ZERO INDUSTRIAL

Monetizing Ethanol CI Reduction Through Electrified Process Heat: Pathway Selection Across 45Z, LCFS, and CFR

Zero Industrial Inc.

July 2026

Abstract

Process heat is the largest controllable contributor to a corn ethanol plant's carbon intensity (CI) score. Roughly 20 gCO2e/MJ of a typical 50-point score comes from natural gas burned for cooking, distillation, and drying, and unlike feedstock or land-use factors, it sits entirely within the plant fence. Electrifying that heat cuts CI, but the value of each point cut depends on where it is monetized: the federal 45Z Clean Fuel Production Credit runs through 2029 and accepts renewable energy certificates (RECs) against grid electricity, while the Low Carbon Fuel Standard (LCFS) and Canada's Clean Fuel Regulations (CFR) persist beyond 2029 and do not. This paper evaluates the three electrification technologies available to producers (electrode boilers, mechanical vapor recompression heat pumps, and Thermal Energy Storage) against the three monetization pathways, and presents a phased deployment model in which near-term 45Z revenue funds the durable, multi-market assets. For a 100 MMGY plant cutting 10 CI points, the opportunity is approximately $20Mn per year, or $2,283 for every hour the plant keeps generating steam with gas. Independent facility-level analysis from UC Berkeley's Goldman School of Public Policy supports the underlying technology economics.

Introduction

A corn ethanol plant's CI score has become a second revenue stream. It determines eligibility for the federal 45Z credit, the netback on gallons sold into California and other LCFS jurisdictions, and the premium available on exports into Canada under CFR. A typical dry mill scores around 50 gCO2e/MJ, and Figure 1 shows where that score lives: feedstock at ~25 points, fuel at ~20, transportation at ~6, with indirect land-use change and small agricultural credits making up the remainder.

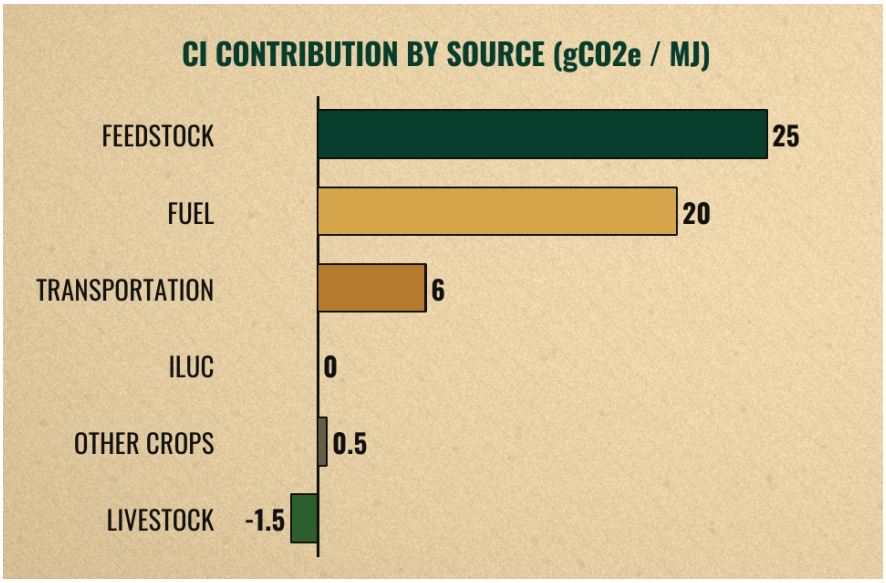

Figure 1. CI contribution by source for a representative corn ethanol plant, in gCO2e/MJ. Source: Zero Industrial analysis.

That fuel bar has been stubborn for structural reasons. Cheap domestic natural gas keeps fossil heat highly competitive, and the assets that deliver process heat are capital-intensive, long-lived, and held to strict reliability requirements, so plants replace them rarely and conservatively. What has changed is the revenue side. The crediting landscape has shifted value from volume to CI: a gallon is no longer just a gallon, and a plant that cuts its score gets paid for the difference in three separate markets. The economics of touching the heat system now include a revenue line that did not exist when most of the installed boilers were specified.

Not all of those points are addressable from inside the plant. The feedstock slice is set by agricultural practice upstream of the gate; a producer needs corn or milo and cannot re-engineer county-level farming from the control room. Transportation is small and largely fixed by geography. The process heat fuel slice is different. It is the second-largest bar on the chart, it is burned inside the fence, and at roughly 85% of plants it is natural gas generating steam for cooking and distillation and firing the DDGS dryers. Fuel is the lever a producer actually controls.

Pulling that lever, however, is not a single engineering problem. The path to reducing fuel CI depends on the CI reduction monetization pathway, because the three markets that pay for CI reduction do not agree on what counts. The federal 45Z credit accepts RECs purchased against grid electricity, so a grid-powered asset can qualify as clean the day it energizes. LCFS and CFR do not recognize unbundled RECs, so the same asset on a high-CI grid produces no creditable reduction in those markets, and can push the score in the wrong direction. Layer on the calendar (45Z sunsets after 2029; LCFS and CFR persist) and the technology choice stops being about boiler efficiency and becomes a market-sequencing question.

Mis-sequencing is expensive in both directions. A producer who optimizes purely for 45Z can end up owning an asset that earns nothing in the markets that outlast it. A producer who waits for the perfect long-term asset forfeits the federal window: a system that takes two years to install still captures roughly two years of 45Z if the decision is made today, and captures close to nothing if the decision is made in 2028.

This paper works through that sequencing problem. It lays out the three monetization pathways and where they disagree, evaluates the three electrification technologies against them, and presents a phased deployment approach in which the fast asset pays for the durable ones. It closes with the cost of waiting, which is the number that should anchor the timing decision.

The Different CI Monetization Pathways

Three CI-linked revenue streams are available to a US ethanol producer today. They differ on duration, on geography, and, critically, on the treatment of RECs.

45Z, the federal window

Section 45Z of the Internal Revenue Code, the Clean Fuel Production Credit, pays registered producers on every gallon of qualifying low-CI fuel produced through the end of 2029. Value scales with the CI reduction achieved below the statutory baseline at roughly $0.02 per CI point per gallon, so a 10-point cut is worth about $0.20/gal. Two features make 45Z the near-term lane. It is federal, so it applies to every gallon regardless of destination market. And RECs count: clean power substantiated with certificates purchased against grid electricity flows through the 45Z CI math, which means a grid-powered electrification asset monetizes immediately without waiting for clean firm supply or co-located generation.

Two operational features are worth noting. The credit is earned on production, so it does not depend on where the gallon ultimately sells, and transferability makes it function like cash rather than a tax position most producers have to shoehorn into their returns. And because the credit scales with the CI achieved

rather than a binary threshold, operational flexibility preserves value: a plant can move between electric and gas-fired steam through the year, as long as total gas consumption nets out at the level that holds the score.

LCFS, the state and provincial programs

Low-carbon fuel standards in California, Oregon, British Columbia, and New Mexico pay for CI reduction on gallons sold into those markets. The programs are durable and the credit prices meaningful, but the accounting is stricter: CI reduction achieved through unbundled RECs is not recognized. The electricity feeding an electrified heat asset must actually be low-carbon, through the grid mix itself, through qualifying supply arrangements, or through co-located renewable generation.

CFR, the durable export market

Canada's federal Clean Fuel Regulations create a compliance market for CI reduction on fuel sold into Canada, with no legislated sunset. For US producers with export logistics, CFR is the market that outlasts the 45Z window, and its REC treatment matches LCFS: the reduction has to be physical.

Stacking, and where the pathways interact

The three pathways are not mutually exclusive. 45Z is earned on production, so it stacks on top of gallons sold into LCFS or CFR; a plant selling into California collects the federal credit and the state credit on the same gallon, each valued on its own CI accounting. The interaction that bites is the accounting divergence itself. Because 45Z accepts RECs and the regulated markets do not, a single asset can move the two scores in opposite directions: a grid-powered E-boiler lowers the CI that 45Z sees while raising the CI that LCFS and CFR see. For a producer selling into both lanes, the relevant quantity is the netback per gallon summed across markets, not the score in any one of them. That is an arithmetic problem, plant by plant, and it has a clean decision rule, covered in the toolkit section.

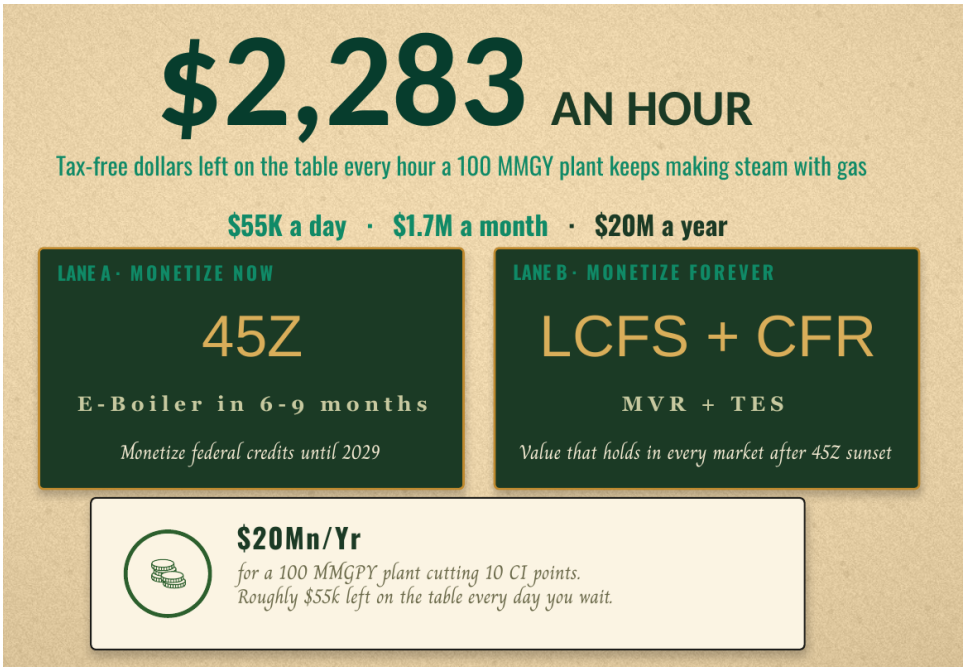

Figure 2. Two monetization lanes for electrified process heat. Lane A monetizes 45Z immediately; Lane B holds its value in every market after the 45Z sunset. Source: Zero Industrial.

The asymmetry that drives sequencing

Figure 2 compresses the pathway landscape into the two lanes that matter. Lane A is 45Z: fast to enter, REC-friendly, and closing in 2029. Lane B is LCFS plus CFR: slower to enter, stricter on accounting, and

open indefinitely. The asymmetry is what makes sequencing consequential. An E-boiler running on grid power with RECs attached is fully creditable in Lane A and invisible in Lane B; on a high-CI grid it raises the score Lane B sees. Worth flagging for producers already selling into LCFS or CFR: switching steam from gas to a grid-powered E-boiler trades regulated-market netback for 45Z value, and that trade has to clear before the fast asset makes sense. Section 5 returns to this test.

Technology Pathways to Monetizing CI Reduction

Three interventions target the fuel slice of the CI stack. Carbon capture is real but slow: permitting timelines stretch to years and the economics depend on proximity to sequestration or pipeline infrastructure, which most plants do not control. RECs are quick but shallow: they are an instrument, not a reduction, and they only travel in the 45Z lane. Electrification of process heat is the intervention that is physical, plant-controlled, and creditable across markets, and it comes in three forms.

E-boiler: the flexible, fast asset

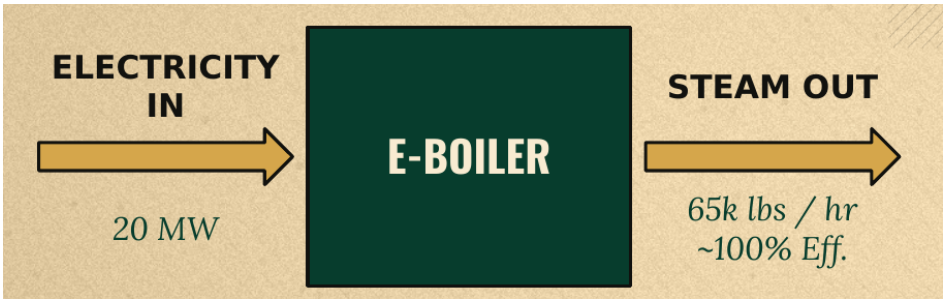

Figure 3. E-boiler energy balance: 20 MWe in, ~65k lbs/hr of steam out at ~100% efficiency. Source: Zero Industrial.

An electrode boiler converts electricity to steam at essentially 100% efficiency; a 20 MWe unit delivers about 65,000 lbs/hr (Figure 3). It installs in 6-9 months, which is the fastest route to 45Z revenue, and it ramps in seconds, which makes it an operating asset rather than a fixed one. That flexibility matters twice. Against power prices, the E-boiler runs when electricity is cheap and yields to the gas boiler or duct burner when it is not. Against the production calendar, it becomes the flex asset between the dryer and the boiler: in heavy drying months the E-boiler runs flat out on steam duty, and in light months it ramps down while gas picks up the difference, holding total plant gas consumption at the level that secures the CI benefit. Run this way, the E-boiler takes 5-10 points off the score versus business-as-usual (BAU) operation.

Dispatch is where the operating economics live. An E-boiler running round the clock is fully exposed to power prices, which is a slam dunk in low-price markets and a problem everywhere else. The standard answer is to run it against the price curve: take electric steam through the cheap hours, yield to gas-fired duct burning when power is expensive, and let the 45Z value carry the average. The economics work where 45Z value bridges the gas-to-power spark spread, and the whole play gates on substation capacity: if the local infrastructure cannot serve 20 MW of new load, the E-boiler is ruled out regardless of the math. Attaching RECs makes it fully 45Z-compliant. It remains a Lane A asset only.

MVR heat pump: COP-driven CI reduction

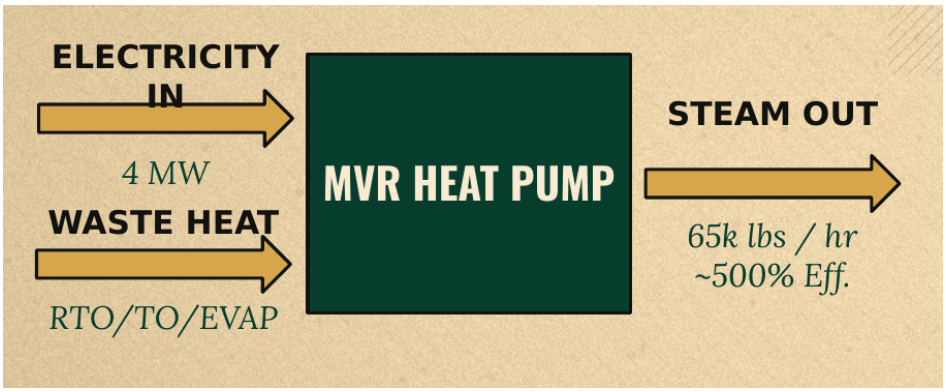

Figure 4. MVR heat pump energy balance: 4 MWe plus recovered waste heat in, ~65k lbs/hr of steam out at ~500% effective efficiency. Source: Zero Industrial.

Mechanical vapor recompression (MVR) recovers waste heat from the regenerative thermal oxidizer (RTO), thermal oxidizer, or evaporator train and mechanically upgrades it to process steam (Figure 4). The energy math is the argument: the same 65,000 lbs/hr of steam that takes 20 MWe in an E-boiler, or 85 MMBtu/hr of gas in a conventional boiler, takes about 4 MWe of compression work in an MVR. 20 ÷ 4 = 5, a coefficient of performance (COP) above 5, or roughly 500% effective efficiency against the 80-90% of a gas boiler.

That ratio is what carries MVR across markets. Using less than a fifth of the energy input of any other steam technology means the CI reduction survives even on an average grid; the reduction is physical, not certificate-based, so it is creditable under LCFS and CFR as well as 45Z. The dependencies are engineering ones. The plant needs enough high-quality waste heat to capture economically, and the temperature lift from the recovered stream to the required steam conditions sets the achievable COP. On timeline, the equipment itself is not the constraint: manufacturing and delivery schedules for MVR are comparatively short, but the upfront design and integration engineering runs long, which is why the installed timeline lands at 1.5-2.5 years unless the design work is parallel-tracked from day one. MVR is steam-only; the dryer stays on gas.

Thermal Energy Storage: electrify the whole fuel load

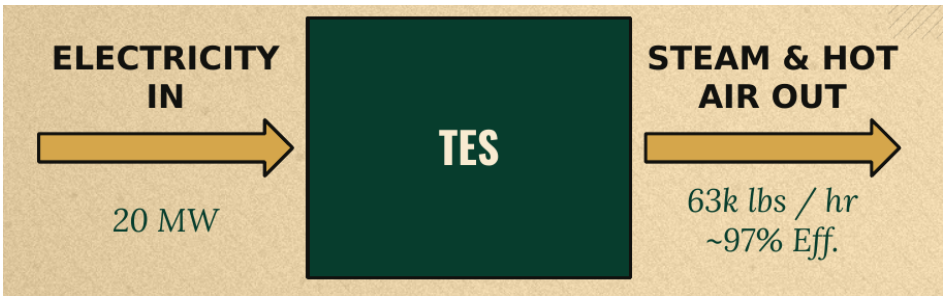

Figure 5. TES energy balance: 20 MWe charged off-peak, ~63k lbs/hr equivalent steam and hot air discharged round the clock at ~97% efficiency. Source: Zero Industrial.

Thermal Energy Storage (TES) decouples when electricity is bought from when heat is used (Figure 5). The system charges during the 4-12 off-peak hours when power is cheapest and the marginal generation is mostly renewable, then discharges heat round the clock: process steam at low, medium, and high pressure through a heat-recovery steam generator, and separately, high-temperature hot air routed directly to the DDGS dryers. The two output streams are split inside the system so each load gets the temperature it needs.

The split matters because the two duties want different temperatures. Producing steam through the heat exchanger takes roughly 312-318°F on the water side; the dryers want air at 400-450°F. Sensible heat

left over after steam-raising is not enough to dry with, so the architecture is not a cascade: the dryer stream comes off the storage medium at full temperature, and the steam duty, being the lower-grade requirement, is served from its own stream through the heat exchanger. Modern modular TES designs handle the dual-output configuration as standard rather than as custom engineering, and oversizing the storage block to cover both duties is a sizing exercise, not a redesign.

TES is the only option of the three that serves the dryer, which makes it the only route to electrifying the whole fuel load rather than just steam, and therefore the deepest available CI cut. Siting next to solar or wind for direct charging makes the supply verifiably low-carbon and the reduction creditable under LCFS and CFR. Off-peak-only charging keeps the operating cost well below gas-fired generation. Leading TES vendors have moved to modular designs with ramped production; for ethanol-scale systems, 2027 delivery is a realistic expectation, with the same 1.5-2.5 year installed timeline as MVR once integration is counted.

Table 1 summarizes the three pathways.

	E-boiler	MVR heat pump	TES
Effective efficiency	~100%	>500% (COP > 5)	~97% plus storage
Electrical load for ~65k lbs/hr steam	20 MWe, round the clock	4 MWe	20 MWe, off-peak only
Deployment	6-9 months	1.5-2.5 years	1.5-2.5 years
Loads served	Steam only	Steam only	Steam and drying hot air
Key dependency	Substation capacity	Recoverable waste heat	Off-peak power access
Markets served	45Z (with RECs)	45Z, LCFS, CFR	45Z, LCFS, CFR

Table 1. Electrification technology comparison for ethanol process heat. Source: Zero Industrial technology assessments.

Technology-stack economics

A facility-level national study published in April 2026 by UC Berkeley's Goldman School of Public Policy[1] evaluated heat pumps and electric thermal storage against delivered natural gas heat across 3,559 US industrial sites. Its findings line up with the pathway logic above. Renewable-powered heat is economic for roughly 1,060 TBtu of US industrial heat demand by 2030 and about 3,255 TBtu, one third of total demand, by 2035, driven by falling electricity costs and TES capital costs projected to drop from $100/kWh in 2025 to $20/kWh by 2030. Heat pumps are the most cost-effective clean option below 200°C, the temperature band that covers ethanol steam duty and 79% of US industrial heat sites, and their advantage compounds where recoverable waste heat is available, which is precisely the MVR configuration. Thermal storage delivers heat at roughly the cost of the electricity that charges it, and the study finds more than half of mid- and high-temperature heat demand becomes economic to electrify by 2030.

The price mechanics behind those findings are worth carrying into any plant-level evaluation. Delivered-heat competitiveness is governed primarily by the electricity-to-gas price ratio at the site and the temperature of the duty. Under the study's baseline of $6/MMBtu gas and $30/MWh electricity, gas remains the least-cost source for low-temperature steam, but heat pumps become least-cost across a wide region of the price space once electricity lands around $10-30/MWh against gas at $5/MMBtu or higher, because a COP above one turns cheap electricity into heat below combustion cost. TES delivers heat at roughly its charging cost adjusted for ~95-98% round-trip efficiency, while gas-fired heat scales nearly linearly with a fuel price that has historically been the volatile input. The study models continuous

industrial operations at a 90% capacity factor with roughly 15 hours of storage, which is the operating shape of an ethanol plant, not a stylized one.

The study also speaks to the interconnection question that hangs over every electrification project. With typical grid interconnection waits stretching to roughly five years, it emphasizes off-grid and behind-the-meter renewable supply, and finds the median US industrial site has nearby buildable renewable resource equal to 60 times its heat demand. The land around most plants is not the constraint; the queue is, and local supply sidesteps it.

ZI's Solution Toolkit

Zero Industrial's toolkit pairs the three technologies with a sequencing model and the capital to execute it. The core of the model is simple: the fast asset funds the durable ones.

The phased approach

Phase 1 is the E-boiler. Installed in 6-9 months, it starts earning 45Z immediately and captures up to 2.5 years of the remaining federal window. The monetization math for a 100 MMGY plant cutting 10 CI points: 10 pts ÷ 50 pts × $1/gal = $0.20/gal, and $0.20/gal × 100Mn gal = $20Mn/yr.

Phase 2 is MVR and TES. Both run 1.5-2.5 years from commitment to commissioning, so they are engineered in parallel while the E-boiler earns. MVR takes the steam load at COP > 5; TES takes the dryer and the pressure-tiered steam the MVR does not cover. When 45Z sunsets, the durable assets are already running and the plant is selling lower-CI gallons into LCFS and CFR. The 45Z revenue is not just income; it buys the time and funds the net spend on the long-term system (Figure 6).

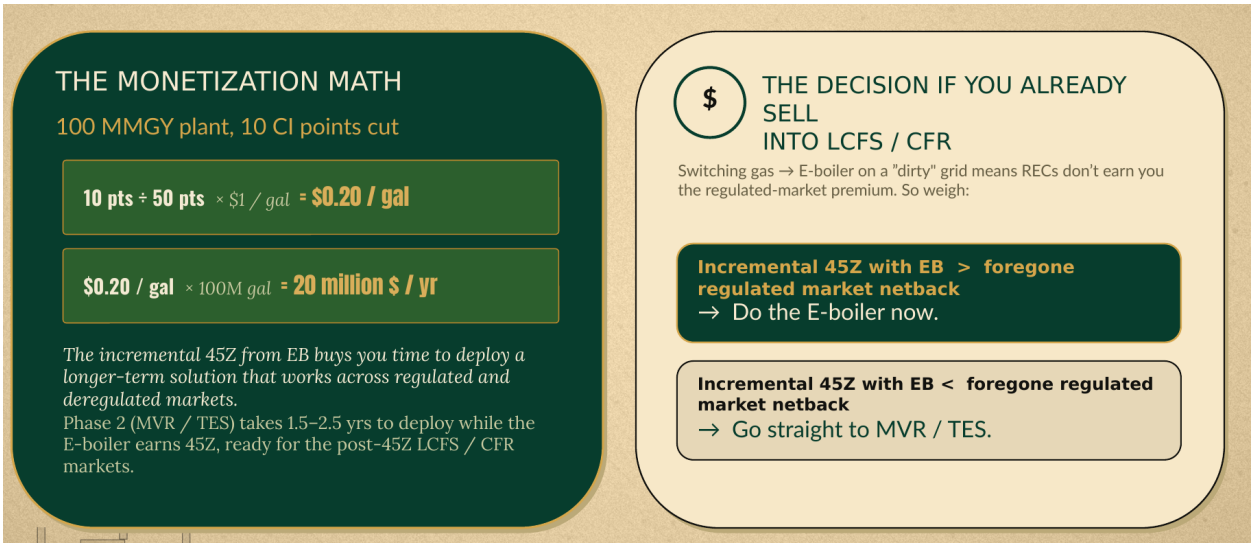

Figure 6. The phased play: monetization math and the decision test for producers already selling into regulated markets. Source: Zero Industrial.

The decision test

For a producer already selling into LCFS or CFR, Phase 1 is not automatic. Switching steam from gas to a grid-powered E-boiler raises the CI those markets see, so the regulated-market netback foregone has to be weighed against the incremental 45Z gained. If incremental 45Z with the E-boiler exceeds the foregone netback, do the E-boiler now. If it falls short, skip Phase 1 and go straight to MVR and TES. Either way, the E-boiler-versus-gas flex can be tuned to hold the plant one CI tier below BAU. This is a plant-specific calculation across substation capacity, market exposure, and spark spread, and it is the first analysis we run. If the E-boiler doesn't pencil for your market position, we won't propose one.

Interconnection, handled in parallel

The binding constraints on any of these assets are access to power, transformer capacity, and substation capacity. Two things blunt them. First, off-peak-only TES charging is a different ask than firm round-the-clock load: a 20 MW draw confined to overnight hours is not a data center requesting 60 MW of firm supply, and utilities can often serve it from existing infrastructure. Second, the interconnection path is parallel-tracked with TES design and fabrication, so the electrical work completes on the same schedule as the equipment rather than after it. Where a plant has spare capacity on its internal distribution infrastructure, MVR can move faster still, taking the steam load early while TES follows for the dryer. And where the utility path is slow, the Berkeley land finding points to the third route: behind-the-meter renewable charging that bypasses the queue entirely.

The commercial structure

The assets are delivered as Heat-as-a-Service. ZI develops, finances, owns, and operates the equipment behind the fence; the producer buys steam and hot air under a long-term supply agreement, with the 45Z, LCFS, and CFR value reflected in the pricing. No capital leaves the producer's balance sheet at any phase, including the 12-18 months an asset spends in engineering and construction before it earns. The Phase 1 revenue is the producer's to direct: take it as margin, or parlay it into the Phase 2 build and let it ride into the assets that earn after 2029. Either way the net spend on the long-term system comes down, because the federal window paid for a piece of it.

What an engagement covers

The scoping sequence runs: (1) substation and internal-capacity screening to establish which assets are feasible at the site; (2) market exposure analysis across 45Z, LCFS, and CFR to run the decision test on plant-specific numbers; (3) load modeling and vendor RFIs to size the E-boiler, MVR, and TES against actual steam and drying profiles; and (4) the financing structure, which Zero Industrial brings fully-funded. The output is a lane recommendation with the math shown, not a hardware pitch.

Cost of Waiting

45Z value goes uncaptured every hour a plant keeps raising steam with gas. At a 10-point CI reduction worth $0.02 per point per gallon, the back-of-the-envelope is quick: $20Mn ÷ 365 = ~$55K per day for a 100 MMGY plant, and $20Mn ÷ 8,760 = $2,283 per hour. Table 2 scales the same math across plant sizes.

Plant size	60 MMGY	100 MMGY	150 MMGY
45Z value per year	$12Mn	$20Mn	$30Mn
Lost per month of waiting	$1.0Mn	$1.7Mn	$2.5Mn
Lost per day	$33K	$55K	$82K
Lost every hour	$1.4K	$2.3K	$3.4K

Table 2. The cost of waiting, by plant size. Illustrative; assumes full 45Z capture at $0.02 per CI point per gallon and a 10-point reduction.

The deadline does the rest of the work. 2029 is fixed in statute and does not move because a project started late. A decision made now leaves up to 2.5 years of capture through a 6-9 month E-boiler install; a month of deliberation at a 100 MMGY plant costs $1.7Mn of that; a decision made in 2028 leaves close to nothing. The window rewards producers who run the math early, even those whose math ultimately says skip Phase 1.

The waiting cost applies to Lane B as well, just on a different clock. MVR and TES carry 1.5-2.5 year timelines regardless of when they start, so every quarter of delay pushes the crossover into LCFS and CFR revenue out by a quarter, and shortens the overlap during which the E-boiler is still earning 45Z while Phase 2 commissions. The phased play works best when both clocks start together.

About Zero Industrial

Zero Industrial develops, funds, owns, and operates electrified process heat assets for industrial facilities, delivered as Heat-as-a-Service. $0 CapEx either way: whether the answer is an E-boiler in nine months or a straight path to MVR and TES over two years, ZI brings the capital, carries the construction risk, and the producer pays nothing while the asset is built. The approach is tech-agnostic across E-boilers, MVR, TES, and hybrid configurations; the recommendation follows the plant's numbers, not a product line. Every engagement starts with the site screening and market exposure analysis described above, and ends with the math on the table. Electrified heat. Lower cost. Lower carbon. Carefree.

Summary

Where to focus: Of the ~50 gCO2e/MJ in a typical corn ethanol CI score, the ~20 points of natural gas process heat are the largest slice a producer controls, and electrifying that heat is how the 45Z, LCFS, and CFR dollars get unlocked.

The End-Market: 45Z accepts RECs and closes after 2029, so the E-boiler, deployable in 6-9 months at ~100% efficiency, is its natural instrument. LCFS and CFR demand physical CI reduction and run indefinitely, so MVR (COP > 5 on recovered waste heat) and TES (off-peak charging, steam plus drying hot air) are theirs. Independent Berkeley analysis lands on the same two durable technologies for exactly this temperature band.

Sequencing: The phased play deploys the E-boiler now, earns up to 2.5 years of 45Z at roughly $20Mn/yr for a 100 MMGY plant, and uses that window to engineer MVR and TES in parallel, ready for the regulated markets when the federal window closes. Producers already selling into LCFS or CFR run the decision test first: if incremental 45Z beats the foregone regulated netback, Phase 1 proceeds; if not, capital goes straight to the durable assets.

Time is money: At $2,283 an hour for a 100 MMGY plant, the cost of waiting compounds daily against a statutory deadline that does not move. The right first step is not a purchase order; it is the plant-specific math, run now.

References

1. Dominguez, J., Paliwal, U., & Phadke, A. (April 2026). U.S. Can Cost-Effectively Supply One Third of Industrial Heat Demand Using Off-Grid Electric Thermal Storage and Heat Pumps. India Energy and Climate Center, Goldman School of Public Policy, University of California, Berkeley.

2. 26 U.S.C. § 45Z, Clean Fuel Production Credit.

3. California Air Resources Board, Low Carbon Fuel Standard; parallel programs in Oregon, British Columbia, and New Mexico.

4. Environment and Climate Change Canada, Clean Fuel Regulations (SOR/2022-140).

All dollar figures are illustrative; site-specific results depend on plant configuration, market exposure, and local energy prices.