Title

Plentiful electricity turns wholesale prices negative

Authors

Seel, Joachim
Millstein, Dev
Mills, Andrew
et al.

Publication Date
2021-11-01

DOI
10.1016/j.adapen.2021.100073

Advances in Applied Energy 4 (2021) 100073

Contents lists available at ScienceDirect

Advances in Applied Energy

journal homepage: www.elsevier.com/locate/adapen

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1. Introduction

The year 2020 upended routines in nearly all aspects of our lives. In the realm of energy economics, we saw prices turn negative for U.S. crude oil [7, 16], natural gas [14], and wholesale electricity. While negative prices were unprecedented for oil, similar conditions existed for natural gas in 2019, when pipeline capacity could not accommodate the rapid expansion of associated gas production in the Permian Basin. For electricity, which in comparison to oil and gas has negligible storage capacity, negative prices have been much more common and growing. Negative prices are interesting (and atypical for most commodities) because producers should theoretically cease production whenever sales prices fall below marginal production costs—let alone if negative prices require them to effectively pay (rather than be paid) to continue producing.

In 2020, average wholesale electricity prices in the United States reached their lowest level since the beginning of the 21st century. Just as the pandemic caused demand reductions for crude oil around the globe, annual total U.S. electricity demand in 2020 fell by nearly 4% below 2019 levels [17], despite a modest consumption increase in the residential sector of 2% as families spent more time at home [4]. But the decline in wholesale electricity prices had already started before the Covid-induced demand shock; in fact, average wholesale prices have fallen by three-quarters since their peak of $84/MWh in 2008, to only $21/MWh in 2020 (all numbers are reported in 2020$). Multiple factors contributed to this reduction, including the decline in natural gas prices associated with the shale gas boom, the addition of low-marginal-cost renewables like wind and solar, average heat rate efficiency gains of thermal generators, and modest demand growth [11]. Beyond a general reduction in average electricity prices, the timing of high and low prices has also shifted. This is especially true in markets like that of the California Independent System Operator (CAISO), where the large shares of electricity provided by solar projects has created a ‘duck-curve’ not only in net load but also in diurnal price profiles [10].

While these themes have been widely discussed in the broader literature looking at increasing penetrations of variable renewable energies (see [8]), an area that has received less attention is the accompanying rise in negatively priced electricity.[1] This article (1) provides an overview of the prevalence of negative prices in U.S. real-time wholesale markets for electricity, (2) identifies key drivers, and (3) concludes with a discussion of the implications of negative pricing for renewable energy development, transmission and storage development, and load growth or load adaptation.

2. Prevalence of negative prices

In 2020, negative real-time hourly wholesale prices occurred in about 4% of all hours and wholesale market nodes (out of >50,000 nodes) across the United States. But, as depicted in Fig. 1, negative prices are not distributed evenly in space. Regional clusters have emerged, for example in the wind-rich central plains, where production tax incentives delay curtailment of wind energy even as prices turn negative. In particular, Kansas and western Oklahoma have nodes where market participants can be paid to buy electricity in more than a quarter of all hours of the year, and negative prices are relatively frequent across much of the Southwest Power Pool (SPP). A second cluster of negative prices can be found in the Permian basin in western Texas, a region with not only many oil and gas wells, but also wind turbines and, increasingly, solar plants, but with limited transmission capacity. These two negative price clusters illustrate two different drivers of negative prices, geographically isolated hotspots driven by transmission constraints (e.g., the Permian basin), and region-wide negative prices driven by the high penetration of wind power (e.g., SPP). Other smaller agglomerations can be found in northern New York and northern New England, again linked to wind generation and transmission constraints. Interestingly, with some nodal exceptions, negative prices were not as common in 2020 in the solar-rich CAISO than in the central plains, despite large shifts in historical diurnal pricing patterns following the infamous “duck-curve” [10]. Unlike wind, solar has access to an investment tax credit not a production tax credit, so solar producers are generally less willing to continue to generate when wholesale prices turn deeply negative, leading to curtailment of ~5% of 2020 CAISO solar generation.

Though Fig. 1 focuses on 2020, wholesale electricity prices have been negative for more than 2% of all hours at major trading hubs going at least as far back as 2006—i.e., before wind and solar played a large role in supply portfolios [19]. Fig. 2 shows average prices and the frequency of negative prices *at all LMPs* from 2006 through 2020. We note that the continued increase of negative price frequency and the decline of wholesale prices was not exceptional in 2020 compared to historical trends, even though COVID-demand shocks may have exacerbated both. The frequency, geography, and temporal profiles of negative wholesale power prices have evolved over time, in response to changing market conditions. One prominent example comes from Texas, where negative prices associated with new wind power were common in western parts of the Electric Reliability Council of Texas (ERCOT) in 2011 and 2012, but were mostly eliminated in 2013, and for a few years following, due to a significant build-out of new transmission [19]. Another example comes from California, where negative prices were often found at night in 2011, but declined in frequency in the following years due to lower hydropower production, nuclear retirements, and reduced numbers of must-run units [9].

The development of negative prices in the SPP has followed a different pattern. Here, the trend in frequency of negative prices has been more steadily upward: in the western wind-rich regions of SPP, negative prices have become more common since 2014, though 2015 and

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[1] For a longer review of literature on negative prices and the relationship to policies see [19]. For a detailed overview of U.S. wholesale market structure (including a description of bidding mechanisms) and its evolution under increasing renewables see [3].

https://doi.org/10.1016/j.adapen.2021.100073
Received 24 May 2021; Received in revised form 9 September 2021; Accepted 7 October 2021

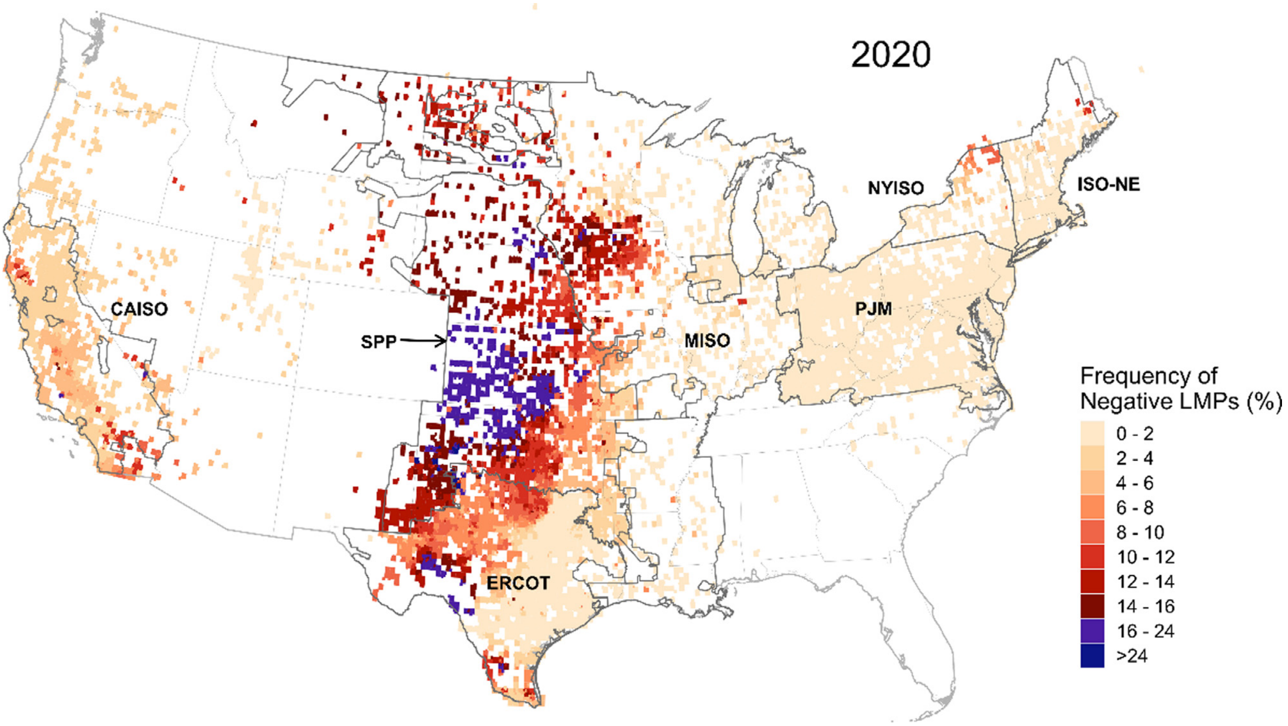

Fig. 1. Frequency of negative locational marginal prices at nodes in the seven organized wholesale markets in the United States.

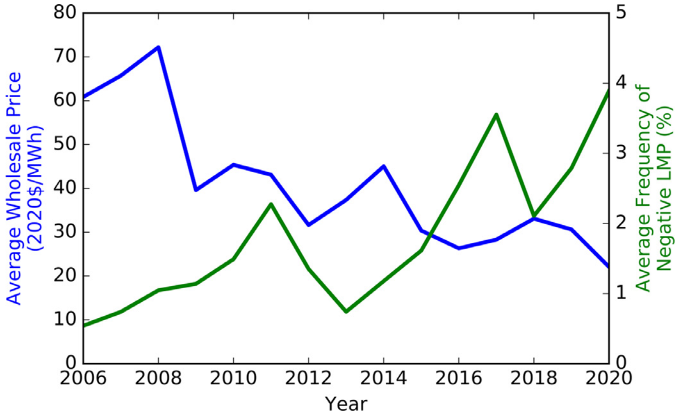

Fig. 2. Average wholesale prices and average frequency of negative locational marginal prices at nodes in the seven organized wholesale markets in the United States.

2018 each brought some temporary relief. 2020 stands out as the year with the most ubiquitous negative prices, both in terms of number of nodes affected and hourly share of negative prices at those nodes. However, the actual magnitude of the negative prices has remained relatively constant; for example, negative prices in SPP averaged -$12.5/MWh in 2016 versus -$14.5/MWh in 2020. Given the relative concentration of negative prices in SPP in 2020, we examine negative price trends in this region more closely below.

3. Genesis of negative prices

Negative prices occur in situations of oversupply, when the marginal generator would prefer to pay a price rather than reduce its output [1]. This can occur for a number of reasons. A generator may have physical constraints that inhibit its ability to ramp down production at a particular moment [13]. Relatedly, a generator may anticipate higher-priced hours in the near term and may not want to shut down due to lengthy start-up procedures. Other generators may ignore wholesale market signals due to bilateral purchase contracts that are settled outside of the wholesale market, or because of “self-scheduled” unit commitments of regulated utilities [2].

Another driver may be monetary production incentives that are awarded separately from the wholesale market. For renewable energy, relevant examples are the federal production tax credit (PTC) for wind and renewable energy credits (RECs) demanded by renewables portfolio standards or private entities. Both can affect the bidding behavior of the recipients and enable negative bids [5,19]. For example, most wind turbines operating in 2020 were eligible for an inflation-adjusted PTC of $25 *per MWh generated and sold*, and therefore were presumably willing to bid (and generate) at prices approaching -$25/MWh. With the rapid buildout of new wind capacity in recent years, along with a recent wave of repowering of older projects (which not only improves their efficiency and increases production, but also requalifies them for another 10 years of PTCs), more wind projects than ever before are receiving production incentives that may delay wind curtailment even as prices turn increasingly negative.

Negative prices can occur at individual pricing nodes or clusters of nodes when transmission capacity is insufficient to export electricity to demand centers, or they can be widespread across an entire market. When widespread, additional intra-regional transmission would not necessarily alleviate negative pricing. Fig. 3 examines such a widespread occurrence, focusing on SPP’s southern trading hub, where 7% of all hours in 2020 had negative prices. Both panels describe, either in absolute (left) or relative (right) terms, average generation levels by fuel type during hours with positive and negative prices. One insight is that all major generation technologies produce in hours of negative prices and thereby contribute to the issue of negative prices. However, most generator types operate at lower production levels (or capacity factors) when prices turn negative. There are two notable exceptions: during negative price hours nuclear projects continue to generate power at near-peak capacity levels, and wind turbines generate at higher-than-average production levels—near 75% of their rated capacity. These trends are not unique to 2020: The top panel shows analogous dynamics for the pre-

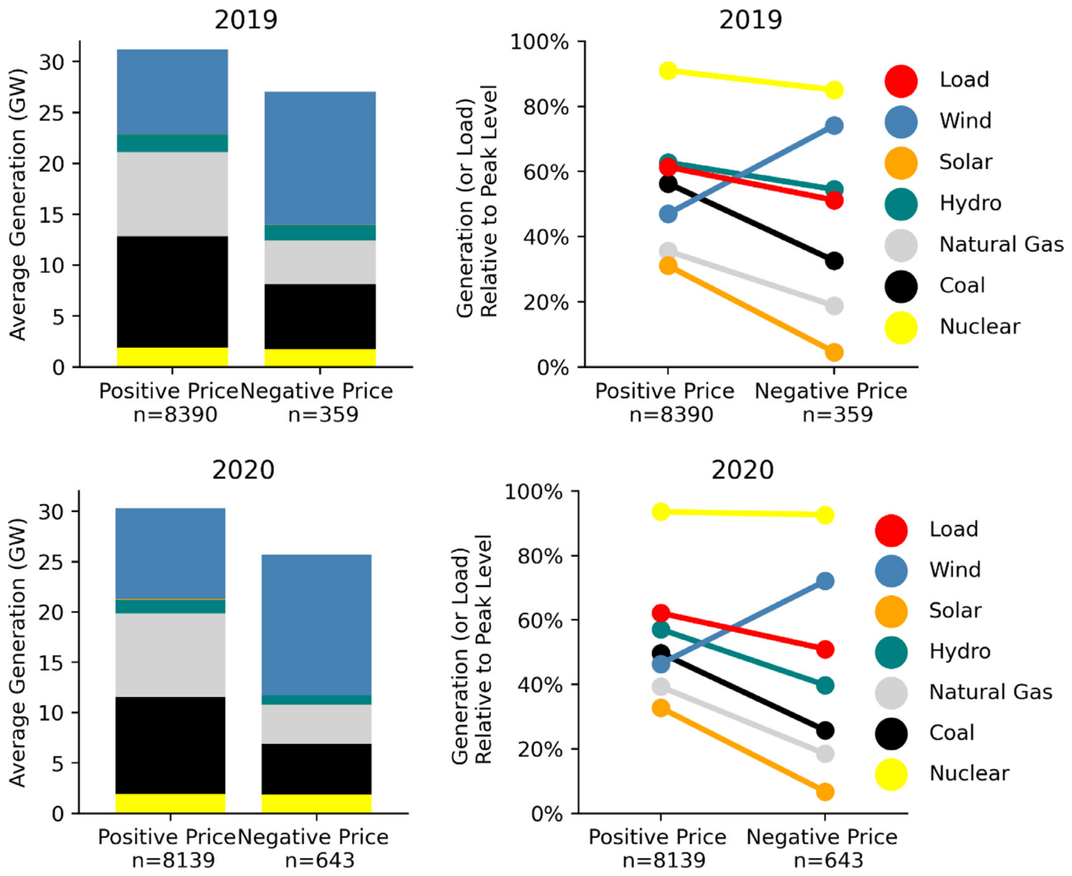

Fig. 3. Average generation levels by fuel type in absolute (left) and relative (right) terms during positive and negative price hours at the southern trading hub in SPP in 2019 and 2020.

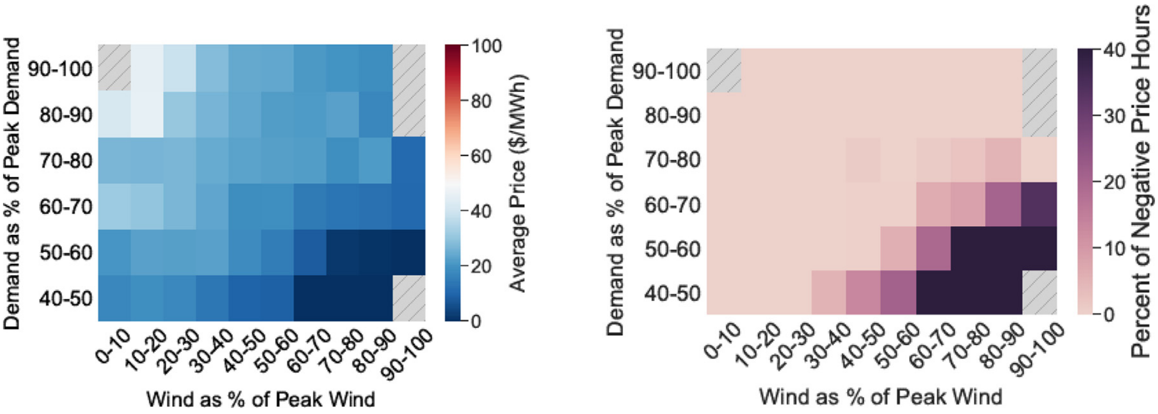

Fig. 4. Average hourly prices (left) and frequency of negative prices (right) in SPP at varying demand and wind generation levels in 2020.

ceding year, and while 2019 had fewer hours with negative prices, the response by generator type was similar to 2020.

Wind turbine output is driven by weather patterns and does not follow aggregate load levels. Fig. 4 showcases the resulting interplay between regional demand, regional wind generation, and wholesale energy prices at SPP's southern trading hub—focusing both on average hourly prices (left panel) and the prevalence of negative prices (right panel). Electricity prices generally rise with increasing load levels, as progressively more-costly marginal generators are required to serve the increasing load. But with rising wind generation, the net demand (demand minus wind) decreases, and electricity prices fall. The right panel shows that negative prices especially occur when load levels are relatively low and wind production is high.

4. Meaning of negative prices

Wind and, to a much lesser degree solar, are increasingly primary drivers of negative prices. That said, they are not the only factors: electricity load and the flexibility of the fleet of power plants all play a role, as does the interplay of those characteristics with wholesale market design and operating and bidding practices. Transmission, or the lack thereof, plays a central role as well. Whereas the United States features widespread nodal LMP prices, many other countries have wholesale markets with less geographic granularity in prices. A consequence of this difference in market design is that wholesale prices in the United States convey information on fine-scale transmission congestion that is sometimes missed in the wholesale pricing patterns of other countries.

But negative prices are not a unique feature to U.S. markets, see Nicolosi [13]. Similar to the U.S. experience, the frequency of negative prices increased in 2020 across multiple European markets [6]. Though the drivers of negative prices in Europe are mostly similar to those in the U.S., the structure of a country's renewable subsidy regime can lead to important differences in negative price patterns. For example, Winkler et al. [18] demonstrate, using a model of the German electricity market, how switching wind subsidies from feed-in tariffs to capacity-based support sharply limits the frequency of negative prices.

Perspectives differ on whether or not the presence of negative prices implies an actual problem that is fundamentally different from very low, but positive, clearing prices caused by low-marginal-cost generators. On one hand, some would argue that policies that encourages negative bidding, including the PTC and RPS mandates, distort the market. Negative prices can increase (at least temporarily) the size of out-of-market payments to inflexible generators that are needed for reliability. On the other hand, renewable electricity is delivering otherwise un-accounted for societal benefits for every MWh delivered. In that case, negative bidding may be an acceptable way to prioritize renewable energy over other generation sources, especially in a 'second-best' world in which a full accounting of negative externalities appears politically infeasible [19].

Though we cannot unambiguously say what it means to have growing frequency of negative prices, we can highlight the shifting economic signals they provide. For example, negative prices have implications for wind (and solar) deployment and associated decarbonization goals in so much as they indicate locations where the economic value of additional generation resources has significantly declined [12]. They illustrate the possible need for, and value of, added transmission that allows excess electricity to reach distant demand centers (we have not yet had negative prices coincide in all US regions at once). They suggest value in extracting more flexibility out of the conventional thermal fleet, especially from those generators that are not closely following economic signals. Related, storage in its various forms can add value by moderating temporal supply and demand imbalances. Finally, with different retail rate designs, more-impactful economic signals to end-use customers could alert them to the availability of low-priced electricity, allowing them to shift demand in time or between locations. Large flexible energy consumers may have the opportunity to increase welfare by availing themselves of plentiful and cheap energy [15].

If you are interested in exploring some of the described dynamics yourself in greater detail, for example, exploring seasonal trends in pricing and net load (nationally or regionally), or examining LMP pricing maps across different years, you can find our interactive visualization tool of nodal electricity prices here: https://emp.lbl.gov/renewables-and-wholesale-electricity-prices-rewep

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Joachim Seel*
Dev Millstein
Andrew Mills
Mark Bolinger
Ryan Wiser
Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, United States
*Corresponding author.
E-mail address: jseel@lbl.gov (J. Seel)

Revised 9 September 2021

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We appreciate the funding support of the Solar Energy Technologies Office and the Wind Energy Technologies Office of the U.S. Department of Energy in making this work possible.

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