What is So Hard About Behind-The-Meter Power For Datacenters? Part 1

数据中心的“表后”电力到底难在哪里？第一部分

Dumb Science Experiments vs. Money Printing Machines

愚蠢的科学实验 vs. 印钞机



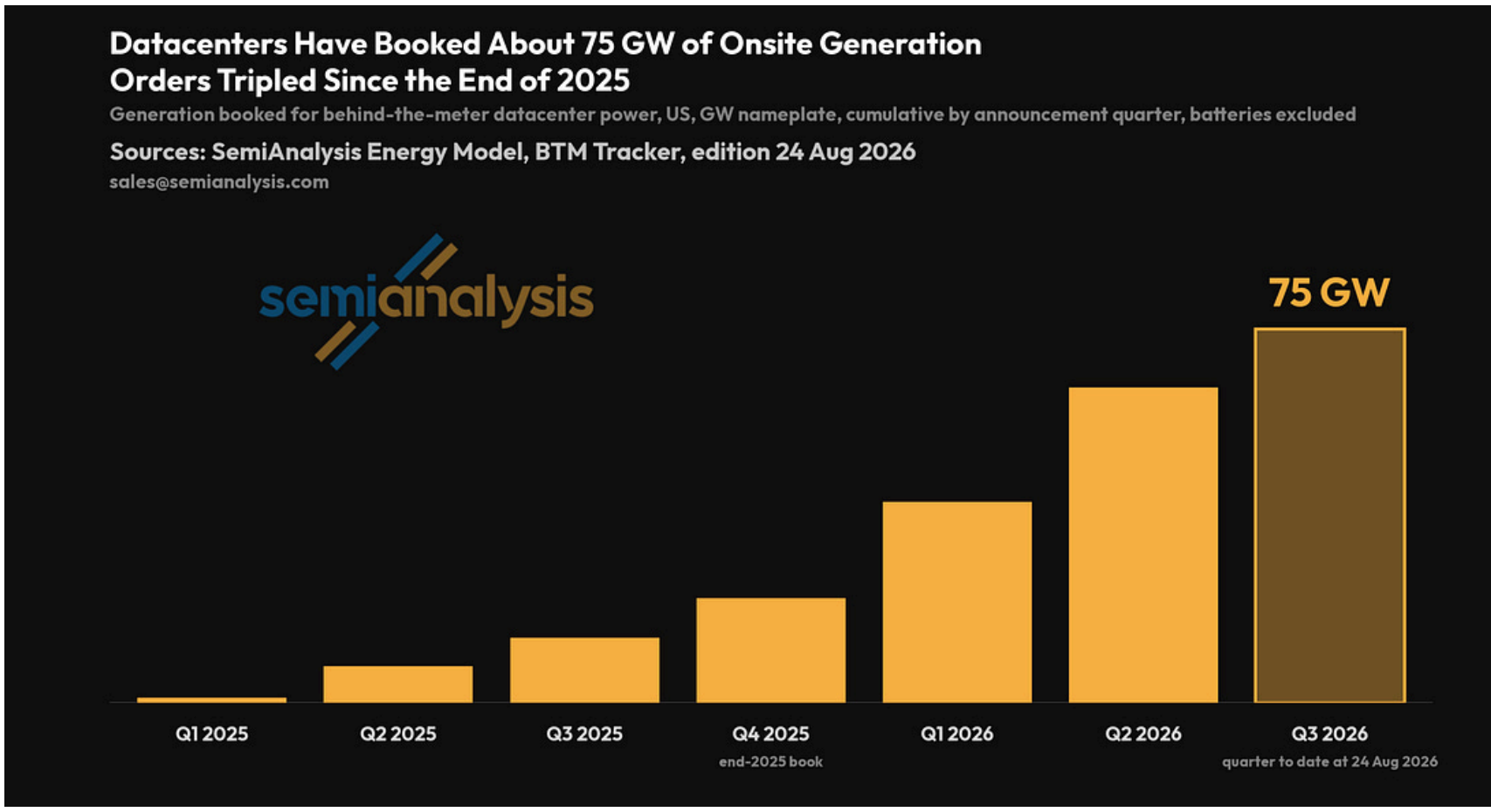
Last year we were the first to call out Onsite Gas Generation as the primary method adopted by AI Labs and Hyperscalers to solve power constraints.

Our positive view was far from being consensus: behind-the-meter primary power solutions have been called all sorts of names, such as “science experiments”, “Dark Gigawatts”, and “literally the dumbest thing that human beings have ever attempted to do”!

去年，我们率先指出现场燃气发电是各 AI 实验室和超大规模云厂商解决电力约束所采用的主要手段。我们的乐观观点远未成为共识：表后主电源方案被冠以各种名号，比如“科学实验”、“黑暗吉瓦（Dark Gigawatts）”，甚至是“字面意义上人类尝试过的最愚蠢的事情”！

But since then, that supply chain has witnessed a massive acceleration. Our Energy Model now tracks 75GW of firm, binding orders in the supply chain **only for for behind-the-meter AI compute** - of which ~20GW alone ordered in Q2 2026. What started as an Elon Musk experiment is now mainstream for every single AI Lab and hyperscaler. To be clear, this data does not include the hundreds of GWs of speculative, baseless announcements that many other analysts track in their numbers - we only focus on binding orders received by OEMs specifically serving BTM AI compute, tracked at the project-level.

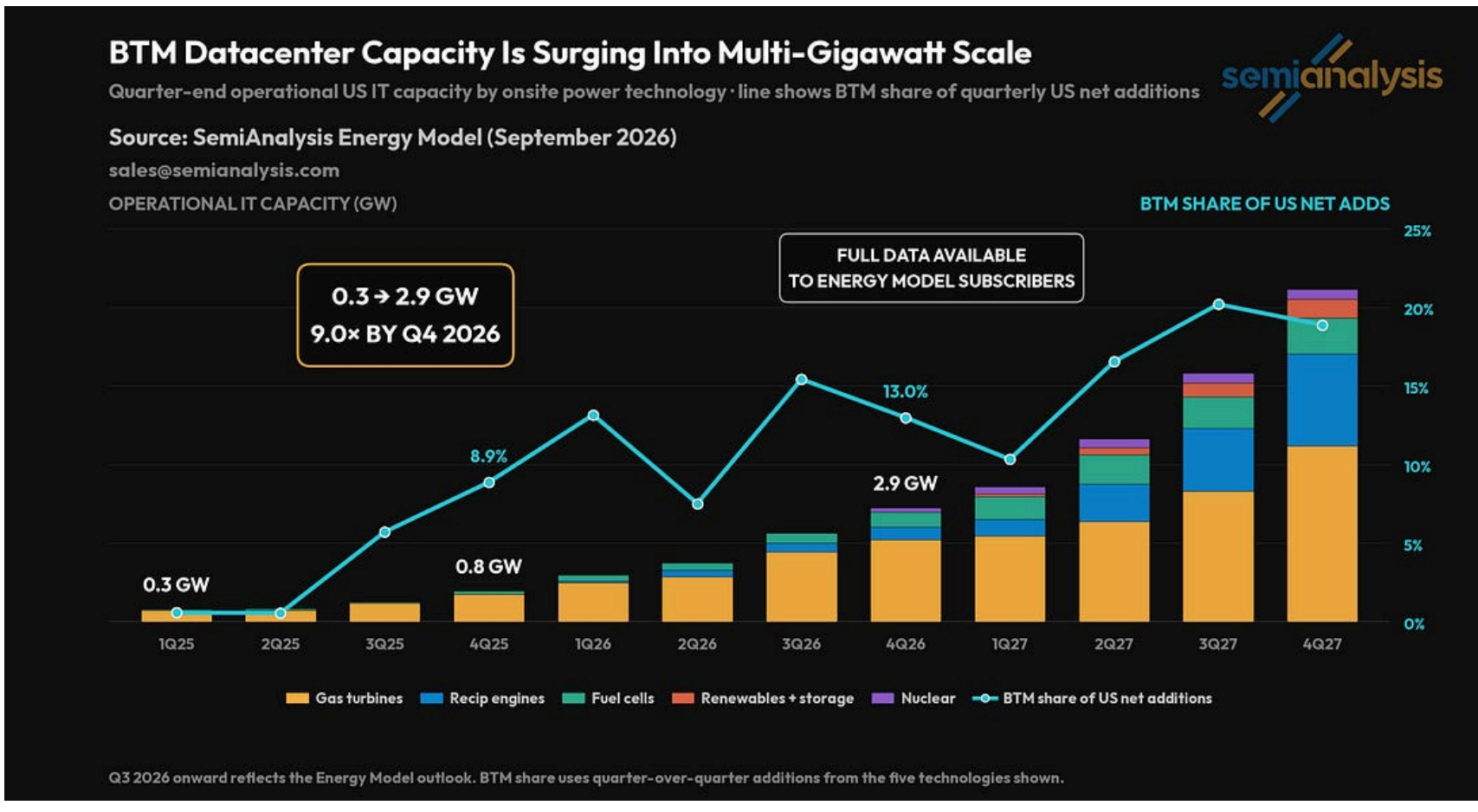
但自那以后，这条供应链经历了大规模加速。我们的能源模型目前追踪到供应链中**仅面向表后 AI 算力**的 75GW 坚定约束性订单——其中仅 2026 年第二季度就下单约 20GW。起初只是埃隆·马斯克的一项实验，如今已成为每一家 AI 实验室和超大规模云厂商的主流做法。需要说明的是，该数据不包括许多其他分析师纳入统计的数百吉瓦投机性、无根据的公告——我们只专注于专门服务表后 AI 算力的 OEM 所收到的约束性订单，并按项目级别进行追踪。



Sources: SemiAnalysis Energy Model; sales@semianalysis.com

The path from firm equipment order to delivered project is still long and challenging. There is substantial execution risk and that's what we'll focus on in this report. But the industry is more experienced than you'd think: by the end of the year, ~3GW of operational US datacenter IT capacity will be powered behind-the-meter, and that number will experience multiple straight years of triple-digit growth. Our Energy and Datacenter models account for all potential delays, as we've explained in depth in our piece Stop Saying Half of 2026 US Datacenter Capacity is Canceled.

从坚定的设备订单到项目交付，前路依然漫长且充满挑战。执行风险相当可观，这也是本报告的重点。但这个行业的经验比你想的要丰富：到今年年底，美国将有约 3GW 在运数据中心 IT 容量依靠表后电力供电，而且这一数字将连续多年保持三位数增长。我们的能源模型和数据中心模型已考虑所有潜在的延期因素，正如我们在《别再说 2026 年美国数据中心产能有一半被取消了》一文中的深入阐述。

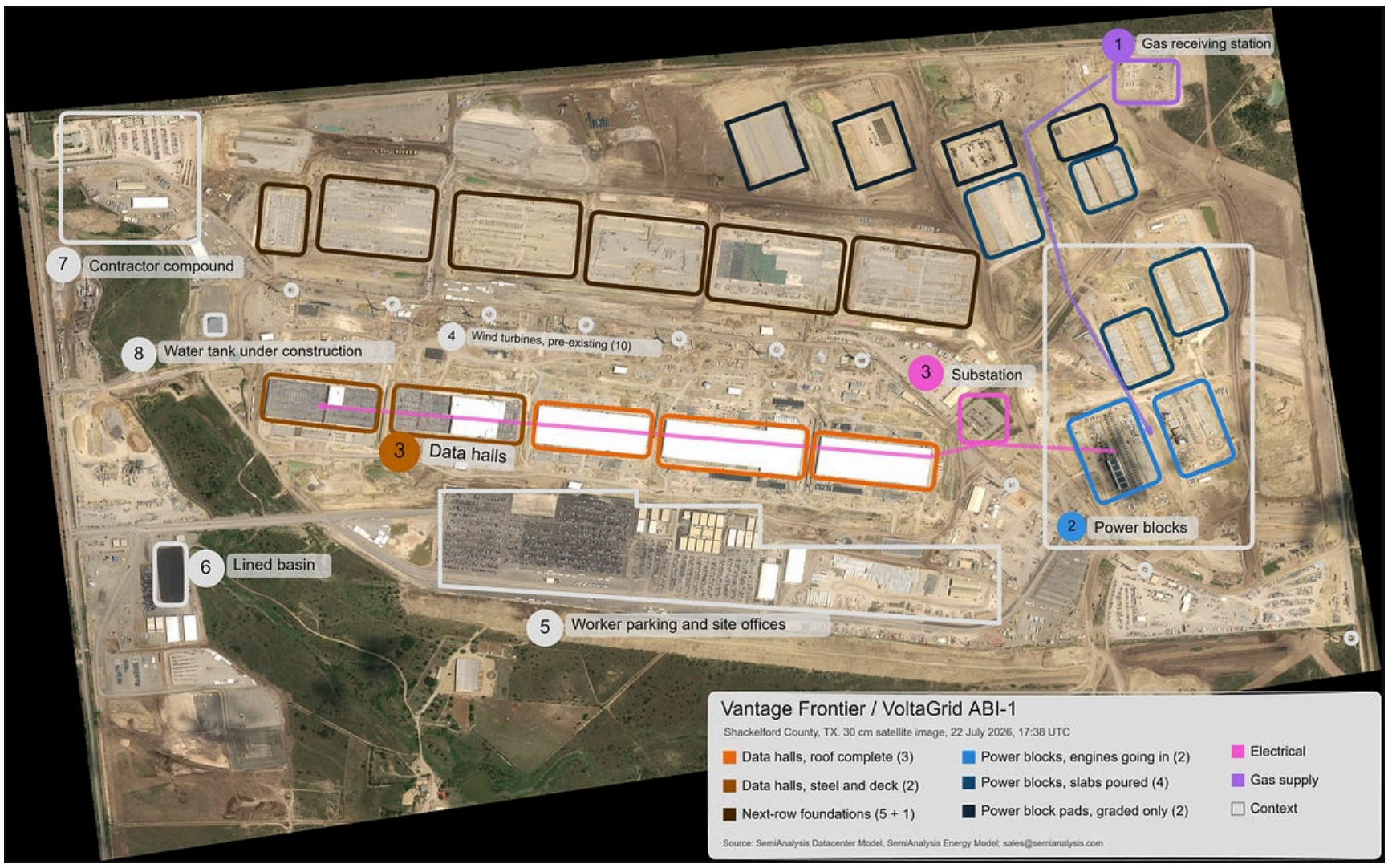


Some of the most strategic projects developed by leading AI labs and hyperscalers are relying on behind-the-meter, supporting hundreds of billions of future revenue. Adoption has never been more broad-based. A few examples:

领先 AI 实验室和超大规模云厂商开发的一些最具战略意义的项目正依赖表后方案，支撑着未来数千亿美元的收入。采用面从未如此广泛。举几个例子：

- In 2026 year-to-date, Microsoft has signed over 5GW of behind-the-meter nameplate capacity, of which 2.7GW with Chevron, and well over 2GW through turnkey datacenter leases with companies like Crusoe. That 5GW encompasses a broad range of different types of power equipment; full breakdown available to our Energy Model subscribers.
- 2026 年至今，微软已签署超过 5GW 的表后铭牌容量，其中 2.7GW 来自雪佛龙，另有远超 2GW 通过与 Crusoe 等公司的交钥匙数据中心租约获得。这 5GW 涵盖多种不同类型的电力设备；完整明细可供我们的能源模型订阅用户查阅。
- Google, historically the most reluctant to onsite gas, is deploying 930MW of off-grid aeroderivative turbines in a flagship campus in Armstrong County. In addition, the Search Giant will deploy 900MW of Bloom Energy Fuel Cells in Wyoming - as we called out back in February 2026 as a huge positive for Bloom Energy. They'll be paired with >1GW of Mitsubishi J-class turbines.
- 谷歌历来对现场燃气最不情愿，如今却正在阿姆斯特朗县的一座旗舰园区部署 930MW 离网航改型轮机。此外，这家搜索巨头还将在怀俄明州部署 900MW 的 Bloom Energy 燃料电池——正如我们早在 2026 年 2 月指出的，这对 Bloom Energy 是重大利好。这些燃料电池将与超过 1GW 的三菱 J 级轮机配套。

- Both Anthropic and Meta have signed 300-500MW deals with Enchanted Rock, a supplier of 0.5MW gensets built around a 21.9-liter V12 gas engine. Separately, Anthropic's flagship campus in Texas, backstopped by Google, will also deploy over 1.5GW of off-grid generation; full breakdown of Anthropic's exact datacenter facilities available to our Datacenter Model subscribers.
- Anthropic 和 Meta 均与 Enchanted Rock 签署了 300-500MW 的协议。该公司供应以 21.9 升 V12 燃气发动机为核心的 0.5MW 发电机组。另外，Anthropic 由谷歌兜底的得州旗舰园区还将部署超过 1.5GW 的离网发电；Anthropic 各数据中心设施的完整明细可供我们的数据中心模型订阅用户查阅。
- OpenAI will imminently start operations in its flagship off-grid 1.4GW (IT capacity) campus in Shackelford County, TX, using over **five hundred 4.25MW Jenbacher J624 engines**. We show below a portion of the campus. Combined with their 1.3GW IT site in New Mexico, that represents over $150B of contracted spending that OpenAI signed with Oracle relying on behind-the-meter power.
- OpenAI 即将在其位于得州沙克尔福德县的旗舰离网 1.4GW（IT 容量）园区开始运营，使用**超过五百台 4.25MW 的 Jenbacher J624 发动机**。我们在下文展示了该园区的一部分。加上其位于新墨西哥州的 1.3GW IT 园区，这代表着 OpenAI 依靠表后电力与 Oracle 签署的超过 1,500 亿美元合同支出。



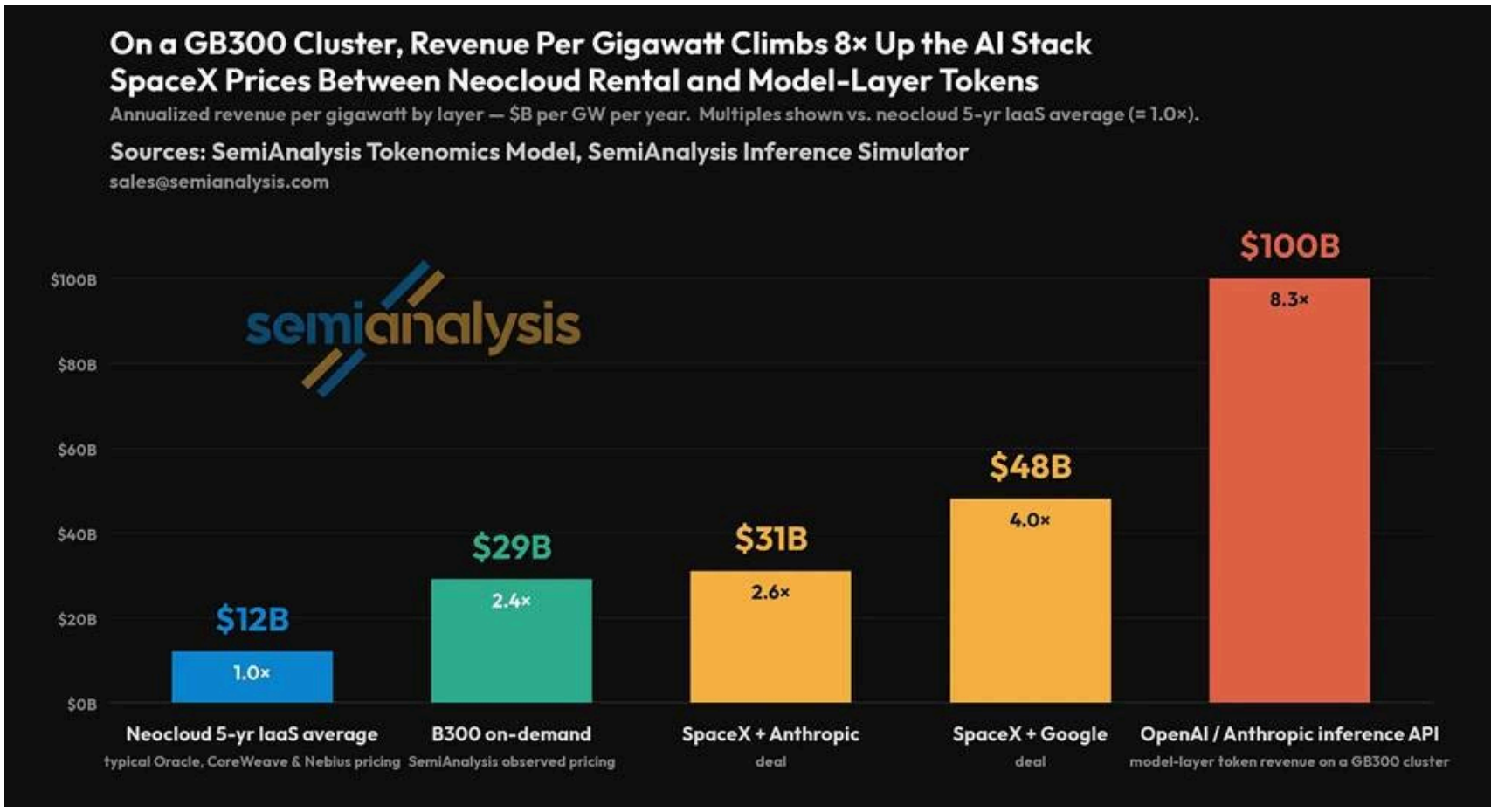
Sources: SemiAnalysis Datacenter Model; SemiAnalysis Energy Model; Sales@semianalysis.com

Why is this happening, and why have many energy experts been so wrong? It comes down to understanding AI economics. We've discussed this at length in many other articles and in our Tokenomics Model. As a quick reminder, the value of megawatts for end-users is skyrocketing. A power plant supporting an islanded 1GW IT datacenter typically costs ~$5B. In today's environment, **inference API revenue can yield $100B per GW per year, at 90%+ gross margins.** Paying 2x more money or accepting 30% lower efficiency for faster speed of deployment becomes a no-brainer**.** Said differently, **Anthropic and its peers can pay back the value of a power plant in 20 days of inference revenue**. As we discussed six months ago, most of the value in the AI infrastructure stack is shifting to frontier model developers.

为什么会这样，为什么许多能源专家错得如此离谱？关键在于理解 AI 的经济学。我们在许多其他文章和 Tokenomics 模型中已有详述。简要提醒一下：兆瓦对终端用户的价值正在飙升。一座支撑 1GW 孤岛 IT 数据中心的电站通常造价约 50 亿美元。在当今环境下，**推理 API 收入可达每 GW 每年 1,000 亿美元，毛利率超过 90%。**为了更快的部署速度而多花一倍的钱或接受 30% 的效率损失，根本无需犹豫。**换句话说，**Anthropic 及其同行用 20 天的推理收入就能收回一座电站的价值。**正如我们六个月前所讨论的，AI 基础设施栈中的大部分价值正在向前沿模型开发者转移。

The grid simply cannot keep up with demand. Building new generation can easily take over five years, and on the demand-side, interconnecting a datacenter takes years. Read more in our article on US Grid Constraints.

电网根本跟不上需求。新建发电设施动辄需要五年以上，而在需求侧，数据中心并网也需要数年。更多内容请参阅我们关于美国电网约束的文章。



Sources: SemiAnalysis

In today's report, we dive into the world of "datacenter microgrids". We consider the challenges and doubts regarding the BTM buildout and look at how it is being done.

在今天的报告中，我们深入"数据中心微电网"的世界。我们审视关于表后建设的挑战与质疑，并看看它是如何落地的。

1. **What** even is 'Behind-the-Meter'. Detailing the ways a datacenter can relate to the grid, between primary and back-up power; including when something is a phony microgrid. How does one define behind-the-meter?
2. "表后"**到底是什么**。详述数据中心与电网之间的各种关系、主电源与备用电源之分；包括什么情况下是假微电网。该如何定义表后？
3. **How** projects succeed or fail. We lay out the six key stages & challenges of BTM projects: contracts & bankability, permitting, fuel supply, equipment procurement, workforce, and the physics of operating without a grid-connection. We start with the financing wall, with chicken-and-egg situations being increasingly common for developers, and the rise of the new "BTM utilities".
4. 项目**如何**成败。我们列出表后项目的六大关键阶段与挑战：合同与可融资性、许可、燃料供应、设备采购、劳动力，以及无电网连接运行的物理学。我们从融资之墙讲起——开发商 increasingly 陷入先有鸡还是先有蛋的困境——以及新晋"表后公用事业公司"的崛起。
5. **Where** we go from here. 'To grid or not to grid'; what happens to these plants when grid power finally arrives; export-to-grid, stay primary power, become backup, or move elsewhere. At the same time what happens with these order books and the manufacturing capacity that has scaled so hard to meet the moment. We'll also give our view on the implications for BTM in Texas.
6. **接下来**走向何方。"接电网，还是不接"；当电网电力最终到来时，这些电站命运如何——向电网送电、继续做主电源、转为备用，还是迁往他处。与此同时，为应对当下而艰难扩张的订单簿和制造产能又将何去何从。我们还将给出表后方案在得州走向的看法。

Over recent months we have published significant research for our Energy Model clients, laying out winners & losers in the equipment landscape (turbine, recips, fuel cells), contractors like AGX, BoP equipment like MV UPS systems and how new LVRT regulations could have negative impact to certain huge industrial companies. Behind the paywall of this report, we have included some of this work for Substack subscribers now to enjoy.

近几个月来，我们为能源模型客户发布了大量研究，梳理了设备领域的赢家与输家（轮机、往复机、燃料电池）、AGX 等承包商、中压 UPS 系统等 BoP 设备，以及新的低电压穿越（LVRT）法规可能对某些大型工业企业造成的负面影响。在本报告付费墙之后，我们为 Substack 订阅者附上了其中部分内容。

> Conferences: in September members of SemiAnalysis' Energy Model team will be at Gastech in Bangkok 14-17th; Data Center World Power in Dallas 21-23rd; Yotta in Las Vegas, and Gulf Coast Power Association in Austin, both 28-30th. Email energy@semianalysis.com and lets talk power!

> 会议预告：9 月，SemiAnalysis 能源模型团队成员将出席：曼谷 Gastech（14-17 日）；达拉斯 Data Center World Power（21-23 日）；拉斯维加斯 Yotta 与奥斯汀 Gulf Coast Power Association（均为 28-30 日）。请发邮件至 energy@semianalysis.com，一起聊聊电力！

What even is "BTM"?

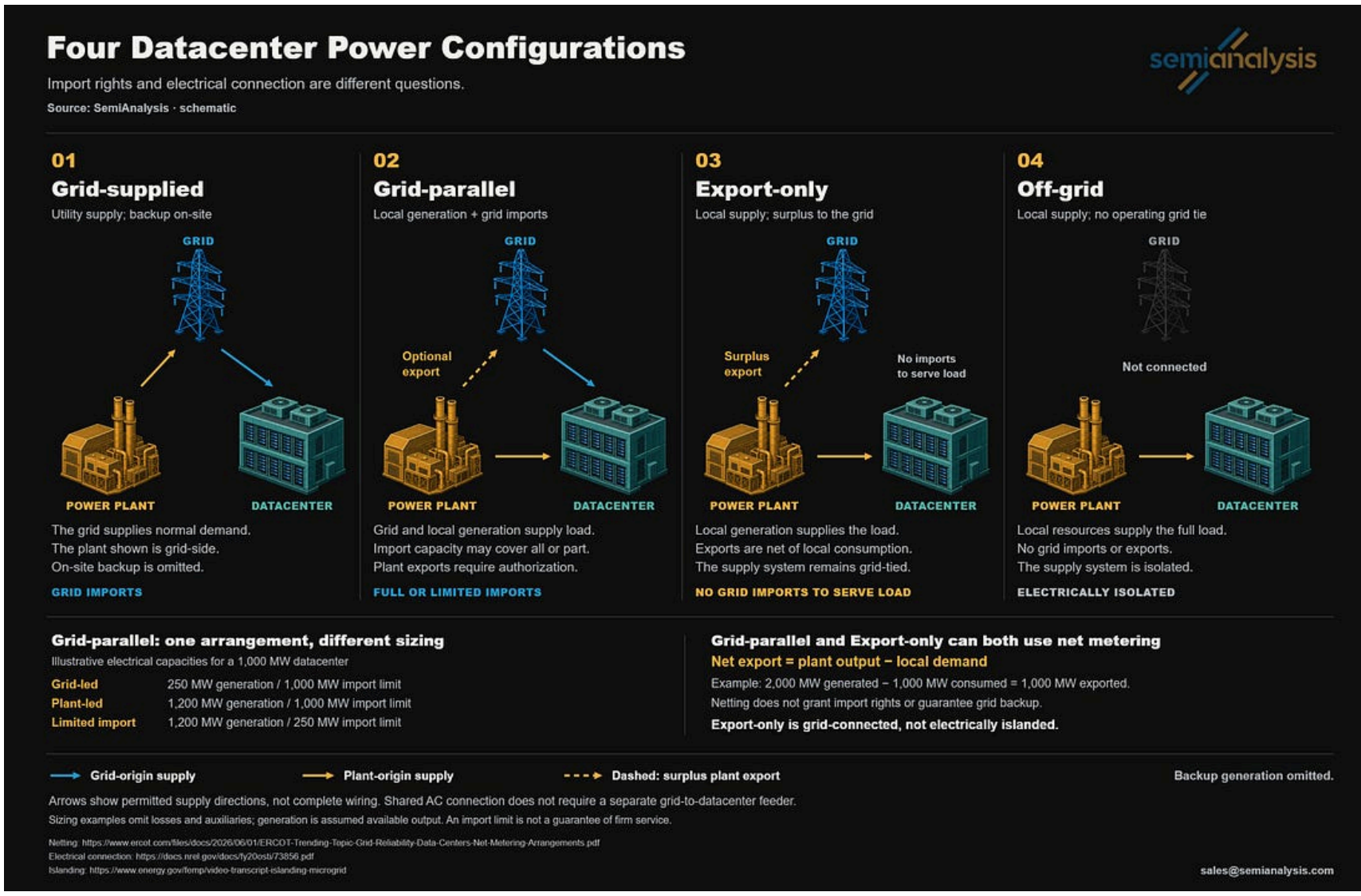
到底什么是"表后"（BTM）？

A meter is a device that counts electricity; it is stationed at the point where the project's wires meet the grid's wires. Everything on the grid side of that point, the substations, the pylons, the power plants, is "front of the meter"; everything on the project's side, the switch-gear, the batteries, and onsite generators, is "behind the meter".

电表是计量电力的设备；它安装在项目线路与电网线路的交汇点上。该点电网一侧的一切——变电站、输电铁塔、电厂——属于"表前"；项目一侧的一切——开关设备、电池和现场发电机——属于"表后"。

There are then specific terms but in practice they get used interchangeably: "behind-the-meter", "off-grid", "islanded", "co-located", and "micro-grid". This is frustrating and leads to common disagreements over the definitions, but one way to think about them is by connection configuration:

此外还有一些特定术语，但实践中常被混用："表后"、"离网"、"孤岛"、"共址"和"微电网"。这令人沮丧，也常导致定义之争，但可以用连接配置来区分它们：



Source: SemiAnalysis

来源：SemiAnalysis

1. **Grid-supplied:** The grid supplies the datacenter; on-site generation is backup only. Power plants supply the public network, which supplies the datacenter.
2. **电网供电：**电网为数据中心供电；现场发电仅作备用。电厂向公共网络供电，再由公共网络向数据中心供电。
3. **Grid-parallel:** Local generation and grid imports can both supply the datacenter. Exports are optional depending on the rights and connections.
4. **电网并行：**本地发电与电网受电均可为数据中心供电。是否可向外送电，取决于权利与连接条件。
5. The relative sizes of the datacenter, its local generation, and its permitted grid imports can vary substantially. ERCOT's Withdrawal-Limited Private Use Network, or WLPUN, framework expressly accommodates on-site generation reducing the transmission capacity a large load requires.
6. 数据中心、其本地发电及获批电网受电规模的相对大小可能差异巨大。ERCOT 的"受取限制私用网络"（WLPUN）框架明确允许通过现场发电来降低大型负荷所需的输电容量。
7. Consider three illustrative configurations, each serving a **1,000 MW datacenter**:
8. 考虑三种示例配置，均服务于 **1,000 MW 数据中心**：
9. **Grid-led:** 250 MW of local generation and a 1,000 MW import limit. Local generation offsets part of grid consumption; when producing 250 MW at full datacenter load, it leaves 750 MW to import.
10. **电网主导：**250MW 本地发电，1,000MW 受电上限。本地发电抵消部分电网用电；在数据中心满负荷、本地发电满发 250MW 时，剩余 750MW 需从电网受电。
11. **Plant-led, full-sized import connection:** 1,200 MW of local generation and a 1,000 MW import limit. The plant can cover normal demand, while the import limit is large enough to accommodate the entire datacenter load.
12. **电站主导、全额受电连接：**1,200MW 本地发电，1,000MW 受电上限。电站可覆盖正常需求，同时受电上限足以承接整个数据中心负荷。
13. **Plant-led, limited import connection:** 1,200 MW of local generation and a 250 MW import limit. At full load, at least 750 MW must come from local resources. Losing all local generation would require replacement supply or at least 750 MW of load reduction.
14. **电站主导、受限受电连接：**1,200MW 本地发电，250MW 受电上限。满负荷时至少 750MW 须来自本地资源。若失去全部本地发电，将需要替代电源，或至少削减 750MW 负荷。
15. **Export-only:** Local generation supplies the datacenter; the grid connection permits exports but not imports to serve the load.
16. **仅送出：**本地发电为数据中心供电；电网连接允许送出，但不允许为负荷受电。
17. **Off-grid:** Local generation supplies the datacenter without an operating grid connection.
18. **离网：**本地发电为数据中心供电，无运行中的电网连接。

Net metering

净计量

In this context, net metering means netting the datacenter's consumption against associated generation at the relevant grid-facing metering or settlement boundary. ERCOT describes it as reducing the customer's metered consumption from the grid; it is not necessarily the retail rooftop-solar

arrangement that credits exports against consumption over a billing cycle.

在此语境下，净计量指在相关面向电网的计量或结算边界处，将数据中心的用电与其相关发电相抵。ERCOT 将其描述为减少客户自电网的计量用电量；它未必是那种在一个账单周期内将送出电量抵扣用电量的零售屋顶光伏安排。

Freestone is an example: ERCOT reports PUCT approval in May 2026 of an arrangement between a 1,099 MW gas plant and a 760 MW datacenter in Freestone County.

Freestone 就是一例：ERCOT 报告称，得州公共事业委员会（PUCT）于 2026 年 5 月批准了 Freestone 县一座 1,099MW 燃气电站与一座 760MW 数据中心之间的此类安排。

Why Export-only is not Off-grid

为什么“仅送出”不等于“离网”

The datacenter does not need a separate grid feeder to remain electrically connected. If its supply circuit connects into the plant’s grid-connected AC system, it is connected to the grid through the plant; the site participates in the interconnection’s frequency dynamics and shared inertial response even while exporting net power. Depending on how well run the grid is this arrangement can be beneficial to the datacenter with improved electrical reliability and quality.

数据中心并不需要单独的电网馈线来保持电气连接。如果其供电回路接入电站的并网交流系统，它便通过电站与电网相连；即使净送出电力，该场址仍参与互联系统的频率动态和共享惯量响应。取决于电网运营水平，这种安排对数据中心可能反而有利，带来更好的电气可靠性与电能质量。

Existing generation adds a regulatory distinction

既有发电带来监管区分

Regulators can also distinguish new generation from a plant that previously supplied the grid. Texas Utilities Code §39.169, “Co-location of Large Load Customer With Existing Generation Resource,” covers certain net-metering arrangements involving an operating facility registered as a stand-alone generation resource **as of September 1, 2025**; it requires ERCOT notification and PUCT review, subject to exemptions and a deemed-approval provision.

监管者还可以区分新建发电与此前向电网供电的电站。《得克萨斯州公用事业法典》第 39.169 条“大型负荷客户与既有发电资源共址”，适用于涉及**截至 2025 年 9 月 1 日**已注册为独立发电资源的在运设施的特定净计量安排；该条款要求通知 ERCOT 并接受 PUCT 审查，同时设有豁免和视为批准条款。

Diverting existing output to a new load can reduce supply available to the wider grid. ERCOT says the two netting arrangements approved by May 2026 required the datacenters to reduce consumption or switch to backup, and the plants to return their full output to the grid within 30 minutes of an ERCOT instruction.

将既有出力改送新负荷会减少更广电网可用的供应。ERCOT 表示，截至 2026 年 5 月获批的两项净计量安排均要求数据中心在收到指令时削减用电或切换至备用，并要求电站在收到 ERCOT 指令后 30 分钟内将全部出力回馈电网。

Operating states and deployment: island, bridge power, grid as backup

运行状态与部署：孤岛、过渡电力、电网作备用

“Islanded” is an operating state: a grid-connected datacenter opens the breaker and runs on its own generation. Then related but separate, the Department of Energy defines a “Microgrid” as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid,” and its Grid Deployment Office adds that a microgrid “can operate in either grid-connected or in island mode, including entirely off-grid applications”. In this piece, “islandable microgrid” means a grid-connected site that can separate; “off-grid microgrid” means a site with no connection at all. Many BTM projects use the term loosely, perhaps because it avoids saying “gas”.

“孤岛”是一种运行状态：并网数据中心断开断路器，以自身发电运行。与之相关但彼此独立的是，美国能源部将“微电网”定义为“在明确划定的电气边界内，一组相互连接的负荷与分布式能源资源，相对于电网表现为单一可控实体”，其电网部署办公室补充称，微电网“既可并网运行，也可孤岛运行，包括完全离网的应用场景”。在本文中，“可孤岛微电网”指能够解列的并网场址；“离网微电网”指完全没有电网连接的场址。许多表后项目对这个用词很随意，也许是因为可以借此不说“燃气”二字。

In practice, this may change a lot over time. Many BTM projects plan for a grid connection and use BTM as a “bridge” - once the utility delivers the connection, the generators can shift into a backup role. We described this in depth the Onsite Gas Deep Dive as the most popular approach because electricity systems benefit from substantial economies of scale in both cost and reliability. xAI’s Colossus 1 in Memphis has taken this route.

实践中，这会随时间发生很大变化。许多表后项目规划了电网接入，并把表后方案当作“过渡桥梁”——一旦公用事业公司交付接入，发电机便可转入备用角色。我们在《现场燃气深度报告》中深入描述过，这是最受欢迎的做法，因为电力系统在成本和可靠性上都受益于显著的规模经济。xAI 位于孟菲斯的 Colossus 1 走的就是这条路。

Other projects plan for a grid connection that will serve as “backup”, i.e. as a new energy resource that will help increase the expected uptime. We’ve seen projects planning for 2 or 3 “nines” of expected uptime while in full island mode, and adding an additional “nine” once grid-connected. We’ll provide more thoughts behind paywall on how many BTM plants will become grid-connected in coming years.

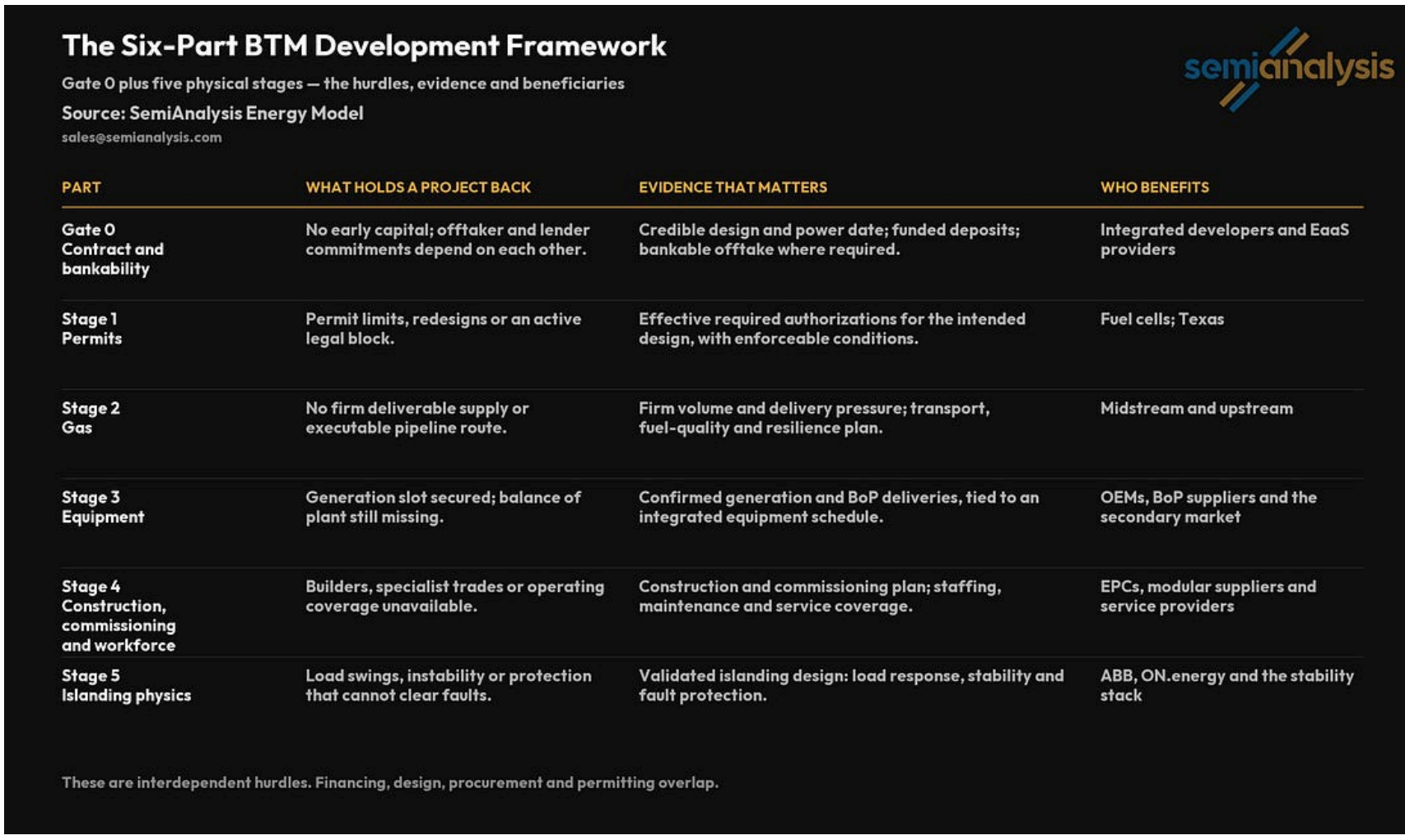
另一些项目规划的电网连接则将充当“备用”，即作为一种有助于提升预期可用运行时间的新增能源资源。我们看到有项目在完全孤岛模式下按 2 到 3 个“9”的预期可用性规划，并在并网后再增加一个“9”。关于未来几年有多少表后电站将实现并网，我们将在付费墙后提供更多思考。

Why is Building BTM So Hard?

为什么表后建设如此之难？

A turbine order and a nearby pipeline do not make a project. Between the press release and first power stand six key hurdles: contract & bankability, permits, fuel, equipment, workforce, and electrical physics. Our permit-level tracking shows booked capacity facing difficulties at nearly every one of them.

一纸轮机订单加一条邻近管道，并不等于一个项目。从新闻稿到首次送电之间横亘着六道关键关卡：合同与可融资性、许可、燃料、设备、劳动力和电气物理。我们的许可级追踪显示，几乎每一道关卡上都有已预订产能遭遇困难。



The Six-Part BTM Development Framework

Gate 0 plus five physical stages — the hurdles, evidence and beneficiaries

Source: SemiAnalysis Energy Model

sales@semianalysis.com

PART	WHAT HOLDS A PROJECT BACK	EVIDENCE THAT MATTERS	WHO BENEFITS
Gate 0 Contract and bankability	No early capital; offtaker and lender commitments depend on each other.	Credible design and power date; funded deposits; bankable offtake where required.	Integrated developers and EaaS providers
Stage 1 Permits	Permit limits, redesigns or an active legal block.	Effective required authorizations for the intended design, with enforceable conditions.	Fuel cells; Texas
Stage 2 Gas	No firm deliverable supply or executable pipeline route.	Firm volume and delivery pressure; transport, fuel-quality and resilience plan.	Midstream and upstream
Stage 3 Equipment	Generation slot secured; balance of plant still missing.	Confirmed generation and BoP deliveries, tied to an integrated equipment schedule.	OEMs, BoP suppliers and the secondary market
Stage 4 Construction, commissioning and workforce	Builders, specialist trades or operating coverage unavailable.	Construction and commissioning plan; staffing, maintenance and service coverage.	EPCs, modular suppliers and service providers
Stage 5 Islanding physics	Load swings, instability or protection that cannot clear faults.	Validated islanding design: load response, stability and fault protection.	ABB, ON.energy and the stability stack

These are interdependent hurdles. Financing, design, procurement and permitting overlap.

Source: SemiAnalysis Energy Model; sales@semianalysis.com

来源：SemiAnalysis 能源模型；sales@semianalysis.com

Gate 0: Contract and Bankability

关卡 0：合同与可融资性

Below, we'll discuss all the physical challenges in bringing online GW-scale islanded datacenters. But before getting there, there's perhaps an even bigger challenge: the financial one. Traditionally, one can connect to the grid very cheaply, with both interconnection requests and letter of credits being very modest. This was enough to develop credible sites, even at GW-scale, and led to a frantic search for power in the US and worldwide. It was easy to turn a quick profit with limited capital, i.e. a few million at most. We discussed this at length in our Onsite Gas Deep Dive, and our US Grid Constraints articles.

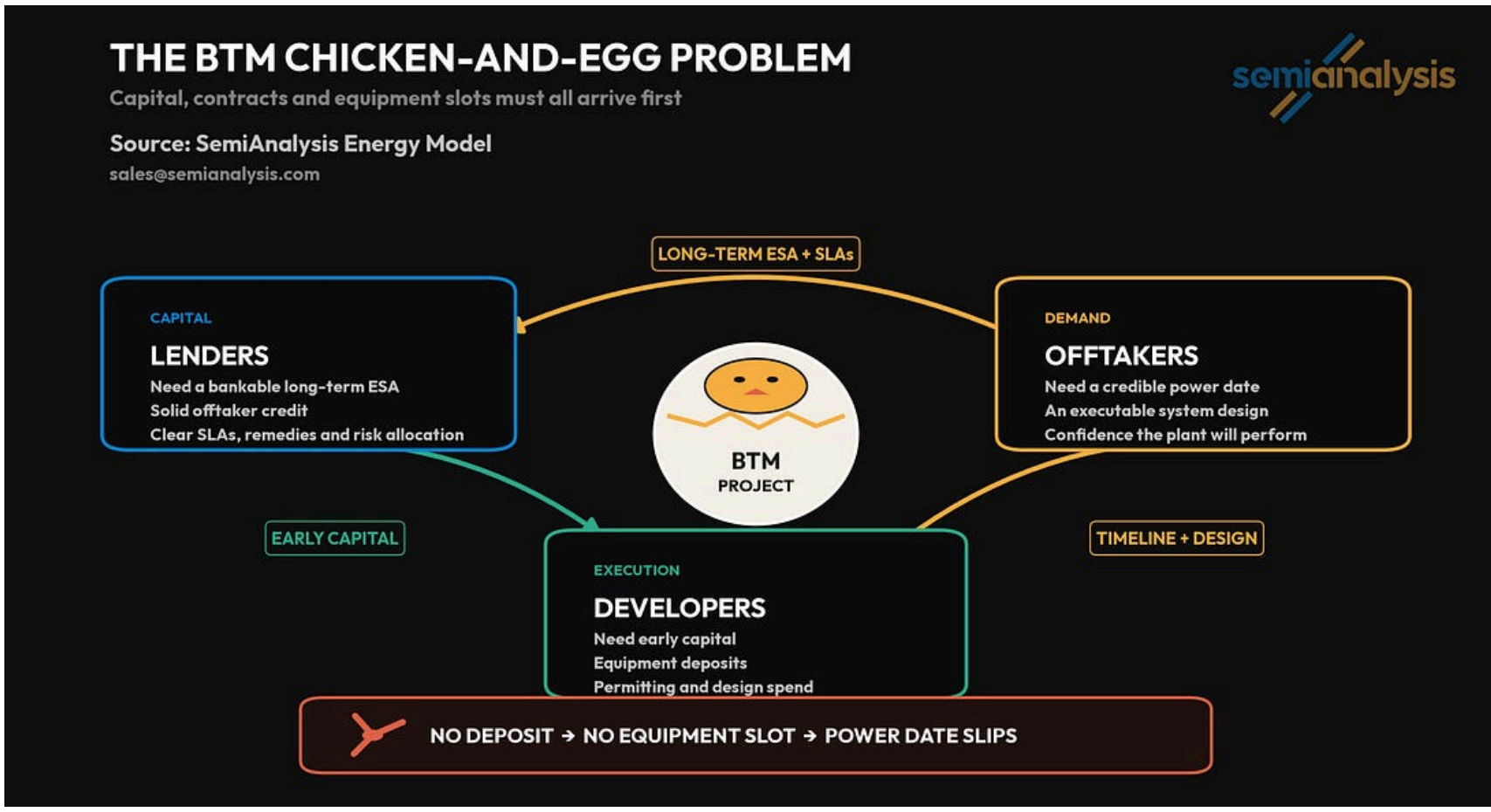
下面我们会讨论吉瓦级孤岛数据中心上线面临的所有物理挑战。但在那之前，还有一个或许更大的挑战：资金。传统上，接入电网的成本很低，互联申请和信用证金额都很小。这足以开发出可信的场址——即便是吉瓦级——并引发了美国乃至全球对电力的疯狂追逐。用有限资本（最多几百万美元）快速获利曾是轻而易举的事。我们在《现场燃气深度报告》和《美国电网约束》等文章中对此有详述。

Islanded datacenters are fundamentally different because there is no existing infrastructure to connect to. With power plants typically at ~5B per GW of IT capacity, and equipment deposits increasingly expensive, the upfront capital expenditure blocks many projects.

孤岛数据中心则有本质不同，因为没有既有基础设施可接。按每吉瓦 IT 容量约 50 亿美元的电站造价、且设备预付款日益昂贵计算，前置资本开支挡住了许多项目。

This leads to the classic BTM chicken-and-egg problem: lenders want a long-term ESA with a solid offtaker, and clear SLAs and other contractual terms. Offtakers want a credible timeline and project system design. Developers need early capital to pay for equipment deposits to provide that credible timeline and design. And with the insatiable demand for gas generation equipment, not having that capital means that timelines keep slipping.

这就引出了经典的表后“先有鸡还是先有蛋”难题：贷款方希望看到与可靠承购方签订的长期能源服务协议（ESA）、明确的 SLA 及其他合同条款；承购方希望看到可信的时间表和项目系统设计；开发商则需要早期资本支付设备预付款，才能给出可信的时间表和设计。而面对对燃气发电设备永不满足的需求，缺乏这笔资本就意味着时间表不断后滑。



Source: SemiAnalysis

来源：SemiAnalysis

Early successes have come in three forms:

早期成功以三种形式出现：

1. Full vertical integration, the Musk playbook: as discussed at length in our Colossus 2 article, xAI built its own power plant for self use, seeing it as the fastest way to build compute. This was most likely equity-funded.
2. 完全垂直整合，即马斯克打法：正如我们在《Colossus 2》一文中详述的，xAI 为自用建造了自己的电站，视其为最快的算力建设方式。这很可能是股权融资。
3. Full-scope datacenter developers: certain developers have both construction and energy in their core capabilities, and take responsibility for the BTM power plant when selling to hyperscalers. In a Yield on Cost model, they typically include the onsite power in the cost envelope - which then commonly crosses the $20M/MW mark. Full site-level details in our Datacenter Industry Model.
4. 全包式数据中心开发商：某些开发商将建设与能源都纳入核心能力，向超大规模云厂商出售时对表后电站负责。在成本收益率模型中，他们通常将现场电力纳入成本包络——这往往越过每兆瓦 2,000 万美元的关口。完整场址级细节见我们的数据中心行业模型。
5. Datacenter + power partnership: datacenter developers go-to-market together with power developers to sell a site to a hyperscaler. But the hyperscaler signs two separate contracts: one for the datacenter, one for power. Certain Oracle Stargate sites are built on such arrangements. The joint go-to-market means that the offtaker is offered a full-stack solution. But the main drawback is dealing with more parties, and facing a risk of paying stranded expenses if either the power or the datacenter are late - given the contracts are independent of each other.
6. 数据中心+电力联手：数据中心开发商与电力开发商共同开拓市场，向超大规模云厂商出售场址。但超大规模云厂商签署两份独立合同：一份针对数据中心，一份针对电力。Oracle Stargate 的某些场址即基于此类安排。联合拓市意味着向承购方提供全栈方案。但主要缺点是要应对更多当事方，并面临一旦电力或数据中心任一方延误便要承担搁浅费用的风险——因为两份合同彼此独立。

For BTM power, all of that complexity has led to the development of a new type of service providers: Energy-as-a-Service (EaaS) vendors. These are the new “BTM utilities”. Companies such as VoltaGrid deliver power, not just equipment, under long-term contracts with guaranteed capacity and up-time commitments. EaaS can do everything from leasing gensets to trucking compressed natural gas to site as ‘virtual pipelines’ while permanent power plants and actual pipelines are permitted, built, and commissioned.

就表后电力而言，所有这些复杂性催生了一类新型服务提供商：能源即服务（EaaS）厂商。它们就是新的“表后公用事业公司”。VoltaGrid 等公司在附带保障容量与可用性承诺的长期合同下交付的是电力，而不仅仅是设备。EaaS 可包揽一切：从租赁发电机组，到在永久电站与真实管道获准、建设与调试期间，用槽车把压缩天然气运到现场充当“虚拟管道”。

VoltaGrid has proved to be one of the winners of that trend, landing multiple gigawatts of orders with top tier developers like Vantage Datacenters. Others like Williams, Solaris are also on the rise and have scored massive contracts. Separately, some manufacturers are increasingly doing that themselves, such as Bloom Energy and Enchanted Rock. We track all of the supply chain, EPCs, BESS/SynCon and such for hundreds of projects in our Energy Model.

VoltaGrid 已证明是这一趋势的赢家之一，与 Vantage Datacenters 等一流开发商签下数吉瓦订单。Williams、Solaris 等其他公司也在崛起，斩获大额合同。另外，一些制造商正越来越多地亲自下场，如 Bloom Energy 和 Enchanted Rock。我们在能源模型中追踪数百个项目的全部供应链、EPC、BESS/同步调相机等。



Source: VoltaGrid

来源：VoltaGrid

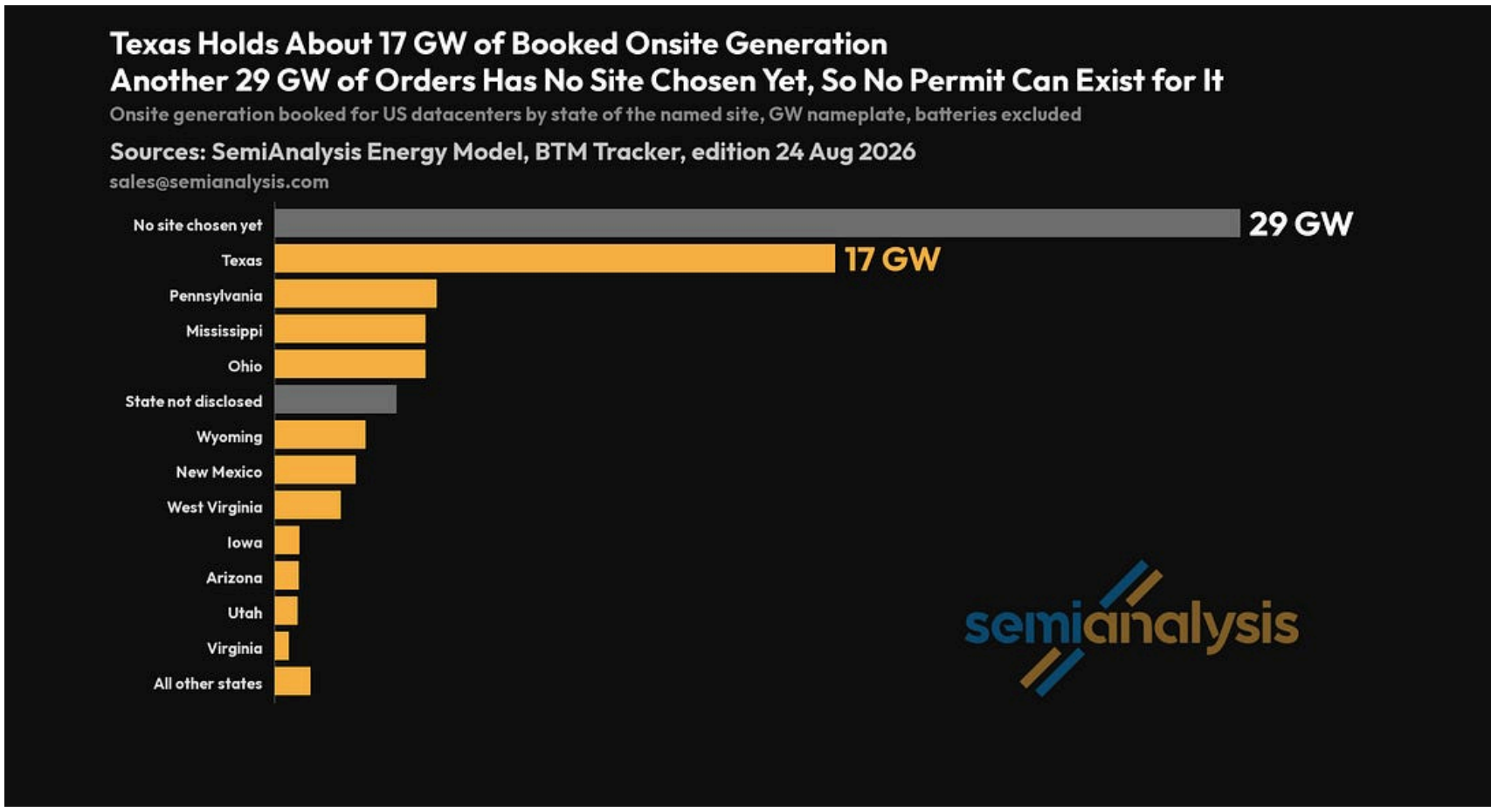
Does this capital wall mean that BTM is structurally disadvantaged versus the grid? ***It used to, but it's not anymore***. US Grid constraints are playing out in real-time, in two ways:

这道资本之墙是否意味着表后相对电网存在结构性劣势？***过去是，但现在不再是了***。美国电网约束正在实时显现，体现在两方面：

1. With firm US grid headroom being exhausted, serving a new GW-scale datacenter requires GW-scale generation paired with it. Capital requirements are commonly in the multi-billion-dollar-per-GW range today. Cheap GW-scale interconnections do not exist anymore.
2. 随着美国电网的确定性富余容量耗尽，服务一个新的吉瓦级数据中心需要配套吉瓦级发电。如今资本需求普遍达到每吉瓦数十亿美元量级。廉价的吉瓦级互联接入已不复存在。
3. Most utilities are notoriously slow and unreliable, and grid ESAs typically aren't as binding and don't have as many penalties as a BTM contracts in case of late delivery or uptime issues. It makes sense, they're very different contracts in nature. As such, for GW-scale projects where speed and credibility of execution matters, BTM is an increasingly competitive play.
4. 大多数公用事业公司出了名的缓慢且不可靠，而且电网 ESA 通常不像表后合同那样具有约束力，在延误交付或可用性问题上也没有那么多违约金。这说得通，因为两者本质上是截然不同的合同。因此，对于速度与执行可信度至关重要的吉瓦级项目，表后日益成为有竞争力的选择。

Therefore,

更大的启示是：开发商如今选择辖区几乎像选择设备一样谨慎。同一座电站在一个州可能走标准化登记，在另一个州可能要逐案审批的空气许可，在第三个州则要分别取得空气、选址和发电批准。



Sources: SemiAnalysis Energy Model; Sales@semianalysis.com

来源：SemiAnalysis 能源模型；Sales@semianalysis.com

That asymmetry between states, as much as cheap gas, explains why Texas is set to host more of the BTM fleet than any other state. The state determines how the process plays out but federal rules set most of the parameters. The Environmental Protection Agency (EPA) sets the core air-quality standards, emissions definitions and major-source framework; state and local authorities usually administer those rules, issue the permits and add their own authorization routes.

州与州之间的这种不对称，加上廉价的天然气，解释了为什么得州承载的表后机组将超过其他任何州。州决定流程如何展开，但联邦规则设定了大部分参数。美国国家环境保护局（EPA）制定核心空气质量标准、排放定义和重大源框架；州和地方当局通常负责执行这些规则、颁发许可并增设自己的审批路径。

How the Air Permit Thresholds Work

空气许可阈值如何运作

Potential to emit (PTE) is the tonnage a plant would emit running flat out all year, counted per pollutant. Every US air permit tests PTE. For a gas generator the two pollutants that matter are nitrogen oxides (NOx) and carbon monoxide (CO). Two federal lines apply. A plant with PTE above 250 tons a year of any pollutant goes through a full major-source review: modeling, a public process, and potentially years added to the timeline. A plant with PTE above 100 tons also needs a Title V operating permit, a second layer of federal oversight. States set their own lines below the federal ones.

潜在排放量（PTE）是电站全年满负荷运行会排放的吨数，按污染物分别计算。美国每一份空气许可都要检验 PTE。对燃气发电机而言，两种关键污染物是氮氧化物（NOx）和一氧化碳（CO）。两条联邦线适用：任何污染物 PTE 超过每年 250 吨的电站须走完整的重大源审查：建模、公众程序，并可能给时间表增加数年。PTE 超过 100 吨的电站还需 Title V 运营许可证，这是第二层联邦监管。各州在联邦线之下自行划线。

Tiers:

层级：

1. Exempt as a nonroad engine: A portable engine that stays on site under 12 months
2. 作为非道路发动机豁免：在现场停留不超过 12 个月的可移动发动机
3. Sits outside stationary-source permitting. Works for reciprocating engines only: any turbine of 10 million Btu an hour or more falls under a federal emission standard, confirmed by EPA's January 2026 turbine rule. Mississippi exempted xAI's trailer-mounted Southaven turbines under a state rule; that decision is being challenged in federal court; 40 CFR 1068.30.
4. 位于固定源许可体系之外。仅适用于往复式发动机：任何每小时 1,000 万英热单位以上的轮机都受联邦排放标准约束，EPA 2026 年 1 月的轮机规则证实了这一点。密西西比州依据州规则豁免了 xAI 拖车式的 Southaven 轮机；该决定正在联邦法院受到挑战；40 CFR 1068.30。
5. Minor New Source Review (NSR): PTE below every major threshold
6. 小型新源审查（NSR）：PTE 低于所有重大阈值
7. A construction permit from the state or county, which sets the exemption cutoffs and how much modeling is needed. Public comment of at least 30 days. A plant that accepts an enforceable cap on hours or fuel to stay under the lines is a "synthetic minor"; changing that cap later triggers a full major-source review as if the plant were new; 40 CFR 51.160 to 51.161; 40 CFR 52.21(r)(4).
8. 由州或县颁发的建设许可，豁免截止线和所需建模量由其规定。至少 30 天公众意见期。接受可执行的运行小时或燃料上限以压在阈值之下的电站属于"合成小型源"；日后更改该上限将触发完整的重大源审查，如同新建电站一般；40 CFR 51.160 至 51.161；40 CFR 52.21(r)(4)。
9. Prevention of Significant Deterioration (PSD), the major-source review: PTE of 250 tons a year of any pollutant. 100 tons for 28 listed industries; EPA reads "steam electric plant" to cover combined-cycle plants, while simple-cycle plants are treated as unlisted and so face the

250-ton limit.

10. 防止显著恶化（PSD），即重大源审查：任何污染物 PTE 达每年 250 吨。28 个列名行业为 100 吨；EPA 将“蒸汽电厂”解读为涵盖联合循环电站，而简单循环电站被视为未列名，因此适用 250 吨上限。

11. Usually issued by the state. Once major for one pollutant, the plant applies Best Available Control Technology to every pollutant above the significance rates (40 tons of NOx, 100 of CO), models its air-quality impact, usually supplies a year of monitoring data, and takes at least 30 days of public comment. The Clean Air Act requires a decision within a year of a complete application (section 165(c)); no national data on actual times exists; 40 CFR 52.21.

12. 通常由州颁发。一旦因某一种污染物被认定为重大源，电站须对每一种超过显著率（NOx 40 吨、CO 100 吨）的污染物采用最佳可用控制技术，对空气质量影响建模，通常提交一年监测数据，并接受至少 30 天公众意见。《清洁空气法》要求在申请材料完备后一年内作出决定（第 165(c) 条）；实际耗时没有全国性数据；40 CFR 52.21。

13. Nonattainment NSR: The area fails a federal air standard for the pollutant. It replaces PSD for that pollutant; PSD still applies to the rest.

14. 未达标区 NSR：该区域未达到该污染物的联邦空气标准。它在该污染物上取代 PSD；PSD 对其余污染物仍然适用。

15. The limit falls to 100 tons a year, then to 50, 25 or 10 tons of NOx and VOC as an ozone area is rated serious, severe or extreme (Clean Air Act 182). The plant must meet the Lowest Achievable Emission Rate and buy offsetting cuts from other sources in the same area, at 1.1 to 1.5 tons per ton. Location sets the line: Dallas and Houston sit at 25 tons, Chicago, Salt Lake City and Las Vegas at 50, Northern Virginia and Phoenix at 100 (EPA Green Book); 40 CFR 51.165.

16. 上限降至每年 100 吨，并随臭氧区被评为严重、较重或极端而进一步降至 NOx 和 VOC 的 50、25 或 10 吨（《清洁空气法》第 182 条）。电站必须满足最低可实现排放率，并以每吨 1.1 到 1.5 吨的比率向同区域其他排放源购买抵减量。地理位置决定上限：达拉斯和休斯敦为 25 吨，芝加哥、盐湖城和拉斯维加斯为 50 吨，北弗吉尼亚和菲尼克斯为 100 吨（EPA 绿皮书）；40 CFR 51.165。

17. Title V operating permit: PTE of 100 tons a year or more, on top of whichever construction permit applies.

18. Title V 运营许可证：PTE 达每年 100 吨或以上，叠加于适用的建设许可之上。

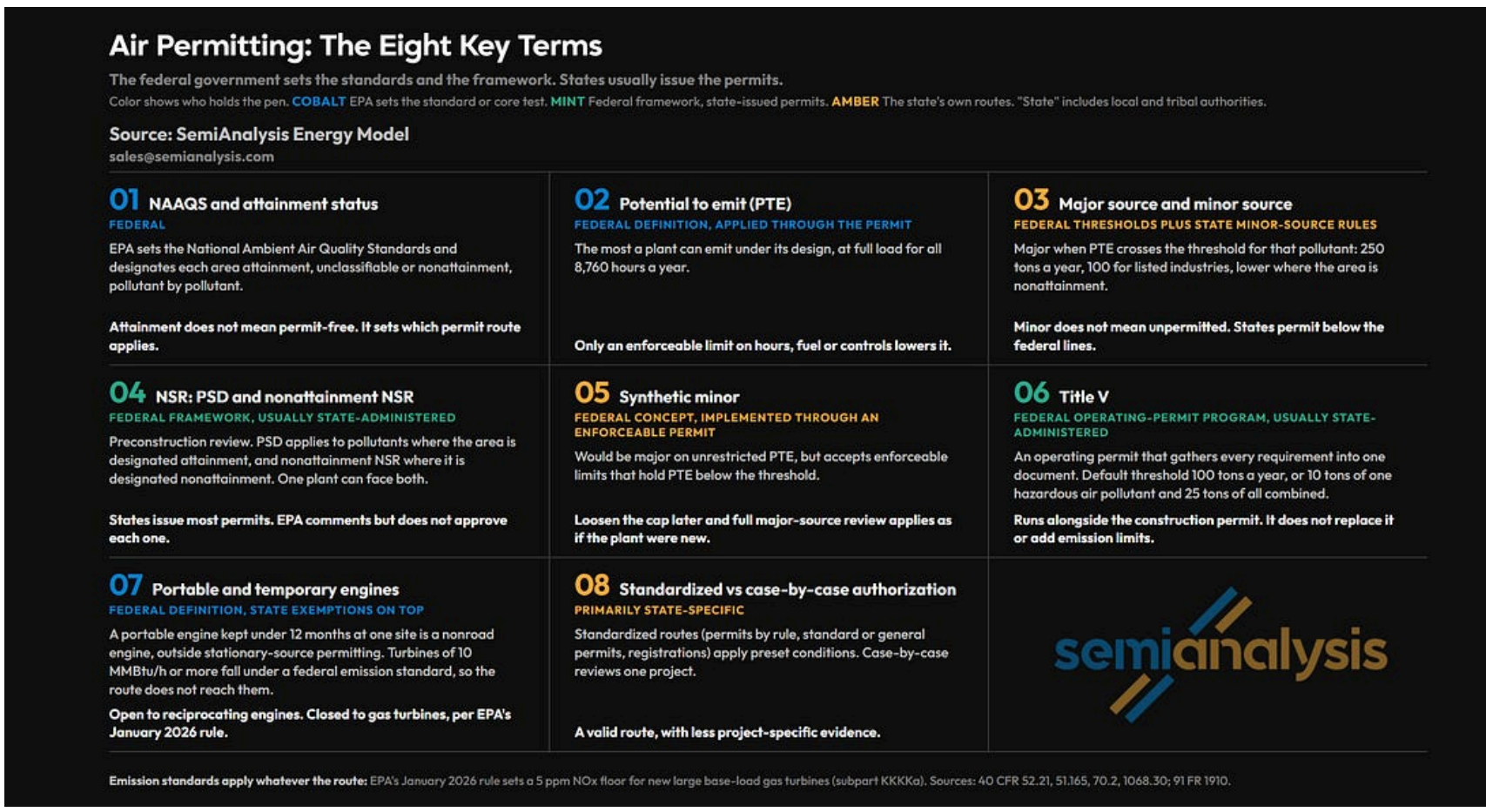
19. Applied for within 12 months of commissioning. Gathers every requirement into one enforceable document with a five-year term. EPA gets 45 days to object and the public 60 days to petition. Adds monitoring, reporting and fees, and sets no new emission limits of its own; 40 CFR 70.2.

20. 须在投运后 12 个月内申请。将所有要求汇入一份可执行的五年期文件。EPA 有 45 天异议期，公众有 60 天请愿期。增加监测、报告和费用，本身不设定新的排放限值；40 CFR 70.2。

Three caveats.

三点说明。

1. The 250-ton line for simple-cycle plants rests on consistent agency practice, including Mississippi’s own xAI permit, not on a written EPA ruling.
2. 简单循环电站适用 250 吨线，依据的是监管机构一以贯之的实践（包括密西西比州自己的 xAI 许可），而非 EPA 的书面裁定。
3. States differ below the federal lines. Texas requires control technology for every new facility. Virginia permits anything above 40 tons of NOx. California districts trigger controls at 10 pounds a day.
4. 各州在联邦线以下各行其是。得州要求每个新设施都采用控制技术。弗吉尼亚州对 NOx 超过 40 吨的设施都要许可。加州各空气区以每天 10 磅为触发控制的标准。
5. Federal emission standards apply whatever the permit tier. The January 2026 rule sets a 5 ppm NOx floor for new large turbines running base load. That means selective catalytic reduction from day one.
6. 无论许可层级如何，联邦排放标准均适用。2026 年 1 月的规则为基荷运行的新大型轮机设定了 5 ppm 的 NOx 下限。这意味着从第一天起就要用选择性催化还原。



Sources: SemiAnalysis Energy Model; Sales@semianalysis.com

来源：SemiAnalysis 能源模型；Sales@semianalysis.com

Small emissions rates become big annual totals at campus scale. At an illustrative controlled NOx rate of 0.10g/kWh, 250MW × 8,760 hours produces about 241 US short tons a year; the same calculation reaches 250 tons at roughly 259MW. The actual answer depends on the equipment's controlled emissions, the applicable threshold and which units the regulator counts together as one source.

在园区尺度上，很小的排放率也会累积成庞大的年度总量。以示例性的受控 NOx 排放率 0.10g/kWh 计算，250MW × 8,760 小时每年约产生 241 美制短吨；同一算法在约 259MW 时达到 250 吨。实际答案取决于设备的受控排放、适用阈值，以及监管者将哪些机组合并计为一个排放源。

That leaves developers working on both plant size and the operating plan. A phased authorization can, where the project and rules allow it, bring an initial tranche online while approval for the larger build progresses. But the hours and emissions limits must survive contact with the intended operating schedule and be enforceable. The regulator needs a credible plan for how the whole campus will run.

这使得开发商不得不在电站规模和运行方案上双管齐下。在项目和规则允许的情况下，分阶段审批可以让首批机组先行上线，同时更大规模建设的审批继续推进。但小时数和排放限值必须经得起既定运行计划的检验并具备可执行性。监管者需要一份关于整个园区如何运行的可靠方案。

Project Jupiter: Grand Designs

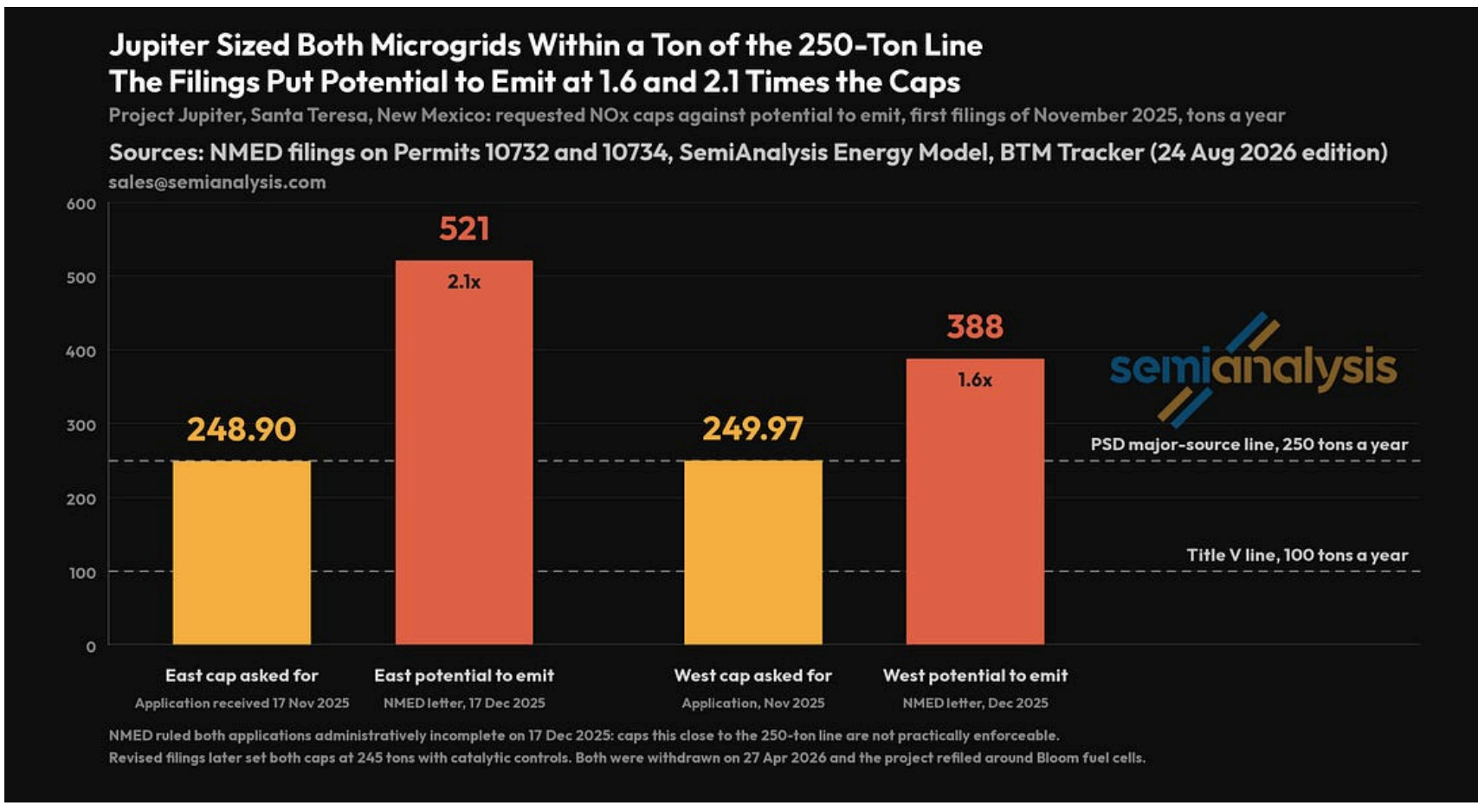
Jupiter 项目：宏大设计

UK television legend and architecture critic Kevin McCloud would be raising his eyebrow at Oracle's Project Jupiter because it shows how permitting can force the redesign of an entire facility at breakneck speed.

英国电视界传奇、建筑评论家凯文·麦克劳德（Kevin McCloud）若看到 Oracle 的 Jupiter 项目，恐怕要挑起眉毛，因为它展示了许可能如何逼迫整个设施以惊人的速度重新设计。

The original applications were filed on 17 November 2025 for two separate microgrids, East and West, each sized to sit just under the federal 250-ton major-source line. The West application proposed 34 GE TM2500 and 20 Mitsubishi FT8 units (54 turbines, roughly 1,677 MW) with the East microgrid at a higher scale. The strategy was to operate as a synthetic minor: install equipment capable of emitting well above the major-source threshold, then accept operating limits that keep permitted emissions just beneath it. The East microgrid reported the potential to emit of 521 tons of NOx a year and requested a cap of 248.90, 1.1 tons under the line.

最初申请于 2025 年 11 月 17 日提交，针对东、西两个独立微电网，各自规模恰好压在联邦 250 吨重大源线之下。西侧申请拟建 34 台 GE TM2500 和 20 台三菱 FT8（54 台轮机，约 1,677MW），东侧微电网规模更大。策略是以合成小型源方式运行：安装排放能力远超重大源阈值的设备，再接受将获准排放压至阈值之下的运行限制。东侧微电网申报的 NOx 潜在排放量为每年 521 吨，申请上限 248.90 吨，比线低 1.1 吨。



Sources: SemiAnalysis Energy Model; sales@semianalysis.com

来源：SemiAnalysis 能源模型；sales@semianalysis.com

New Mexico's Environment Department determined that limits set so close to the threshold were not practically enforceable. The applicant resolved that by dropping both caps to 245 tons, and the department ruled both applications complete and published its intent to issue - but some 7,155 public comments came in, the Secretary concurred in holding a hearing, and the applicant withdrew both on 27 April 2026, the day it announced the fuel-cell redesign.

新墨西哥州环境部认定，如此贴近阈值的限值在实践中不可执行。申请人将两个上限均降至 245 吨以解决该问题，该部门随即裁定两份申请材料完备并公布签发意向——但收到约 7,155 条公众意见，部长同意举行听证会，申请人遂于 2026 年 4 月 27 日撤回两份申请，当天即宣布了燃料电池重新设计。

The project then abandoned the turbine design and refiled around Bloom Energy solid-oxide fuel cells in April. The revised proposal targets roughly 37 tons per year of NOx, around 92% below the original turbine configuration.

项目随后放弃轮机方案，于 4 月围绕 Bloom Energy 固体氧化物燃料电池重新申报。修订后的方案 NOx 目标约为每年 37 吨，比原轮机配置低约 92%。

The technology change did not make the permit issues disappear. On August 23, 2026, the New Mexico Supreme Court stayed the administrative air-permitting proceeding until further order. The stay paused the process rather than deciding the merits of the application, and on September 1 the

justices unanimously refused the developer's request to lift it even temporarily. The regulator's decision deadline is November 23, 2026.

技术路线的更换并未让许可问题消失。2026 年 8 月 23 日，新墨西哥州最高法院中止了行政空气许可程序，直至另行命令。该中止令只是暂停流程，并未对申请本身的是非曲直作出裁决；9 月 1 日，大法官们一致驳回了开发商即使临时解除中止令的请求。监管机构的决定截止日期为 2026 年 11 月 23 日。

The Fuel-Cell Escape Hatch

燃料电池的逃生通道

Fuel cells offer an escape hatch from the trickiest part of permitting but not from the permit process itself.

燃料电池为许可中最棘手的部分提供了一条逃生通道，但并不能绕开许可程序本身。

The technology generates electricity electrochemically rather than through flame combustion, generally producing far less NOx and other conventional pollutants than a comparable fleet of turbines or reciprocating engines. Depending on the site and configuration, fuel cells can keep a project below PSD major-source thresholds and allow it to follow a standardized or minor-source route instead. They still require permits and still produce CO_2 and smaller quantities of other pollutants, but the advantage here is a lighter regulatory profile, not zero emissions.

该技术通过电化学反应而非火焰燃烧发电，通常产生的 NOx 和其他常规污染物远少于同等规模的轮机或往复式发动机群。视场址和配置而定，燃料电池可使项目低于 PSD 重大源阈值，转而走标准化或小型源路径。它们仍需许可，仍会产生二氧化碳及其他少量污染物，但其优势在于更轻的监管负担，而非零排放。

AEP Ohio's 72.9MW Bloom installation at AWS's Hilliard site in Ohio shows the wrinkles in permitting fuel cells, remaining below the thresholds that would have triggered the major-source route. The project still required an Ohio EPA air permit and separate state siting approval, while the air permit was appealed by the City of Hilliard in November 2025.

AEP Ohio 在 AWS 位于俄亥俄州 Hilliard 园区的 72.9MW Bloom 装机展示了燃料电池许可中的波折：项目维持在会触发重大源路径的阈值之下，但仍需俄亥俄州 EPA 空气许可和单独的州选址批准，且空气许可于 2025 年 11 月被 Hilliard 市提起上诉。

Nebius also made the technology trade in its first BTM US deployment, replacing the previously planned combustion-based generation with 328MW of Bloom fuel cells under a 10-year power agreement, with the company pointing to faster deployment and the lighter permitting burden as advantages of the switch.

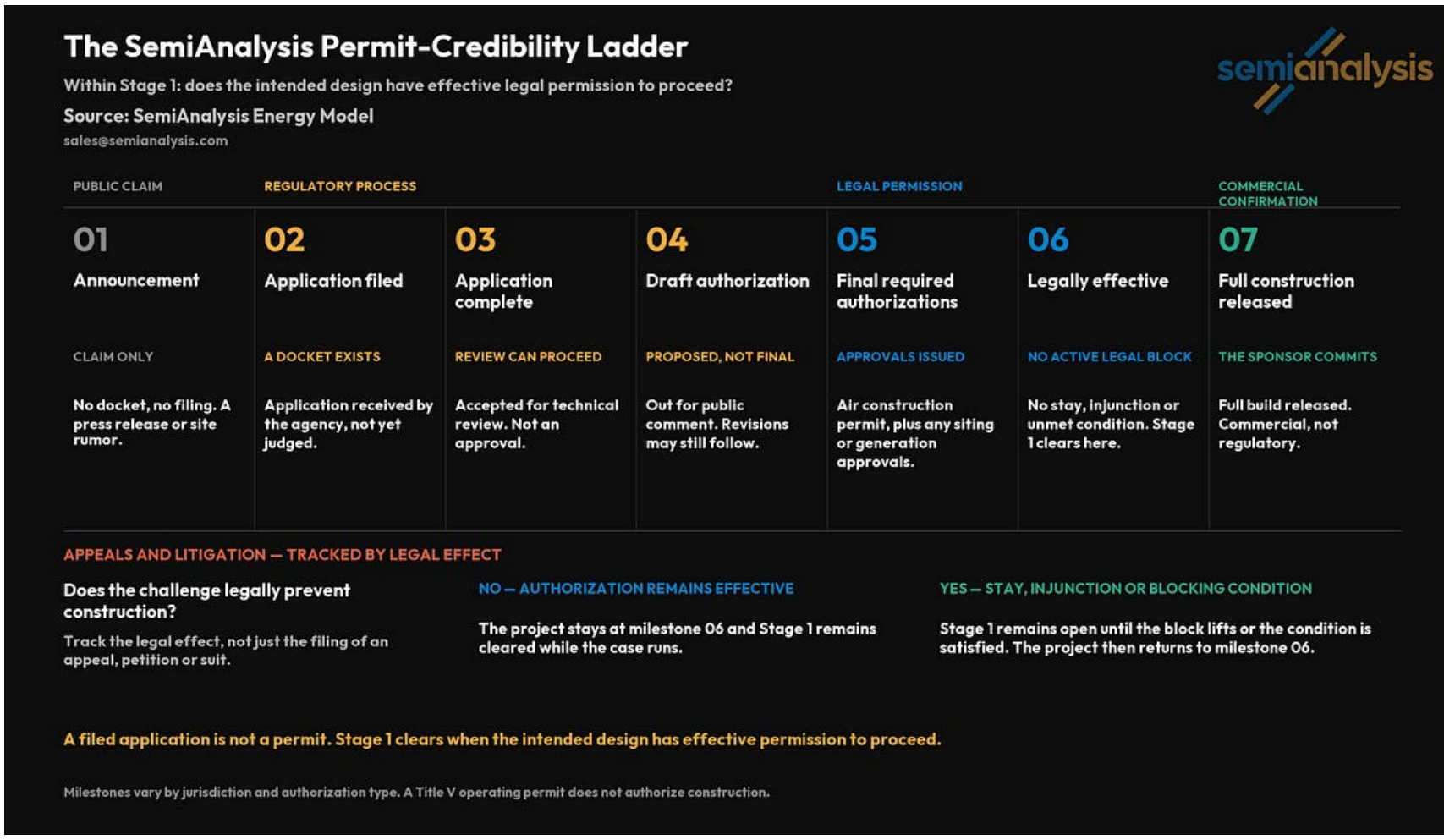
Nebius 在其首个美国表后部署中也做了技术取舍，以 10 年期电力协议用 328MW 的 Bloom 燃料电池取代原计划的燃烧式发电，公司称部署更快、许可负担更轻是该切换的优势。

Fuel cells can accelerate projects through the permitting matrix but can also make speculative projects easier to decorate. In one Texas filing we found, a proposed 560MW Bloom fuel-cell plant paid a $900 standard-permit fee and moved from application receipt on December 19, 2025, to authorization on January 14, 2026, TCEQ concluding that the installation was not a major source under either PSD or Title V.

燃料电池可以加速项目穿越许可矩阵，但也让投机性项目更容易"涂脂抹粉"。在我们发现的一份得州申报中，一座拟建的 560MW Bloom 燃料电池电站缴纳了 900 美元标准许可费，从 2025 年 12 月 19 日收到申请到 2026 年 1 月 14 日获得批准，TCEQ 认定该设施在 PSD 和 Title V 下均非重大源。

A standard permit confirms that a proposed equipment configuration fits a pre-written emissions envelope. It does **not** prove that the datacenter has a committed tenant, financing, purchased equipment, firm gas supply or a construction notice to proceed. That is why we do not treat "permitted" as a greenlight for a new BTM project.

标准许可只能确认拟议设备配置符合预先写好的排放包络。它**不能**证明数据中心已有确定的租户、融资、已购设备、确定性燃气供应或施工开工令。这就是为什么我们不把"已获许可"视为新表后项目的放行信号。



Source: SemiAnalysis Energy Model

来源：SemiAnalysis 能源模型

Note that another often overlooked constraint for permitting is water. For radiator-cooled recips, process-water demand can be very low: the radiators dump engine heat into the air. But for certain single cycle turbines, water or steam injection for NOx control creates a continuing water requirement, while dry low-emissions (DLE) combustion avoids that injection. The turbine package matters as much as the technology label. For example, the Pratts FT8 MOBILEPAC use water injection.

请注意，许可中另一个常被忽视的约束是水。对散热器冷却的往复式发动机而言，工艺用水需求可以很低：散热器把发动机热量直接排入空气。但对某些单循环轮机，用于 NOx 控制的水或蒸汽喷射会造成持续的用水需求，而干式低排放（DLE）燃烧则避免了这种喷射。轮机整体方案与技术标签同样重要。例如，Pratt 的 FT8 MOBILEPAC 就使用注水。

Combined cycle adds another decision. Wet recirculating cooling loses water through evaporation and blowdown, the discharge used to keep dissolved material from building up. Dry cooling rejects that heat to the air.

联合循环则增加另一项决策。湿式循环冷却会通过蒸发和排污（为防止溶解物累积而排放的水）损失水量；干式冷却则将热量散给空气。

Stage 2: Gas

阶段 2：天然气

Now, while permits are a core site selection constraint, fuel adds a second one. The US is awash with natural gas: high oil prices maintain the incentive to drill baby drill, and the gas that comes out as a by-product needs to find a home somewhere, while Appalachia and the Haynesville add ample supply of dry gas (not associated with oil extraction).

许可固然是选址的核心约束，燃料又添一道。美国天然气泛滥：高油价维持着“放开钻探”的动力，作为副产品产出的天然气需要找到去处，而阿巴拉契亚和 Haynesville 则提供充足的干气（不伴生石油开采）供应。

However, the hard part is transportation of that gas. Building pipelines can be simultaneously the hardest and easiest aspect of the BTM datacenter construction process, but like permitting, it depends quite significantly on geography. In addition, one pipeline typically isn’t enough. A firm contract is tied to a maximum daily quantity, specific receipt and delivery points and, where agreed, minimum delivery pressure; interruptible service can be curtailed when the pipe tightens. A line on the map is therefore weak, what matters is how much firm gas can physically reach the plant’s meter. The physical fuel system also has to survive a failure. Depending on the site, that can mean independent feeds, redundant internal distribution, stored LNG or dual-fuel capability, plus redundant boost compression where inlet pressure requires it. Gas quality matters too: changes in methane number, heating value and Wobbe index can force control changes or derating if they move outside the machine’s fuel envelope.

然而，难点在于天然气的运输。建设管道既可能是表后数据中心建设过程中最难的一环，也可能最容易，但与许可一样，这在很大程度上取决于地理条件。此外，一条管道通常不够。确定性合同与最大日供量、指定接收与交付点以及（如经约定）最低交付压力挂钩；当管道趋紧时，可中断服务会被削减。因此，地图上的一条线说明不了什么，关键是有多少确定性天然气能实际输到电站计量表前。物理燃料系统还必须能扛住故障。视场址而定，这可能意味着独立气源、冗余的内部配气、储存的 LNG 或双燃料能力，外加在进气压力有要求时的冗余增压压缩。天然气品质同样重要：甲烷值、热值和沃贝指数的变化一旦超出机器的燃料包络，就可能迫使控制调整或降额。

A couple of examples of large projects:

几个大型项目的例子：

- To build a pipeline in Texas, you only have to answer the Texas Railroad Commission, meaning datacenter developers in the state are increasingly just building the pipeline themselves. Federal water-crossing permits and easements still apply, and a purely private lateral gets no condemnation power, so a single holdout forces a reroute. Crusoe filed by itself for the 16-inch line to Duroc power plant at Abilene, and Trailblazer Infrastructure - the Sweetwater developer, unrelated to Tallgrass’s Trailblazer system - budgets $120M for a 31-mile extension in its tax-increment finance plan. Add this to ERCOT’s connection rules and some of the cheapest gas in the country, and you have another explanation for why so much of this build-out is planned in Texas.
- 在得州建管道，你只需要对得州铁路委员会一个机构交代，这意味着该州的数据中心开发商正越来越多地自己动手建管道。联邦跨水域许可和地役权仍然适用，而一条纯私有支线没有征收权，因此一个“钉子户”就能迫使改线。Crusoe 自行为通往阿比林 Duroc 电站的 16 英寸管道提出申请；Trailblazer Infrastructure——Sweetwater 的开发商，与 Tallgrass 的 Trailblazer 系统无关——在其税收增额融资计划中为一条 31 英里延长线编列了 1.2 亿美元预算。再加上 ERCOT 的接网规则和全美最便宜的天然气之一，你就有了为什么这么多建设规划落在得州的另一个解释。
- In Louisiana, Energy Transfer subsidiary ETC Tiger Pipeline is building the Franklin Farms lateral - 13.2 miles of 36-inch pipe at a billion cubic feet a day, plus a shorter branch - to feed Entergy Louisiana’s new combined-cycle plants, which in turn power Meta’s Hyperion campus over the grid. Entergy, not Meta, is the shipper, so this is the utility-served route rather than a behind-the-meter one. Even with no compression, it still runs 19 months from the federal filing in July 2026 to a February 2028 in-service date.
- 在路易斯安那州，Energy Transfer 旗下 ETC Tiger Pipeline 正在建设 Franklin Farms 支线——13.2 英里、36 英寸、日输量 10 亿立方英尺，外加一条较短的分支——为 Entergy Louisiana 的新联合循环电站供气，后者再通过电网为 Meta 的 Hyperion 园区供电。托运方是 Entergy 而非 Meta，所以这是公用事业供电路线，而非表后路线。即便无需增压，从 2026 年 7 月联邦申报到 2028 年 2 月投运仍需 19 个月。
- New Mexico. Again we arrive at Oracle’s Project Jupiter. The campus is set to received pipeline gas from the Transwestern-built Green Chile pipeline. That pipeline was contractually due in service on 15 August this year, but the date passed without even an approved route, let alone a start to pipe laying. On 14 August Transwestern filed a new in-service date of 1 February 2027, with the federal apparatus moving unusually fast. This speed will need to continue if that start date of February next year is to be met, with a FERC order required in the next two months. No comparable certificate on record has been issued that fast, and none of the 33 comparable projects we have tracked was approved before the public comment period closed. Our estimation is first gas in April or May 2027, with full ramping up to the 2.45 GW in mid-2028, however, there are several hurdles to overcome before that.
- 新墨西哥州。我们又回到了 Oracle 的 Jupiter 项目。该园区将从 Transwestern 建设的 Green Chile 管道获得管道气。这条管道合同约定于今年 8 月 15 日投运，但该日期已过，路由甚至尚未获批，更不用说开始铺管。8 月 14 日，Transwestern 申报了新的投运日期：2027 年 2 月 1 日，联邦机构的推进速度异常之快。若要赶上明年 2 月的开工日期，这种速度必须保持下去，未来两个月内就需要 FERC 出具命令。有记录以来没有任何类似证书以这种速度签发，我们追踪的 33 个可比项目中，没有一个在公众意见期结束前获批。我们估计首次供气在 2027 年 4 月或 5 月，到 2028 年年中全面爬坡至 2.45GW，不过在此之前还有几道坎要过。

The fuel contracts and pipeline filings can also help separate wheat from the chaff. A nearby pipeline doesn’t prove much, but a firm transportation contract, signed gas supply agreement, or a pipeline application filed at the regulator can help understand which sites may be on the way to receiving gas for their site.

燃料合同和管道申报也有助于去芜存菁。附近有管道说明不了什么，但一份确定性运输合同、已签署的供气协议，或在监管机构提交的管道申请，能帮助判断哪些场址可能正在获得供气的路上。

Some interesting observations:

一些有意思的观察：

- Energy Transfer contracted 150 MMcf/d to the Nexus Hubbard campus, enough to run about 750 MW of the reciprocating engines actually ordered. But the campus's pending air permit covers a 5,230MW fleet, meaning it needs about seven times the contracted gas supply , so either there are more gas contracts are coming, or permitting was a hedge ahead of contracting gas supply.
- Energy Transfer 向 Nexus Hubbard 园区签约供气 150 MMcf/d，足以运行约 750MW 实际订购的往复式发动机。但该园区待批的空气许可覆盖 5,230MW 机组，意味着它需要约七倍于已签约的供气量，因此要么还有更多天然气合同在路上，要么许可是提前于供气签约的对冲之举。
- Liberty Energy's joint venture with PowerBridge covers a planned 2 GW campus in West Texas, with more than 300 MW of generation in a first phase targeted for the fourth quarter of 2027. Liberty told investors on July 22, 2026 that the site would start behind the meter, likely inside ERCOT's Batch Zero, and could take a grid connection of undetermined size in 2028. Most of the campus would then sit behind a private use network, the ERCOT structure that nets a site's generation against its load at a single connection, which we explain in US Grid Constraints.
- Liberty Energy 与 PowerBridge 的合资企业覆盖西得克萨斯一座规划 2GW 的园区，首期超过 300MW 发电产能的目标是 2027 年第四季度。Liberty 于 2026 年 7 月 22 日告诉投资者，该场址将以表后方式启动，很可能位于 ERCOT 的 Batch Zero 之内，并可能在 2028 年接入规模未定的电网连接。园区大部分届时将处于私用网络之后——这是 ERCOT 在单一接入点将场址发电与负荷相抵的结构，我们在《美国电网约束》中有解释。

Stage 3: Equipment

阶段 3：设备

The market for turbines, reciprocating engines and other types of generation equipment has grown significantly so far this year, with new manufacturers coming into the fold and existing OEMs increasing manufacturing capacity to keep pace with the growing demand for onsite power generation.

今年以来，轮机、往复式发动机及其他发电设备市场显著增长，新制造商不断加入，现有 OEM 也在扩大制造产能，以跟上现场发电日益增长的需求。

In our Onsite Gas Deep Dive we went through the new types of technology and incumbent manufacturers, so you can go through the different types of equipment available to datacenter operators in that article.

我们在《现场燃气深度报告》中梳理了新技术类型和在位制造商，读者可在该文中了解数据中心运营商可用的各类设备。

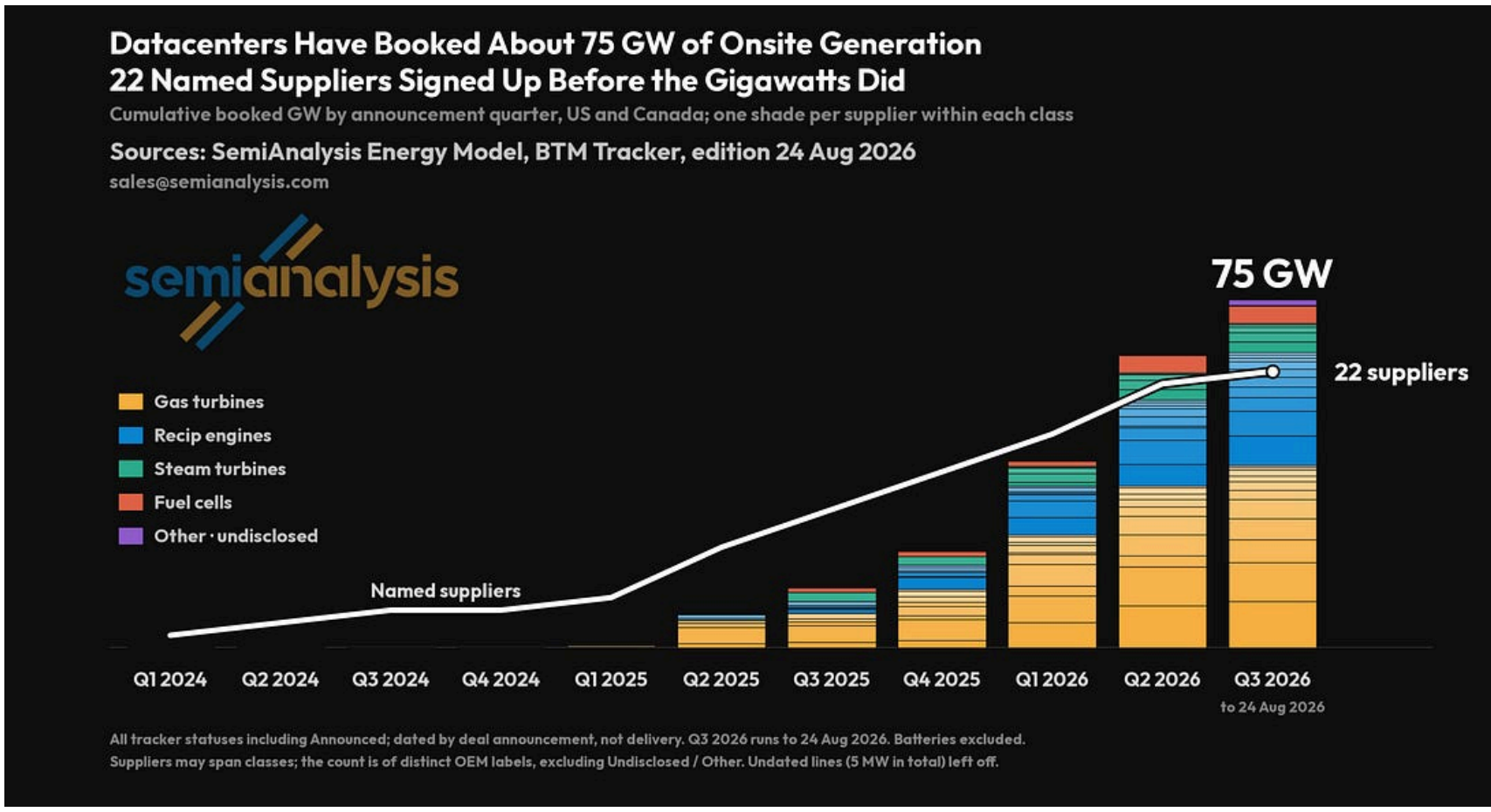
Since writing in December 30, 2025 article, the three broad categories have remained unchanged:

自 2025 年 12 月 30 日的文章以来，三大类设备保持不变：

1. Gas turbines (GTs):
2. 燃气轮机（GT）：
3. industrial gas turbines (IGTs), smaller, heavier machines in the tens of megawatts;
4. 工业燃气轮机（IGT），数十兆瓦级、更小更重的机器；
5. aeroderivatives (aeros), jet engines repackaged for power in the 30 to 115 MW range and able to ramp in 5 to 8 minutes; and
6. 航改型（aero），即重新封装用于发电的喷气发动机，功率 30 至 115MW，可在 5 到 8 分钟内完成爬坡；
7. heavy-duty frame turbines of roughly 400 MW, with increased fuel efficiency when put into a combined cycle with steam turbines.
8. 约 400MW 的重型框架式轮机，与汽轮机组成联合循环时可提升燃料效率。
9. Reciprocating internal combustion engines (RICEs), or "recips":
10. 往复式内燃机（RICE），俗称"往复机"：
11. high-speed engines (1,500 to 1,800 rpm) of roughly 0.5 to 4.5 MW per unit, such as INNIO's Jenbacher Type 6 and Caterpillar's G3520; and
12. 高速发动机（1,500 至 1,800 转/分），单机约 0.5 至 4.5MW，如 INNIO 的 Jenbacher 6 型和卡特彼勒的 G3520；
13. medium-speed engines (500 to 1,000 rpm) of roughly 5 to 20 MW, such as Wärtsilä's 34SG, 31SG and 50SG, INNIO's J920 and Everllence's 51/60G.
14. 中速发动机（500 至 1,000 转/分），单机约 5 至 20MW，如瓦锡兰（Wärtsilä）的 34SG、31SG 和 50SG、INNIO 的 J920 以及 Everllence 的 51/60G。
15. Fuel cells: solid-oxide units from Bloom Energy carry nearly all the orders (3.8 GW of the tracker's fuel-cell bookings against 0.03 GW for FuelCell Energy).
16. 燃料电池：Bloom Energy 的固体氧化物机组几乎拿下全部订单（追踪口径的燃料电池订单中占 3.8GW，FuelCell Energy 仅 0.03GW）。

While turbines captured most of the initial orders, they very quickly ended up being sold out, with first slots now past 2030. This is because BTM developers compete with utilities for these turbine slots. However, recips are much less popular among utilities and they are increasingly aking to AI compute pure-plays. That's why our quarter-by-quarter tracker of firm orders for BTM AI compute has seen sign a drastic shift towards recips.

虽然轮机拿下了最初的大部分订单，但很快就售罄，首批交付档期已排到 2030 年之后。这是因为表后开发商要和公用事业公司抢轮机档期。而往复式发动机在公用事业公司那里远没那么受欢迎，越来越像是 AI 算力"纯玩家"的选择。正因如此，我们对表后 AI 算力确定性订单的逐季追踪出现了向往复式发动机的剧烈转变。



Sources: SemiAnalysis Energy Model; sales@semianalysis.com

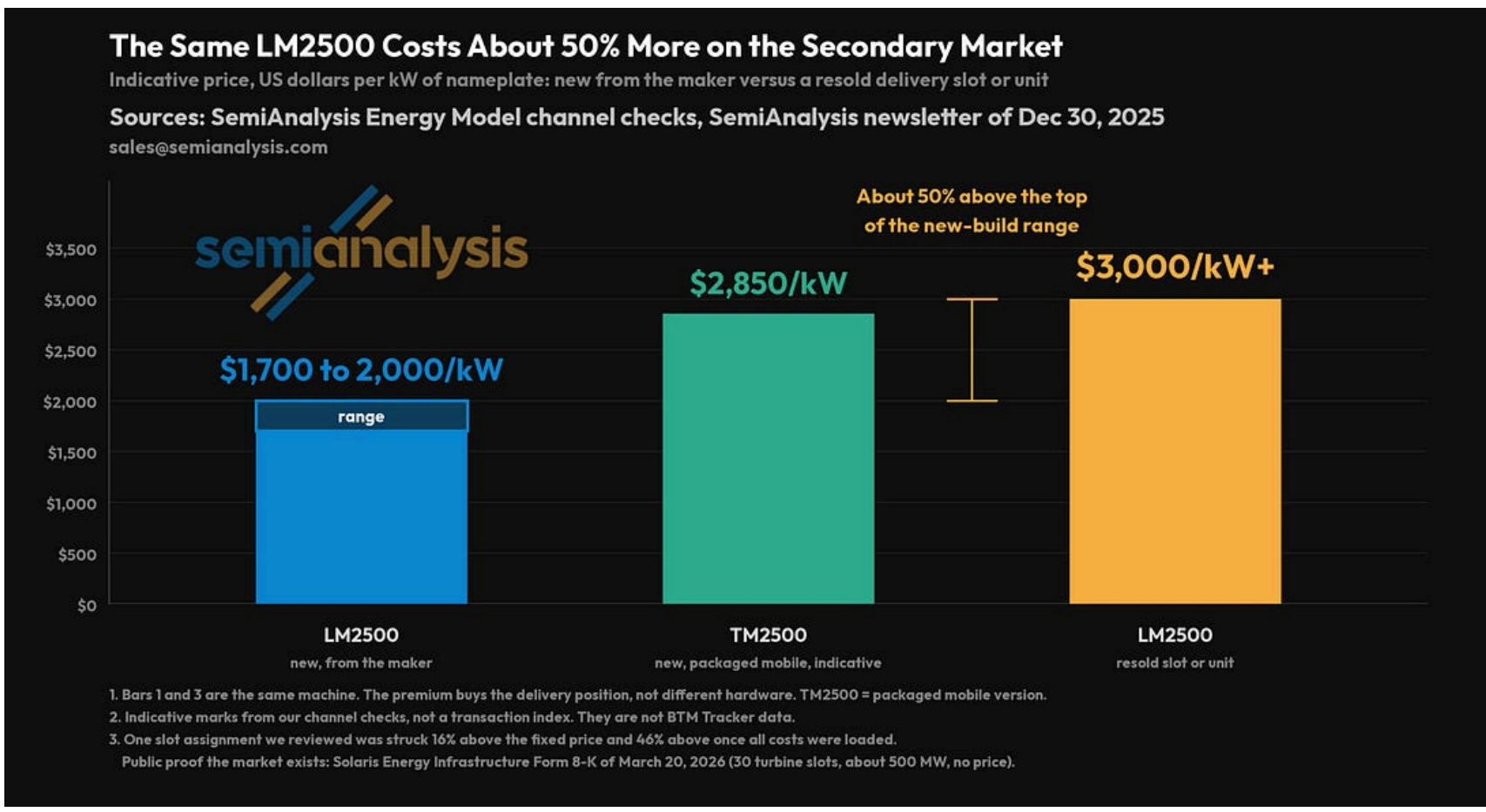
来源：SemiAnalysis 能源模型；sales@semianalysis.com

And we expect the trend to continue. Folks like EROCK, FTAI Power and Dynamis, alongside INNIO, Wartsila, Caterpillar and Cummins, and Bloom Energy, are expanding capacity more aggressively than incumbents like GEV, and directing more supply to the datacenter market. Caterpillar is lifting its large reciprocating-engine output to nearly 3x 2024 levels, while INNIO expects to roughly triple total capacity from 3.5 GW a year in 2025 to around 10 GW a year by 2030.

我们预计该趋势将持续。EROCK、FTAI Power 和 Dynamis 等公司，连同 INNIO、瓦锡兰、卡特彼勒和康明斯，以及 Bloom Energy，正以比 GEV 等在位者更激进的步伐扩产，并将更多供应导向数据中心市场。卡特彼勒正把大型往复式发动机产量提升至接近 2024 年的三倍，INNIO 则预计总产能从 2025 年的每年 3.5GW 到 2030 年增至约每年 10GW，大约增至三倍。

We have also seen the emergence of a secondary turbine market. They don’t come cheap, though! The scarcity across the main OEMs has built a secondary market where the premium buys time. A released delivery slot trades at a real premium to a factory order - the clearest public mark is a slot assignment struck 16% above the fixed price, and 46% above once all costs are loaded - and what the premium buys is a slot delivery in the next couple of years (or sooner) rather than in the next five years, and quicker energization.

我们还看到轮机二级市场的兴起。不过代价不菲！主要 OEM 的普遍稀缺造就了这个用溢价换时间的二级市场。一个释放出来的交付档期相对工厂新单存在实实在在的溢价——最清晰的公开案例是一笔档期转让，价格较固定价高出 16%，计入全部成本后高出 46%——而溢价买到的是未来一两年（或更早）而非未来五年的档期交付，以及更快的通电。



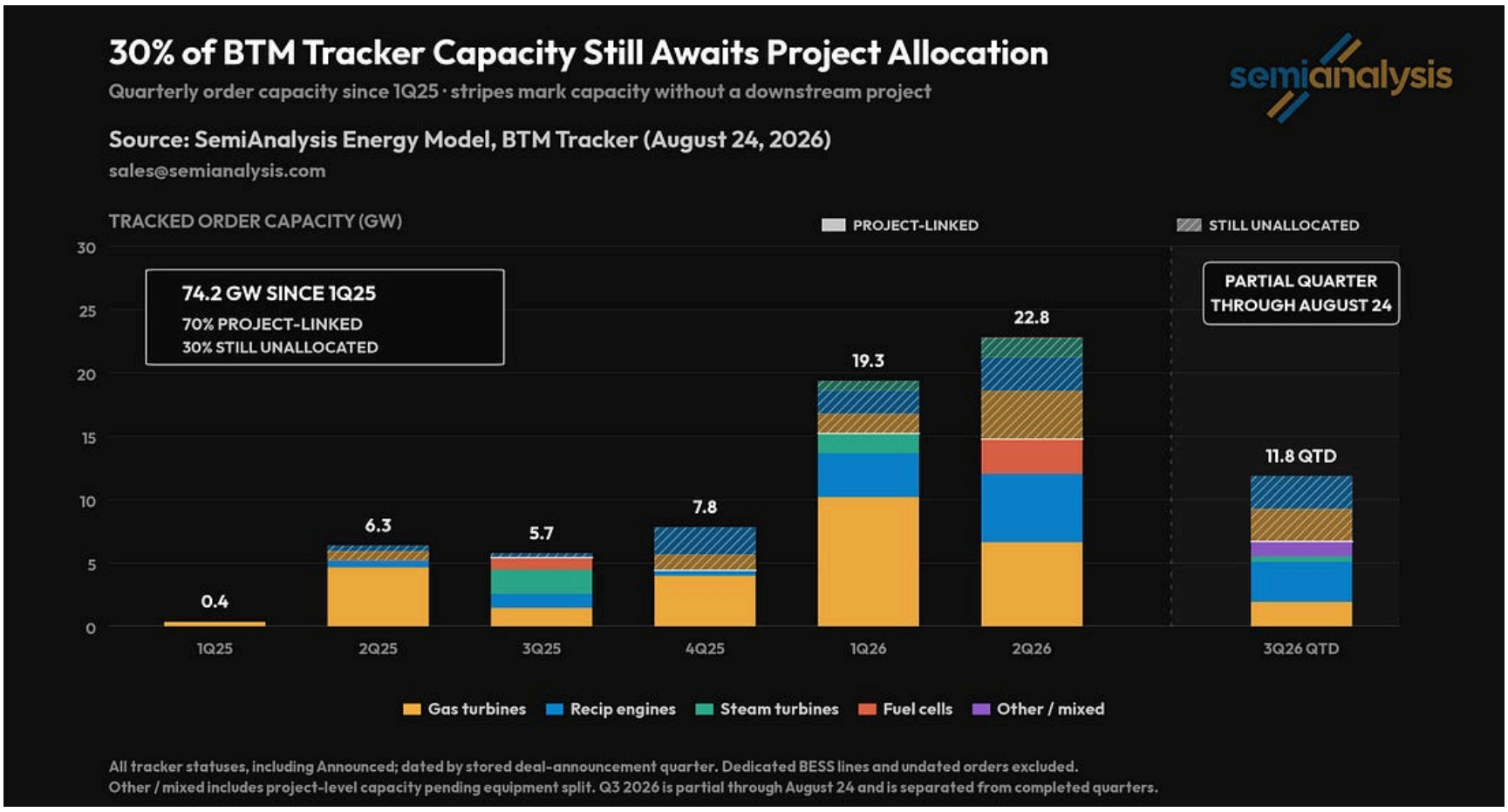
Sources: SemiAnalysis Energy Model; sales@semianalysis.com

来源：SemiAnalysis 能源模型；sales@semianalysis.com

Key to chat secondary market is the presence of speculative orders in the supply chain. Folks commit to buying turbines or sign minimum purchase agreements, and pay deposits, yet don’t have actual datacenter sites to deploy them. We’re seeing that behavior primarily impacting the gas turbine

market, notably incumbents GEV and Siemens. That equipment remains premium today and in high demand, and some “speculators” have been nicely rewarded given the secondary market prices discussed above.

该二级市场的关键在于供应链中存在的投机性订单。有些买家承诺购买轮机或签署最低采购协议并支付定金，却并没有实际的数据中心场址来部署这些设备。我们看到这种行为主要影响燃气轮机市场，尤其是 GEV 和西门子等在位者。这些设备如今依旧紧俏、需求旺盛，鉴于上文讨论的二级市场价格，一些“投机者”已获益颇丰。



Source: SemiAnalysis Energy Model, sales@semianalysis.com

来源：SemiAnalysis 能源模型，sales@semianalysis.com

No BTM Plant Without Balance of Plant

没有配套设施（BoP），就没有表后电站

While generation equipment is typically the center of the conversation when discussing BTM constraints, we think that’s increasingly shifting to BoP. Generation equipment will be useless if the campus waits for transformers, medium-voltage switchgear or the e-houses that hold the electrical equipment. The collection system and controls also have to bring the fleet’s output together into a working plant. And this electrical equipment, often at medium voltage and sometimes high voltage (depending on plant size and system design), is in very high demand due to being standardized and often used by datacenters themselves, as part of their electrical systems (see our deep dive on the topic here).

讨论表后瓶颈时，发电设备通常是话题中心，但我们认为焦点正日益转向配套设施（BoP）。如果园区要苦等变压器、中压开关柜或安放电气设备的电气室，发电设备就形同虚设。集电系统和控制系统还必须把整个机群的出力汇聚成一座可运行的电站。而这类电气设备——通常为中压、有时为高压（视电站规模和系统设计而定）——由于标准化程度高且常被数据中心自身用作其电气系统的一部分，需求非常旺盛（相关深度研究见此处）。



Sources: SemiAnalysis Datacenter Model; SemiAnalysis Energy Model; Sales@semianalysis.com

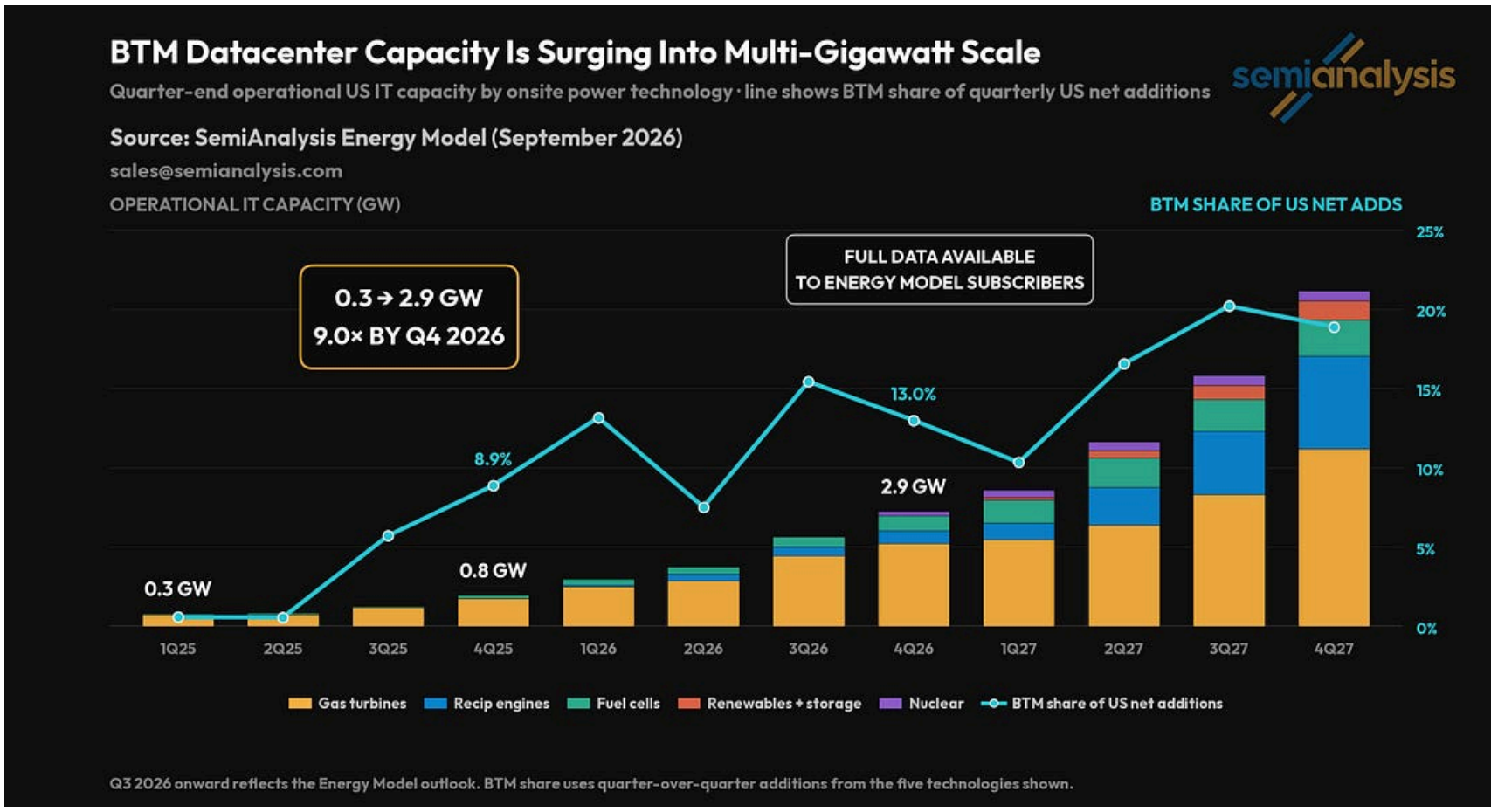
来源：SemiAnalysis 数据中心模型；SemiAnalysis 能源模型；Sales@semianalysis.com

Stage 4: Construction, Commissioning and Workforce

阶段 4：建设、调试与劳动力

Once capital, permits, gas and equipment are solved, a whole other challenge arises. Building the power plant, and operating it at the contractually defined SLA standards needs highly qualified labor, contractors and EPCs. To be clear, folks calling this a “science experiment” are entirely missing that 3GW of Datacenter IT capacity is already running with behind-the-meter power plants. Our Datacenter Model and Energy Models track every single project and exact timelines and supply chain.

一旦资金、许可、天然气和设备问题解决，另一重挑战随之而来。建设电站并按合同约定的 SLA 标准运行，需要高素质的劳动力、承包商和 EPC。需要说明的是，把这一切称作“科学实验”的人完全忽略了：已有 3GW 的数据中心 IT 容量正在依靠表后电站运行。我们的数据中心模型和能源模型追踪每一个项目及其确切时间表与供应链。



Source: SemiAnalysis Energy Model, sales@semianalysis.com

来源：SemiAnalysis 能源模型，sales@semianalysis.com

But as the scale dramatically increases, there will be issues, particularly in the context of surging labor scarcity driven by the datacenter buildout.

但随着规模急剧扩大，问题在所难免，尤其是在数据中心建设潮导致的劳动力稀缺加剧的背景下。

Our labor market modeling in The Wild Wild West of LEGO Datacenters sized the 2027 gap at 288,000 workers, based on our Labor Model included in our Industrials Model. Electricians are the largest trade at about 30% of site hours, drifting toward 40% by 2030 as liquid cooling adds mechanical work.

我们在《乐高数据中心的狂野西部》中的劳动力市场建模（基于工业模型中的劳动力模型）测算 2027 年缺口为 28.8 万名工人。电工是最大工种，约占现场工时的 30%，随着液冷增加机械工作量，到 2030 年将趋向 40%。

Moving the mechanical and electrical work into a factory cuts on-site labor by about 63% and on-site licensed-electrician hours by about 85%, which is why prefabricated eHouses, skidded plants, and full modular offerings are spreading through the vendor list: they are labor arbitrage as much as an opportunity to shoot ahead of schedule.

把机械和电气工作搬进工厂可使现场人工减少约 63%、现场持证电工工时减少约 85%，这正是预制电气室（eHouse）、撬装电站和全模块化方案在供应商名单中普及的原因：它们既是劳动力套利，也是抢在进度之前的机会。

But plenty of labor is still needed onsite. When it comes to power plants, the US has been building them for decades, meaning a healthy labor supply pool and lower costs than the datacenter build. Large combined cycle gas plants peak at about half a construction worker per megawatt:

但现场仍需要大量劳动力。就电站而言，美国已经建了几十年，意味着劳动力供给充足、成本低于数据中心建设。大型联合循环燃气电站高峰期约为每兆瓦半个建筑工人：

- Palomar, 546MW in California, peaked at 283 craft
- 加州 Palomar（546MW），高峰期 283 名技工
- Guernsey, 1,875MW in Ohio and fifteen years later, at close to 1,000
- 俄亥俄州 Guernsey（1,875MW），十五年后，接近 1,000 人

So, on a gigawatt campus the power plant build can be a fifth to a quarter of the peak headcount.

因此，在吉瓦级园区，电站建设高峰人数可能只占整个园区高峰人数的五分之一到四分之一。

However, ***it is not the same labor.*** A CCGT plant is a mechanical pressure project, meaning boilermakers setting HRSG pressure parts, pipe welders whose welds have to pass radiography, and millwrights aligning a turbine to thousandths. **There are 10,200 boilermakers in the United States, the occupation turns over about 800 people a year, and the Bureau of Labor Statistics projects it to shrink.**

然而，***这并非同一批劳动力***。联合循环电站是机械承压工程：锅炉制造工安装余热锅炉（HRSG）承压部件，管道焊工的焊缝必须通过射线检测，机修钳工要把汽轮机对中到千分之一英寸。**美国共有 10,200 名锅炉制造工，这一职业每年流失约 800 人，而劳工统计局预计其规模还会萎缩。**

That said, the BTM buildout is set to use a variety of solutions and each generation type draws on different trades, and each have their pros and cons regarding labor.

话虽如此，表后建设将采用多种方案，每种发电类型依赖的工种各不相同，在劳动力方面各有优劣。

- Reciprocating engines need no boilermakers, but they lean on electricians and millwrights, so the power plant competes with its own datacenter for the same people.
- 往复式发动机不需要锅炉制造工，但依赖电工和机修钳工，因此电站要和自己的数据中心争夺同一批人。

- Fuel cells need none of the scarce trades: no pressure parts, so in a labor-constrained buildout, that is a strong argument. But at mutli-gigawatt scale, hundreds of fuel cell banks and the required supercapacitors, BESS and so on, make for a different kind of configuration which has never been done at scale.
- 燃料电池完全不需要稀缺工种：没有承压部件，因此在劳动力受限的建设中是强有力的论据。但在数吉瓦规模下，数百组燃料电池阵列加上所需的超级电容器、BESS 等，构成一种从未大规模实践过的配置。

This is why “labor-light” power solutions are increasingly attractive to end-customers. As the US grid runs out of power & headroom in 2028, these solutions will be the primary way to solve datacenter power constraints.

这就是“省人力”电力方案对终端客户吸引力日增的原因。随着美国电网在 2028 年耗尽电力与富余容量，这些方案将成为解决数据中心电力约束的主要途径。

Of course, commissioning is not the finish line. A permanent island needs daily operating coverage, remote monitoring, local response, scheduled maintenance, spare parts and service coverage for unplanned work. The cadence is measured in operating hours. Caterpillar illustrates a 20,000-hour top-end and an 80,000-hour major overhaul; Jenbacher packages can require major work at 60,000 or 80,000 hours. At 8,000 running hours a year, that is roughly 2.5 years to the Caterpillar top-end and 7.5–10 years to a major. The exact answer varies by engine and duty cycle.

当然，调试不是终点。永久孤岛需要日常运行值守、远程监控、本地响应、定期维护、备件以及计划外工作的服务保障。节奏以运行小时计。卡特彼勒给出 2 万小时上部大修和 8 万小时全面大修的例证；Jenbacher 机组可能需要在 6 万或 8 万小时进行大修。按每年 8,000 运行小时计算，卡特彼勒上部大修约 2.5 年一次，全面大修 7.5 至 10 年一次。确切答案因发动机和工况而异。

To counter both issues, some OEMs are increasingly going vertical. Bloom Energy is the main example, as their solution is of course not as broadly established than turbines and engines. Bloom takes care of most installation and O&M work for its deployment, and hires and trains staff to do that. Others are following, and both issues are increasingly a deciding factor for equipment orders. EROCK has also relied on this, and their use of smaller truck-derivative engines means that both installation and O&M are much simpler than for a traditional turbine-based power plant. PROENERGY also discloses a large in-house staff that can act as EPC and O&M if need be.

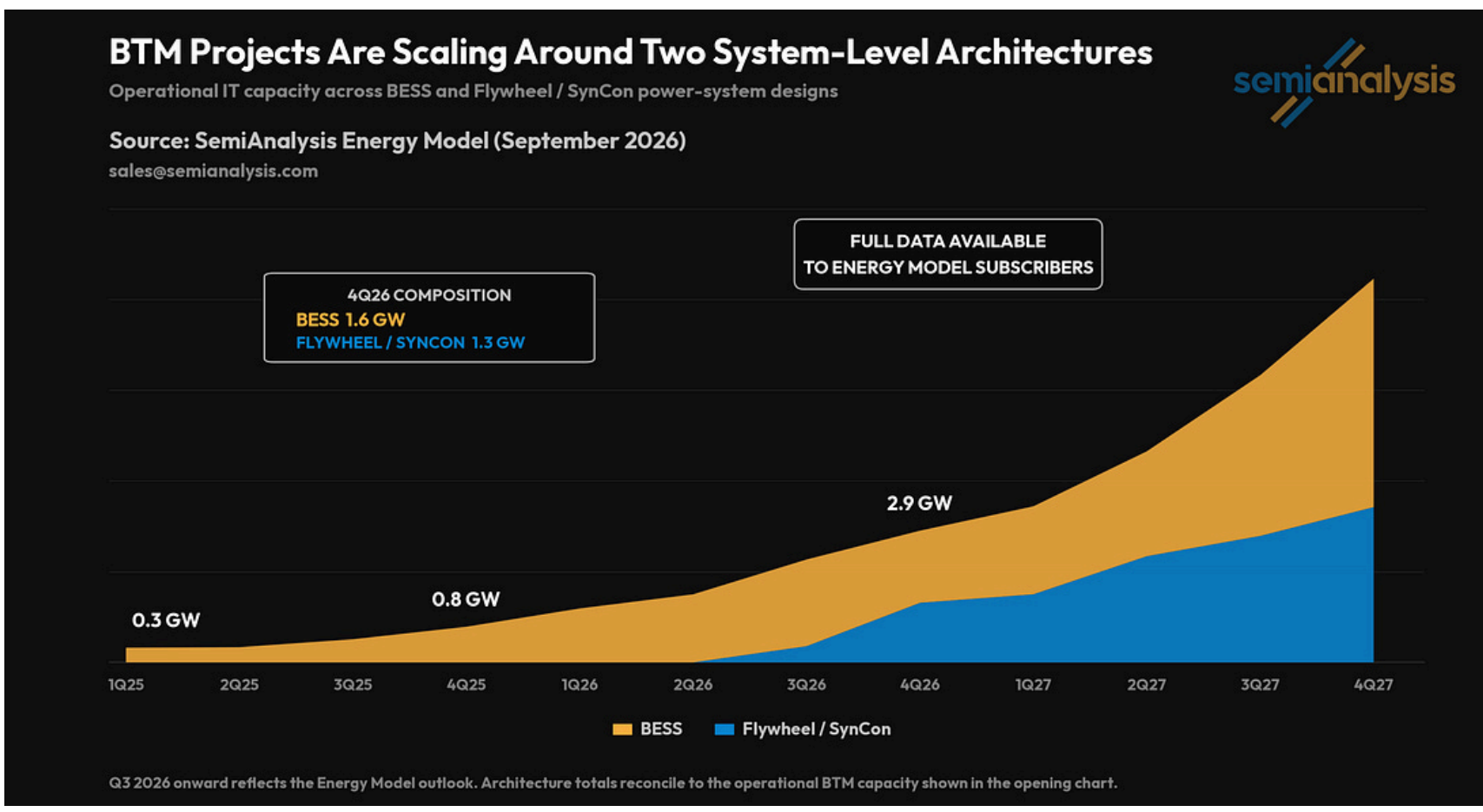
为应对这两个问题，一些 OEM 日益走向垂直化。Bloom Energy 是最主要的例子，因为其方案当然不如轮机和发动机那样广为确立。Bloom 负责其部署的大部分安装和运维工作，并招聘和培训人员来完成。其他厂商也在跟进，这两个问题日益成为设备订单的决定性因素。EROCK 也依赖这一点，其使用较小的卡车衍生发动机意味着安装和运维都比传统的轮机电站简单得多。PROENERGY 也披露了庞大的自有员工队伍，必要时可充当 EPC 和运维方。

Stage 5: Islanding Physics

阶段 5：孤岛物理学

The last stage is the least visible and the least forgiving. At xAI’s Colossus 1, matching gas turbines to GPU load proved harder than expected, with jitters of 10 to 20MW several times a second and oscillations like these exciting torsional modes and eating up turbine-generator shaft life. This issue led to xAI deploying the first phase of 150MW Tesla Megapacks. We’ve discussed at length here the issues with AI Training load fluctuations. This has led to the rise of a new battle: BESS vs Flywheels / SynCons to be paired with generation equipment at BTM sites.

最后一道关卡最不显眼，也最不容有失。在 xAI 的 Colossus 1，让燃气轮机匹配 GPU 负荷比预期更难：每秒数次出现 10 到 20MW 的抖动，这类振荡会激发扭振模态，消耗汽轮发电机轴的寿命。这一问题促使 xAI 部署了首期 150MW 的 Tesla Megapack。我们在此详细讨论过 AI 训练负荷波动的问题。由此引发一场新的战事：BESS 对阵飞轮/同步调相机，争夺与表后场址发电设备搭档的位置。



Source: SemiAnalysis Energy Model, sales@semianalysis.com

来源：SemiAnalysis 能源模型，sales@semianalysis.com

The combustor technology that makes modern gas turbines permittable holds its emissions performance only above rou
about 35% with turndown upgrades. AI training loads, which swing hard and fast, can push turbines below that floor, whe
revert to diffusion mode and NOx, CO and unburned hydrocarbons all jump. A permit is written based on potential emiss
integrated into the application.

人在草木间

让现代燃气轮机能够通过许可的燃烧室技术，只有在约为额定负荷一半以上（经降负荷改造后约 35% 以上）才能保持排放性能。AI 训练负荷又猛又快的摆动可能把轮机压到这一下限之下，此时控制系统会添加引燃燃料或切回扩散燃烧模式，NOx、CO 和未燃碳氢化合物全都会跳升。许可是按潜在排放量撰写的，因此这一下限被整合进申请之中。

A grid-connected plant borrows two services from the system: inertia, the spinning mass that resists frequency change, and fault current, the surge that lets a breaker recognize a short circuit and trip. An islanded plant must make both itself. Engines and turbines deliver five to ten times rated current into a fault; batteries, solar and fuel cells are clamped by their electronics to roughly 1.2-2x, thin enough that conventional overcurrent protection loses its margin. An island built only on inverters can fail to clear its own short circuits.

并网电站从系统借用两项服务：惯量——抵抗频率变化的旋转质量，以及故障电流——让断路器识别短路并跳闸的涌流。孤岛电站必须自行提供这两者。发动机和轮机向故障点送出五到十倍额定电流；电池、光伏和燃料电池受电力电子钳制在约 1.2-2 倍，低到常规过流保护失去裕度。仅靠逆变器搭建的孤岛可能无法切除自身的短路故障。

Fuel cells answer the same question with supercapacitors, which dump into a step load and recharge as the stack ramps. Channel checks for Bloom's sizing ratio put it near 3:2 on a power basis, which would make Project Jupiter's 2.45GW imply about 1.6GW of supercapacitors, far above the existing precedent of 58MW.

燃料电池用超级电容器回答同一问题：超级电容在阶跃负荷时倾泻放电，随电堆爬坡再充电。我们对 Bloom 配比的渠道调研显示，按功率计接近 3:2，照此推算，Jupiter 项目 2.45GW 意味着约 1.6GW 超级电容器，远高于现有 58MW 的先例。

Can You Do This Without Gas?

不用天然气能行吗？

Plenty are trying, and after six stages of difficulty you may well think renewables could dodge the permitting, fuel, and supply chain bottlenecks. Some are already trying, notably Crusoe with Redwood. Others like Google are deploying renewables & BESS at very large scale, but these sites remain grid connected.

尝试者众多。经历六道难关之后，你很可能会认为可再生能源可以避开许可、燃料和供应链瓶颈。有些公司已经在试，尤其是 Crusoe 与 Redwood。谷歌等其他公司则在超大规模部署可再生能源与 BESS，但这些场址仍保持并网。

Renewables clear air permitting far more easily, since there is no combustion source to permit, the fuel costs nothing, and there is no pipeline to route. The catch is electrical physics. In an off-grid context everything connects through inverters. Inverter-based sources push only a thin multiple of rated current into a short circuit, a fraction of what an engine or turbine delivers, too little margin for conventional overcurrent protection to trip reliably. So a clean renewable island has to buy grid-forming inverters plus synchronous condensers.

可再生能源通过空气许可要容易得多：没有燃烧源需要许可，燃料零成本，也没有管道需要选线。问题出在电气物理上。在离网环境下，一切都通过逆变器连接。基于逆变器的电源向短路故障送出的电流只有额定电流的薄薄几倍，远低于发动机或轮机的输出，常规过流保护没有足够的裕度可靠跳闸。因此，一个干净的可再生孤岛必须购置构网型逆变器加同步调相机。

Our December 2025 onsite-gas piece measured average US grid availability at about 99.93%, roughly three nines, and showed that onsite supply has to be overbuilt to match it.

我们 2025 年 12 月的现场燃气报告测得美国电网平均可用性约为 99.93%，大致三个 9，并表明现场供电必须过度建设才能与之匹敌。

Crusoe and Redwood Materials' operating datacenter microgrid in Sparks, Nevada has run since June 2025 on 12 MW of solar and 63 MWh of second-life electric vehicle batteries, with the grid as backup. In a March 24, 2026 release Crusoe reported 99.2% availability over seven months of continuous operation and announced an expansion to 20 MW. Scaling a solar-and-battery design to a gigawatt campus requires substantial generation capacity, storage and land; the amounts depend on the load profile, weather, reliability target and availability of grid backup. Batteries earn their place inside gas projects: ride-through, load smoothing and backup energy. Liberty Energy's chief financial officer said on July 23, 2026 that battery power capacity averages 50% of gas capacity across its datacenter clients.

Crusoe 与 Redwood Materials 在内华达州斯帕克斯运行中的数据中心微电网自 2025 年 6 月起依靠 12MW 光伏和 63MWh 电动汽车退役电池（二次利用）运行，电网作备用。在 2026 年 3 月 24 日的新闻稿中，Crusoe 报告连续运行七个月实现 99.2% 的可用性，并宣布扩建至 20MW。把光伏加电池的设计放大到吉瓦级园区需要庞大的发电产能、储能和土地；具体数量取决于负荷曲线、天气、可靠性目标以及电网备用的情况。电池在燃气项目中自有其位置：穿越扰动、负荷平滑与备用能量。Liberty Energy 首席财务官于 2026 年 7 月 23 日表示，在其数据中心客户中，电池功率容量平均为燃气容量的 50%。

Buyers are becoming more tolerant of interruption. Microsoft says its Fairwater Atlanta site was selected for resilient utility power and is "capable of achieving 4x9 availability at 3x9 cost," four nines of availability (99.99%) at the cost of three nines (99.9%), which lets it forgo onsite generation, uninterruptible power supply (UPS) systems and dual-corded distribution for the GPU fleet (Scott Guthrie, Microsoft, November 12, 2025). In our Industrials Model, we track the expected uptime for 30+ different datacenter designs, based on our deep bottoms up equipment-by-equipment BoM. We track desings of Anthropic, OpenAI, Meta and all other hyperscalers and we are seeing a clear trends towards lower redundancy.

买方对中断的容忍度正在提高。微软表示，其 Fairwater 亚特兰大片区的选址看中的是韧性电网供电，"能够以三个 9 的成本实现四个 9 的可用性"，即以 99.9% 可用性的成本实现 99.99% 的可用性，这使其可以为 GPU 集群省去现场发电、不间断电源（UPS）系统和双路配电（微软 Scott Guthrie，2025 年 11 月 12 日）。在我们的工业模型中，我们基于逐设备自下而上的物料清单（BoM），追踪 30 多种不同数据中心设计的预期可用运行时间。我们追踪 Anthropic、OpenAI、Meta 及其他所有超大规模云厂商的设计，并看到明显趋向更低冗余的趋势。

Currently, no pathway clears all six gates: gas is exposed on permits and on the pressure trades (the boilermakers and pipe welders), fuel cells on stability spend and unproven scale, solar and batteries on the island itself.

目前，没有任何一条路线能闯过全部六道关卡：燃气在许可和承压工种（锅炉制造工和管道焊工）上有暴露，燃料电池在稳定性投入和未经验证的规模上有暴露，光伏加电池则卡在孤岛本身。

Where do we go from here?

接下来走向何方？

Let's now discuss the longer-term outlook and winners&losers. We'll discuss our outlook for BTM plants and whether they are all destined to be grid-connected or not, and how solar and batteries fit into that outlook.

现在来讨论长期前景与赢家输家。我们将给出对表后电站的展望——它们是否注定全部并网——以及太阳能和电池在其中的位置。

We'll also discuss winners and losers in the OEM market, and in the BoP market. Some big industry changes are negative for certain large industrial companies, but there are balancing factors within their portfolio.

我们还将讨论 OEM 市场和 BoP 市场的赢家与输家。一些重大的行业变化对某些大型工业企业不利，但其投资组合内部存在对冲因素。

First of all, we see the Texas moratorium as a strong positive for BTM. Projects getting large-scale hyperscale leases are increasingly behind-the-meter, as they can provide much more certainty on timelines.

首先，我们将得州的暂停令视为表后的重大利好。获得超大规模租约的项目正日益走向表后，因为它们能在时间表上提供大得多的确定性。

Backup, Peaker, or Rate Base?

备用、调峰，还是纳入费率基数？

Every datacenter which uses onsite prime power eventually faces the same question: what happens when the grid becomes available? Most sites are not planned to be permanently off-grid, they are bridges to energize quickly while the connection queue clears.

每一个使用现场主电源的数据中心最终都会面临同一个问题：当电网电力可用时会怎样？大多数场址并不打算永久离网，它们是在排队等待并网期间快速通电的过渡桥梁。

We have seen the migration of turbines as prime power to back-up power at Colossus 1. But this cannot be the only solution for the tens of gigawatts of BTM power generation equipment set to come online in the coming year.

我们已在 Colossus 1 见证了轮机从主电源向备用电源的迁移。但对于未来一年即将上线的数十吉瓦表后发电设备而言，这不可能是唯一的出路。

There are a few more options: moving to the equipment to peakers and reserve, selling into the utilities rate base, redeployment to the next site or staying on as an additional flexibility layer, letting the site offer demand flexibility without interacting with the compute.

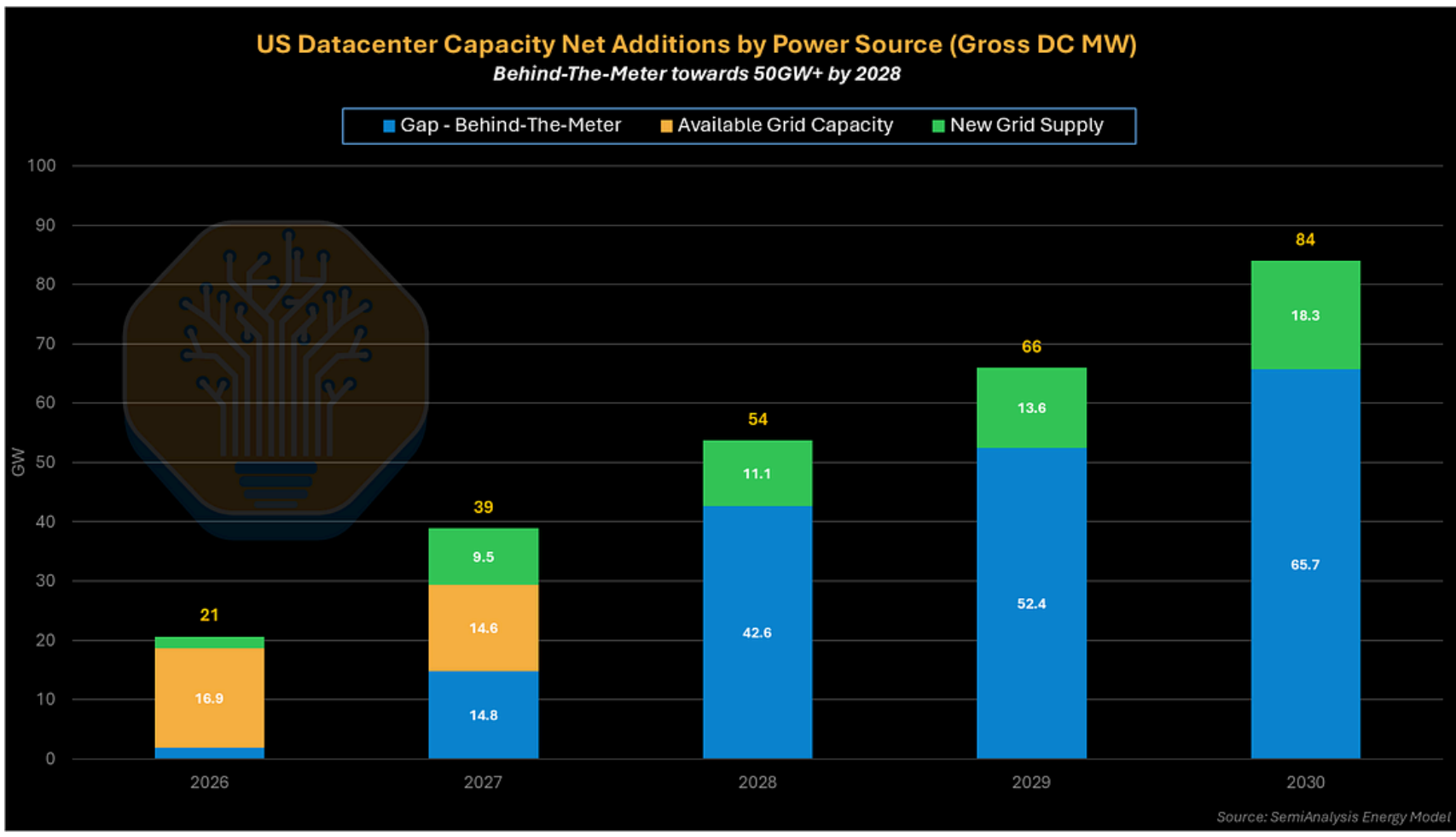
还有几种选择：将设备转为调峰和备用机组、出售给公用事业公司纳入费率基数、转移到下一个场址重新部署，或继续留作额外的灵活性层，让园区在不影响算力的情况下提供需求侧灵活性。

Overall, we continue to stand by our behind-the-meter and long-term power forecast. The grid will expand, but will be materially slower than AI's infrastructure requirements. As such, we do not expect every single BTM plant to end up being grid-connected.

总体而言，我们继续坚持我们的表后及长期电力预测。电网会扩张，但会明显慢于 AI 的基础设施需求。因此，我们并不预期每一座表后电站最终都会并网。

Rather, we think BTM campuses will become larger and larger, and start integrating a broader mix of energy resources. They'll become true microgrids (or macrogrids?). Ultimately, this will be a strong positive for solar and batteries, in our view. Stay tuned for much deeper content.

相反，我们认为表后园区会越做越大，并开始整合更广泛的能源资源组合。它们将成为真正的微电网（或者说是"宏电网"？）。在我们看来，这最终将是太阳能和电池的重大利好。更深入的内容敬请期待。



Source: SemiAnalysis Energy Model

来源：SemiAnalysis 能源模型

Winners and losers:

赢家与输家：

This is a taste of what Energy Model and Industrials Model clients read this summer.

以下是我们能源模型和工业模型客户今夏所读内容的冰山一角。

Pistons at the Gate (2 July 2026)

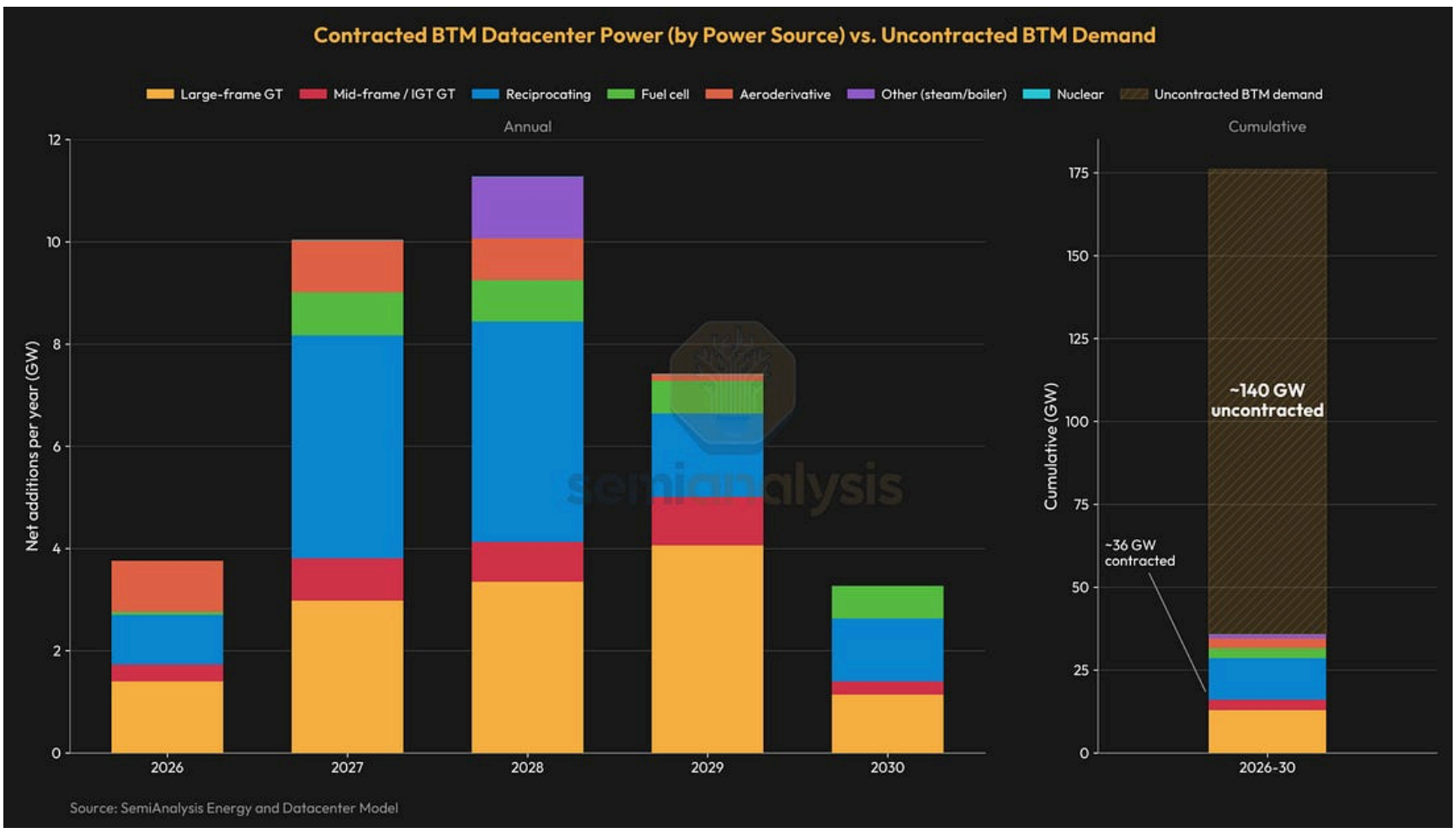
活塞在关卡前（2026 年 7 月 2 日）

In the recip market we like Caterpillar (CAT), INNIO (INIO), Rolls Royce (RR.LN), and Cummins (CMI). We see Caterpillar and INNIO continuing to win orders off the back of aggressive capacity expansion plans and strong bench of PaaS partnerships. We prefer Caterpillar on relative value, and INNIO's customer concentration risk bears watching with Voltagrid accounting for >40% of orders. Rolls-Royce is seeing strong growth in orders, and we think they have yet to see material orders from their just-launched gas-prime product and we see upside to orders. However, screens more expensive on relative value, and dependent on Liberty Energy (PaaS) to win deals. We expect Cummins and Generac will remain predominantly backup power stories. Cummins' purpose-built gas-prime engine launches only in 2028, and the bulk of its prime-power opportunity will land after 2031. However, it screens well on relative value to Generac, which unlike Cummins lacks datacenter prime power optionality.

在往复机市场，我们看好卡特彼勒（CAT）、INNIO（INIO）、罗尔斯·罗伊斯（RR.LN）和康明斯（CMI）。我们认为卡特彼勒和 INNIO 将凭借激进的产能扩张计划和强大的 PaaS 合作伙伴阵容持续赢得订单。从相对估值角度我们更偏好卡特彼勒；INNIO 的客户集中度风险值得关注，VoltaGrid 占其订单超过 40%。罗尔斯·罗伊斯订单增长强劲，我们认为其刚刚推出的燃气主电源产品尚未带来实质性订单，订单存在上行空间。不过其相对估值显得更贵，且依赖 Liberty Energy（PaaS）来赢得交易。我们预计康明斯和 Generac 仍将主要是备用电源的故事。康明斯专用燃气主电源发动机要到 2028 年才推出，其主电源机会的大头将在 2031 年之后落地。不过相对于 Generac，康明斯的相对估值更有吸引力；与康明斯不同，Generac 缺少数据中心主电源的期权价值。

Overall, we see substantial growth coming and see recips as best positioned to serve it.

总体而言，我们看到巨大的增长即将到来，并认为往复机最有条件承接这一增长。



Source: SemiAnalysis Energy Model

来源：SemiAnalysis 能源模型

While lead times are now also extending, an order put in for recips today will be operational in ~20 months compared to 60+ months for a CCGT.

虽然往复机的交货期如今也在拉长，但今天下一笔往复机订单约 20 个月即可投运，而联合循环机组需要 60 个月以上。

The UPS-less Era (Part 2): MV UPS and ERCOT Ride-Through Regulation (7 August 2026)

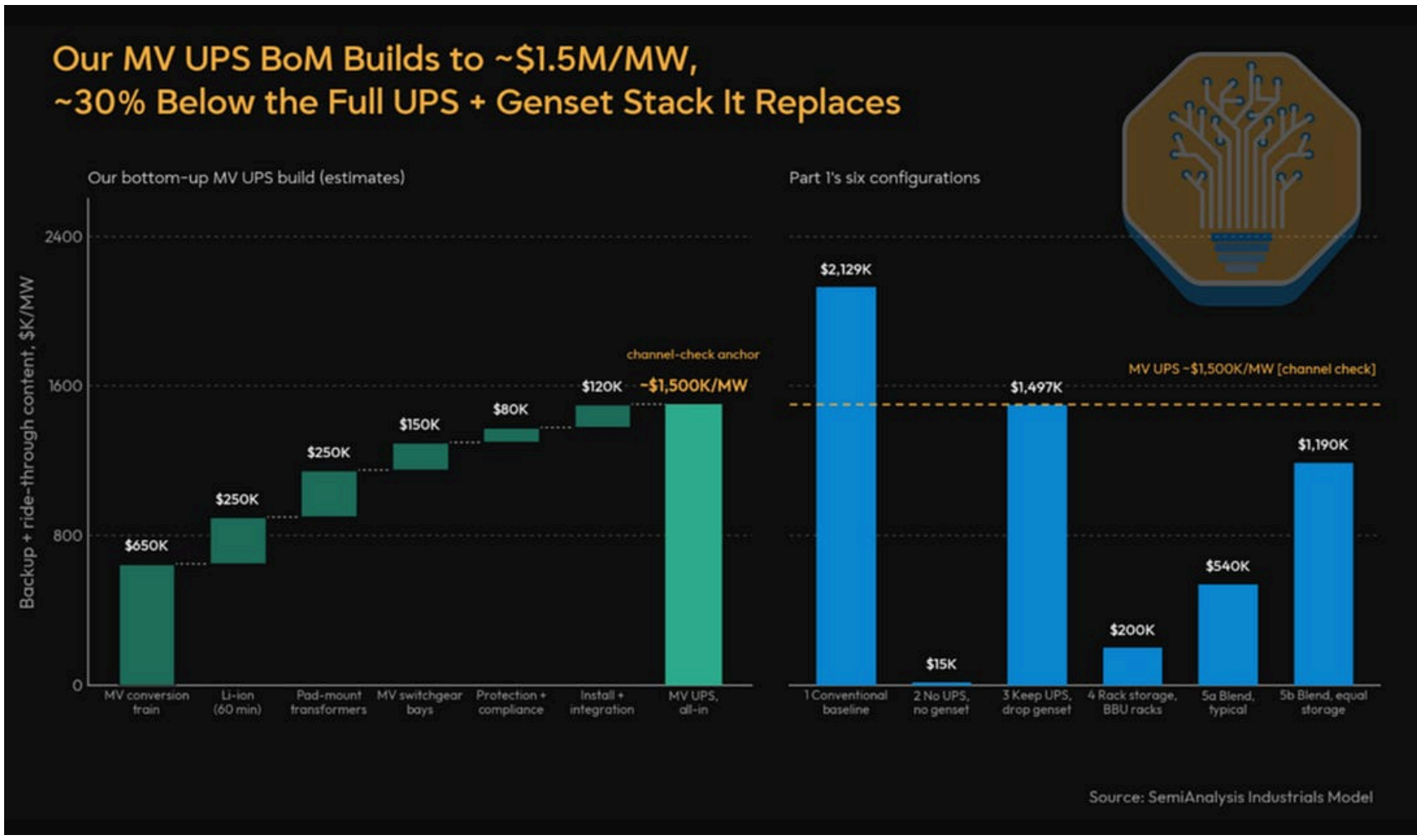
《无 UPS 时代》（第二部分）：中压 UPS 与 ERCOT 穿越新规（2026 年 8 月 7 日）

Every large site, grid-connected or BTM, now has to hold its load through voltage and frequency swings instead of dropping it. That has created a new piece of kit: the medium-voltage UPS, or MV UPS, one big unit at the point where the campus meets the grid, in place of the dozens of small ones inside the building.

如今每个大型园区，无论并网还是表后，都必须在电压和频率波动中保住负荷，而不是甩负荷。由此催生了一种新装备：中压 UPS（MV UPS），即在园区与电网交汇处放置一台大机组，取代楼内数十台小型 UPS。

Riding through a fault the way Texas and other grids now require costs about a quarter more per MW than the kit it replaces, roughly $300K per MW. Our bottom-up BoM build puts all-in MV UPS content around $1.5M/MW, against the ~$1.2M/MW LV UPS line per our Industrials Model. It is not quite apples to apples: the MV box carries 60 minutes of storage against the old line's five, and absorbs the dedicated transformer and grid interface.

按得州及其他电网如今的要求实现故障穿越，每兆瓦成本比被替换设备高约四分之一，约每兆瓦 30 万美元。我们自下而上的物料清单测算显示，中压 UPS 全包内容物约每兆瓦 150 万美元，而我们工业模型中的低压 UPS 约为每兆瓦 120 万美元。两者并不完全可比：中压机型自带 60 分钟储能，而老产品线为 5 分钟，且中压方案吸收了专用变压器和电网接口。



Source: SemiAnalysis Industrials Model

来源：SemiAnalysis 工业模型

Main beneficiaries are ABB and ON.energy first, then: Prolec GE on transformers, EPC Power on inverters, and ~$250K/MW of Li-ion demand. At our numbers, Crusoe's 5GW commitment alone implies roughly $7.5B of all-in content. Genset OEMs and the LV UPS lines sit on the other side, though the incumbents are moving too, as Vertiv's early MV BESS UPS line shows. However we still see traditional UPS winners, like Vertiv, as key losers of this trend. They've been slow and late. But Vertiv has many other parts of its portfolio that are more exciting and make them a good pure-play on datacenters, as opposed to a share loser. We notably like their modular exposure, which dramatically increases their content per MW. We've discussed at length in our modular datacenter primer.

主要受益者首先是 ABB 和 ON.energy，其次是：变压器方面的 Prolec GE、逆变器方面的 EPC Power，以及约每兆瓦 25 万美元的锂电需求。按我们的数据，仅 Crusoe 的 5GW 承诺就意味着约 75 亿美元的全包内容物。发电机组 OEM 和低压 UPS 产品线处于另一侧，不过在位者也在跟进，Vertiv 早期的中压 BESS UPS 产品线即是例证。不过我们仍将传统 UPS 的赢家（如 Vertiv）视为这一趋势的主要输家。它们动作又慢又晚。但 Vertiv 投资组合中还有许多更亮眼的部分，使其仍不失为数据中心的好纯标的，而非份额流失者。我们特别看好其模块化业务敞口，这大幅提升了其每兆瓦内容物。我们在模块化数据中心入门报告中已有详述。

The Incoming Construction Supercycle (10 March 2026)

《即将到来的建设超级周期》（2026 年 3 月 10 日）

The labor and power shortage has resulted in highly attractive economics facing the few EPCs equipped to construct and install gas power plants. The capital cost of a combined cycle gas power plant has risen from ~$750/kW for turbines that came online in 2018 to ~$2,000/kW. In dollar terms, nearly half of the increase accrues to the EPCs, more than the OEMs (~40%).

劳动力和电力短缺使得少数有能力建设安装燃气电站的 EPC 面临极具吸引力的经济回报。联合循环燃气电站的资本成本已从 2018 年投运机组约 750 美元/千瓦升至约 2,000 美元/千瓦。按美元计，近一半的增量归于 EPC，超过 OEM（约 40%）。

We like Primoris, given the size of the opportunity relative to revenues and the severity of the EPC constraint, which suggests a high likelihood of pipeline conversion.

我们看好 Primoris，因为相对于其收入，这一机会体量巨大，且 EPC 约束之严重意味着其储备项目转化的可能性很高。

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