Crypto mining's electricity dilemma

In response to criticism over their rapacious energy use, crypto miners have argued they help promote renewable development, decarbonize the grid, and increase reliability, particularly in ERCOT. But do they promise too much?

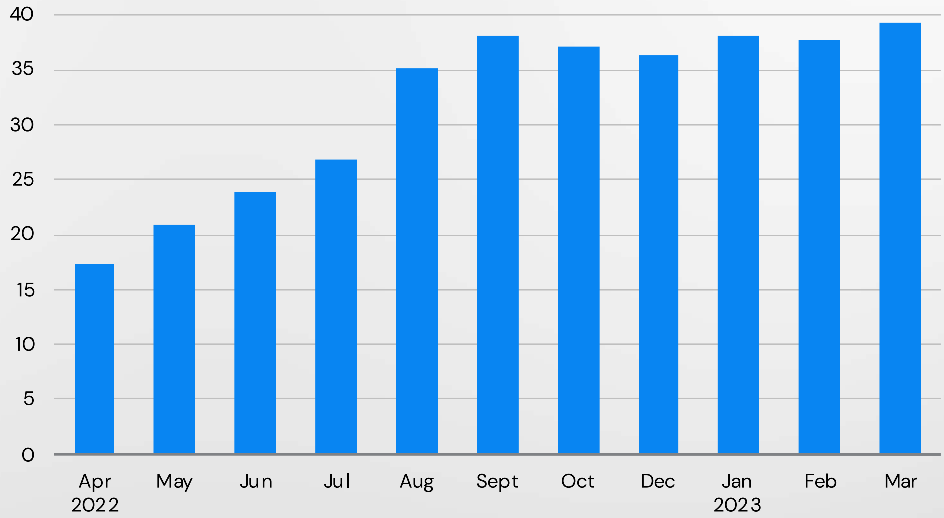
By Ian Bowen, Pat Milligan, and Reed Leon-Hinton

Crypto has had a rough year. The trouble started last May with the collapse of TerraUSD, a cryptocurrency designed to be pegged to the U.S. dollar without any centralized control or currency reserves. Once investors lost faith in this mechanism, a sell-off ensued, which spread to other cryptocurrencies, including bitcoin and ether. Bankruptcies began to cascade throughout the crypto ecosystem. The downturn was compounded by the energy crisis caused by the Russian invasion of Ukraine, aggressive central bank interest rate hikes, and the collapse of the crypto exchange FTX.

Crypto Winter, as the downturn has come to be known, may still be upon us, but it doesn't seem to be cooling down interconnection requests in **ERCOT**. The large load interconnection (LLI) queue, which is largely composed of cryptocurrency miners, grew steadily for months even after the collapse of TerraUSD in May 2022. The collapse of FTX in November, which triggered bankruptcies and liquidity problems among miners, was followed by only a modest one-month decline in the LLI queue. The queue has since managed to grow by nearly 3 GW, reaching over 39 GW in March. For context, peak summer load in ERCOT in 2022 was about 80 GW. Even a mere fraction of the load in the current queue would have substantial power market impacts. Indeed, **in our last piece** on this topic, we modeled the impacts of 7.7 GW of crypto mining additions in ERCOT and concluded they would put strong upward pressure on power prices.

Figure 1: Crypto winter or crypto spring?

ERCOT large load interconnection queue, GW



Source: ERCOT Large Flexible Load Task Force

These large energy impacts stem from proof-of-work blockchains, like Bitcoin, which are designed to require large quantities of energy to validate transactions securely. Proof-of-stake blockchains utilize significantly less energy; for example, Ethereum's transition from proof-of-work to proof-of-stake reduced its energy use by over 99%. But proof-of-work remains dominant, with a nearly 75% market share by market capitalization. The large growth of the LLI queue in ERCOT suggests that many market participants expect that proof-of-work isn't going away any time soon.

The ravenous energy demand by proof-of-work cryptocurrencies is controversial. Critics argue that it is being satisfied by large quantities of fossil fuels; in some cases, crypto mining has been paired with fossil fuel plants that would have otherwise retired. Proponents counter that crypto miners need not rely on fossil fuels. Rather, by ramping their loads up and down, they can improve the economics of renewables, reduce emissions, and increase grid reliability.

Assessing these claims is difficult not only because it involves the intersection of an emerging technology—proof-of-work cryptocurrency—with the world's most complex machine—the electricity grid—but also because it requires thinking about causality. This, in turn, requires assessing counterfactuals, which are impossible to observe directly. However, models can help give us a proxy. After peeling away the factors obscuring causality, it becomes clear that crypto-mining advocates promise too much. While there are forces that can drive the outcomes they identify individually, there is no force that ensures they can be achieved simultaneously. Moreover, there are more effective tools available to address the problems they purport to solve, and crypto mining reduces the incentive to deploy them.

Ramping up

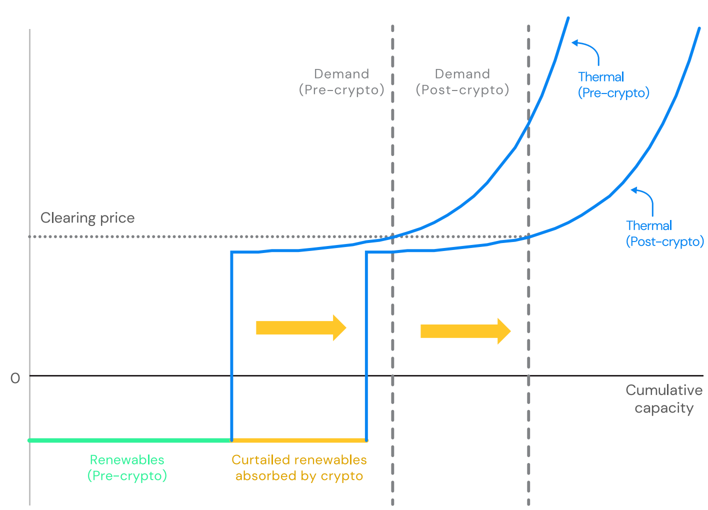
Advocates of proof-of-work argue that the additional load from crypto mining can improve renewable economics by absorbing generation that would otherwise be curtailed and countering the downward pressure that renewables exert on prices. (Curtailment arises when generation is too great to be absorbed by the grid. Renewables tend to depress power prices since they have the lowest variable costs among generation sources.) Furthermore, by improving renewable economics, they argue that crypto mining would help to decarbonize the grid.

To analyze these claims, it's necessary to distinguish between two common frames in economic models: the short run and the long run. In the former, the impacts of crypto mining are analyzed with the generation and transmission system held constant, while the long run allows for these factors to change. It is also necessary to distinguish between the cases where crypto load is kept at most equal to the energy that would otherwise be curtailed and those where it is greater. These distinctions help to conceptualize the causal impact of crypto mining on renewable economics and emissions.

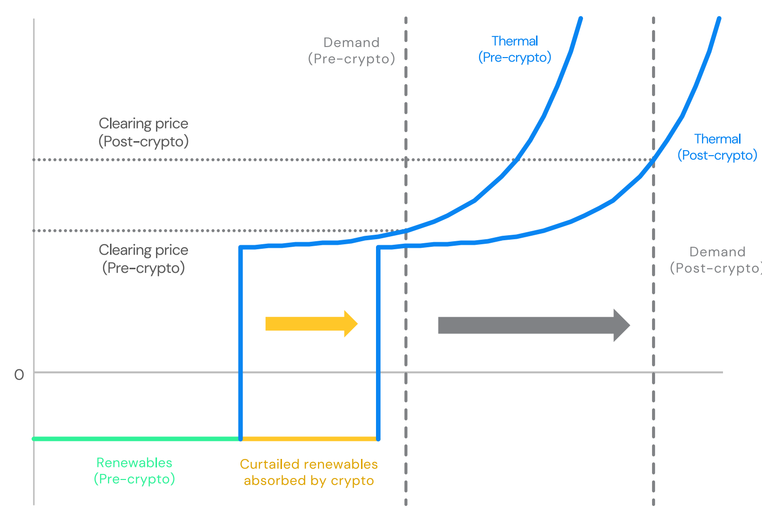
Consider first the short run. The outcomes cited by crypto mining advocates would be most likely to occur if crypto miners were directly connected to renewable facilities and kept their loads equal to otherwise curtailed energy. In this case, crypto miners would reduce curtailment without any impact on the marginal energy component (MEC) of energy prices, the price when system-wide supply equals system-wide demand (see Case 1); supply and demand would shift by the same amount. Nor would there be any impact on emissions because the otherwise curtailed renewables would serve a new load. It could, however, buoy nodal prices, as grid congestion is reduced. (For prices at a given node, the cost of congestion at that node, which can be positive or negative, is added to the MEC.)

Figure 2: Price hike, emissions spike

Case 1: Crypto load is equal to curtailed output
Marginal Cost, $/MWh



Case 2: Crypto load is greater than curtailed output
Marginal Cost, $/MWh



Source: ICF

Notes: Both cases assume that all renewables are paired with crypto loads. Due to the nature of electricity and the grid, miners with grid connections cannot ensure that they only increase demand at facilities with curtailed output, even if total demand from crypto miners were equal to total curtailment.

With increased nodal prices and capacity factors in the short run, the margins for renewables would rise, which would induce investment in the long run. However, this still might not decarbonize the grid. If transmission capacity from the nodes experiencing these impacts is constrained, then the additional renewable generation at those nodes would fail to reach load elsewhere. Instead, the prices at those nodes would decrease as congestion costs rise again, and the capacity factors of renewables there would fall due to curtailment. Therefore, short-run gains for incumbents would fail to translate into long-term declines in prices and emissions for the rest of the system. The solution in this case would be to build more transmission capacity or install **storage**. Installing crypto mining capacity could reduce the incentive to do so.

System-wide gains would be even less likely if crypto load is greater than curtailed output in the short run. Additional thermal generation would be required to meet the load in excess of curtailed renewable output. This would increase emissions and the MEC in the short run as the load curve shifts up the supply curve (see Case 2 above). Emissions would also rise in some cases even if miners were grid-connected and total crypto load was kept equal to total curtailment; due to the nature of electricity and the grid, miners with grid connections cannot ensure that they only generate demand for the facilities with curtailed output. As for nodal prices, if load occurs at nodes with congestion, it would decrease congestion and increase prices relative to the MEC.

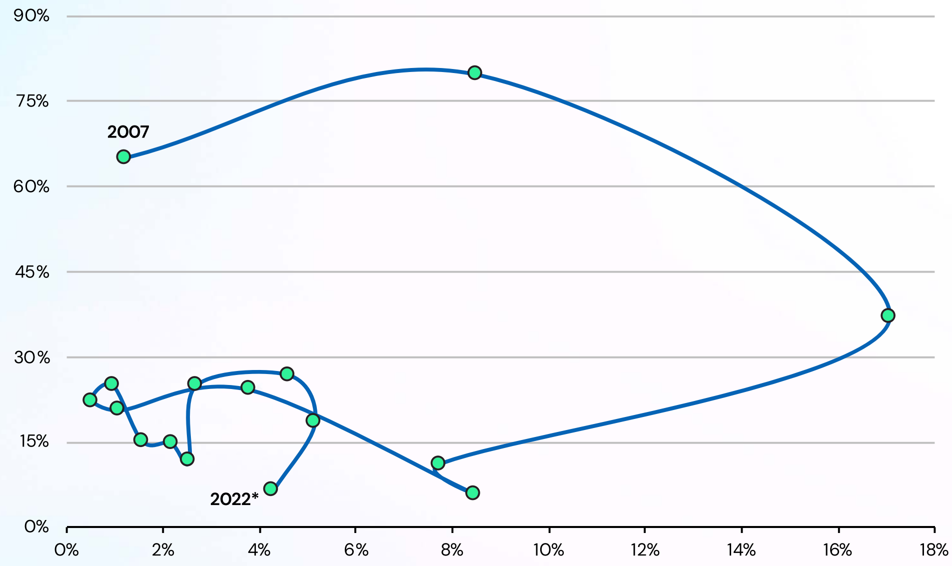
In our modeling for our previous paper on this topic, we found that adding 7.7 GW of crypto miners in West Texas would result in something resembling Case 2. With the conservative assumption that miners break even with power prices below $50/MWh, 7.7 GW of miners would generate around 30 TWh of additional load—a 7% rise relative to the base case. However, curtailment of renewables decreased by only 0.8 TWh while gas generation rose by over 29 TWh. In other words, 98.5% of the additional load was met by gas generation. Therefore, though 7.7 GW of miners would improve renewable economics in the short run, it would also improve thermal economics and result in increased emissions. These effects would be greater with more installed mining capacity and higher breakeven prices.

In the long run with crypto load greater than curtailment, the increase in renewable economics could also induce investment. This could help reduce emissions and put downward pressure on prices. But emissions would already be elevated due to additional thermal generation in the short run. It would take time for any induced renewable investment to compensate for the higher short-run emissions; the 30 TWh of load we found in our modeling, if deployed in 2021, would have been equivalent to all the energy from the renewable capacity installed over the prior two years. Meanwhile, higher prices and capacity factors would also improve the economics of thermal units. Existing units could remain online longer. Whether the long-run investment in renewables would counter the short-run worsening of emissions is therefore not guaranteed. Crypto mining may improve renewable economics, though at the expense of increasing emissions.

These cases demonstrate that even though crypto sends an economic signal to increase investment in renewables, there is no economic mechanism keeping these miners from exceeding curtailment. Whenever it is more profitable to mine crypto than supply the grid, more renewable energy than would otherwise be curtailed could be withdrawn. As a result, crypto will put upward pressure on emissions despite boosting renewable investment. Note that this is also the case for miners with loads greater than renewable curtailment that are directly connected to renewable facilities: reducing renewable energy from reaching the grid and increasing crypto mining load on the grid have broadly the same effects.

Figure 3: Not quite correlated

ERCOT wind; Capacity growth rate vertical; curtailment rate, horizontal



**Curtailment rate for 2022 based on data through November*

Source: Lawrence Berkeley National Laboratory, Hitachi Velocity Suite

There is also the question of the responsiveness of investment in renewables to improved project economics due to crypto mining. Since 2007, actual curtailment has shown no relationship with the growth rate of investment in wind capacity (see Figure 3). Even over the last eight years, as curtailment has risen steadily—reaching around 4% in 2022—there is no correlation. Of course, simple correlations do not provide a complete picture of causation. Investment could have been higher with lower curtailment.

Renewable investment could certainly be constrained in the future if transmission buildout does not keep pace with development. However, supply chain constraints appear to be more binding. Projects are being delayed. Development is also being boosted by **incentives from the Inflation Reduction Act**, potentially exacerbating supply constraints in the near term. All that is to say, even without additional crypto mining load, investment in renewables has probably reached its speed limit for the foreseeable future.

Ramping down

To ensure that crypto mining matches curtailment, it needs to not just ramp up but also ramp down flexibly. This is technically feasible. But crypto advocates take this flexibility too far: they argue that it can help improve reliability as renewable penetration increases. In reality, crypto miners will struggle to address the reliability challenges of renewable integration without also increasing emissions.

The reliability challenges of renewable integration are certainly real. Due to their dependency on inherently unpredictable weather, renewables create challenges in maintaining a continuous supply-demand equilibrium, which must always be the case for the electricity grid to function smoothly. If renewable output falls suddenly because of incorrect renewable output predictions by grid operators, either the output of dispatchable generation must rise or demand must fall. Furthermore, if non-crypto loads spike, as occurred during Winter Storm Uri and in the summer of 2022, renewables cannot be readily dispatched.

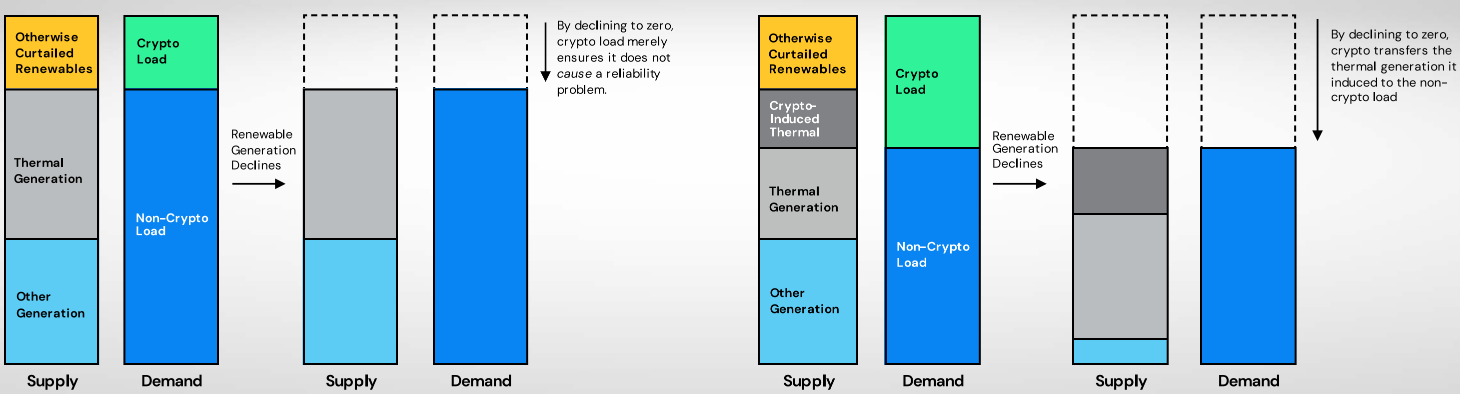
Then there is the "duck curve" effect. With high penetrations of solar, the amount of dispatchable generation is pushed down to low levels during the hours when the sun is shining. Then output falls sharply just as demand peaks towards the end of the day. To manage these periods, flexible generation must be available to ramp up quickly, or demand must be flexible enough to be moved to other periods when solar is more abundant.

To demonstrate how crypto load is a poor tool to solve these problems, it is once again necessary to distinguish between the short-run and long-run and cases where crypto is at most equal to curtailment and those where it is greater. Start with the short-run case where crypto load is initially equal to curtailment. If there is an unexpected fall in renewable generation less than or equal to otherwise curtailed renewable generation, flexible downward ramping would merely ensure that crypto does not cause a reliability problem by leaving excess crypto demand after the fall in renewables (see Case 1 below). However, with an unexpected fall greater than curtailment, crypto would not be able to ramp down by the same amount. There would be excess demand that crypto mining would be powerless to address. As for the duck curve, if crypto miners absorb otherwise curtailed energy during the middle of the day, down-ramping also does nothing to solve reliability challenges; the upward ramping for thermal plants would be the same as if crypto load hadn't been there at all.

Figure 4: Gas reserve

Case 1: Crypto load less than or equal to curtailment in the short run

Case 2: Crypto load greater than or equal to curtailment in the short run



Source: ICF

Now say that crypto load is greater than curtailment in the short run (Case 2 on page 6). The portion of load above curtailment would induce thermal generation. Crypto mining could only reduce reliability problems by keeping this additional thermal generation online as a reserve for periods when renewable generation declines. For example, if renewables decline unexpectedly, crypto could ramp down to zero, effectively transferring the thermal generation from the reserve to the remaining load. It could also help with the duck curve by inducing thermal generation in the middle of the day and night and then ramping down in the evening and morning; this would flatten the net load (i.e., load minus renewables), reducing the need for steep thermal ramping (see the short-run cases in Figure 5). But in either case, the reliability benefits of crypto would come at the expense of increased emissions.

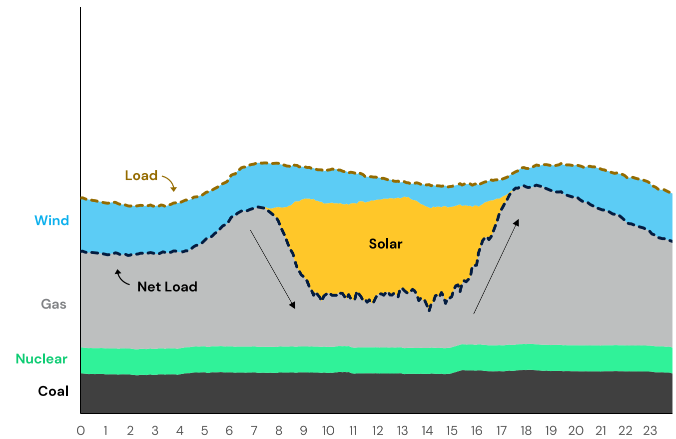
Figure 5: Duck, duck, gas

Hourly generation

Short run

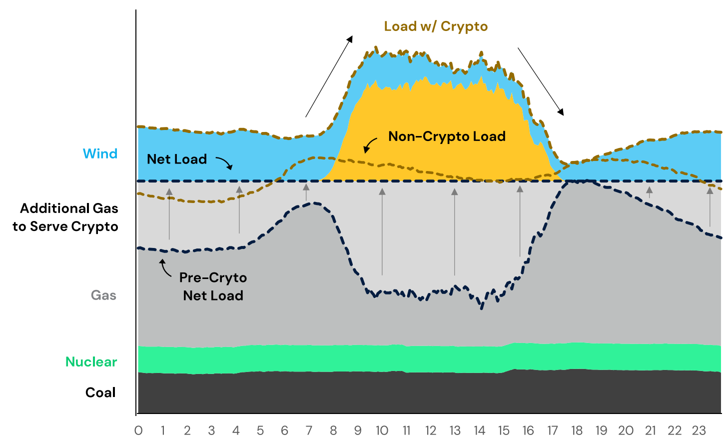
Managing the duck curve with flexible gas generation

With low penetrations of crypto load, storage, and demand response, gas plants engage in a delicate dance with renewables: they must ramp down rapidly before solar generation emerges early in the day and ramp up sharply to meet the evening peak.



Managing the duck curve with crypto load

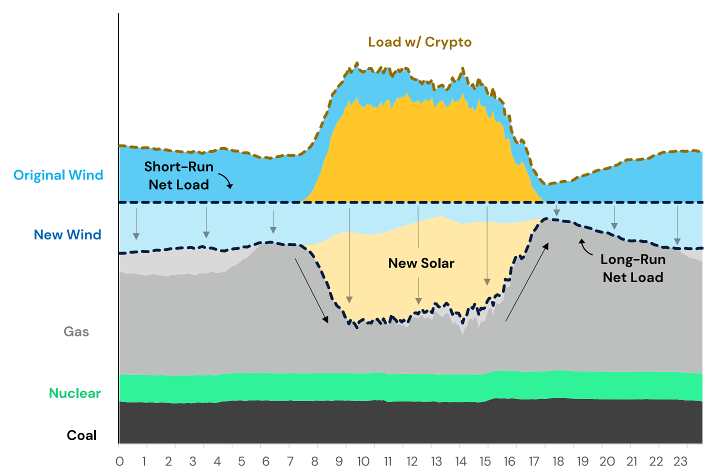
In the short run, crypto load can reduce the need for ramping by gas plants. Crypto load takes over as the renewables' dancing partner. Note that in the right-hand figure, only gas generation (and thus the net load) and total load differ from the top figure.



Long run

The duck curve returns

By increasing load, crypto mining improves the economics of renewables in the short run, inducing investment in the long run. The generation from the new renewables reduces the gas generation induced by crypto in the short run (see the previous graph). Other than in the unlikely case where the induced investment is mostly wind capacity, the duck curve will return.



Source: ICF

So, the reliability benefits of crypto mining in the short-run amount to either not creating a reliability problem or improving reliability while also increasing emissions. By contrast, energy storage or demand response—that is, the substitution of existing loads with smart technologies that respond to grid conditions—do not run into these issues. Storage can be used to address the duck curve by moving excess energy to the peak, reducing the need for rapid upward thermal ramping. It also provides a reserve of energy that can be rapidly dispatched when renewables fall unexpectedly. Demand response can also address the duck curve by shifting the existing peak load to the middle of the day, and it can postpone demand whenever renewables are lower than expected. However, the deployment of these technologies depends on price differentials, such as lower prices in the middle of the day than in the evening. Since crypto mining tends to smooth out these differentials, it would reduce the incentives to deploy storage and demand response.

In the long run, the ability of crypto load to mitigate the duck curve depends on the type of renewables it induces. Additional solar would only make the duck curve worse, as it would depress the net load again in the middle of the day. Wind generation could help; its profiles are inversely correlated with solar, so more wind could help bring the net load down in hours when solar is not generating. But there is no guarantee that there would be the right balance of wind and solar investment to result in a flat net load profile. In all likelihood, the duck curve would simply return as both wind and solar eat into the gas generation induced by crypto mining (see the bottom graph in Figure 5).

As for unexpected falls in renewables in the long run, the impacts once again differ depending on whether crypto load differs from curtailment. If crypto load is greater than curtailment, additional renewable investment would generally increase renewable generation. A portion of this would displace some of both the non-induced thermal generation (see the dark grey bar in Case 2) and gas generation reserve (see the light grey bar).

The gas generation reserve would thus transition to a renewable generation reserve. When renewable generation falls unexpectedly, crypto load can ramp down and transfer its consumption from the reserve to the grid. A similar dynamic would occur if crypto load were less than or equal to curtailment, the only difference being that there would be no gas generation reserve to displace.

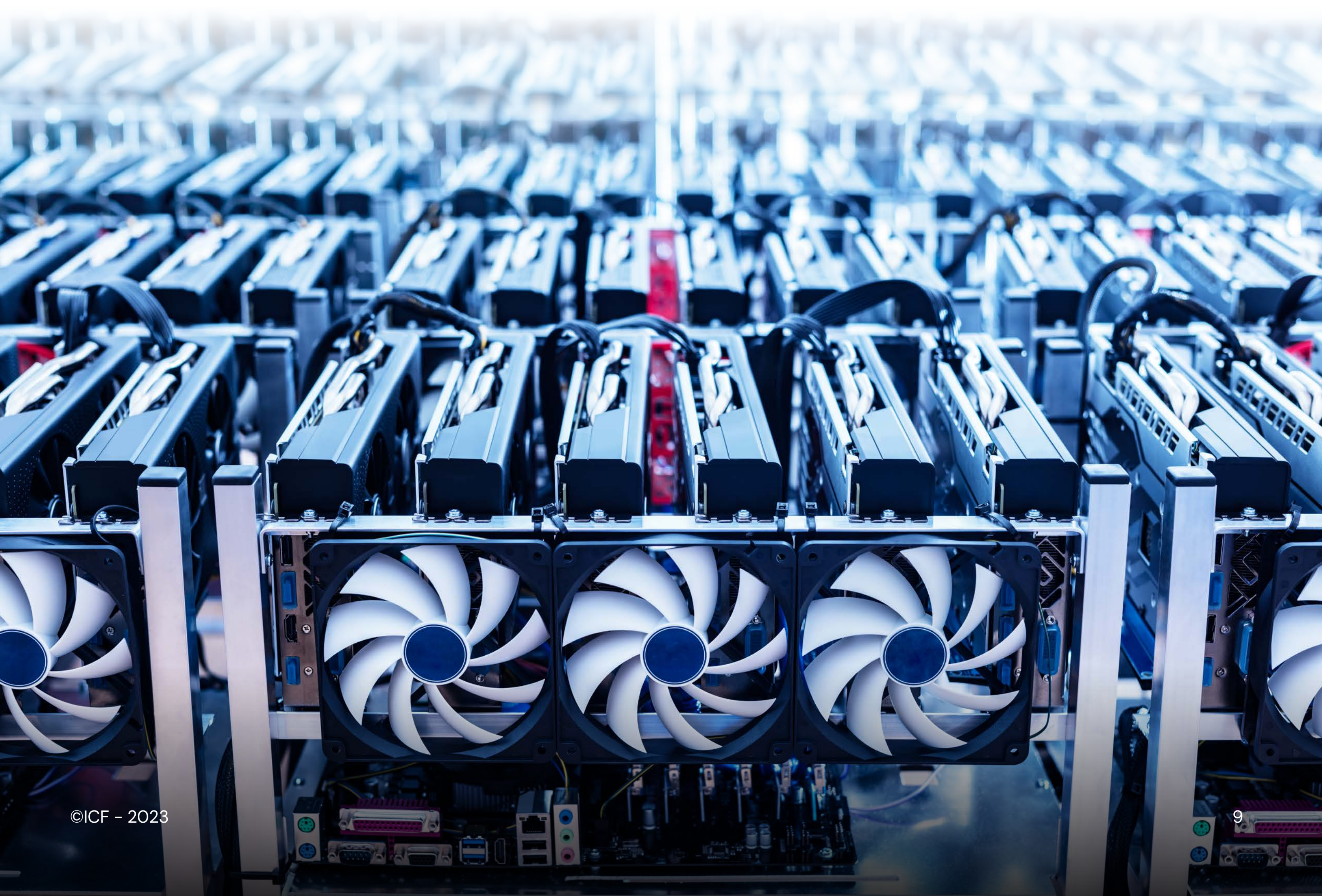
The problem with this solution is that the ERCOT grid is quite isolated, so declines in renewable generation are correlated. An unexpected fall in renewables would likely exhaust any renewable reserve within ERCOT. Since the renewables induced by crypto mining will have displaced some of the non-induced thermal generation, this could make it worse than before crypto was added. Furthermore, whether the transition from the gas buffer to the renewable buffer occurs is not clear; there is no mechanism to ensure that renewable investment is sufficiently responsive to fully reduce the gas reserve. Even if it does, crypto will have increased emissions throughout the transition process.

No easy answers

Crypto mining thus faces an electricity dilemma. It can help improve renewable economics or address the reliability challenges posed by renewables but, in the process, exacerbate emissions. Part of the reason for this dilemma is that crypto miners create a new electricity demand without replacing another.

The exception is when crypto manages to consume only wasted energy, such as from curtailed renewables. There is also the potential to capture wasted energy outside the electricity grid, such as waste methane from landfills. In these cases, crypto can help bring renewables online, which would supply more energy than crypto needs, thereby helping to decarbonize the grid. However, given the tremendous amount of crypto load queued up in ERCOT, it is unlikely that mining there would be restricted to wasted energy. Moreover, ERCOT will only allow such large amounts of crypto load to come online if reliability is maintained. While crypto mining's flexibility can help it from causing a reliability problem, it may in fact cause one.

Other sources of demand also introduce trade-offs. While electrification in general also puts upward pressure on energy prices and worsens short-run emissions, it also directly decarbonizes other sectors. To stabilize the climate, electrification in these sectors will have to grow significantly. Non-crypto loads can also more effectively address the challenges of curtailment, congestion, and grid stability that crypto mining advocates purport to solve. Crypto mining would reduce the incentive to deploy them. It seems, then, that crypto is not as much of a boon for the climate and grid as its advocates claim.



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