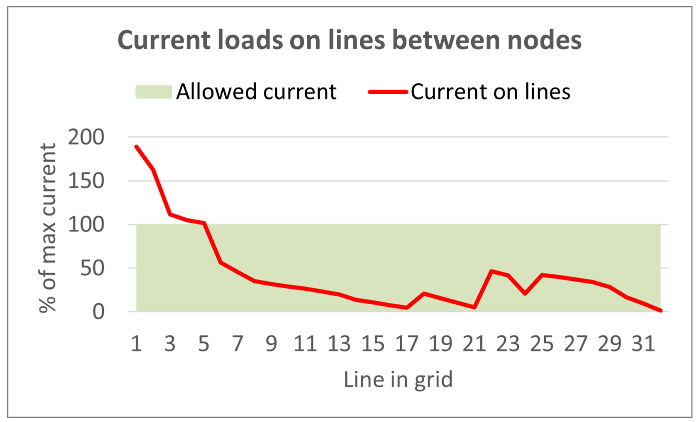


Fig. 7. Current on lines as a percentage of the maximum allowed current in the PV Congestion Case. The highest value is 189.02%.

the node closest to the edge of the grid where the cable is connected. The remaining congested lines are identified and the process repeats until no congested lines are left. If both algorithms are executed consecutively, the algorithms compute the maximum number of necessary miners.

If all the Bitcoin miners are left on at all times, the grid will be congested due to overconsumption at time intervals when there is little PV production. To avoid this, an overproduction profile is calculated by taking the difference between PV production and grid consumption. The negative values are neglected, and the positive values are normalized and multiplied with the maximum number of miners per node, creating a dynamic miner profile. This results in miners being turned off when the PV production minus consumption is lower than 0, and turned on proportionally to how much excess PV production is present.

At this stage, the algorithm is designed to keep the voltages and currents just within the allowed limits. It is desirable to keep the voltage closer to its nominal value as it risks fewer problems, thus the parameters can be set to add miners until all nodes are under 1.05 p.u. and 75% current congestion for example. Several parameters for these algorithms will be used to see how they affect the congestion levels.

V. Results

A. Realistic Load Case

The voltage profile of the node that comes closest to the lower voltage congestion limit is shown in figure 5. Since there is no PV generation in this scenario, the voltage never rises above 1 p.u. and an upper limit is not interesting to assess.

B. PV Congestion Case

Adding PV generation to all nodes results in voltage congestion in nodes as shown in figure 6; current congestion in lines as shown in figure 7; and the power fed into the grid transformer is at its maximum 10.58 MW, which is above the limit of 10 MW. The distribution of voltage and current congestions are shown in figure 8. This figure shows that the current congestion happens close to the grid transformer and the voltage congestion close to the edge of the grid, as is mentioned in section III.

C. Bitcoin Miner Flat Addition Case

As shown in figure 9, the addition of a flat number of Bitcoin miners to each voltage-congested node alleviates the upper limit voltage congestion. It also creates voltage congestion at the lower voltage limit. As seen in figure 10, the flat amount of Bitcoin miners is unable to alleviate current congestion. The maximum power delivered to the grid transformer is 9.61 MW, which is under the congestion limit. The total number of Bitcoin miners is calculated with 14 congested nodes, each with 30 miners, so 420 miners are used in the Bitcoin Miner Flat Addition Case.

D. Bitcoin Miner Dynamic Control Case

Figures 11(a) and 11(b) show that if a Bitcoin miner placement algorithm with miner control is added to the feed-in congested grid, both voltage and current congestion can be alleviated. The maximum power delivered to the grid transformer is 5.17 MW, so the grid transformer congestion is also alleviated. Table I shows that if parameters for the algorithm are changed, voltage variation, line current, and

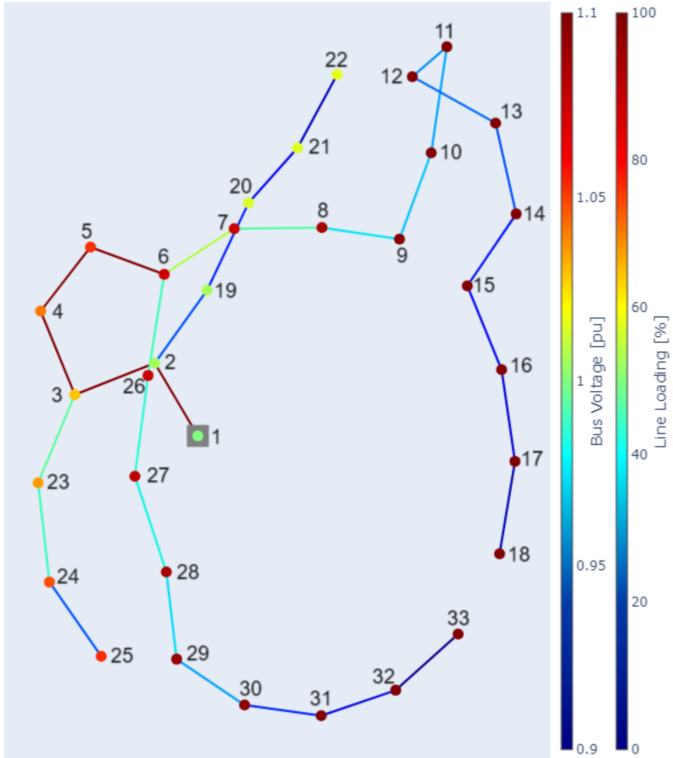


Fig. 8. The distribution of congestion over the whole grid. The numbers correspond to the nodes.

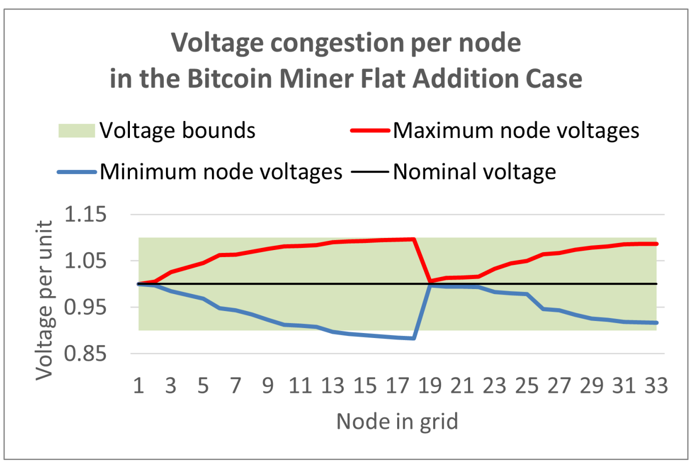


Fig. 9. The voltage at each voltage congested node in the Bitcoin flat amount of miners case. The maximum voltage is 1.096 p.u. and the minimum is 0.883 p.u.

power delivery to the grid transformer can all be further reduced by adding more miners according to the algorithm.

Figure 12 shows the number of necessary Bitcoin miners per node following figure 11(a), and figure 13 shows the profile of the number of miners that are turned on throughout the day. The power consumption of this profile can be deduced from table I and figure 13.

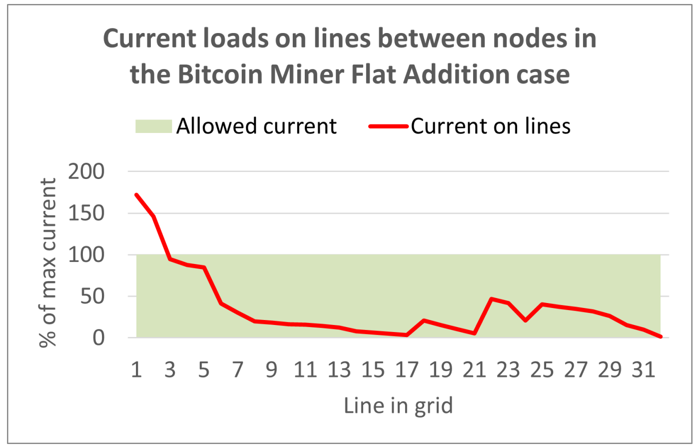


Fig. 10. Current on lines as a percentage of the max allowed current in the PV congestion case. The highest value is 172.07%.

VI. Discussion

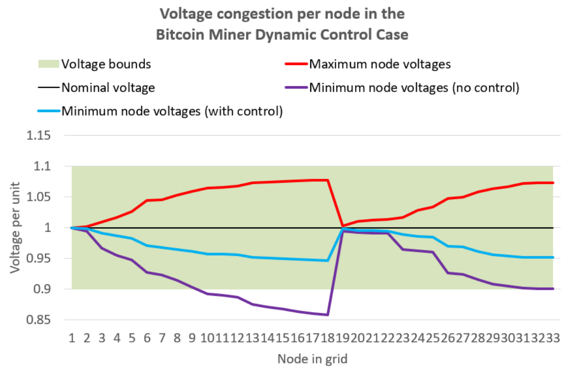
A. Results

The results were mostly as expected. The algorithm is not perfect but is adequate for this paper. In this paper, a known PV production profile is used for determining the number of miners that are turned on, as well as for scaling calculations. The maximum PV production value changes per day and varying production profiles change the optimal number of miners and the miner turn-on profile. If a PV value is higher than expected based on the calculations, it can still cause feed-in congestion. Voltage and current limits that leave larger margins can be used as shown in table I. A larger dataset of PV production profiles can be used to calculate safer and more effective values and profiles. This can be explored in future work. Moreover, in future work, a more advanced algorithm can be designed to prioritize a higher degree of concentration when placing miners instead of spreading the miners over more nodes. This will introduce more variance in voltage but also requires less infrastructure and maintenance and thus reduces operational costs.

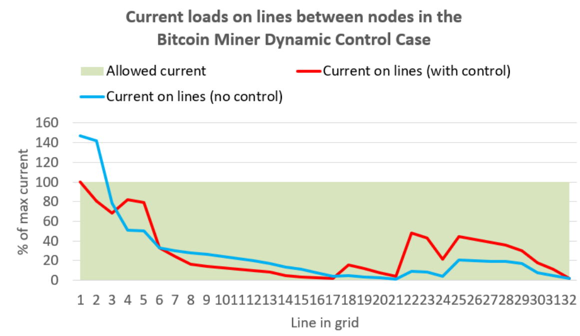
B. Bitcoin mining and other energy capturing methods

An important question is when Bitcoin mining should be used over other energy-capturing methods. Throughout this paper, an attempt has been made to describe the importance of the Bitcoin network. With its decentralized, online, verification-based, and incorruptible nature, it has value to humanity and thus it is important to protect this payment network.

Other energy capturing and storage methods are expensive to construct and offer little short-term return on investment. Infrastructure such as hydrogen gas generators, batteries, or EV charging stations require large capital investments and take a relatively long time to become operational, which often makes it financially unviable to use these methods. For example, hydrogen gas is currently cheaper to import from a seller from another country than to build the infrastructure and produce it in the Netherlands, even with free electricity. Furthermore, Bitcoin miners can be placed and maintained in a shipping



(a) The voltage at each node in the grid. The maximum voltage of the case without Bitcoin miner control is 1.077 p.u. and the minimum is 0.858 p.u. The maximum voltage of the case with Bitcoin miner control is 1.077 p.u. and the minimum is 0.947 p.u.



(b) Currents on lines as a percentage of the maximum allowed current in the Bitcoin Miner Dynamic Control Case. The maximum current in the case without Bitcoin miner control is 147.28%. The maximum current in the case with Bitcoin miner control is 99.84%

Fig. 11. The resulting voltages and currents from the Bitcoin Miner Dynamic Control Case and the same case without control.

TABLE I

THE MAXIMUM AND MINIMUM P.U., THE MAXIMUM % LINE CURRENT, THE MAXIMUM FEED-IN POWER TO THE GRID TRANSFORMER, AND THE RESPECTIVE AMOUNT OF MINERS AND MAXIMUM MINER POWER USAGE USED FOR DIFFERENT SPECIFIED P.U. AND LINE CURRENT LIMITS OVER ALL NODES AND OVER A WHOLE DAY.

Specified limit p.u.	Specified limit current %	Max p.u.	Min p.u.	Max % line current	Max in-feed (MW)	# of miners	Max miner cons (MW)
1.0	50	1.000	0.947	49.4	0.12	3360	11.79
1.025	62.5	1.017	0.947	62.8	2.74	2550	8.95
1.05	75	1.031	0.947	76.2	3.68	2280	8.00
1.075	87.5	1.053	0.947	88.5	4.47	2010	7.06
1.1	100	1.077	0.947	99.8	5.17	1750	6.14

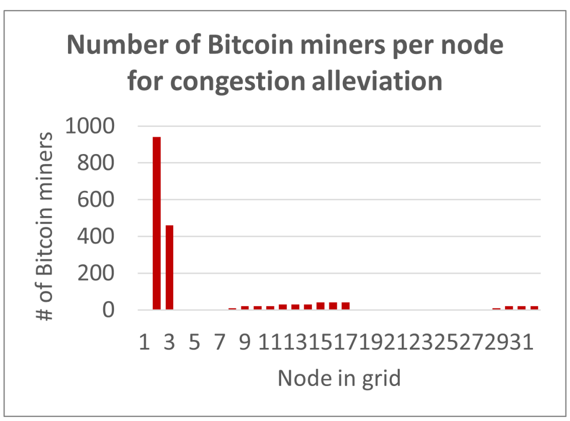


Fig. 12. The number of miners per node as determined by the Bitcoin Miner Dynamic Control Case algorithm. The largest number of miners is 940 at the first node.

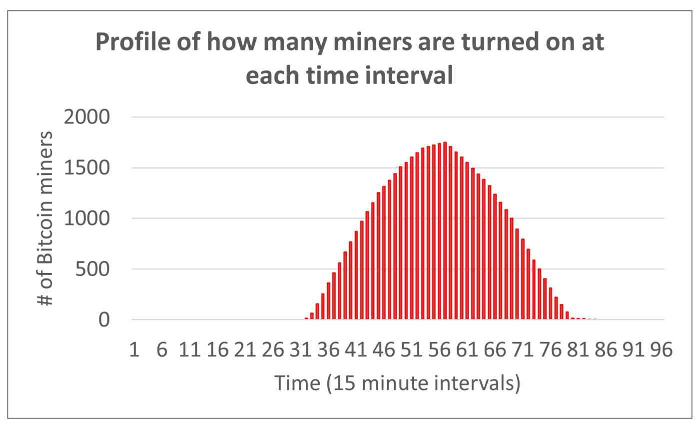


Fig. 13. The number of Bitcoin miners turned on at each 15-minute interval. The maximum amount of Bitcoin miners turned on concurrently is 1750.

container and only need electricity to be deployable, making them highly mobile. Some locations do not require energy storage due to having sufficient 24-hour power availability. Bitcoin mining can serve as a mobile and flexible solution without need for extra infrastructure in cases where no energy storage is necessary. Bitcoin miners also offer near-immediate financial rewards, making them expectedly profitable over a miner's lifetime. This is briefly discussed in section II, but is not yet explored for the case of larger grids, which can be done in future research.

C. *Can Bitcoin mining be beneficial in feed-in grid congestion reduction?*

This paper has indicated that Bitcoin mining can serve a unique role as a flexible load that requires little infrastructure and is highly mobile. Bitcoin mining for feed-in congestion reduction is well justified in scenarios where energy storage is not economically viable or necessary, and where mobile solutions are required.

If Bitcoin miners are placed according to need, and if the miners are controllable, Bitcoin miners can reduce the feed-in voltage congestion, current congestion, and grid transformer congestion.

VII. Conclusion

In this paper a RES generation feed-in grid congestion scenario is simulated using a 33-node distribution system and a method for reducing the congestion using Bitcoin miners is explored, simulated, and evaluated. The method is designed by first creating a grid with a realistic load, then adding PV generation to each node until current congestion occurs in lines; voltage congestion in nodes; and power congestion in the grid transformer. Then a Bitcoin miner placement algorithm is added. This algorithm places Bitcoin miners around the location of the congestion, and a control algorithm turns Bitcoin miners on only if there is excess RES generation and is thereby able to completely alleviate all feed-in congestion caused by the RES generation. The problem of feed-in congestion is discussed, Bitcoin miners and their operations and the goal of Bitcoin mining is explained and a case is made for why Bitcoin is necessary. The difference between Bitcoin mining and examples of other energy-capturing and storing methods is explored and discussed, and scenarios in which Bitcoin mining can be used as the appropriate energy-capturing method are given.

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Appendix

During the preparation and the writing of this paper, the author has used the AI program ChatGPT to generate code in the Python programming language from which inspiration has been taken and to get explanations of functions in Python. ChatGPT has also been used to give synonyms for words and to give suggestions for reformulations of previously existing sentences. The spelling and grammar checking program Grammarly was used to identify and correct language mistakes. The author has reviewed the content and takes full responsibility for the content of the work.