

ENERGY INNOVATION
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# CLEAN ENERGY PARKS WITH THERMAL INFRASTRUCTURE

## Achieving the last few percent of Reliability to break AI's infrastructure deadlock

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Energy Innovation,
November 2026

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# EXECUTIVE SUMMARY

**We propose a new kind of clean data center energy park that can be built without any initial connection to the power grid or gas pipelines, able to quickly leverage new clean energy resources wherever available to supply data center's with clean power available 24/7.**

The United States' insatiable demand for new data centers could reach 118 gigawatts (GW) installed capacity by 2030, according to a Bloomberg BNEF forecast[1], but powering these data centers faces bottlenecks, chief among them building new electric generation and connecting to grid and natural gas infrastructure.

"Speed to power" pressure to meet new data center demand has encouraged developers to consider co-located generation, including a proposed pipeline of roughly 90–189 GW of gas generation[3] for so-called "bridge power," off-grid or near-grid generation that bridges a data center's needs until a grid connection can be achieved.

Project developers for data center energy parks have the freedom to choose whichever power delivery option makes the most sense if it complies with local permitting and air pollution rules.

Matching with clean energy resources is just one more option. Where many projects lack freedom, however, is the way they must tether to existing energy infrastructure.

### INTERSECT'S MEITNER PROJECT

In 2023, developer Intersect proposed Meitner as a Texas Panhandle energy park where wind and solar would power 400 megawatts (MW) of flexible hydrogen electrolyzers and supply surplus electricity to the grid. In 2024, Cross Texas Transmission applied for a 345-kilovolt line to connect Meitner to the Texas grid. That application was already on file a year later when New Project Media reported Intersect's pivot to an 840 MW data center at the site. Google and Intersect expect on-site gas generation to supply a minority of the center's power.[2]

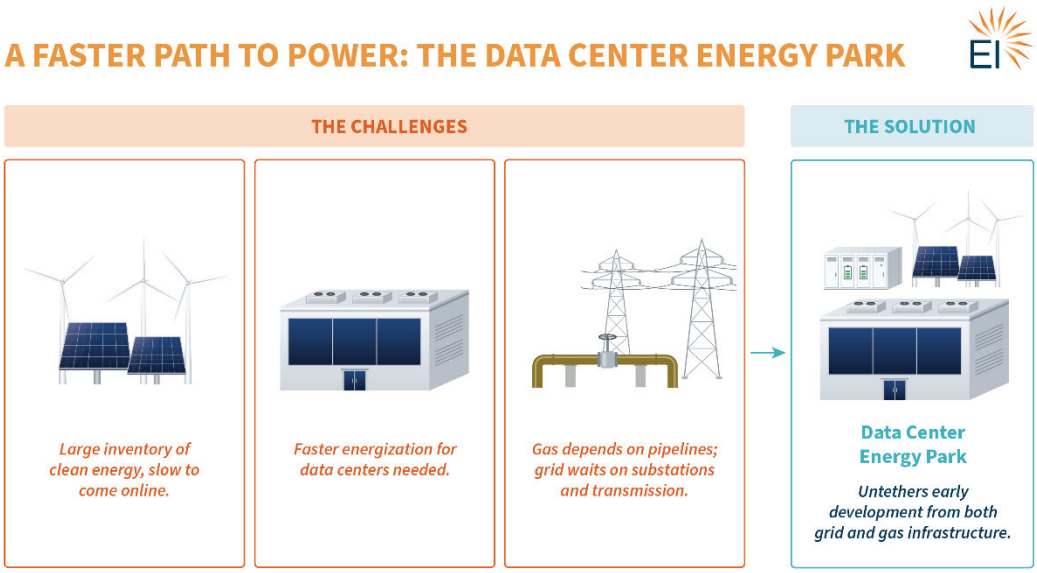
Gas plants still depend on pipelines, while grid-connected projects depend on substations and transmission upgrades, precisely the infrastructure bottlenecks that can delay energization for years.

Meanwhile the U.S. also has 773 GW of solar, 220 GW of wind, and 749 GW of battery storage in interconnection queues, struggling to reach operation due to long delays that drive historically low completion rates[4]. Historically, only 13 percent of capacity submitted from 2000 through 2020 to interconnection queues ended up connected and commissioned by December 2025.

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More than 170 GW of clean energy projects have been "safe-harbored" for federal tax credits, meaning developers have already made meaningful progress although they may not yet have viable end-customers and paths to market. Circumstantial evidence exists that some of these projects might end up co-located with data centers: Enlight Renewable Energy, which has safe-harbored 17.9 factored GW of U.S. capacity, is developing approximately 2 GW of data-center capacity and has explicitly identified using its own electricity to support data centers as an alternative to signing conventional power purchase agreements[5]. These will likely be grid-connected from the start though.

Co-locating generation, storage, and load in a data center energy park offers a potentially valuable outlet and could be a tailwind for renewables[6] but the match between renewables, batteries and data centers is incomplete – historical renewable energy projects typically cannot meet data center power availability metrics without other supply tied to existing wires and pipelines.




This paper proposes a solution: Matching renewable energy projects and data centers in energy parks[7] alongside BESS and a collection of thermal energy storage, steam turbines and boilers – a concept we call "thermal hybrid power." This type of energy park can be built without any initial connection to wires and pipelines.

An hourly resolution screening model shows this concept can remove pipeline bottlenecks by requiring up to around 1 percent fuel-use to meet data center electricity needs—a threshold that removes the need for a pipeline. This path combines wind, solar, and battery storage (four hours of storage at full output) with a thermal hybrid power layer consisting of thermal batteries (54 hours of storage at full output), steam generation, and backup boilers.


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This thermal layer is the missing piece that allows variable renewable generation to approach the availability required by large data centers: Thermal storage carries excess renewable energy across longer periods (nine times more electrical storage capacity versus the chemical battery), while inexpensive fuel-fired boilers provide a limited backup energy source using the same steam turbines to supplement supply during the most difficult renewable droughts and contingencies.

The result is an energy park that can initially operate without waiting for either a grid connection or a gas pipeline, accelerating speed-to-power while providing reliable and resilient supply—creating an attractive platform for later grid connection and additional onsite data center capacity.

Our modeling:

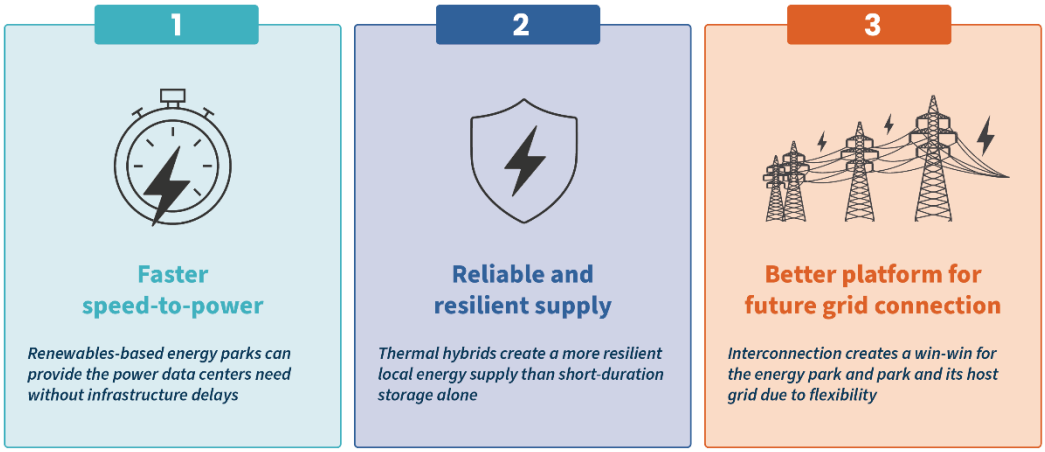
- Identifies two scenarios with candidate clean "speed-to-power" portfolios of resources in energy parks that can cost-effectively supply a data center for a first-pass annual reliability study with one percent on-site fuel use. These don't need a pipeline or grid connection and thus could provide faster speed-to-power. The first uses only renewables and BESS backed up by diesel engines, while the second features novel hybrid thermal power.
- Provides candidate portfolios with a deeper analysis including multiple scenario sensitivities that show a clear resilience advantage for the hybrid thermal power scenario, while raising doubts about the scenario with just conventional elements. This separation in reliability outcomes for hybrid thermal power is the result of a larger (4x) possible stock of stored clean energy in all modeled hours.
- Compares the performance and grid-trading behavior of energy parks in each scenario once connected to the bulk power system, varying the interconnection size. It finds considerable reliability and financial connection benefits for the data center energy park and the host grid without needing firm grid delivery service commitments. This might accelerate connection timetables and allow increased hosting of data center capacity on site at a small incremental cost.

We encourage data center site developers interested in "speed-to-power" and renewable energy developers interested in increased business opportunities to consider an energy park solution with thermal hybrid power. The underlying thermal battery technology is already commercially deployed for industrial heat and steam, including an operating installation supplying steam for electricity generation[8]. The conventional boilers and steam turbines we include in our models draw on established industrial equipment and supply chains[9]. Thermal hybrid energy parks are a promising option worthy of further detailed engineering study and commercial development.

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- **Key Finding 1: Reliable cost-effective, independent of the grid and pipeline, renewables-based data center energy parks are possible.**
- **Key Finding 2: The hybrid thermal power renewable data center energy park performs better under multiple reliability stress-tests. It represents a superior risk management approach versus just using short-duration storage for balancing local renewable energy supply.**
- **Key Finding 3: Co-optimizing renewable data center energy park dispatch with a local price series unveils hybrid thermal power's flexibility value. Interconnection creates a win-win for the park and its host grid, which need not be available on a firm basis. Further data center capacity can be hosted with little incremental investment in energy supply.**

## THREE BIG BENEFITS FOR DATA CENTER ENERGY PARK





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# THERMAL HYBRID POWER: AN ATTRACTIVE NEW RESOURCE SET TO ADD FLEXIBILITY, FIRMING, AND BACKUP TO A DATA CENTER ENERGY PARK

**The first step to matching safe-harbored clean energy with data center demand is assembling energy parks that fully meet data center needs and avoid supply chain constraints.**

A data center energy park can be conceptualized as a set of building bricks that contribute different essential elements to powering a data center. Combining these bricks can achieve the end-customer's goal of reliable power for IT infrastructure.

This paper uses a lightweight hourly dispatch screening model[i] to test thousands of possible energy park portfolio designs (bricks combination) and examine key cost trade-offs. The model takes inputs like demand and variable renewable energy profiles for a specific site, equipment costs, fuel costs, and electricity prices, then optimizes the dispatch of this system for each hour, with or without a grid connection.

After defining key building bricks for energy park portfolios in this section, we will focus on two clean energy park scenarios, with and without thermal hybrid power (outlined below), for data centers in the next section, that meet initial reliability and cost metrics for running a 400-megawatt (MW) data center off grid. The next two sections explore the advantages of the hybrid thermal brick for matching safe-harbored renewable projects with data center demand.

## Data center energy parks are assembled modularly out of different bricks

The bricks we modeled fall into four main categories: the data center itself, energy supply, flexibility plus firming and backup. We highlight (with color in Figure 1) bricks with mature supply chains and ability to scale.

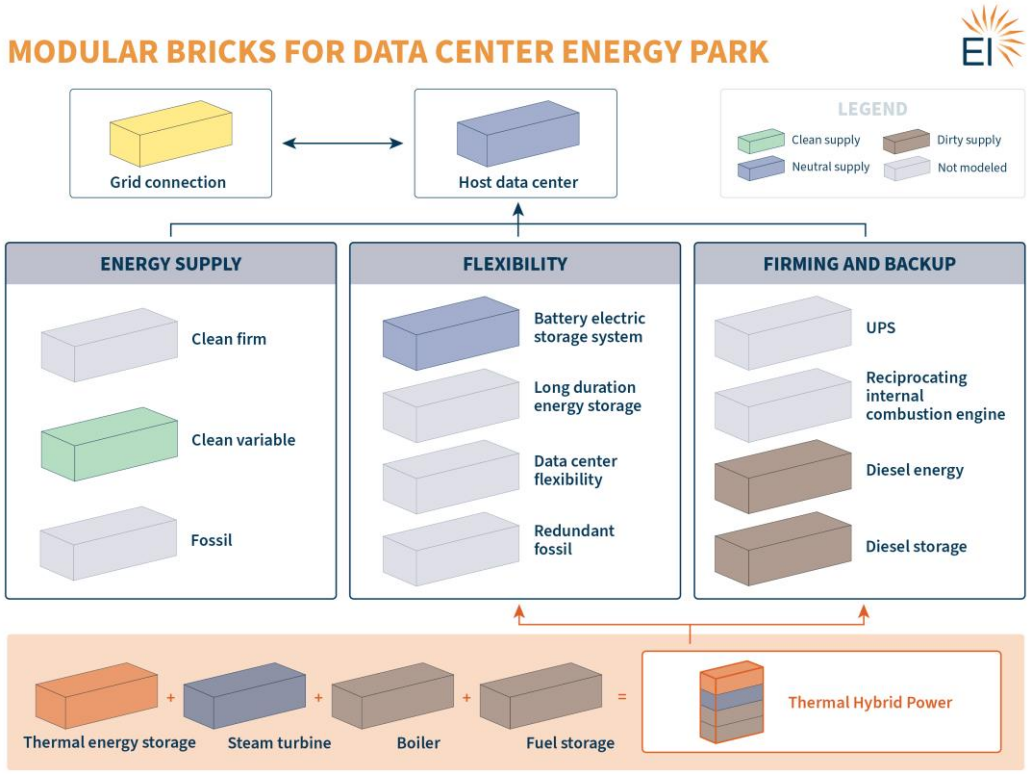
[i] Energy Innovation is collaborating with ZeroNode to make this tool available online as an open-source repository. Contact the author for more information.

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## Host data center

The host data center includes compute infrastructure, cooling infrastructure, and power conditioning equipment. Our unit of analysis is a 400 MW data center with a 24/7 baseload profile and steady low cooling load of 22 MW[ii]. Under real operating conditions, while a data center customer may demand 99.999 percent ("five nines") availability, the actual load factor is in the low 80 percents with hourly fluctuations between 60-100 percent of max demand and even wider ranges on a sub-hourly basis.

*Figure 1 Modular bricks for data center energy park. Colored bricks are used in our modeling.*




For our hourly dispatch model, modeling a flat block of 400MW of demand sufficiently illustrates the potential of this speed to power pathway. Additional details on data center operations could refine the concept, but detailed operational data is typically proprietary and was unavailable for this modeling.

[ii] A 22MW cooling load for 400 MW of IT load represents a best-in-class data center. However, since we assume a flat load profile for both IT load and cooling load, this could easily be a 390 MW IT load with 32 MW of cooling.


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## Grid Connection

Grid connection can provide all three categories of services below (energy supply, flexibility, and firming/backup) or consume them depending on the arrangement made with the data center energy park. In many places today, like Northern Virginia, a new grid connection can take up to seven years[10].

## Conventional options for energy park bricks

### Prime energy supply

Prime energy supply composes more than 95 percent of input energy for a data center energy park. Options include grid supply, clean variable generation like wind and solar, clean firm generation like geothermal or nuclear, and fossil generation with fuel-supply infrastructure. This paper mostly models clean variable generation and grid-supplied energy.

### Flexibility

Data center energy use can fluctuate on rapid time scales unseen in traditional loads, which means they increasingly need a flexibility buffer to smooth generation. Flexibility options include a variety of possible short duration battery systems (BESS), long duration energy storage (LDES), data center flexibility and redundant fossil generation (e.g., peaking resources). Flexibility is also key to matching with variable energy inputs such as variable renewables, non-firm grid supply or limitations of fossil generators. Out of these conventional sources of flexibility, this paper primarily looks at BESS.

### Firming and backup

Firming moves beyond flexibility in closing the gap between energy supply and expected data center needs, while backup refers to resources the data center can fully rely on during unforeseen contingencies. The line between the two functions is not clear but can be drawn as non-emergency (a guard-rail against the most extremes of expected downward variations in renewable generation) versus emergency (a guard-rail against unexpected reductions in available energy, like point failure for the medium voltage grid inside the energy park) similarly to how air regulators differentiate between emergency and non-emergency generator operations for permitting purposes. Typical resources used here are reciprocating internal combustion engines using diesel or other fuels, generally relying on large stores of onsite fuel. If used more than a percent of the time without emissions control technology, they can quickly run afoul of air permits. This paper focuses on diesel engines as the main source of conventional firming and backup when fuel is stored on-site.

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### New hybrid thermal power brick provides a new option for both flexibility and firming/backup to increase speed-to-power

Advances in thermal energy storage that move quickly to market can serve data center needs across the flexibility and firming and backup categories, providing a solution to increase speed-to-power and relieve the bottleneck currently faced by data center and renewable energy developers alike.

The thermal layer consists of three components: thermal energy storage, a steam turbine, and a backup boiler. These components first convert and store electricity as heat at a 95 to 99 percent efficiency (87 percent fuel-to-heat for the boiler), then convert heat on demand to power a steam turbine and produce electricity for either a roundtrip efficiency close to 40 percent for electricity or 35 percent throughput for fuel.

Steam turbines are widely used in industrial and utility power applications; they are available in many sizes from a wide variety of vendors and thus don't suffer from the same supply chain constraints as gas turbines and other gas generators. A backup boiler (and associated fuel storage) completes the stack to provide electricity when the thermal energy storage is getting too low or backup power is needed. This relatively cheap and simple equipment burns fuel to produce high-temperature, high-pressure steam from any number of fuels to power the steam turbine.

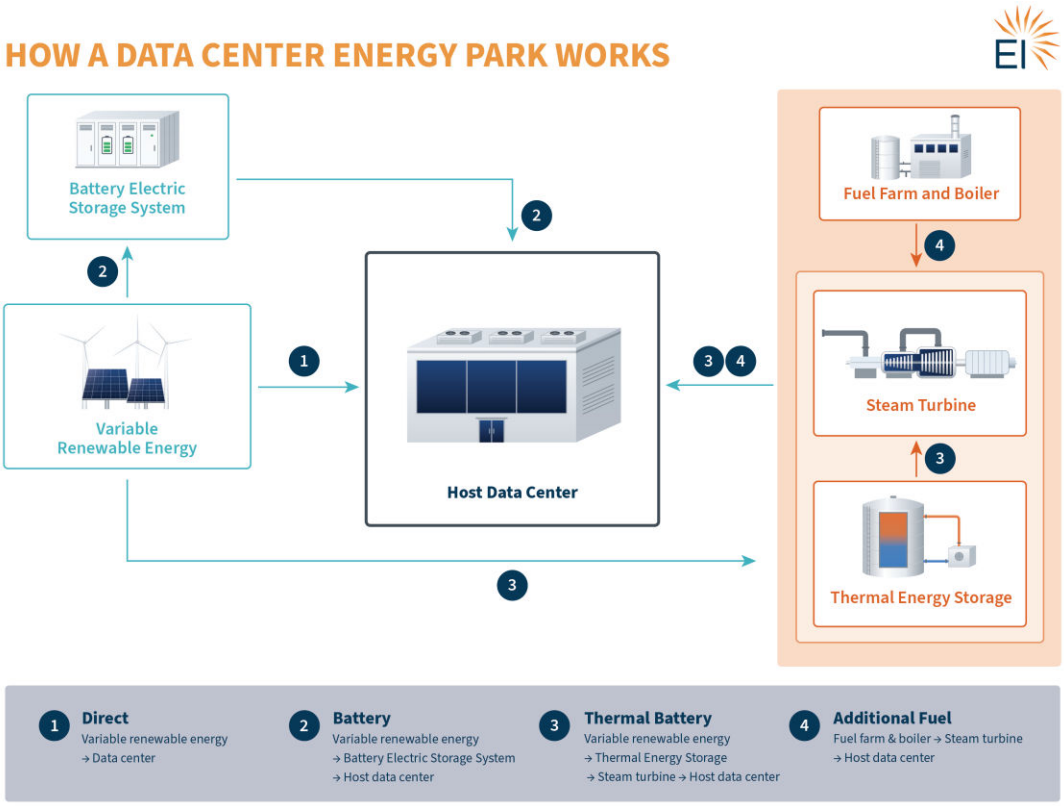
### Defining "Hybrid" in the thermal hybrid power brick

We use the term "thermal hybrid power" where in common parlance "thermal power" refers to electricity generation from combustion or steam supply (like a nuclear reactor) and "hybrids" refers to combining generation and storage systems. "Thermal hybrid power" captures both ideas, while augmenting the contributions of stored heat with additional energy from fuels (and flexibly switching between these energy sources) by combining thermal energy storage with a boiler and steam turbine.

Most of the bricks described above supply the data center in a simple manner. Fossil generators burn fuel and generate electricity for all services. Renewables directly produce electricity while BESS buffers that supply for flexibility. All bricks are on a common electrical bus.

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*Figure 2 Data center energy park layout with thermal hybrid power*




The thermal hybrid power brick introduces both an electrical and heat layer (blue and orange arrows in Figure 2). These two layers interact in several ways: electricity is transformed to heat and stored via the TES then transformed back to electricity via the steam turbine. The steam turbine, however, can source heat energy from either the TES or the boiler. Its output is a blend of energy inputs that started out either as electricity or heat. This makes the TES-plus-steam turbine combination superior to other commercially available long-duration energy storage solutions today: It has similar round-trip efficiency[11] but also accepts alternate energy supply.

The elements of a hybrid thermal power brick form a versatile addition to a data center energy park—an insurance policy—when a project seeks to run in an off-grid mode and when it connects to the grid. We focus first on what our hourly screening model reveals about off-grid operations because this new brick creates an attractive path for speed-to-power, matching readily available renewable resources with data center demand without waiting on permitting, construction and commissioning of large bulk power and natural gas supply infrastructure.

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# CLEAN POWER WITH STORAGE ALLOWS FOR MINIMAL ON-SITE FUEL USE

**Key Finding 1: Reliable cost-effective, independent of the grid and pipeline, renewables-based data center energy parks are possible.**

A necessary element for connecting safe-harbored clean energy projects and data center demand via energy parks, at least until infrastructure can catch up, is showing that these parks can run reliably independent of that infrastructure. Without transmission, pipelines, or other infrastructure to provide outside energy supply, the principal options are local clean generation like renewables and fuels that can be delivered to the site.

### Using 1 percent annual on-site fuel-use as a practical benchmark for limiting on-site energy use to avoid extra infrastructure.

For the hourly dispatch model, we limit annual fuel use to 1 percent of total energy. We picked this percentage to limit fuel truck delivery count and on-site fuel storage to practical levels: At 1 percent annual on-site fuel use, our screening model still uses almost 400,000 gallons of diesel per day (about 40 trucks) on a peak day, storing over 1.4 million gallons of diesel on site for a 48-hour backup supply.

Screening for roughly 1 percent annual fuel use, with the featured (in color) bricks in the section above, allows us to study data center renewable energy park designs that remove key infrastructure bottlenecks, helping increase speed-to-power with:

(1) more readily available equipment supply chains,[iii]
(2) freedom from the bulk power grid and gas pipeline network,
(3) limiting fuel-use that also limits local air pollution,
(4) a modular design architecture that allows you to build incrementally.

### Two examples of energy parks with approximately 1 percent fuel use that meet the initial clean data center energy park reliability screen

In looking for energy park designs that fulfill our vision facilitating speed-to-power by matching safe-harbored cleaner projects with data center demand, we used a

[iii] Some supply chain issues, like medium-voltage transformer backlogs, are unavoidable. Many safe-harbored projects, however, may have already ordered transformers in order to qualify as in-progress for tax purposes.

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simplified version of our hourly dispatch model to study thousands of possible brick combinations of wind, solar, BESS and hybrid thermal power to serve a 400 MW data center baseload (22 MW cooling) at one geographic location (Southwest New Mexico) with available solar and wind, varying:

(1) solar and wind installed capacity,
(2) BESS charging/discharge power and duration (hours of electric discharge)
(3) TES duration (hours of full thermal output) with a range of zero to 54 hours.

A standard practice for studying the operations and economics of renewables and storage power systems is considering a least cost system for specified reliability and emissions constraints[12]. We used 1 percent fuel use as a fraction of annual electric demand[iv] as a constraint for our simpler screening tool (see Appendix for modeling approach). Surprisingly,[v] we found a cost convergence for models with and without TES at that 1 percent threshold. To contrast the advantages of including a thermal hybrid power brick, we present two cost-optimized wind and solar data center energy park designs with 1 percent annual fuel use: a base case with just renewables plus a massive BESS system and a hybrid thermal power case.

### Thermal Hybrid Scenario

The Thermal Hybrid scenario starts with 1,250 MW of solar and 650 MW of wind supply. Some short-duration flexibility is provided by a 600 MW 4-hour BESS, while the heart of the thermal hybrid power block is a TES with 2.4 GW of input power, 1 GW of thermal power output and 54 hours of thermal storage. This is buttressed by a 1 $GW_{thermal}$ of backup boilers and 400 MW[vi] of steam turbine generation (1 GW thermal power input at 40 percent efficiency).

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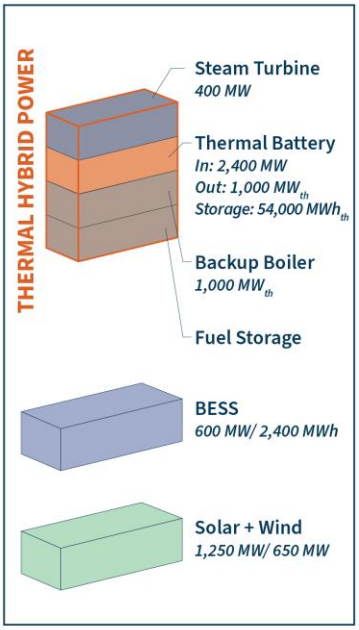
[iv] A deeper analysis with a constrained boiler and steam turbine nudged the number up above 1 percent but still represents a viable off-grid project. 1 percent was a useful optimization target for our scanning tool but not a hard target.

[v] We assumed, perhaps falsely, that the lack of renewable + BESS off-grid solutions was an indication they might not be viable. See next section on stress-testing reliability for why that might be the case.

[vi] Astute readers will notice 400 MW is not enough to completely cover a net 422 MW of IT plus cooling. We assume the modular wind+solar+BESS will always be able to cover this residual 22 MW, but an extra 50 MW of steam turbine can be added at a small relative cost to the whole project.

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*Figure 3 Thermal Hybrid scenario for data center energy park (one-year summary results)*




## THERMAL HYBRID SCENARIO FOR DATA CENTER ENERGY PARK

| AVAILABLE ENERGY (MWh) | | ENERGY ACCOUNTING (MWh) | | DATA CENTER DEMAND SUPPLY (MWh) | | |
|---|---|---|---|---|---|---|
| Total Renewables | 5,584,480 | Data Center Demand | 3,698,667 | From Renewables | 2,393,060 | 65% |
| | | Curtailed Power | 761,099 | From BESS | 593,661 | 16% |
| Fuel Output (Thermal) | 102,167 | BESS Losses | 65,657 | From TES | 671,079 | 18% |
| Total Available Energy | 5,686,647 | Thermal Losses (40% eff) | 1,161,224 | From Firming Fuel | 40,867 | 1% |

The high thermal losses in this scenario are mostly due to converting heat energy in steam form to energy in electric form via the 40 percent efficient steam turbine. The high intake power of the thermal battery means that unless energy stocks are near full, the battery can always accept full renewable output.

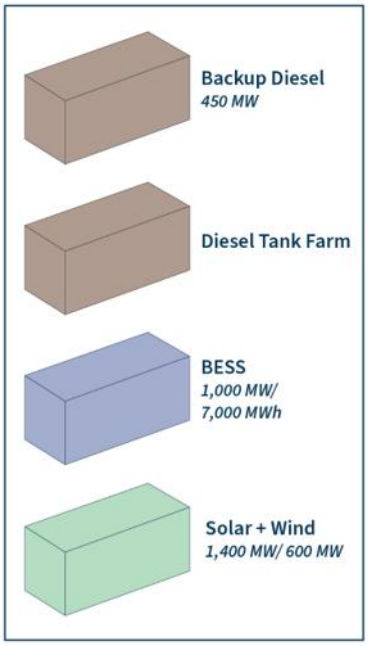
### High-Capacity BESS Scenario

The High-Capacity BESS scenario compensates for a lack of thermal energy storage by increasing renewable energy supply (1,400 MW of solar and 600 MW of wind) and BESS (1,000 MW/7,000 megawatt hour (MWh)) capacity. Firming and backup are now provided by a separate diesel generation block.

This second scenario has much lower thermal losses (they only occur from diesel combustion) but double the BESS losses (from increased cycling at higher capacity) and significantly more curtailed energy. More BESS capacity would allow the reduction of renewable supply and curtailed MWhs but at the cost of reduced utilization of that capacity – the cost/benefit ratio for incremental BESS capacity drops quickly as percentage of data center demand served by fuel drops.

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*Figure 4 High-Capacity BESS scenario for data center energy park (one-year summary results)*




## HIGH-CAPACITY BESS SCENARIO FOR DATA CENTER ENERGY PARK

| AVAILABLE ENERGY (MWh) | | ENERGY ACCOUNTING (MWh) | | DATA CENTER DEMAND SUPPLY (MWh) | | |
|---|---|---|---|---|---|---|
| Total Renewables | 5,923,357 | Data Center Demand | 3,698,667 | From Renewables | 2,463,396 | 66.6% |
| Fuel Output (Thermal) | 92,665 | Curtailed Power | 2,128,622 | From BESS | 1,198,205 | 32.4% |
| | | BESS Losses | 133,134 | From TES | 0 | 0.0% |
| Total Available Energy | 6,016,022 | Thermal Losses (40% eff) | 55,599 | From Firming Fuel | 37,066 | 1.0% |

### The thermal hybrid scenario and high-capacity BESS scenario have roughly equivalent costs, but achieve results with very different components

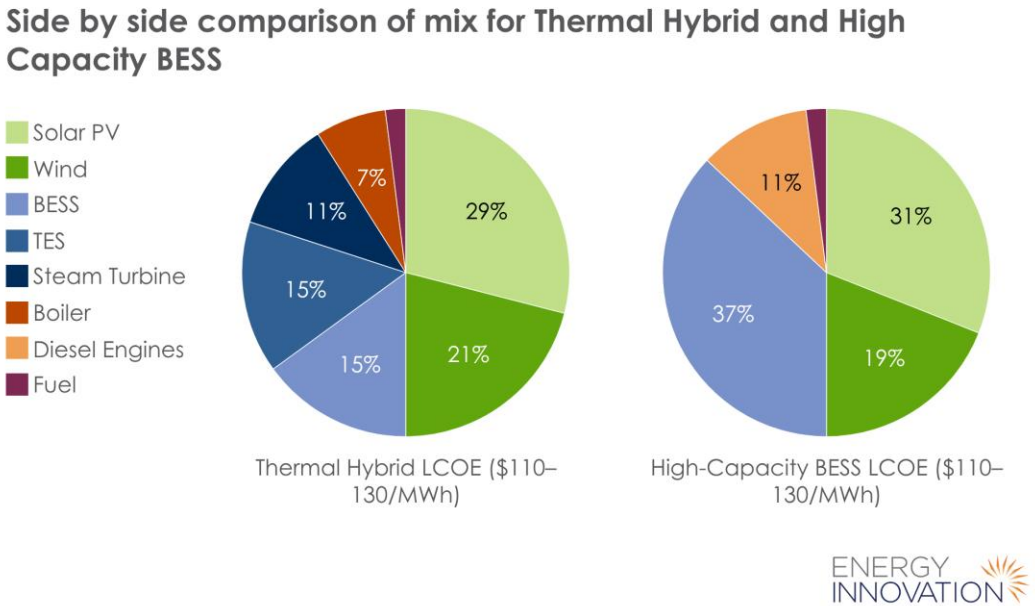
Our screening tool found a remarkable convergence in cost between scenarios with and without TES, achieved with a very different mix of resources. Using cost inputs detailed in the Appendix, we came up with a common point estimate of $120/MWh. Because large inherent uncertainties surround technology costs, resource variability, and financing terms for individual projects, we assume a minimum uncertainty of +/- $10/MWh around that point estimate.

Given the current premium for speed-to-power the exact cost figures need not be exact so long as costs are in the right ballpark. Even if we added another $20/MWh premium to take into account a shorter financing life and so-called "sleeving" deals with local utilities, these costs are well below the premium[13] (see inset box below) for a speedy project of interest to data center developers eager for power.

Aside from a slight increase in wind and solar costs, most of the trade-off between the two cases involves swapping out the thermal hybrid power brick with incremental BESS and diesel backup. 1 percent fuel converts to 2 percent cost because the marginal cost of fuel is just under twice average cost of energy.

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*Figure 5 Total cost fraction by technology element for two widely different but similarly priced 1 percent annual fuel use off-grid scenarios.*




This illustrates that by doubling capital investments, a renewable developer can convert a renewables-only project that might receive $40/MWh through a standard power purchase agreement (if a grid interconnection is made available in a timely way) into a project that sells firm electric capacity for three times those prices to a data center interested in speed-to-power.

## Costs of off-grid clean energy parks are competitive with existing parks with available gas infrastructure

Since most current bridge or behind-the-meter data center energy parks currently assume ready gas access, we provide a quick cost comparison here to both a renewable plus gas hybrid data center energy park cost and a survey of publicly known figures for behind-the-meter (BTM) gas. This comparison illustrates that our off-grid scenarios do not incur costs out of line with the speed advantage they offer. Because of limited pipeline access, projects that require gas access will be much slower to power at scale except in special geographies near gas supply such as West Texas.

Assuming easy gas access, we modeled a balanced BESS and renewables scenario (1,000 MW solar, 500 MW wind, 750MW/6,000MWh BESS) with up to 10 percent annual energy consumption from natural gas or liquified natural gas (LNG) via gas powered dual-fuel engines. This scenario includes 72 hours of LNG fuel storage capacity to cover any gas supply interruptions, re-gasification capacity, and gas lateral construction.

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Including such redundancies and using similar financial assumptions as the fully off-grid scenarios, such a gas-supported scenario is roughly $10/MWh cheaper on an LCOE basis. If gas supply is available and emissions concerns are less important, this is a viable option, but the cleaner, less infrastructure-dependent options above are not much more expensive and their financials are less dependent on the price of natural gas.

For gas-only data center energy parks, even more tightly bound to constraints on gas infrastructure, we observe a wide variety of reported costs for power in the market. Reported levelized costs estimates and estimates for prices paid[vii] for BTM gas powered data center energy parks range from $70-$165 per MWh. For example, a leading energy sector strategist from Rabobank recently quoted data center companies paying $100-165 per MWh BTM gas power[14]. An analyst at the investment firm Jefferies estimated Meta was paying $140-$165 per MWh for BTM gas power for a project near Columbus, Ohio[15]. These relatively high prices may correspond to projects closer to urban demand with more expensive gas. Projects in areas with lots of land and proximity to cheap and easily available gas would be more comparable to isolated clean energy parks. Other financial analysis points to costs as low as $70 per MWh where abundant cheap gas is available without incurring transport costs[16].

### DATA CENTER WILLINGNESS TO PAY FOR POWER

In a recent podcast, SemiAnalysis founder Dylan Patel estimated frontier AI inference can generate as much as $50 million in annual revenue per megawatt (MW) of compute capacity, against $10–15 million in compute costs, suggesting limited access to power gates economic potential. For comparison, recent high prices for capacity in the PJM market were a fraction of these profit margins at $120,000 per MW-year. The gap between how much money can be made with power available and how much power normally costs has created tremendous pressure for alternative options to power data centers. A conservative $2.5M per MW of profit margin available for power purchases converts to a $285/MWh willingness to pay at the margin.[13]

In summary, if gas infrastructure is easily available, projects with exceptionally good gas supply will be less expensive than off-grid clean energy parks meeting our initial reliability screen (no missing energy with less than 1 percent backup fuel). However, any cost gap is not large, and the ability to quickly build a clean energy park independent of any initial grid or gas connection will likely more than compensate for any premium. The key, however, is addressing lingering doubts from data center customers and energy park financiers that an off-grid or bridge clean energy park can

[vii] So far, we have mostly looked at energy park levelized cost estimates, without including taxes and profits. Prices paid by data center end-consumer will be higher than cost estimates.

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deliver clean power under a broader, less predictable set of conditions than those used in our screening tool.

## STRESS-TESTING RELIABILITY: HYBRID THERMAL POWER PERFORMS BETTER THAN HIGH-CAPACITY BESS

**Key Finding 2: The hybrid thermal power renewable data center energy park performs better under multiple reliability stress-tests. It represents a superior risk management approach versus just using short-duration storage for balancing local renewable energy supply.**

Data center customers have high expectations for reliability from their power supply. For example, the Electric Power Research Institute (EPRI) describes the current standard as "five-nines availability (99.999 percent, under 6 minutes downtime annually)[17], typically achieved by combining high grid reliability with backup generation[viii]. Hence, our hourly screening tool, applied over just one year with perfect foresight, is only a first step in demonstrating the commercial viability of an off-grid or bridge clean energy park from a reliability point of view.

An hourly model can establish capacity and energy sufficiency within its assumptions; it cannot by itself demonstrate five-nines availability, especially for sub-hourly reliability concerns. However, some of those shorter-duration concerns, like responding to short demand spikes, should be clearly addressable with nimble assets like the BESS included in our model[18]. The resistors that charge thermal batteries can also adjust input up and down[19] to accommodate variations in data center demand. Generally, shorter duration operational challenges are beyond the scope of this paper, but no obvious engineering or financial obstacles exist to resolving them. Of more concern is how our hourly-modeled energy park might respond to stresses like equipment failures, loss of energy supply, or unusual weather over longer time periods.

The subsections below provide sensitivity analysis results from our hourly screening model that stress-tested for reliability. For the last few percent of reliability, two elements are key: redundancy and stored energy supply. With modular design that includes separate and independent thermal power blocks, sufficient redundancy can

[viii] Some hyperscalers are relaxing individual facility power reliability standards in a bid for speed-to-power with datacenters built in tents with no backup generators: https://semianalysis.com/2025/07/11/meta-superintelligence-leadership-compute-talent-and-data/

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be achieved at equipment level. Hybrid thermal power has the additional advantage of having four electricity supply pathways to the data center (direct from renewables, direct from BESS, thermal from TES through turbines, thermal from boilers through turbines) versus three for the high-capacity BESS scenario (direct from renewables, direct from BESS and direct from diesel engines). Still, both cases provide room to build in redundancy, so the key differentiator becomes energy supply. Our sensitivities illustrate the important role that superior stored energy supply plays for the hybrid thermal power energy park.

## Equipment size sensitivities for boiler, turbine and engine power reveal plentiful redundancy

Both the off-grid scenarios developed with our screening model studied sensitivities that reduce available dispatchable steam and engines. These sensitivities under normal operations give us insight into two issues: equipment redundancy and balancing power (the ability to cover for low renewables by injecting instantaneous energy) versus supply (the ability to supplement renewables over longer periods of time).

The Appendix and summary table below show that our modeled portfolios have very high levels of redundancies for this equipment and the energy from fuel or stored heat incremental to renewables + BESS supply can be injected over longer periods of time.

### Equipment Sensitivities Results

| Scenario / equipment | Tested range and modeled result |
|---|---|
| **Thermal hybrid: boiler** | 0–1,000 $MW_{thermal}$. Fuel use rises modestly below ~500 $MW_{thermal}$; unserved energy appears below 150 $MW_{thermal}$. |
| **Thermal hybrid: steam turbine** | 0–400 MWe. No supply degradation down to 250 MW — a 37.5 percent capacity reduction. |
| **High-capacity BESS: diesel engines** | 0–450 MWe. Unserved energy appears below 150 MW — a two-thirds capacity reduction. |

### Conclusions Drawn from Equipment Sensitivities

In both the thermal hybrid power and high-capacity BESS cases, the underlying equipment set-up will be modular. For the former, a good estimate for minimum steam turbine size available at 40 percent efficiency is 50 MW[20], so the park could be organized

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around eight or nine hybrid thermal power blocks[ix] of boiler + TES + steam turbine with 50 MW max output, with the ability to lose three full blocks (and even more boiler capacity) and maintain firming service.

For the high-capacity BESS case, 450 MW splits into individual engines in the 2-4 MW size, providing redundancy to fully back up a 422 MW load. Our results show generation equipment sized to carry all the load in an emergency will be highly redundant under normal or expected conditions. When planning for extraordinary circumstances, park developers will need to think about how they want to count tail-event scenario contributions for the RE+BESS section of the park when sizing secondary equipment.

Adjusting equipment sizing also shows on-site fuel use can be spread over time more than the naïve initial model runs might indicate. This implies less on-site storage for fuel is needed relative to financial model assumptions (a small savings) to provide backup, with looser fuel re-supply schedules possible. When thinking about down-sizing on-site fuel storage, thermal hybrid power scenario offers an advantage due to its superior existing stock of onsite energy covered by thermal storage.

In the end, these equipment sensitivities reveal that much of the challenge of reaching high reliability revolves around stored energy supply constraints rather than backup or firming capacity.

### Energy supply sensitivities reveal the importance of firming capacity in winter months and the energy stock advantage of thermal hybrid power.

With large amounts of available short-duration storage (BESS) and longer-duration storage (in the hybrid thermal scenario) our off-grid energy park model becomes more sensitive to seasonal patterns in renewable energy supply when it comes to providing 24/7 availability for a co-located data center.

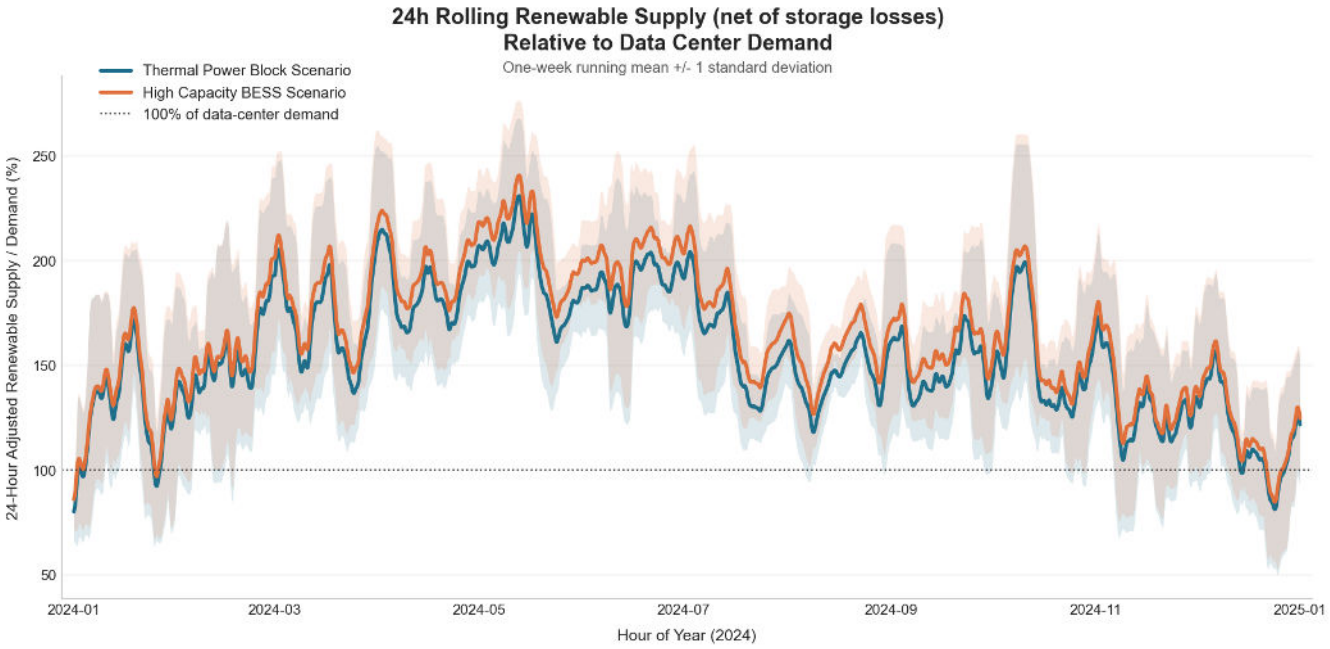
[ix] Splitting the steam capacity over multiple power blocks also resolves or minimizes many potential equipment constraints such as minimum run rates and limits on cold/warm/hot stops, as these stresses can be spread around the power blocks, e.g. staggered use of boilers and turbines.

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## Available Energy Supply

In Figure 6, we computed the available wind and solar energy supply (net of storage losses) over a rolling 24-hour period for every hour, then charted average and standard deviation over a week. Most of the year this supply is well above what is needed to run the center (dashed line) and surplus energy that can't be stored must be curtailed for lack of a grid connection. Energy deficits only occur in winter months; these are when on-site fuel plays its most important firming role[x].

*Figure 6 Rolling 24h available renewable energy supply relative to data center demand.*




In general, because the high-capacity BESS scenario starts with more renewable energy supply and suffers fewer round-trip storage losses, its net energy available is typically higher than the thermal hybrid case, except in the tighter winter months. The hybrid thermal power scenario compensates for this by maintaining a higher stock of stored energy throughout most of the year.

[x] We have taken as our remit absolute 24/7 availability, but it would be interesting to see how data centers willing to take a winter break (say a reduction to 50%) of two weeks could achieve even faster speed-to-power and need less onsite fossil fuel infrastructure.

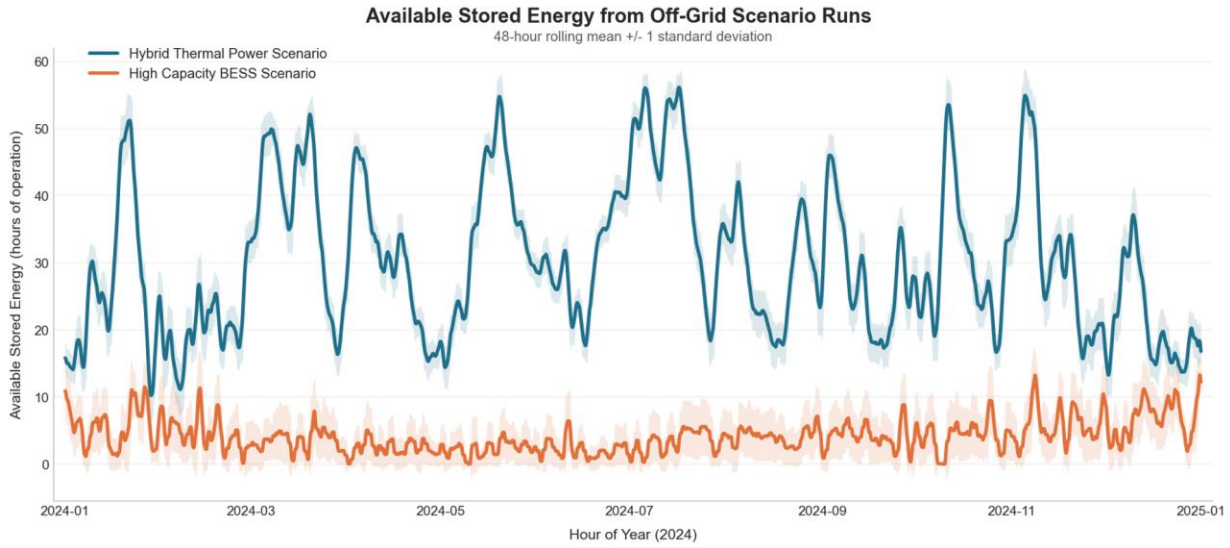

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### Available Hour-by-Hour Stored Energy

Figure 7 charts the hour-by-hour available energy stores in both scenarios. Throughout most of the year, outside a couple tight winter weeks, the thermal battery holds an order-of-magnitude more energy, with less variability (shaded region) than is possible with just the enhanced BESS in the high-capacity BESS scenario (BESS cycles almost daily so has a much more variable state of charge). We imagine an energy park operator concerned with maintaining reliable power would favor the hybrid thermal power scenario with its much larger stores of energy in reserve, a valuable insurance policy.

Our deterministic screening tool inserts a small bias in the objective function towards

*Figure 7 Available stored energy (measured in hours of full electrical supply to the data center). Data is available for each hour, but we display a rolling mean and standard deviation for clarity. State of charge for storage is matched at the beginning and end of year with an optimized floating value.*




maintaining at least a 20 percent state of charge. Ironically, in our deterministic model metrics this thermal insurance policy (relative to the naïve screening model with identical resources but no constraints on the hybrid thermal power block) is reflected as an increased cost (more on-site fuel use) for the same outcome (100 percent hourly coverage in modeled year). Moving from no favored margin to a 20 percent target increased total fuel consumption by 10 percent (from 1 percent to 1.1 percent of annual energy), a further move to a 30 percent reserve margin added another 7.5 percent to on-site fuel use.

Beyond the commonsense notion that a thermal insurance policy should improve reliability under uncertainty, getting a clear accounting of the reliability value of the thermal energy source requires more analysis.

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### The Hybrid Thermal Power Energy Park is better adapted to sudden changes in wind and solar supply

To better understand how each of our two off-grid scenarios might react to unexpected conditions, we modeled a situation where randomly generated 36-hour outages in renewable supply occur with 24 hours' warning[xi]. We sampled 100 different possible incidents with varying starting times during the day and allowed the model 30 days to adjust in the wake of a disruption. Our measure of operator adaptability was the proportion of the lost supply that had to be made up using incremental on-site fuel after a disturbance and recovery. We never saw unserved energy.

*Figure 8 Impact of a 36-hour interruption in renewable supply (with 24h warning)*

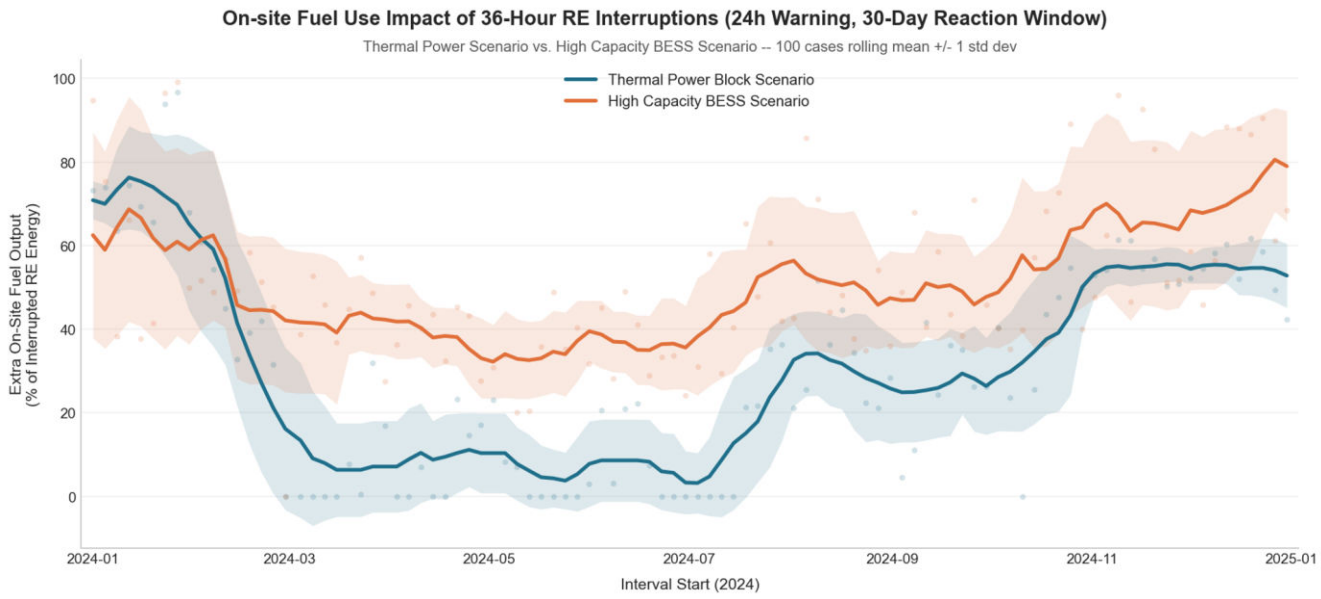



Figure 8 clarifies that outside tight winter months, the hybrid thermal power scenario is more resilient (lower extra on-site fuel to compensate for a sudden loss of supply) than the high-capacity BESS scenario. In winter months, supply and stored energy stocks are especially lower due to seasonal effects on solar power.

[xi] Outages likely will happen with less warning, but on the other hand given the modular nature of renewable supply a total cut-out over 36 hours seems uncertain. The 24-hour-warning 36-hour outage was an easily implementable compromise first step.

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Multi-weather-year modeling reveals that annual on-site fuel needs can vary by a factor of two or three, potentially requiring more truck rolls, stress on backup equipment and broader air permits.

All the presented model data came from using our screening model on one year (2024) of data at a specific location in New Mexico that provided three years (2022-2024) of a developer's estimated wind and solar production on actual studied projects. To examine variation across years, we gathered production simulated data for 45 years (1980-2024) at the same longitude and latitude as the modeled wind and solar projects from the Renewables Ninja database[21], calibrated it to our three annual time series, and reran the screening tool against all 45 proxy data sets.

We found our modeled resources stayed reliable across all 45 years in both off-grid scenarios. However, the required annual on-site fuel use varies between 0 percent (2013) and 2.7 percent (1993) for the hybrid thermal power portfolio of resources, with a similar range for the high-capacity BESS portfolio. As expected, production in winter months drives these numbers, when storage is of limited use if renewables under-produce.

It is encouraging that we can adequately firm our energy parks during challenging renewable production years with more diesel burn in a boiler without missing electricity. The implications of this stretch burn are different for the two clean park scenarios we have modeled though.

Because of the thermal hybrid's much greater capacity to store energy, a stretch burn during the winter months can be better mitigated by substituting for renewable energy ahead of production droughts and stretching out fossil contribution over longer blocks with flat profiles. Meanwhile, the high-capacity BESS needs re-filling much more often and may not fully cover night-time gaps in energy supply, meaning the backup diesel engine will be ramping up and down much more than the backup boilers in the hybrid thermal case.

The upshot is that in challenging years, the hybrid thermal power energy park can spread out extra truck deliveries over time, avoid stressing backup equipment, and manage emissions better by operating closer to optimum conditions and not concentrating operations in short windows that might push up against near term emissions limits[xii].

[xii] Air pollution is a complex and location dependent topic beyond the expertise of the author, so we will avoid any concrete comparison in emissions between the backup boilers and diesel engines. However, we believe emissions will play an important role in the proper planning of clean energy parks.

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# MODELING GRID CONNECTION FURTHER ILLUSTRATES THE ADVANTAGES OF THERMAL HYBRIDS.

**Key Finding 3: Co-optimizing renewable data center energy park dispatch with a local price series unveils hybrid thermal power's flexibility value. Interconnection creates a win-win for the park and its host grid, which need not be available on a firm basis. Further data center capacity can be hosted with little incremental investment in energy supply.**

We have detailed how well data center energy parks supplied with on-site renewables, batteries and thermal hybrid resource could run on their own. Yet despite this secure foundation, good reasons exist for all types of supply to seek a grid connection. These include improved reliability, resilience, electricity supply economics, and long-term financial risk. Hence, it is interesting to model these same energy parks with grid-trading allowed using locational marginal prices at a nearby node.

Re-running our hourly screening model while co-optimizing the renewable data center energy park dispatch with a local wholesale electricity price series provides two insights. First, the trading behavior probes the flexibility potential of energy parks as it co-optimizes: bi-directional trading revenues (i.e., adjusted for surplus exports) act as a grade of sorts for flexibility at multiple time scales. Second, bi-directional trading measures how "grid-friendly" a given energy park is and how adaptive it might be to non-firm service. The win-wins between park and grid expressed as grid-trading activity represent social capital on the grid. This virtual battery can potentially be used to accelerate a grid connection or allow the energy park to host incremental IT capacity.

## Background: Renewable data center energy parks and host grids face different and often complementary challenges

Any discussion of grid trading must start with granular grid prices. We are not yet modeling the reaction that wholesale markets might have to actively trading large data center energy parks, we will use only static prices. Still, these are dynamic enough to help "score" our energy parks and think about grid benefits.

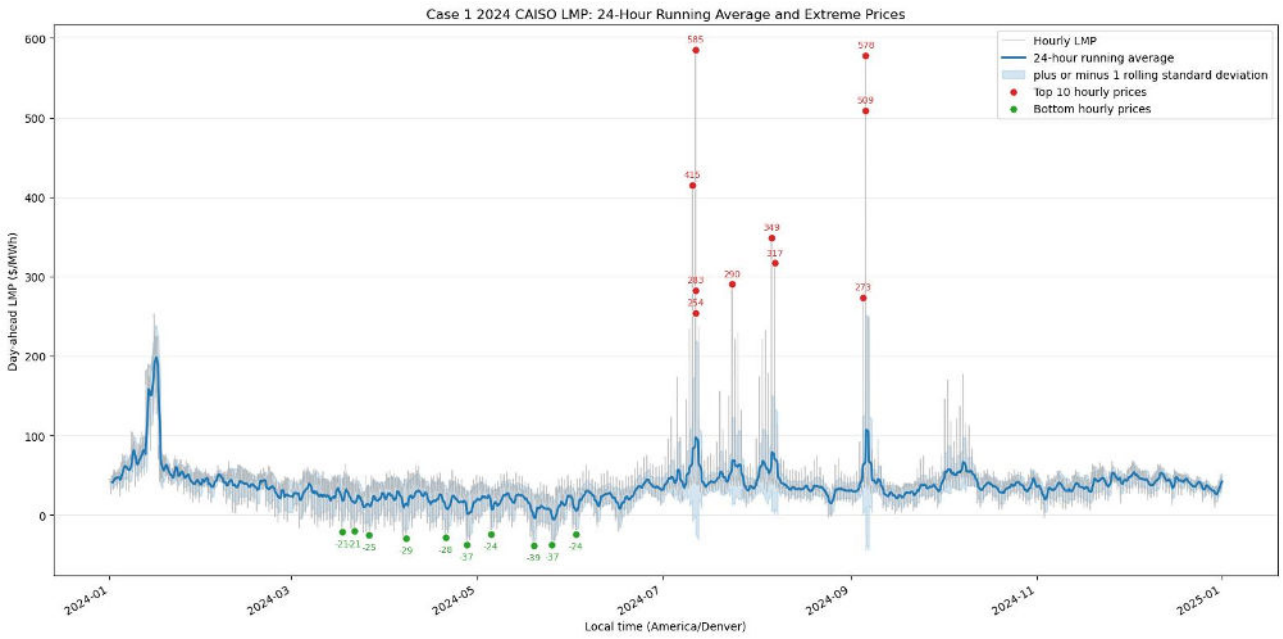
The figure below presents hourly, day-ahead locational marginal price (LMP) time series at a CAISO Energy Imbalance Market node not far from our modeled project in New Mexico. An important element to note is that the price extremes in Figure 9 below match up to periods of maximum flexibility for the hybrid thermal power scenario as shown in Fig 8 above: Low prices in the spring mean cheap energy can be stored using

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capacious on-site energy storage; higher prices in the summer can be managed with the large available storage power capacity. From the start we expected significant win-wins from connecting our off-grid projects to the grid, especially with the hybrid thermal power block in place.

This section measures these win-wins through export and import activity at the point of interconnection. Of course, these benefits are only available as grid connection becomes available.

*Figure 9: 2024 CAISO day-ahead LMP time series (24-hour average with one standard deviation) and price extremes at a New Mexico node near our studied project.*




## Current trends: Non-firm capacity is key to faster connection for energy parks

Non-firm grid capacity isn't necessarily a familiar term, but this term, or some version of it, is increasingly entering regulatory and market design conversations. A simple exemplar is the ERCOT concept of "connect and manage" whereby new generation can connect to the ERCOT grid (one of the three main independent grids in the U.S.) so long as it is deemed electrically safe to do so, but market access is not guaranteed. Under certain grid conditions and upon instruction this new generation may be forced to turn down or curtail its output. In response to a concentrated surge in data center demand in various parts of the U.S., grid operators have introduced similar concepts for adding new large loads. For example, in the Pacific Northwest, adding a 31 MW two-hour battery accelerated deployment of a 100 MW data center load[22] by at least four years, according to a Calibrant case study[23].


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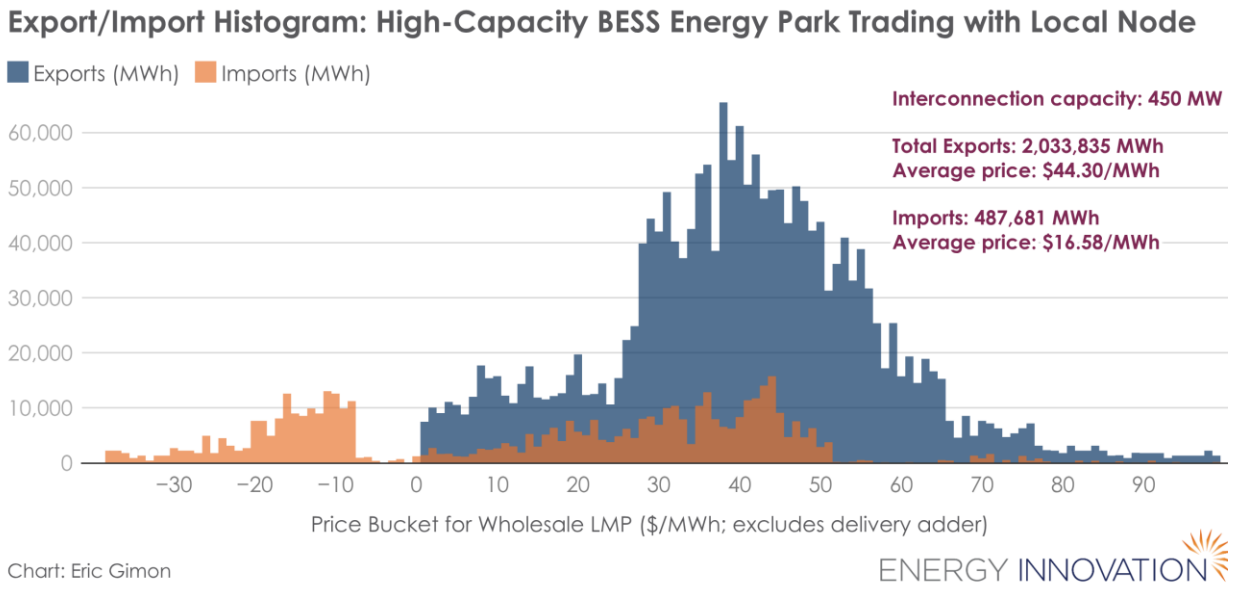
Data centers are faced with a mix of three choices for provisioning electricity: provide your own on-site or nearby power and capacity, connect and get-what-you-get, or connect and get firm power like any smaller load. The last option is usually preferred but the grid is increasingly over-subscribed and firm service can take years. Hence, for the purposes of this paper, we only consider the middle option. The two key questions for developers that are marketing to data center customers starving for power are then: how quickly can I connect new non-firm capacity to my energy park, and by leveraging new non-firm capacity at my site, how much more compute capacity can I host without making large new material investments?

On both these questions, energy parks with thermal hybrids have a significant advantage.

## Creating a baseline: grid-trading with a high-capacity BESS scenario

To understand the grid-connection advantages of a clean data center energy park with hybrid thermal power, it helps to look at baseline behavior for a high-capacity BESS project. In that case, shown by Figure 10, almost 40 percent of over 5 million MWhs of renewable generation was curtailed. For such a project, huge advantages exist to being able to export that excess energy for potential profits. On-site fuel use is also completely

*Figure 10: Overlapping histograms for imports and exports in a high-capacity BESS scenario with POI capacity constrained at 450 MW. Overlap between exports and imports is in darker red. Exports show a double hump distribution because some seasons don't allow surplus sales at attractive prices.*




eliminated as the grid provides extra energy at lower prices. On-site BESS storage, after


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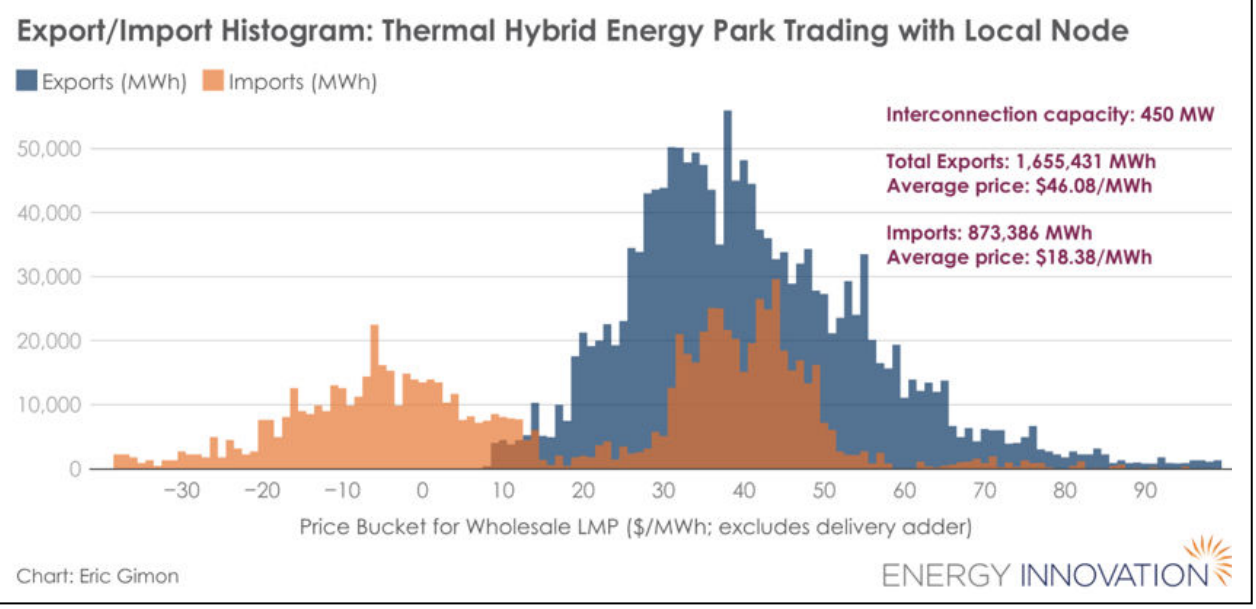
guaranteeing data center supply, can manage those exports for maximum value, with limited remaining flexibility for the energy park to act as a virtual battery.

The histogram in Figure 10 below tells the story: Most grid trading focuses around selling what was surplus/curtailed power in the off-grid model and buying power below negative $8/MWh (the cost added) while simultaneously curtailing internal renewable production. While surplus sold with some flexibility is valuable to the grid, we don't see much sign of "virtual battery" activity beyond about 300 GWh of mid-priced imports a year, amounting to about one to two hours of bi-directional trading a day. Table 2 below shows that allowing the point-of-interconnection (POI) to reach 1,125 MW allows for some more virtual battery value but it also helps improve export prices and absorb more negative price power for disposal[xiii].

## Energy parks with hybrid thermal power are more versatile grid traders

The hybrid thermal case shows full "virtual battery" type benefits of interconnection. In our off-grid analysis above, the hybrid thermal power scenario needed an input of 41 GWh (electric) from onsite fuel with 761 GWh of curtailed power. After interconnection,

*Figure 11: Overlapping histograms for imports and exports in a hybrid thermal scenario with POI capacity constrained at 450 MW, overlap is darker red. Imports show a double hump distribution because the large amount of onsite energy storage in the thermal battery allows it to buy very cheap power for later.*




[xiii] "Disposal" here includes imports accompanied by onsite renewable curtailment. The electricity is not physically destroyed; imported electricity substitutes for renewable generation that is turned down.


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the former can be obtained from the grid in an opportunistic way, and the latter can be exported, assuming sufficient capacity. Coupling our off-grid model to a local price series highlights a significant incremental volume of mutually beneficial trade with the grid in "virtual battery" behavior. We see imports at 873 GWh (833 GWh higher than the naïve need for grid support), and tallying exports we see 1,655 GWh or almost 900 GWh higher than needed to sell all previously curtailed power.

The thermal hybrid essentially acts as a virtual battery providing around 800 GWh of grid support a year, approximately four or five hours of trade each way per day at the full 450 MW. This is in line with what a merchant BESS facility might do[xiv], but with more flexible timing on imports and exports. Note that by scaling this level of trade to match with the Calibrant case study above (31MW/62MWh to accelerate 100 MW of interconnection), the available "virtual battery" capacity more than justifies faster connection time. The double hump distribution is now just with imports, showcasing the ability of the hybrid thermal energy park to absorb significant amounts of the cheapest available power for later use or resale, not just for disposal.

*Table 2 Exports and Imports for hybrid thermal power energy park with 450 MW POI*

| Type | Price Range | Volume (MWh) | Fraction |
|---|---|---|---|
| Exports | < $10/MWh | 8,958 | 0.5% |
| Exports | $10–$54/MWh | 1,298,475 | 78.4% |
| Exports | > $54/MWh | 347,998 | 21.0% |
| Imports | < $10/MWh | 381,579 | 43.7% |
| Imports | $10–$54/MWh | 466,186 | 53.4% |
| Imports | > $54/MWh | 25,621 | 2.9% |

Letting the optimizer triple POI capacity to 1,436 MW, balancing increased revenues with increased grid connection costs, doubles the "virtual battery" trading flows. The battery now has daily flows around two to three hours of max capacity, still well justifying a faster connection time.

[xiv] It would be interesting to conduct a more detailed analysis that disentangles long-duration from short-duration behavior as well as surplus exports in the trading picture, perhaps comparing this trading behavior with a mixture of actual BESS and LDES located at the same node with no internal load to serve.

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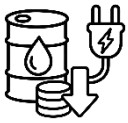
We leave this quantitative section with a net revenue matrix — high-capacity BESS and thermal hybrid scenarios with fixed and optimized POI capacity — with an adjusted matrix that crudely attempts to adjust for surplus sales. The high-capacity BESS scenario clearly shows a strong advantage to connect in order to sell surplus, but the thermal hybrid case shines once revenues are adjusted for these exports.

*Table 3 Annual value to developer of grid connection and estimated annual "virtual battery' mutual value with the grid.*

| Grid Connection Value | Fixed 450 MW POI | Maximized POI |
|---|---|---|
| Thermal Hybrid | $58,659,247 | $72,841,620 |
| High-Capacity BESS | $82,583,926 | $96,521,643 |
| **Battery Value Only** | Wholesale market "virtual "battery" value | |
| Thermal Hybrid | $25,800,406 | $50,501,436 |
| High-Capacity BESS | $5,842,642 | $12,222,381 |

## Grid connection advantages: a qualitative comparison

Having covered some quantitative analysis for our clean data center energy park models co-optimized with the grid, we then expanded our scope of consideration to the costs and benefits of connecting other energy park types (a third case balanced BESS and all-gas fourth case) models to the grid and other advantages to connection not covered by our analysis. We assembled a qualitative connection advantages matrix with our expert sense of this broader discussion.

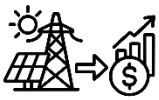


**Fuel Savings:** These opportunities arise when the marginal cost of running lower efficiency gas, diesel generators, or boiler/turbine combos is higher than grid power prices. The savings are significant for an all-gas data center energy park, while for renewable energy-first projects savings are more modest: removing the need for fuel burns except for backup.



**(Imports) Reliability and Resilience:** Having access to another source of electricity immediately creates valuable redundancies for purposes of evaluating reliability and resilience, since the bulk grid can draw power from many redundant generators and is not usually limited by fuel supplies.

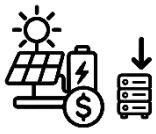
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**(Exports) Surplus Sales:** With all-gas supply, extra generation capacity is kept in reserve to deal with breakdowns, maintenance, and other outages. With grid supply as a backup, extra generation could be sold as capacity or used to feed extra power to the grid during short periods of high wholesale prices.



**(Import/Export) Grid Trading:** This is the "virtual battery" behavior: buying extra power when wholesale prices are low and selling that power back to the grid when wholesale prices are high. This direct arbitrage is not available for gas supplied projects unless they have some onsite BESS (or data center flexibility) they can leverage.



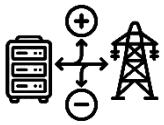
**Residual Energy Asset Value:** Since data center energy parks are in a boom and maybe bust cycle, investors can reasonably ask what residual value installed energy assets might retain if co-located data center demand doesn't materialize, goes away early in the energy asset's life, or significantly reduces. Energy assets can be repurposed for other on-site large industrial uses; the thermal hybrid can also be re-purposed to provide industrial heat. For all-gas, generation will be uncompetitive in electricity markets because they are less efficient. For renewable energy first projects, grid connection – even a non-firm one – offers significant insurance on capital investments in most markets.



**Incremental Compute from Non-Firm Capacity:** Data center energy parks can take advantage of their flexibility by adding extra data center halls incrementally if they get access to the bulk power system, even with a non-firm connection. All-gas projects create more of an obstacle to incremental compute capacity without extra firm grid capacity.

The bridging strategy used at the Stargate project in Abilene, Texas provides an interesting example. The project quickly brought roughly 300 MW of data center load online despite having only about 200 MW of initial grid capacity, using a 360 MW onsite gas plant comprising 10 simple-cycle turbines to bridge the gap while a new 1 GW grid interconnection was built to support expansion of the campus toward 1.2 GW[24]. The plan is for the gas plant to then act as backup power, but this means at most 360 MW of firm power out of 1.2 GW if the ERCOT connection is non-firm[25]. However, Stargate is also planning to bring a 1 GW/4 GWh BESS online at the site, presumably both for firming purposes and to help ensure that net load at the point of interconnection meets emerging large-load grid-performance requirements[26].

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**Grid Impacts:** Data center energy parks impact the grid in essentially two ways. The first is as a large load that consumes electricity and capacity the grid needs to provide. The second is as an active trader that can help the grid manage supply and demand balancing both locally on the grid and at a system-wide level. Mainly gas-driven energy parks can mitigate their capacity impacts (i.e., use non-firm capacity instead of firm capacity) by running their gas capacity when needed along with whatever BESS capacity they have onsite. However, they still require annual energy supply from the grid; their demand will compete with other users until more affordable generation is added to the grid. Furthermore, when they do use onsite gas capacity during a period of grid constraint, they will typically rely on the same gas pipelines as local power utilities, competing for gas and raising energy prices (gas and electric) through the back door. For these reasons, we judge all-gas scenarios as neutral to negative for the grid upon connection. Balanced BESS energy parks also compete for gas supply but will have more onsite BESS capacity to offer to the grid as compensation. We have not modeled these effects. We readily admit that "grid impacts" is a somewhat vague term, but the shifts in transaction patterns in the histograms above are striking and definite.

Ultimately, the question of how a given data center energy park can secure faster grid access as a function of the grid benefits it provides is as much a function of policies and market design as it is one of economics, engineering and grid operations. Promising signs exist in venues all across the U.S. that more nimble large loads (or load, storage and generation hybrids like energy parks) will benefit from faster access[27], so thermal hybrid advantages are an important aspect for developers to consider when planning a new data center energy park.

We are hopeful that as the positive grid impacts of data center energy parks with hybrid thermal power become apparent, they will gain in priority for connecting to the grid faster (non-firm) and thus accrue all the advantages described in this section, as well as the big prize: speed-to-power on yet more compute demand.

# HOW TO APPLY THE THERMAL HYBRID CONCEPT TO PROJECTS

If the arguments for studying a data center energy park anchored around renewables, BESS, and thermal hybrid capacity are compelling, developers can take a few obvious next steps to bring the thermal hybrid power concept into real projects:

A. **Identify good candidate safe-harbored renewable energy projects for data center energy parks**: Developers should look for projects large enough to support

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meaningful data center capacity, but far enough away from available gas supplies that an off-grid approach makes sense. Many projects will have had some kind of line of sight on interconnection to proceed far enough for safe-harboring, but may have stalled out. Some may already have their hands on key equipment like medium voltage transformers currently in short supply as part of their construction progress.

B. **Overcome policy barriers**: A previous energy parks paper[28] identified multiple policy barriers for energy parks. Luckily most of these are not as relevant in an off-grid configuration, but they should be considered with eventual grid-connection as a goal.
C. **Confirm the viability of Thermal Energy Storage**: Specifically understand the TES deployment path and supply chain constraints for power applications like a data center energy park. Large commercial TES deployments today include molten-salt at coal plants and combined heat and power (CHP) systems in China; Rondo's CHP deployments in California, Europe, and Thailand; Antora's Big Stone project (heat-only so far but 5 GWh); and Electrified Thermal Solutions' Texas deployment (also heat-only, 20 MWh). It is possible that in early project stages, backup boilers could stand in for thermal batteries and run steam turbines for firming until thermal batteries are installed.
D. **Check other supply chains:** Wind and solar generation equipment, BESS, boilers, and steam turbines should be readily available.
E. **Find integrators:** All data center energy parks will need a specialized party to integrate on-site assets into a working portfolio and guarantee power performance (even the 90–189 GW of offsite gas mooted earlier).
F. **Better understand and mitigate steam turbine constraints:** From scanning the literature, we believe steam turbines can ramp up and down adequately fast on an hourly timescale matching our model outputs. Usual flexibility constraints with steam in super-critical coal plants usually tie back more to the boiler (in our case the boiler doesn't need to flex) than the turbines, but some constraints may remain and are worth investigating. Turbines cannot start/stop on a dime and might have minimum power setpoints that need to be respected. Using modular design (with 50 MW turbines) should obviate many of these concerns.
G. **Better understand sub-hourly and Volt/VAR behavior:** This could be as much good news as bad news for thermal hybrids, as input resistors for thermal storage provide very fast response on the input side, and heat exchangers are quite flexible on the scale of minutes. When steam turbines are operating, they also offer valuable spinning mass, short circuit current and reactive power. Some could be "clutched" to operate as synchronous condensers when steam power isn't required.

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# APPENDIX

## Screening models

This report used two versions of a screening model: a primitive model, optimized for speed, meant only to study off-grid energy parks and a more versatile screening model, built on the first with more adjustable parameters for the thermal block and the ability to interact with an hourly price series to optimize exports and imports. Both models use a linear solver to minimize an objective function (dominated by a high cost for unserved energy) and provide an hourly dispatch for storage. The more sophisticated model also provides an hourly profile for dispatchable generation and grid trades.

### We used a primitive model for fast scans of possible equipment options and multi-decadal simulations.

The primitive model uses the linear solver to dispatch curtailment, a BESS system, and part of a hybrid thermal block (thermal battery and steam turbine) in an hourly time series (usually a year's worth) in order to match renewable supply with fixed data center demand. It takes as inputs:

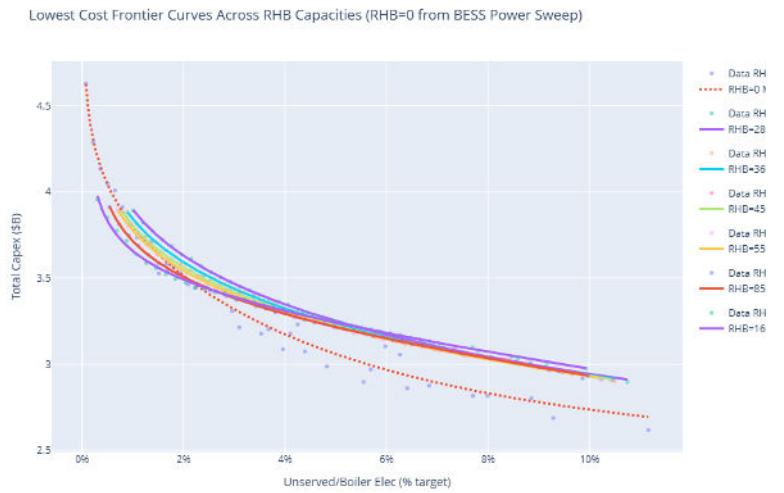
- IT + cooling demand, solar and wind installed capacity multiplying an hourly time series for wind and solar production,
- BESS power, hours of storage and roundtrip efficiency,
- Thermal storage input power (electric), energy storage (thermal) and output power (thermal); it also includes conversion efficiency for electric into thermal as well as thermal standing losses and conversion losses for thermal energy back into electricity (i.e., steam turbine/generator efficiency). Output is limited by thermal output power and steam turbine capacity. For historical reasons, our thermal storage was organized in units (i.e., total thermal storage = # of units x MWh of thermal energy storage per unit),
- Solver costs for unserved IT and unserved cooling energy in any given hour, and a small solver bonus to prioritize surplus over energy losses (to better align with the second model).

The model treats IT load and cooling load as fixed static demand over all hours (with cooling load a multiple of IT load). In practice this split never matters but we left the distinction in case we might later want to model a separate cooling profile (potentially weather dependent). We did not have access to a site-by-site proxy for variable demand, so chose to model fixed 24/7 demand. In practice, an energy park configured for 422 MW of 24/7 energy can probably serve a 500 MW nameplate data center load running at 80 percent load factor

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The advantage of having a simple screening model to start is that each annual run took only a few seconds, so we could model thousands of potential parameter-sets to assemble proxy frontier cost curves identifying, given some capital cost inputs, the cheapest way to serve the data-center load within a certain tolerance band (i.e., naïve unserved energy).

*Figure A.1: Frontier cost curves for serving a clean energy park in one location with various levels of thermal storage. With our cost assumptions, longer-duration thermal batteries start conferring a cost advantage below 3% naive unserved energy.*




We show an example set of frontier curves in Figure A.1 (inset). Note total capital costs are not full net-present-value, just a useful proxy (initial capital cost of solar, wind, storage, and steam turbine) for scanning purposes. An interesting feature of our scans was that models with TES gain a cost advantage over BESS-only models for reliability targets below 3 percent but then converged again around 1 percent. This is likely due to the dominance of reduced renewable output in some winter weeks at the highest reliability thresholds.

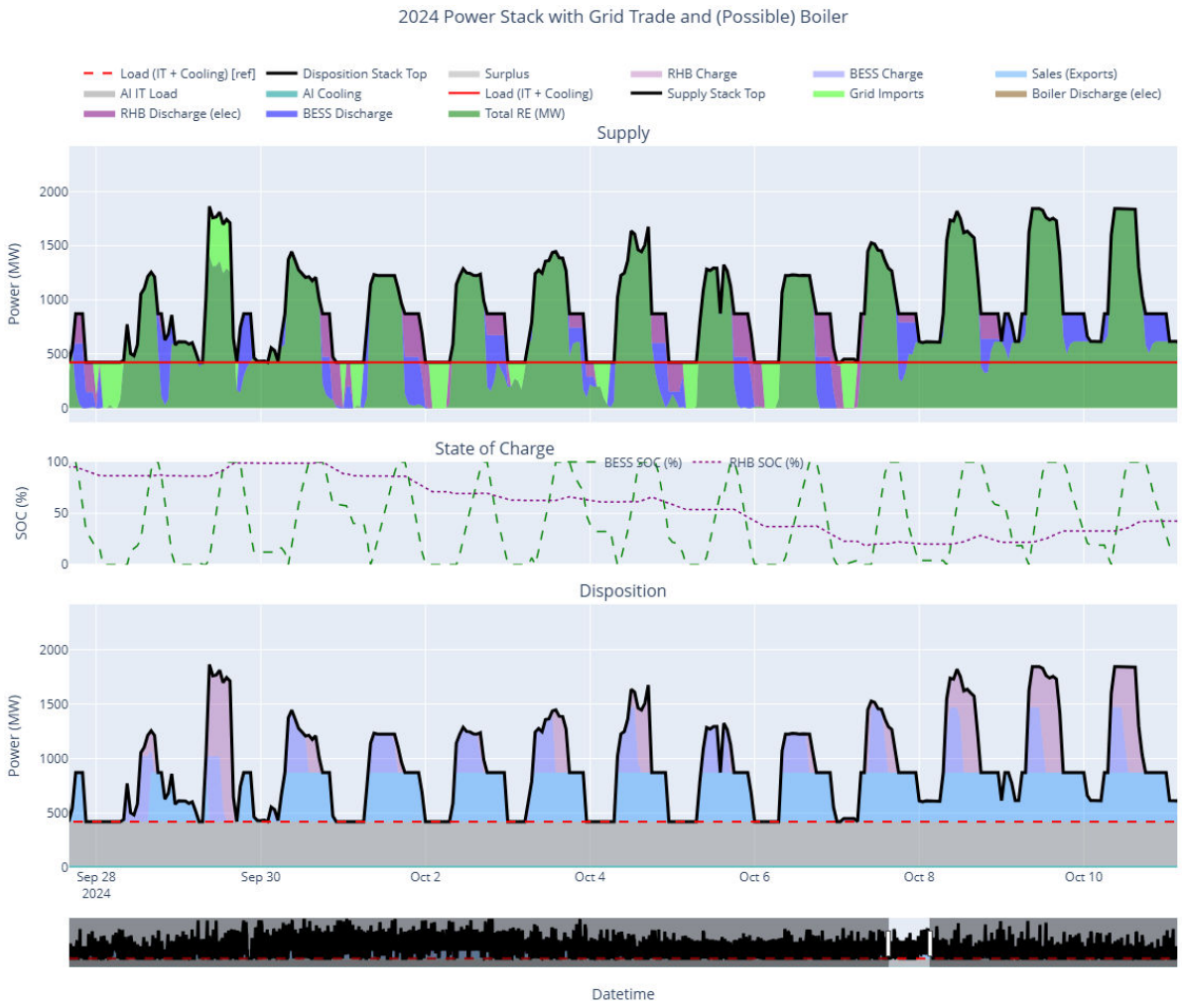
Once cost-optimized configurations were identified at a given tolerance threshold (such as less than 1 percent naïve unserved energy), we modeled them more closely with the more sophisticated screening model, where unserved energy is now covered by a backup boiler. This usually leads to a little more fuel use than by our naïve model, but close enough for our purposes.

Any dollar figures in the linear solver are purely there on a relative basis to prioritize outcomes in the objective functions: for example, the solver might penalize unserved energy at $10,000 per MWh and incentivize surplus at $1 per MWh.

With selected energy park configurations, we used a more versatile screening model for detailed work.

*Figure A.2: Sample two-week hourly time series illustrating screening model optimized hourly battery operations and grid trading.*


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In the more versatile screening model, we added parameters for the thermal block:

- Ramp limits for the boiler and the steam turbine, separate boiler output and steam turbine input power with the possibility of optimizing each of those (floating input with solved output). Also includes an optional weight to smooth turbine output.
- A target reserve fraction for the thermal battery energy store (to simulate conservatism over forecast errors) and a penalty term for missing the target.
- Boiler fuel prices (in $ per MWh thermal) and boiler efficiency.

We also added a flag to trigger trade with a local grid node (requires a matching local marginal price hourly time series) with a couple more options:

- Flags for import-only, export-only, or both,


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- Point-of-interconnection power level (either fixed or floating). For the floating case (where the model solves for optimal size), the model also requires a $ per kW-year price for the grid connection,
- A cost adder for importing power (this is to model various fees that a load might pay for importing power at wholesale rates, excluding the cost of the sub-station).
- A potential penalty for curtailing power to discourage losses.

In this more versatile model, some of the dollar weights in the objective function take on more real-world meaning than others. On the one hand, objective function weights that are orders of magnitude apart, such as $10,000 per MWh for unserved energy versus $240 per MWh net for burning fuel versus $1 per MWh reserve deficit penalties, create a clear hierarchy of priorities (e.g., burn fuel if energy is tight and load might not be served and keep reserves in the thermal battery unless this causes too much fuel use). On the other hand, in the rare intervals when wholesale prices are in the hundreds of dollars, that fuel cost is instrumental in determining trade-offs between buying power or burning fuel on site.

Finally, we implemented model specific toggles. We allowed the user to choose whether to force matching initial and final state of charge for the BESS and thermal battery or set initial and final states. We also note that linear solvers can sometimes make unexpected, or at least un-intuitive choices, like charging and discharging a battery at the same time in response to a ramping penalty on the turbine. We added a post-processing loop option that eliminates some of this simultaneous charge and discharge behavior. With a lot of curtailed power available in the offgrid mode, a certain level of degeneracy exists such that different modeling choices can increase the use of TES versus BESS and adjust steam turbine cycling without affecting overall performance.

We also used this model to simulate outages by fixing a baseline run, knocking out wind and solar production for a period of time (e.g., 36 hours) and then re-running the solver to a period stretching from 24 hours before the “event” and a month after with baseline BESS and thermal battery state-of-charge as boundary conditions on either end. This allowed us to simulate an operator reacting to an outage with 24 hours’ warning and a month to adapt after.

Figure A.2. above is a sample set of hourly supply, state-of-charge and demand stacked plots which illustrate the outputs from our screening model.

### Cost assumptions for energy parks

To estimate the total cost of serving an off-grid data center clean energy park, we based key figures for our analysis on public data like the National Laboratory of the Rockies (NLR) Annual Technology Baseline. For other figures, we estimated based on conversations with industry contacts and other sources. The largest source of

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uncertainty for capital heavy projects like clean energy parks is the cost of money, i.e., weighted average cost of capital and project terms, packaged in a so-called "capital recovery factor" (CRF). Central price estimates in this report assume a CRF of 10 percent, as you might get from a weighted average cost of capital (WACC) of 9.3 percent over a 30 year amortization. Equally valid might be a CRF of 12 percent, e.g. WACC of 8.5 percent over 15 years, reflecting a shorter time horizon with revenues backed by a datacenter purchase guarantee and not merchant tail. All cost figures are illustrative for screening purposes (e.g., are project costs in the right ballpark) and do not indicate a firm financial estimate.

### We used wind and solar from NLR ATB

Because we are interested in safe-harbored projects that qualify for tax credits, we assumed a 30 percent investment tax credit over 2025 NLR ATB renewables prices (2028 Moderate Scenario). This gave us post-tax credit wind at $1.2 per watt with $27 per kW-year in fixed O&M and solar at $0.9 per $W_{AC}$ (one-axis tracking) with $12 per kW-year in fixed O&M.

### We extrapolated costs for generic duration for BESS from NLR ATB's costs at two-, four-, six-and eight-hour duration

A linear fit to NLR ATB provided a stable estimate for separate $/kW and $/kWh cost figures. These are added up as follows: for a 100-kW battery with three hours of storage the total cost is 100 times our $ per kW figure plus 300 times our $/kWh figure.

We estimated $465 per kW for power capacity, and $205 per kWh for energy capacity before tax credits. Hence a six-hour battery would combine these to be $283 per kWh or $1,695 per kW. After a 30 percent tax credit, this works out to $198 per kWh for six-hour BESS. We used a $5/kWh-year fixed O&M (middle of the Lazard range of $3-8/kWh-year) but doesn't include topping off failed storage cells over time.

### Thermal battery cost estimates are a moving target

These are the most challenging to estimate as this technology has just entered commercialization without publicly available data on what new deployment might cost, especially at the scale of a 400 MW data center. Furthermore, U.S. installations can tap the generous 45X tax credit of $45 per kWh of unit storage, available on a unit-of-stored-energy basis, which helps incentivize longer duration installations like Antora's recent multi-day thermal energy storage projects: 5 GWh installed for the POET project[29] and 5.8 GWh announced for Pratt Energy[30]. At this point in the technology's cost curve, cost estimates are a moving target. We did our best to reflect our impression of costs from conversations with OEMs with a point estimate of:

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- $40/kWh$_{thermal}$ for a 14-hour battery with 80MW in/280 MWh$_{thermal}$l/20 MW$_{thermal}$ out reflecting older estimates on the technology cost[31]
- $5/kWh$_{thermal}$ per incremental unit of thermal storage (reflecting the tax credit)
- $100/kW$_{thermal}$l for additional heat-exchanger capacity on the output[32].

Putting these together, we modeled cost for a basic 80MW/1,800MWh$_{thermal}$/35MW$_{thermal}$ thermal storage module at $20 million.

### Boilers, turbines and fossil generators

We use a recent cost number from Babcock and Wilcox[33] for a $2.4 billion, 1.2 GW design build with gas boilers and steam generators for a combined $2,000 per kW. We split the cost to $1,000/kW for the steam turbine and generator, $750 for the boiler, and $250 for balance-of-system (BOS, common electrical like medium voltage transformers covered with other equipment) to get an estimated cost of $300/kW$_{thermal}$ for our industrial boilers (accounting for 40 percent efficiency) and $1,000 per kW for the steam turbines. This split fits with our survey of the literature.

We assumed diesel generator capital costs of $800/kW without advanced exhaust aftertreatment and $1,000/kW with emissions controls, synthesizing published installed-cost benchmarks and estimates of emissions-control costs[34]. These rounded allowances retain some balance-of-plant costs that may overlap with our separate common-electrical budget but also undercount recent inflation in fossil generation equipment.

For natural gas reciprocating engines, we assume $1,525 per kW following a 2024 EIA estimate[35]. That figure includes some balance of plant we might normally subtract, but we keep as is since reported total installed costs are reported to have climbed to $1,700-2,000 per kW since[36].

### Fuel costs and fuel storage

For #2 low-sulfur diesel, burned either in a boiler or a diesel engine, we used historical prices around $3.50 per gallon, not today's higher prices, in anticipation that prices may go back down by the 2028+ time frame. We also added an allowance for 48 hours or 1.4 million gallons of diesel storage. At this scale, fuel farms are a complicated compliance affair, with cost estimates hard to come by. We assumed $3 per stored gallon along the lines of various (old) public figures[37].

For our higher fossil-use gas case, we assumed readily available local gas at $3.50 per MMBtu, along with $67.5 Million for a gas lateral (at $4.5M per mile for a 16-inch diameter 15-mile pipe and associated equipment). Similar to the Vineland project[38], we assume onsite LNG storage for backup provided by truck. We sized it for 72-hour backup (3.5 million gallons of storage at $30/gal).

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We assumed truck-delivered LNG costs of $12/MMBtu, rounded from the approximately $12.63/MMBtu average of available monthly U.S. truck-export LNG prices from January 2025 through July 2026. Export prices serve as a proxy for delivered fuel costs; we cover onsite storage and regasification budgets separately.

LNG fuel needs to be re-gasified for use in gas reciprocating engines as backup fuel. We estimate $90/kW$_{thermal}$ with one percent fixed O&M for vaporizer units at full backup output based on a National Grid Study[39]. We assumed LNG storage and receiving infrastructure costs of $30 per gallon, informed by Holyoke's $70.1 million estimate for a 1.7-million-gallon facility, less an estimated $20.5 million vaporization allowance using our $90/kW$_{thermal}$ assumption and the existing Holyoke plant's approximately 228 MWth send-out capacity as a proxy[40].

## Secondary generation equipment size sensitivities

### Hybrid thermal power scenario – boiler thermal power reduction

We varied the boiler size from 0 to 1,000 MW$_{thermal}$ and looked for the emergence of increased boiler fuel (from reduced thermal efficiency in the boiler and TES combination) and unserved energy for the data center:

- Boiler use increased around a reduction to 500 MW$_{thermal}$ maximum output in the boiler size with minor increases down to about the 150 MW$_{thermal}$ mark. This reflects the large stock of TES thermal energy's ability to manage a spread in boiler support of the energy park over time. The boiler can run in fixed blocks at optimum combustion efficiency without affecting operational flexibility.
- Below 150 MW$_{thermal}$ max boiler output we start seeing unserved energy emerging in our annual model — the boiler cannot keep up with demand.

We conclude that the functions of the boiler are split 85/15 between backup and firming, i.e., if the idea is to reassure clients that backup energy will always be available at full power, a project needs the full GW$_{thermal}$ of boiler capacity, but as projects like this become more common and operational experience accrues, next-of-a-kind projects may choose to explore some savings by reducing boiler capacity.

### Hybrid thermal power scenario – steam turbine power reduction

We varied the steam turbine size from 0 to 400 MW and looked for emergence of unserved energy. For the hybrid thermal power scenario, the steam turbine is an important component of everyday operations as part of the loop for reconverting thermal energy transformed from renewable generation into electricity, operating in just over 50 percent of hours and providing just under 20 percent of the direct energy to the data center. It speaks well to flexibility and resiliency of having two types of storage (BESS and TES) that for this sensitivity we found no degradation in performance for data center supply until the model dropped to 250 MW steam power (a 37.5 percent

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buffer). Still, a full backup guarantee from onsite fuel would require a 422 MW turbine (assuming no data center flexibility and a complete incapacity of the RE+BESS system to provide even 22 MW). Ultimately, the size of the steam turbine will come down to balancing costs versus risk. A conservative build-out might be nine or ten 50 MW turbines (N-1 or N-2 reliability for 400 MW) while further modeling or operational experience might find developers comfortable with risk levels achieved with only five or six 50 MW turbines.

### High-capacity BESS scenario – diesel engine power reduction

We varied the diesel engine size from zero to 450 MW and looked for emergence of unserved energy. Unserved energy started appearing in our model runs only when diesel power dropped below 150 MW (a 2/3 buffer). This further demonstrates that more of the role of diesel engines under normal operations is around providing missing energy rather than missing power. As with discussions above, when thinking about backup and redundancy under extraordinary circumstances, park planners will need to think about how they want to count tail-event scenario contributions for the RE+BESS section of the park when sizing the diesel engine fleet.

## Export/import patterns

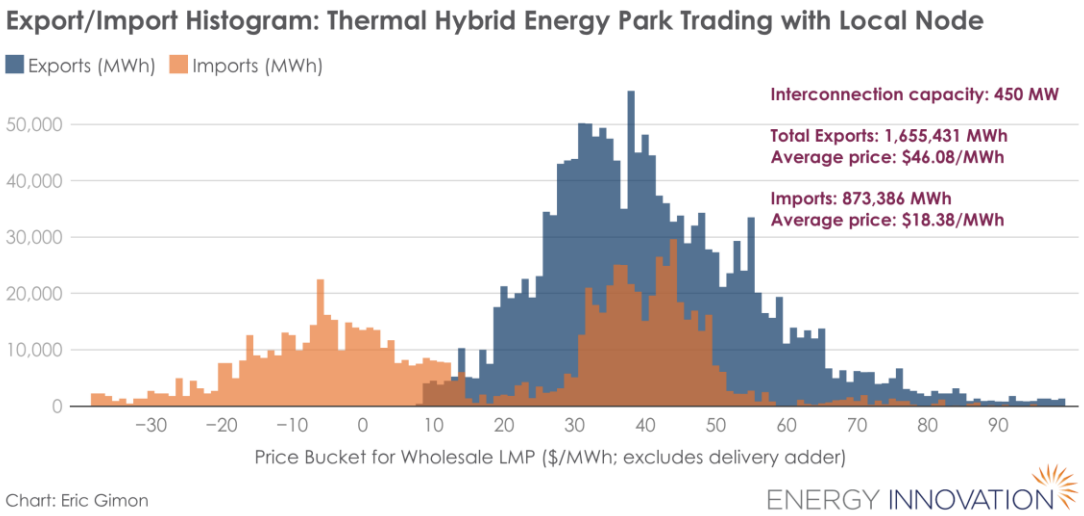
We implemented the ability for our hourly dispatch model to trade with the CAISO grid at a specific location near our modeled resource. The model was able to sell any power it wanted at wholesale prices (locational marginal price) in any hourly interval up to a POI limit. It was able to buy power at the same price plus a small cost adder of $8/MWh to represent a minimum of grid charges with the same maximum.

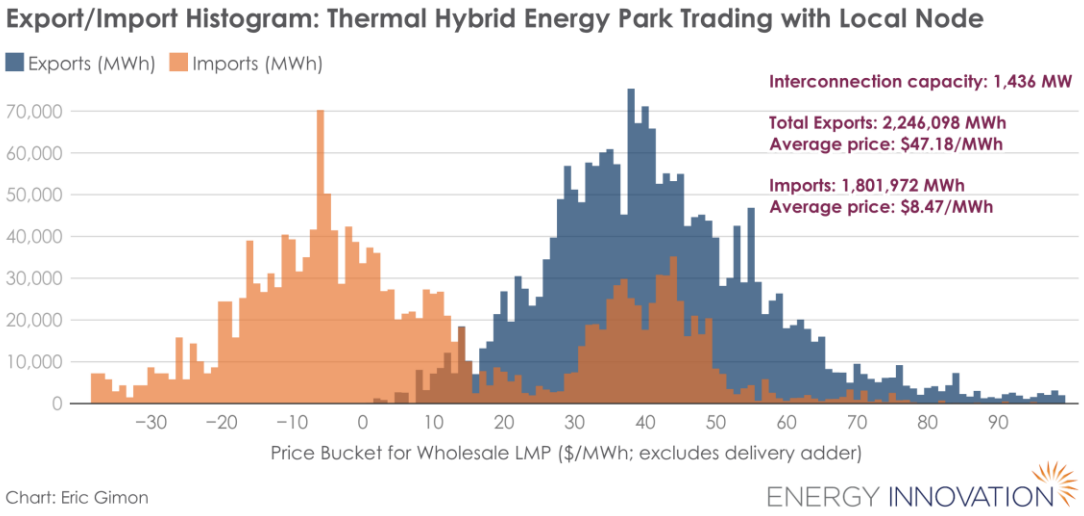
### Thermal hybrid and high-capacity BESS scenarios both exhibit active trading patterns

We modeled both the hybrid thermal power scenario and the high-capacity BESS scenario this way. In each case we either assumed a 450 MW POI capacity (approximately matching the data center maximum load) and a floating POI capacity (1,436 MW for the hybrid thermal scenario and 1,125 MW for the high-capacity BESS scenario) that maximized total revenue for a given cost of interconnection (we used $9 per kW-year of grid connection capacity, a little less than 10 percent (using CRF) of the NLR 2025 ATB estimate of $104/kW[41] because some of these costs are also covered by the $8/MWh adder). Our histogram figures excluded volumes outside -40 to 100 $/MWh (MWh) for a more compact visual but they are included in the summary inset.

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*Figure A.3: Export and Import behavior of hybrid thermal data center energy park with two different maximum POI capacities. Darker orange is overlap of histogram (not stacking).*

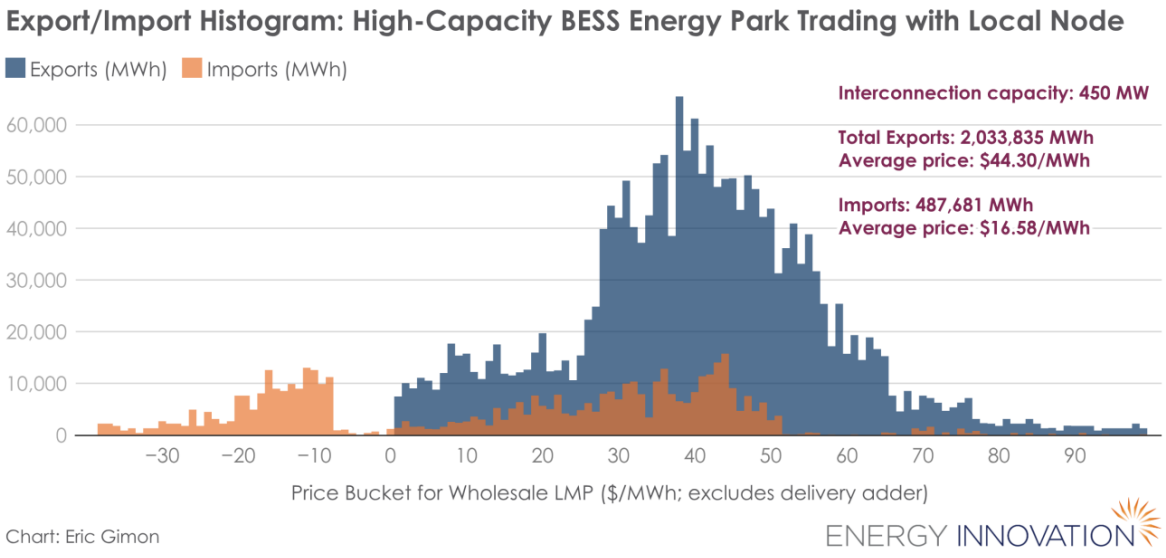


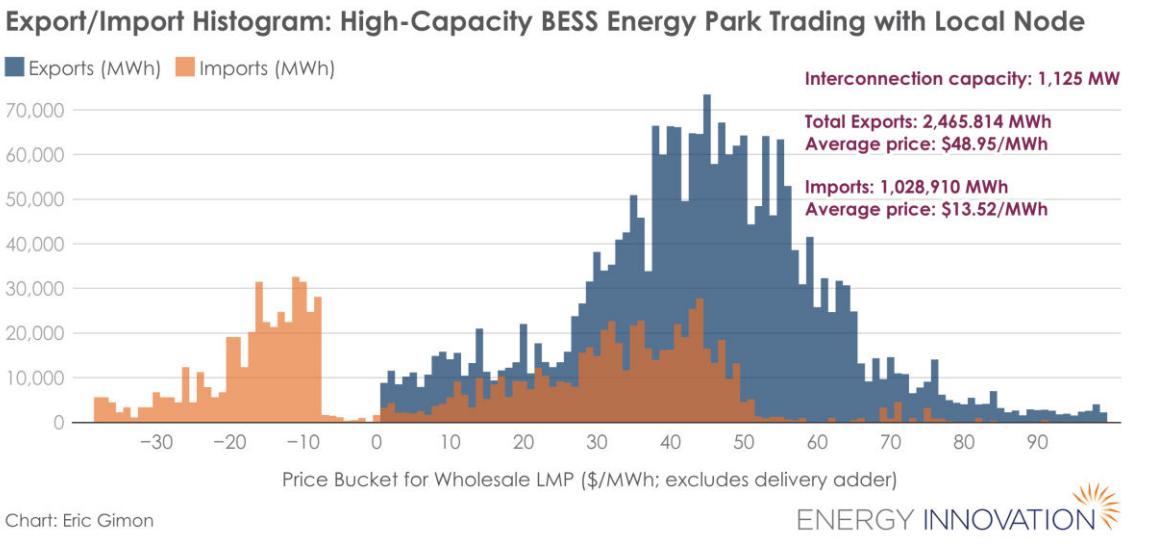




Net exports are higher for the high-capacity BESS scenario for two reasons. First, this portfolio starts with more wind and solar capacity, so naturally creates more surplus that would otherwise have to be curtailed. Second, in the thermal hybrid scenario some potential surplus is consumed by higher round-trip losses in the TES system used as long duration storage. These come from storing some electricity as heat and then re-converting to electricity.

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*Figure A.4: Export and Import behavior of high-capacity BESS data center energy park with two different maximum POI capacities. Darker orange is overlap of histogram (not stacking).*




It's interesting to note here that the imports for negative price power we see in the high-capacity BESS scenario are almost all balanced out by curtailing internal renewable production. This was not the case in the thermal hybrid scenario, where these negative price imports are either used to cover round-trip thermal losses in the TES or are saved for later using the larger internal energy store inherent in the TES.

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### Estimating grid connection value and virtual battery revenues

Grid connection value is an estimate of what the energy park stands to gain annually from connecting to the grid, while battery revenues are an estimate of the virtual battery value to the grid of the energy park.

By virtual battery value, we mean isolating a remainder value from the net trading benefits (export sales – import costs) by excluding activities we don't count as "pure trading." Concretely

**[Battery Value]** = [Net Revenues] – [Revenues from exporting otherwise curtailed power] + [Cost of importing power to replace boiler use] – [Disposal Revenue]

where

- **[Net Revenues]** = Export sales – (import costs without adder) with same POI size
- **[Disposal Revenue]** = Revenue from any MWh bought and immediately curtailed excluding the $8/MWh adder

and we use models with "export only" and "import only" flags turned on to compute

- **[Revenues from exporting otherwise curtailed power**] = "Export only" model sales – any incremental fuel costs, with the same POI size as the full-trade model
- **[Cost of importing power to replace boiler use**] = Import costs without adder for an "import only" model at a reduced optimized POI (the optimum POI size for import-only thermal hybrid). We also remove any disposal revenues.

For example, with a POI capacity of 1,436 the thermal hybrid data center energy park had $105,968,042 in export receipts and paid $15,257,876 in import prices (excluding $14,414,462 from the $8/MWh adder) for **[Net Revenues] of $90,710,166**. In "export only" mode, the park had $44,665,672 in export receipts with an incremental fuel bill of $2,688,263 so **[Revenues from exporting otherwise curtailed power] were $41,977,409**. In "import only" mode at reduced POI of 93 MW, the import bill **[Cost of importing power to replace boiler use] was $1,837,901. [Disposal Revenue]** was **$69,222.** So putting it all together **[Battery Value] was $50,501,436,** about 56 percent of net revenues. Thus $50 million is our best proxy for the annual virtual battery value of the thermal hybrid data center energy park connected to the grid at 1,436 MW.

In these battery value calculations we removed the $8/MWh import adder from import costs to isolate the value from a pure wholesale market standpoint.

We also defined "Grid Connection Value" (what the solver is solving for) as exports receipts minus import receipts (including the adder this time) minus the annualized cost of the POI plus fuel savings. In the thermal hybrid 1,436 MW POI case this comes out to **$72,841,620**.

We tabulated these calculations with fixed and floating POI size in Table 3.

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