

Emirati Journal of Business, Economics and Social Studies
Vol 5 Issue 2 (2026)
Pages 248 - 275
Available at
www.emiratesscholar.com

From Waste to Wealth: The Economic Case for Valorising the United Arab Emirates' Agricultural and Food-Processing Biomass Residues Energy Production, Carbon-Credit Revenue, and Net-Zero Contribution Across Three Deployment Scenarios

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ARTICLE INFO

KEYWORDS
biomass valorisation; bioenergy; biochar; carbon credits; BECCS; In-Country Value; Net Zero 2050; circular economy; United Arab Emirates

HOW TO CITE
Alnuaimi, M. (2026). From Waste to Wealth: The Economic Case for Valorising the United Arab Emirates' Agricultural and Food-Processing Biomass Residues Energy Production, Carbon-Credit Revenue, and Net-Zero Contribution Across Three Deployment Scenarios. Emirati Journal of Business, Economics and Social Studies, 5(2), 248-275.
https://doi.org/10.54878/dwob8r57

ABSTRACT

The United Arab Emirates (UAE) generates an estimated 8–12 million tonnes of agriculture- and food-related organic residue each year, a stream presently treated overwhelmingly as a disposal liability rather than an economic asset. This article makes the economic case for valorising that residue and argues three propositions. First, the costliest element of any biomass value chain—collection and logistics—already exists in the UAE, because municipal waste utilities, a commercial waste-to-energy facility, agricultural extension services, source-segregation regulation, and permitted geological carbon-dioxide storage are all operational. Second, three deployment scenarios—energy-only, carbon-only, and a hybrid carbon-plus-energy pathway—are evaluated with a transparent, parameter-tabulated model, distinguishing measured statistics, literature coefficients, and author estimates, and are tested with one-at-a-time sensitivity analysis and low, central, and high cases. The energy-only pathway can supply approximately 2.1–3.5 terawatt-hours per year (central 2.8), or roughly 1.4–2.3% of national electricity consumption, but does not recover its cost of capital at prevailing wholesale prices without a dispatchability premium. The hybrid pathway delivers approximately 1.9 terawatt-hours per year (range 1.3–2.4) of dispatchable, carbon-negative electricity together with approximately 3.4 million tonnes of permanent carbon-dioxide removal per year (range 2.4–4.5). Third, the hybrid pathway stacks electricity sales, disposal fees, biochar credits, and engineered-removal credits into a central direct revenue of approximately US$1.1 billion per year (range US$0.5–1.9 billion) against an annualised cost of roughly US$0.65 billion, with a central net margin near US$0.4 billion and a breakeven engineered-removal credit price of about US$125 per tonne; the engineered-removal price is the dominant sensitivity. The carbon-credit component constitutes a new, foreign-exchange-earning In-Country Value revenue stream, and the hybrid pathway outperforms composting, animal-feed, cement co-processing, and biomethane alternatives on revenue and permanent climate benefit per tonne. A staged deployment gated on credit-price thresholds and storage access is recommended.

Double-blind peer review by independent reviewers.
Received: 18 Jul 2026, Accepted: 25 Oct 2026, Published: 01 Nov 2026
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Introduction

The economic development model that built the modern United Arab Emirates (UAE) was founded on the monetisation of an abundant natural resource. As the country pursues diversification away from hydrocarbons, a quieter resource accumulates each year, largely unmonetised and frequently treated as a cost to be disposed of: the organic residue of the nation's farms, food-processing plants, livestock holdings, and food-supply chains. Drawing together statistics from the Food and Agriculture Organization (FAO), the UAE Ministry of Climate Change and Environment (MOCCAE), and the peer-reviewed literature, this stream can be placed at roughly 8–12 million tonnes per year, comprising date-palm residue, other agricultural and horticultural waste, livestock and poultry manure, and food and supply-chain waste (Ashraf et al., 2016; Ben Salem et al., 2021). The central argument of this article is that this material is not waste in the economic sense—it is a stranded feedstock whose conversion into energy, carbon removal, and soil products can generate a new, durable revenue stream aligned precisely with the UAE's twin objectives of economic diversification and decarbonisation.

The case for valorisation in the UAE is unusually strong for three reasons that this article develops in turn. The first is infrastructural. In most jurisdictions the binding economic constraint on biomass utilisation is not the conversion technology but the cost of collecting dispersed, low-density, often wet material and transporting it to a processing facility; collection and transport routinely account for a substantial, frequently dominant, share of delivered-feedstock cost, especially for residue-based feedstocks (Gold & Seuring, 2011; Omidkar et al., 2025). The UAE is distinctive in that the bulk of this collection infrastructure already exists and is already paid for. The second reason is economic structure. Because the country imports most of its food and much of its fertiliser, and is actively seeking new non-oil and export-earning sectors, the products of biomass valorisation—electricity, carbon-removal credits, and soil amendments—map directly onto import-substitution and In-Country Value (ICV) objectives. The third reason is strategic alignment. The UAE has committed to net-zero greenhouse-gas emissions by 2050 and, in its third Nationally Determined Contribution, to an absolute emissions reduction to 103.5 million tonnes of carbon dioxide equivalent by 2035, a 47% reduction relative to 2019 levels (Government of the UAE, 2024a; Climate Action Tracker, 2024). It has also set an explicit engineered-removal target and possesses, through the Abu Dhabi National Oil Company (ADNOC), one of the region's first permitted geological carbon-dioxide storage operations (ADNOC, 2023; Climate Action Tracker, 2024). Biomass valorisation is one of very few domestic levers that can deliver renewable energy, permanent carbon removal, and waste diversion simultaneously.

The timing of this assessment is not incidental. Two global markets have matured to the point where the economic logic of biomass valorisation has fundamentally changed. The first is the market for durable carbon-dioxide removal, which has shifted from a speculative concept to a transacting market in which permanent removals command prices an order of magnitude above conventional avoidance offsets, drawing large corporate buyers with binding net-zero commitments (CDR.fyi, 2025; Puro.earth, 2025). The second is the market for dispatchable low-carbon power, whose value has risen as electricity systems worldwide absorb large volumes of intermittent solar and wind and consequently place a premium on generation that can be scheduled (IEAGHG, 2024; International Energy Agency [IEA], 2023). The UAE sits at the intersection of both trends: it is expanding solar capacity rapidly, which raises the value of dispatchable balancing power, and it is positioning itself as a regional hub for carbon markets and climate finance, which raises the value of a domestic supply of high-integrity removal credits. A residue base that was uneconomic to exploit a decade ago, when neither market existed at scale, is economically defensible today precisely because the products it yields now have buyers and prices. This article quantifies that proposition for the UAE specifically.

The article proceeds as follows. Section 2 sets out the theoretical framework that organises the analysis. Section 3 establishes the scale and composition of the residue base and Section 4 documents the existing collection and storage infrastructure. Section 5 describes the scenario model, classifies every input by evidential status, and specifies the cost model and the sensitivity design. Sections 6 to 8 evaluate the three deployment scenarios—energy-only, carbon-only, and hybrid—for their contribution to national electricity production, carbon-credit revenue, gross domestic product (GDP) and ICV, and the Net Zero 2050 target. Section 9 compares the scenarios on both revenue and cost; Section 10 reports the sensitivity analysis; Section 11 benchmarks the scenarios against alternative biomass-utilisation pathways; and Sections 12 and 13 draw out the investment sequencing, policy implications, and conclusions.

2. Theoretical Framework

The analysis rests on five strands of economic reasoning that are made explicit here because they determine how the scenarios are constructed, how costs and revenues are attributed, and why the hybrid pathway is expected a priori to dominate. Together they constitute the conceptual framework within which the quantitative results of Sections 6 to 10 should be read.

2.1 Joint Production and the Energy–Carbon Trade-Off Frontier

Biomass conversion is a case of joint production: a single input yields several outputs in proportions that the operator can vary only within technical limits. Pyrolysis is the clearest instance. The same tonne of lignocellulosic residue can be driven towards a stable carbon solid or towards combustible volatiles, and the split is governed principally by temperature and residence time; Woolf et al. (2014) formalise this as a trade-off frontier between energy yield and durable soil-carbon addition, along which no configuration maximises both. Anaerobic digestion is similarly joint, yielding biogas and a nutrient-bearing digestate that can itself be pyrolysed. The economic implication of joint production is that revenue from a feedstock should be evaluated across the whole product set rather than product by product, that the optimal operating point depends on relative output prices, and that costs cannot be meaningfully allocated to one product in isolation. The three scenarios examined below are three positions on this frontier: an energy-maximising corner, a carbon-maximising corner, and an interior point chosen to capture most of both.

2.2 Circular Bioeconomy, the Waste Hierarchy, and Cascading Use

The circular-economy literature frames residues as resources whose value should be retained within the economic system for as long as possible, with recovery options ordered by their contribution to that retention (Kirchherr et al., 2017). Applied to organic residues this ordering is codified in the food-waste hierarchy—prevention, redistribution, animal feed, anaerobic digestion, composting, and finally disposal (Papargyropoulou et al., 2014)—and in the bioeconomy principle of cascading use, under which material is directed to its highest-value application first and energy recovery is reserved for fractions that cannot be used materially. These principles have two consequences for the present analysis. First, valorisation is assessed against a counterfactual of landfilling or open storage, which is the prevailing fate of most UAE organic residue, so that the avoided emissions and avoided disposal costs of that counterfactual are legitimate components of the benefit. Second, the ordering obliges the article to compare its preferred pathways with higher-hierarchy alternatives—feed, materials—rather than assuming energy and carbon conversion are the best use of every tonne; Section 11 does this explicitly.

2.3 Delivered-Feedstock Cost and the Value of Pre-Existing Infrastructure

The bioenergy supply-chain literature establishes that the delivered cost of biomass—acquisition, collection, handling, storage, and transport—is typically the largest operating-cost line and the principal determinant of project viability, and that it is dominated by the logistics of moving low-density, often wet material from dispersed origins to a central plant (Gold & Seuring, 2011; Omidkar et al., 2025). The theoretical point is that this cost is largely a fixed network cost: once a collection system exists for another purpose, the marginal cost of routing its output to a valorisation plant is small. Where a public mandate has already financed collection, the private developer faces only a gate charge and a marginal aggregation cost, and the economic rent created by the public network accrues to the project. This is the mechanism behind Proposition One (Section 4) and it is modelled explicitly in Section 5 as a low net feedstock cost at the plant gate combined with a disposal fee received for wet municipal streams.

2.4 In-Country Value and the Quality of Revenue

Resource-exporting economies pursuing diversification distinguish revenue not only by magnitude but by quality: whether it is externally earned, whether the value chain is domestically retained, and whether it substitutes for imports. The UAE operationalises this through its ICV programme, which scores suppliers on the share of spending retained in the national economy and rewards local manufacturing, employment, and investment (ADNOC, 2018). This framework is applied in Sections 8 and 9 to classify each revenue stream by its quality: electricity sales recirculate domestic spending and substitute for gas; biochar substitutes for imported fertiliser and improves water productivity; and carbon-removal credits are an exportable product earning foreign exchange from international buyers. The same magnitude of revenue can therefore have very different strategic value depending on its composition.

2.5 Staged Investment Under Price Uncertainty

Finally, because the largest revenue component depends on carbon-removal prices set in a young and volatile

market, the analysis treats the investment as a sequence of options rather than a single commitment. Deploying the mature, lower-capital stages first—anaerobic digestion and biochar pyrolysis—creates the physical platform onto which the carbon-capture leg can be added if, and only if, engineered-removal prices and storage tariffs clear explicit thresholds. The value of this staging lies in preserving a profitable fallback (energy plus biochar) while retaining the option to capture the high-value stream. The breakeven prices derived in Section 9 and the sensitivity ranking in Section 10 are the quantitative inputs to those thresholds.

3. The Residue Base and Its Composition

Any economic assessment must begin with the physical resource. Drawing together statistics from the FAO, MOCCAE, the Abu Dhabi Agriculture and Food Safety Authority (ADAFSA), and the peer-reviewed literature, the national residue base can be disaggregated into four principal streams, each classified here by evidential status as a measured or official statistic, a literature estimate, or an author derivation (Section 5.2). Date-palm agriculture is the foundational stream: the UAE cultivates approximately 40 million date palms and ranks among the world's leading date producers—eighth globally, at roughly 400,000 tonnes of dates per year (ADAFSA, 2023; Manikandan et al., 2025). The associated residue—fronds, rachis, leaf stems, empty fruit bunches, trunks, surface fibre, and date pits—is estimated in the literature at approximately 2 million tonnes per year (Ben Salem et al., 2021). The date palm is attractive as a feedstock precisely because its residue is naturally low in moisture and has a measured lower heating value in the range of 16.5 to 18.9 megajoules per kilogram on a dry basis, which exceeds generic biomass defaults and makes it well suited to thermochemical conversion without the energy penalty of drying (Nasser et al., 2016).

The second stream is other agricultural and horticultural waste, dominated by forage crops such as Rhodes grass and alfalfa together with vegetable and non-date fruit residues, estimated in the literature at approximately 1.79 million tonnes per year, of which only a small fraction is currently recycled (Ashraf et al., 2016). The third stream is food and supply-chain waste. MOCCAE, through the national food-loss-and-waste initiative ne'ma, estimates that approximately 3.27 million tonnes of food are wasted annually in the UAE, at a cost to the national economy of roughly US$3.5 billion per year (MOCCAE, 2024); this is an official statistic. The figure is significant not only as a feedstock but as a standing economic loss, although it should be stressed that the greater part of that loss is recoverable only through prevention, not through valorisation of what is discarded. The fourth stream is livestock and poultry manure. The UAE livestock herd exceeds five million head, with goats the most numerous at over 2.2 million animals, alongside large camel, sheep, and cattle populations (FAO, 2023). Applying standard per-animal excretion coefficients (IPCC, 2019) yields an author-derived manure stream on the order of 4.8 million tonnes per year, although a substantial share of grazing-animal manure is not practically collectable. Aggregating these streams gives a total of approximately 11.9 million tonnes per year as generated, at the upper end of the 8–12 million tonne range and the working figure adopted throughout this article. Table 1 summarises the base. The distinction between the tonnage generated and the tonnage recoverable for conversion is central to everything that follows: only about half of the generated mass—6.0 million tonnes in the central case, 4.3 to 7.8 million tonnes across the low and high cases—is assumed to reach a conversion plant (Section 5).

Table 1

Composition of the UAE Annual Biomass-Residue Base and Recoverable Fractions Assumed

Residue stream	Generated (Mt/yr)	Evidence class	Moisture (as generated)	Recoverable fraction (low / central / high)	Principal source(s)
Date-palm residue	~2.0	L	15%	55% / 70% / 85%	Ben Salem et al. (2021); Nasser et al. (2016)
Other agricultural / horticultural waste	~1.79	L	45%	45% / 60% / 75%	Ashraf et al. (2016)
Food and supply-chain waste	~3.27	M	70%	35% / 50% / 65%	MOCCAE (2024)
Livestock and poultry manure	~4.8	A	75%	25% / 40% / 55%	FAO (2023); IPCC (2019)
Total	~11.9	A	—	4.3 / 6.0 / 7.8 Mt/yr recoverable	Author aggregation

Note. Evidence class: M = measured or official statistic; L = literature estimate; A = author derivation (Section 5.2). The manure figure is a first-order estimate derived from standard excretion coefficients (IPCC, 2019) and is the largest single source of uncertainty in the base; a national manure inventory should precede any large commitment of digestion capacity. Moisture and recoverable fractions are author assumptions (A) informed by the cited literature. Mt/yr = million tonnes per year.

4. Proposition One: The Collection Infrastructure Already Exists

The single most consequential economic fact in the UAE biomass opportunity is that the feedstock supply chain does not need to be built from scratch. In the international literature on bioenergy economics, feedstock collection, handling, and transport typically constitute a dominant component of delivered cost and a principal reason that otherwise abundant residues remain unused: material is dispersed across a landscape, has low energy density, is frequently wet, and is expensive to gather and move (Gold & Seuring, 2011; Omidkar et al., 2025). Where a project must finance new collection fleets, transfer stations, and haulage contracts, the capital and operating burden often renders marginal feedstock uneconomic. The UAE is an exception because the collection systems that would ordinarily have to be financed are already operational, already staffed, and already amortised across other public mandates. The economic implication is direct: the incremental cost of feedstock to a valorisation plant is far lower than a greenfield analysis would suggest, because the most expensive link in the chain is a sunk cost borne elsewhere.

4.1 Municipal and Commercial Waste Collection

The emirates operate mature, well-capitalised municipal waste utilities that already collect the food and organic fraction of the waste stream. Sharjah's integrated environmental operator and the equivalent authorities in Abu Dhabi and Dubai run city-scale collection, transfer, and treatment networks. The most economically telling demonstration is that one emirate already converts collected waste into dispatchable power at commercial scale. The Emirates Waste to Energy facility in Sharjah, a joint venture between the

ISSN: 2791-3171 - https://doi.org/10.54878/dwob8r57

national waste operator (BEEAH) and Masdar and inaugurated in 2022 as the region's first commercial-scale plant, generates approximately 30 megawatts of low-carbon power—enough for roughly 28,000 homes—while displacing close to 450,000 tonnes of carbon dioxide and conserving up to 45 million cubic metres of natural gas annually, processing up to 300,000 tonnes of waste per year; an announced second phase, signed in 2025, will roughly double output to nearly 60 megawatts and processing capacity to some 600,000 tonnes per year (BEEAH Group, 2025; Masdar, 2022). The existence of this plant is proof of concept that the collection-to-conversion chain functions in the UAE today, and that the institutional, regulatory, and offtake arrangements for converting waste into grid electricity are already in place.

4.2 Source Segregation and the Food-Waste Initiative

Feedstock quality is as economically important as feedstock quantity, because contamination and moisture degrade conversion efficiency and depress the value of outputs such as compost and biochar. Two policy developments materially improve feedstock quality at no cost to a prospective valorisation investor. First, Federal Law No. (12) of 2018 on Integrated Waste Management establishes source-level waste segregation as a national requirement, and Federal Decree-Law No. (11) of 2024 on the Reduction of Climate Change Effects—in force from 30 May 2025—obliges public and private entities, including hospitality and food-sector businesses, to measure, report, and reduce emissions, including those from food waste (Government of the UAE, 2018, 2024b). Second, the national food-loss-and-waste initiative has built measurement, awareness, and diversion programmes that further structure the supply of organic material (MOCCAE, 2024). From an investment standpoint, mandatory segregation transfers the cost and effort of feedstock preparation from the plant operator to the waste generator and the regulator, improving project economics and de-risking output quality.

4.3 Agricultural Aggregation Points

The agricultural residue streams benefit from a different but equally important form of pre-existing aggregation. Date and field-crop production in the UAE is concentrated on a large but enumerated population of farms—Abu Dhabi alone contains tens of thousands of registered holdings under the supervision of a single food and agriculture authority—and date-palm cultivation in particular generates residue at predictable points and times through routine pruning and harvest cycles (ADAFSA, 2023). This means agricultural residue is not randomly dispersed but is produced at known, mapped, regulated locations that are already visited by extension services and input suppliers. Aggregation of pruning residue at farm or cooperative level is therefore a marginal logistical addition rather than a new network, and the seasonality of date-palm pruning provides a degree of supply predictability that supports plant scheduling and financing.

4.4 Carbon-Dioxide Storage Infrastructure

The final and most strategically distinctive element of pre-existing infrastructure concerns not the input but the disposal of captured carbon, and it is the precondition for the hybrid scenario's carbon-capture component. ADNOC operated the region's first commercial-scale carbon-capture facility (Al Reyadah, from 2016) and has announced plans to expand capture capacity to 10 million tonnes per year by 2030, supported by permanent geological storage that includes injection into saline aquifers (ADNOC, 2023; Climate Action Tracker, 2024). For a bioenergy-with-carbon-capture pathway, the availability of permitted, certified storage transforms the economics, because the cost and regulatory burden of developing dedicated storage—often prohibitive elsewhere—is replaced by access to shared national infrastructure at a tariff; the cost model in Section 5 therefore treats transport and storage as a per-tonne charge rather than as project capital. While other Gulf states are now developing comparable capacity, the UAE was among the first in the region to combine abundant residue with permitted carbon storage, and this combination is the foundation of its comparative advantage in carbon-negative biomass valorisation. It should be noted that point-source capture of fossil carbon dioxide is an emissions-abatement activity rather than carbon removal; the carbon-negative claim in this article rests specifically on the capture of biogenic carbon dioxide, discussed under Scenario 3. Taken together, these four infrastructural endowments mean that the UAE biomass opportunity is principally an investment in conversion capacity and market access rather than in the costly supply chain that ordinarily dominates biomass project budgets.

4.5 Quantifying the Avoided Supply-Chain Cost

The economic weight of this infrastructural inheritance can be made concrete. In conventional biomass project finance, delivered-feedstock cost frequently represents the largest line in operating expenditure and can

determine whether a project clears its hurdle rate (Gold & Seuring, 2011; Omidkar et al., 2025). Where a developer must procure collection vehicles, build transfer and storage facilities, and contract haulage across a dispersed rural or urban catchment, these costs are both large and front-loaded, and they fall disproportionately on the wet, low-density streams—food waste and manure—that are most valuable for anaerobic digestion. In the UAE, the municipal fraction of the feedstock arrives at the plant gate through systems already financed by waste-management mandates, and the agricultural fraction is produced at enumerated, regulated holdings already served by extension and input-supply networks. The developer's feedstock cost is therefore reduced to a marginal aggregation and gate charge rather than the full economic cost of a bespoke collection network, and for the municipal wet streams the developer can reasonably expect to receive a disposal fee, since the alternative disposal routes carry a cost to the municipality. The model in Section 5 represents this as a net aggregation cost of US$5 per wet tonne across all streams and a disposal fee of US$25 per wet tonne received for food waste and manure, both author estimates tested in the sensitivity analysis. This suppression of the dominant cost line is the mechanism by which an otherwise marginal residue stream becomes bankable, and the corollary for policy is that the public investment required to unlock the opportunity is far smaller than the gross capital figures might imply.

5. Methods and Assumptions

5.1 Scope and System Boundary

The analysis is a national-scale, steady-state, annual techno-economic assessment. Its system boundary begins at the plant gate—feedstock collection is treated as pre-existing, per Proposition One—and ends at the sale of electricity, carbon-removal credits, and the receipt of disposal fees. Biochar is valued at its carbon-credit price only; its agronomic product value (Section 7.3) and the value of digestate are discussed qualitatively and excluded from the central revenue figures so that those figures remain conservative. Upstream and construction-phase emissions are excluded from the carbon accounting, which is therefore a gross operational figure; a full life-cycle assessment is identified as further work. All monetary values are in nominal 2025 US dollars, converted from euros where necessary at US$1.08 per euro. The electricity denominator is final consumption of approximately 153 terawatt-hours in 2023 (U.S. Energy Information Administration [EIA], 2025); gross generation reached a record 177 terawatt-hours in 2024 (MEES, 2025), and shares expressed against generation would be correspondingly smaller.

5.2 Evidence Hierarchy

To address the distinction between what is measured, what is drawn from the literature, and what is assumed, every quantitative input is assigned one of three evidence classes, which are carried through Tables 1 and 2 and referred to in the text. Class M (measured or official) denotes a statistic published by a government or intergovernmental body or a laboratory measurement reported in a peer-reviewed source, such as national electricity consumption, the ne'ma food-waste estimate, or the measured heating value of date-palm residue. Class L (literature coefficient) denotes a conversion factor, yield, or cost drawn from peer-reviewed reviews or recognised technical bodies, such as methane yields in anaerobic digestion or the levelised cost of bioenergy. Class A (author estimate) denotes a parameter the author has set by judgement within a range bounded by the literature, such as recoverable fractions, the net feedstock cost at the gate, or the capacity factor. Every scenario output is therefore a derived quantity, and the reader can trace each one to the class of evidence on which it rests. Outputs are reported as a central value with a low and a high case rather than as point estimates.

5.3 Model Structure and Parameter Values

The model proceeds in four steps. First, each generated stream (Table 1) is converted to a recoverable dry or wet mass by applying its moisture content and recoverable fraction. Second, recoverable mass is converted to primary energy using a dry-basis lower heating value for the lignocellulosic streams and a methane yield per wet tonne for the digestible streams, then to net electricity through conversion efficiencies, an availability factor covering downtime and process losses, and, where carbon capture is applied, a parasitic-load deduction. Third, carbon outcomes are computed separately as permanent removal—biochar carbon multiplied by a 100-year permanence factor, plus captured biogenic carbon dioxide—and as avoided emissions from displaced gas-fired generation and from diverting food waste and manure out of landfill and open storage; the two categories are never added into a single 'removal' figure. Fourth, revenue is computed from unit prices and cost from annualised capital expenditure, operating expenditure, net feedstock cost, and per-tonne capture, transport, and storage charges. Table 2 lists every parameter, its central value, the low–high range used in the cases and the sensitivity analysis, its evidence class, and its source. The model is deterministic and reproducible from Table 2 alone.

ISSN: 2791-3171 - https://doi.org/10.54878/dwob8r57

Table 2

Model Parameters, Ranges, Evidence Class, and Sources

Parameter	Central value	Low – high	Class	Source / basis
Feedstock and recovery				
Generated tonnage by stream	Table 1	—	M / L / A	Table 1
Moisture content (date palm; other agricultural; food; manure)	15%; 45%; 70%; 75%	—	A	Nasser et al. (2016); Ashraf et al. (2016)
Recoverable fraction (date palm; other agricultural; food; manure)	70%; 60%; 50%; 40%	Table 1	A	Author judgement; segregation law (Government of the UAE, 2018)
Energy conversion				
Lower heating value, dry basis (date palm; other agricultural)	17.5; 15.0 MJ/kg	16.5–18.9 (date palm)	M / L	Nasser et al. (2016); Ashraf et al. (2016)
Methane yield (food waste; manure)	100; 25 m^3 CH_4 per wet t	80–120; 15–40	L / A	Zhang et al. (2007): ~435 m^3/t VS food waste; Song et al. (2023): 150–400 m^3/t VS manure, discounted for aged, sand-contaminated UAE manure
Net electrical efficiency (combustion; biogas engine; pyrolysis-gas engine)	28%; 38%; 30%	—	L	IRENA (2025); Martis et al. (2020)
Availability and process-loss factor	0.90	—	A	Author judgement
Capacity factor for megawatt equivalents	0.85	—	A	Author judgement
Volatile energy fraction (carbon-max pyrolysis; intermediate pyrolysis)	40%; 55%	—	L	Woolf et al. (2014)
Carbon				
Biochar mass yield (carbon-max; intermediate)	38%; 30%	—	L	Ben Salem et al. (2021); Woolf et al. (2014)

Parameter	Central value	Low – high	Class	Source / basis
Biochar organic-carbon content (carbon-max; intermediate; digestate char)	75%; 72%; 45%	—	L	Rodrigues et al. (2023)
100-year permanence factor (both pyrolysis routes, 450–600 °C)	0.80	0.70–0.89	L	IPCC (2019) Table 4Ap.2; Woolf et al. (2021); Petersen & Sanei (2025)
Digestate dry-matter fraction (food; manure)	10%; 12%	—	A	Author judgement
Biogenic CO_2 intensity of pyrolysis-gas and residue combustion	0.100 t CO_2 per GJ	—	L	IPCC (2019) biomass default
Capture rate (flue gas; biogas-upgrading stream)	90%; 98%	80–95% (flue)	L	Rosa et al. (2021): 90% bio-power, 99.5% biomethane streams
Capture parasitic load on electricity	15%	10–25%	L	IEAGHG (2024)
Avoided landfill emissions, food waste	0.90 t CO_2e per wet t	—	L	IPCC (2019) first-order decay, no gas capture
Avoided storage emissions, manure	0.30 t CO_2e per wet t	—	L / A	IPCC (2019) manure-management defaults
Grid displacement factor	0.44 t CO_2 per MWh	—	L	Gas-fired generation at ~50% efficiency
Prices				
Wholesale electricity price	US$70/MWh	50–90	A	Author judgement on UAE wholesale and bulk-supply tariffs
Biochar carbon-removal credit	US$140/t CO_2 (≈ EUR 130)	70–210	M	Puro.earth (2025); CDR.fyi & OPIS (2025): supplier breakeven ≈ US$143/t
Engineered (BECCS) removal credit	US$300/t CO_2	200–400	M / L	CDR.fyi (2025): 2024 market-wide weighted average US$320/t; CDR.fyi & OPIS (2025): BECCS supplier breakeven ≈ US$212/t; Drax (2024); Abegg et al. (2024)
Disposal fee received (food waste; manure)	US$25 per wet t	0–50	A	Author judgement on municipal disposal costs

Parameter	Central value	Low – high	Class	Source / basis
Net feedstock aggregation cost at gate, all streams	US$5 per wet t	—	A	Proposition One; Gold & Seuring (2011); Omidkar et al. (2025)
Exchange rate	US$1.08 per EUR	—	M	2025 average
Costs				
Anaerobic-digestion capital cost (food waste; manure), incl. engines	US$400; US$150 per wet t/yr	−30% to +60%	L / A	IEA Bioenergy Task 37 (2018); Walla & Schneeberger (2008): EUR 3,500–4,500/kWel
Pyrolysis capital cost (incl. gas engine / heat recovery)	US$900 per dry t/yr	600–1,300	L	Campion et al. (2023)
Biomass combustion plant capital cost	US$3,500/kW	3,000–4,200	L	IRENA (2025)
Non-feedstock operating cost	4.5% of capex per yr	—	L	IRENA (2025)
Capture cost, dilute flue gas (incl. compression)	US$80/t CO_2	60–120	L	IEA (2021): US$40–120/t for dilute streams; Fuss et al. (2018)
Capture cost, biogas-upgrading stream	US$25/t CO_2	—	L	IEA (2021): US$15–25/t for concentrated streams
Transport and storage tariff	US$20/t CO_2	10–40	L	Smith et al. (2021): US$4–45/t onshore pipeline and saline storage
Weighted average cost of capital; asset life	8%; 20 years	6–12%	A	Capital recovery factor 0.102
National benchmarks				
Final electricity consumption (2023); gross generation (2024)	153 TWh; 177 TWh	—	M	EIA (2025); MEES (2025)
Nominal GDP (2023)	US$510 billion	—	M	World Bank (2024)
National GHG emissions, 2019 baseline; 2035 NDC target	196.3; 103.5 Mt CO_2e	—	M	Government of the UAE (2024a)

Parameter	Central value	Low – high	Class	Source / basis
Engineered-removal ambition, 2050	9.5 Mt CO_2/yr	—	M	Government of the UAE (2024c)

Note. Class: M = measured or official; L = literature coefficient; A = author estimate. Ranges are those used in the low and high cases (Section 10) and in the one-at-a-time sensitivity analysis; parameters without a range are held fixed. BECCS = bioenergy with carbon capture and storage; GHG = greenhouse gas; NDC = Nationally Determined Contribution.

5.4 Scenario Definitions

Scenario 1 (energy-only) routes the wet streams through anaerobic digestion to biogas-fired generation and the dry lignocellulosic streams through direct combustion in a steam cycle; it books no permanent removal. Scenario 2 (carbon-only) routes the dry streams through carbon-maximising slow pyrolysis at around 550 °C, with roughly 40% of feedstock energy liberated as volatiles, most of which is consumed in drying and process heat and a minority of which generates a small electricity surplus; the wet streams are composted. Scenario 3 (hybrid) allocates each stream to the conversion route in which it has comparative advantage and overlays carbon capture on every combustion step: date-palm residue, the superior biochar feedstock, is pyrolysed at an intermediate 450–500 °C that preserves a credit-eligible char while liberating roughly 55% of feedstock energy as volatiles; the lower-grade crop and horticultural residue is combusted in a steam cycle with post-combustion capture; and the wet streams are digested, the biogas upgraded—yielding a near-pure carbon-dioxide stream captured at low cost—and the biomethane fired in engines with flue-gas capture, with the digestate pyrolysed to additional biochar. This allocation differs from a naive configuration in which all dry residue is pyrolysed, and it is adopted because it raises both electricity and captured carbon dioxide for a given biochar output.

5.5 Cost Model

Costs are built from unit capital costs per tonne of annual throughput (digestion and pyrolysis) or per kilowatt (combustion), annualised with a capital recovery factor of 0.102 (8% weighted average cost of capital, 20-year life), plus non-feedstock operating costs at 4.5% of capital per year, the net feedstock cost at the gate, and, in the hybrid, per-tonne capture costs differentiated between dilute flue gas and the near-pure upgrading stream, plus a transport-and-storage tariff for access to national storage. Pyrolysis capital in the hybrid carries a 10% premium for heat-recovery integration. The model reports, for each scenario, the annualised cost, the net annual margin (revenue less annualised cost), the levelised cost of electricity for the energy-only scenario, the all-in cost per tonne of permanent removal, and the breakeven credit prices at which the net margin is zero. These are first-order, pre-tax, pre-incentive figures intended to show whether each scenario is in the region of commercial viability, not to replace project-level financial modelling.

5.6 Sensitivity Design

Uncertainty is treated in two complementary ways. First, a one-at-a-time sensitivity analysis varies each of fifteen parameters across the range in Table 2 while holding all others at their central values, and ranks them by the swing they induce in the hybrid pathway's net annual margin (Figure 1a). Second, coherent low, central, and high cases are constructed by setting all uncertain parameters simultaneously to their pessimistic, central, or optimistic values (Table 6; Figure 1b). The low case therefore represents a conjunction of adverse outcomes—low recovery, low prices, high costs, high cost of capital—rather than a likely outcome, and the high case the converse; the central case is the author's best estimate. Breakeven engineered-removal prices are also reported as a function of the biochar credit price.

5.7 Limitations

Four limitations bound the interpretation of the results. The manure tonnage and its recoverable share are derived, not measured. Unit costs are international literature values not yet calibrated to UAE engineering, procurement, and construction conditions, where land and labour costs may differ in either direction. Carbon-removal credit prices are drawn from a young voluntary market whose depth for engineered removals is still forming. And the carbon accounting is gross and operational, excluding construction, transport fuel, and any indirect land-use effects, none of which is expected

to be large for a residue-based system but all of which would be required for a certified credit.

6. Scenario 1: Biomass-to-Energy and Its Economic Contribution

The energy-only scenario routes wet streams—food waste and manure—through anaerobic digestion to produce biogas for power generation, and dry lignocellulosic streams—date-palm and crop residue—through combustion. Using the heating values and methane yields in Table 2, the gross theoretical primary energy of the full generated base is approximately 61 petajoules per year, of which the recoverable fraction represents approximately 37 petajoules (range 28–46). After conversion at the efficiencies in Table 2 and after the availability deduction, the realistically recoverable electricity output is approximately 2.8 terawatt-hours per year in the central case, with a range of 2.1 to 3.5 terawatt-hours, corresponding to an installed-capacity equivalent of roughly 375 megawatts (range 280–470) at an 85% capacity factor. Roughly three-quarters of this electricity comes from combustion of the dry streams and one-quarter from biogas.

6.1 Contribution to National Electricity Production

The economically meaningful benchmark is national electricity demand. UAE final electricity consumption was approximately 153 terawatt-hours in 2023 (EIA, 2025), while gross generation reached a record of roughly 177 terawatt-hours in 2024, of which low-carbon sources supplied close to 30% (MEES, 2025). Against consumption, the recoverable biomass electricity of 2.8 terawatt-hours represents approximately 1.8% of national demand (range 1.4–2.3%). This is a modest but non-trivial share, and its economic character is distinctive in three respects. It is dispatchable, unlike the solar generation that dominates UAE renewable expansion, and dispatchable low-carbon capacity commands a premium in a grid balancing large intermittent additions (IEAGHG, 2024). It is fuelled by a domestic residue rather than by imported or opportunity-cost fuel, so each unit generated frees an equivalent quantity of natural gas—on the order of 0.5 billion cubic metres per year at the central recoverable level—for higher-value export or industrial use. And it is co-located with waste-management mandates, so the generation asset simultaneously discharges a disposal obligation that would otherwise be a pure cost.

6.2 Revenue, Cost, and GDP Contribution

At the central wholesale power price of US$70 per megawatt-hour, electricity sales of 2.8 terawatt-hours generate approximately US$196 million per year (range US$116–297 million), to which disposal fees on the wet streams add approximately US$89 million in the central case, for a direct revenue of roughly US$285 million. Against this, the annualised cost of the digestion and combustion plant is approximately US$312 million per year on a capital base of US$1.9 billion, so that the energy-only scenario shows a small negative central net margin of about US$27 million per year (range –US$185 to +US$167 million) and a levelised cost of electricity of approximately US$111 per megawatt-hour (range US$92–154)—above the assumed wholesale price. This finding is consistent with international experience: the global weighted-average levelised cost of bioenergy generation was about US$87 per megawatt-hour in 2024 and rising (IRENA, 2025), and residue-fed plants are cost-competitive only where feedstock is nearly free and plants are large, and digestion of dilute manure is intrinsically expensive per unit of energy. Energy-only valorisation in the UAE is therefore viable only if it earns a dispatchability or capacity premium that lifts the realised price to about US$80 per megawatt-hour, or a disposal fee above roughly US$33 per tonne reflecting the fuller social cost of landfill, neither of which is assumed in the central case. To the direct figures the energy scenario adds two indirect benefits that belong in any complete GDP accounting: the value of natural gas freed for alternative use, plausibly US$100–150 million per year depending on the gas price realised, and avoided long-term landfill liability. The energy scenario, however, captures none of the carbon-removal value that is the subject of Scenario 2, because combustion returns the biogenic carbon to the atmosphere. Its climate contribution is confined to avoided emissions—displaced fossil generation of roughly 1.2 million tonnes of carbon dioxide per year plus avoided landfill and storage methane of roughly 2.1 million tonnes of carbon-dioxide equivalent, for total mitigation of about 3.3 million tonnes (range 2.3–4.2)—rather than permanent removal. In GDP terms, the energy-only scenario is best understood as a waste-management service with a generation co-product, and one that leaves the most valuable product of the residue base, durable carbon removal, on the table.

It is worth isolating the economics of the anaerobic-digestion component, because it carries a benefit that pure thermochemical generation does not. Digestion of food waste and manure produces biogas that can be combusted for power or upgraded to biomethane for injection into the gas network or sale as a transport fuel,

and the residual digestate retains fertiliser value (Ashraf et al., 2016; IEA, 2020; IEA Bioenergy Task 37, 2018). The dispatchability of biogas-fired generation is its distinctive economic strength: unlike solar, it can be stored as gas and called upon when the system needs it, which in a solar-heavy grid is precisely when wholesale prices are highest. A biomass plant that earns a capacity or balancing premium in addition to an energy price improves its revenue per unit substantially, and this premium is likely to grow as the UAE's intermittent fleet expands (IEA, 2023). The avoided-methane benefit is equally consequential. Food waste and manure decomposing in landfill or in open storage emit methane, a greenhouse gas far more potent than carbon dioxide over the near term, so diverting these streams into a sealed digester avoids emissions that would otherwise occur. This avoided-methane value is real and creditable, but it is an avoidance rather than a removal, and it is the limitation that motivates the shift toward permanent storage in the scenarios that follow.

7. Scenario 2: Biomass-to-Carbon and the Carbon-Credit Revenue Stream

The carbon-only scenario reorients the same feedstock toward maximum carbon storage. The dominant pathway is pyrolysis of dry lignocellulosic residue into biochar, a stable, carbon-rich solid that sequesters carbon over century timescales when its hydrogen-to-organic-carbon ratio is low enough to qualify under recognised permanence standards (Rodrigues et al., 2023; Petersen & Sanei, 2025; Woolf et al., 2021). Date-palm residue is an excellent biochar feedstock, yielding approximately 35 to 45% biochar by mass at intermediate to high pyrolysis temperatures, with a high fixed-carbon content (Ben Salem et al., 2021). Applying the central parameters—1.78 million dry tonnes recoverable, a 38% yield, 75% organic carbon, and a 0.80 hundred-year permanence factor consistent with the IPCC (2019) default for pyrolysis at 450–600 °C and with the Woolf et al. (2021) inventory model—the scenario produces approximately 0.68 million tonnes of biochar and 1.5 million tonnes of carbon dioxide per year of permanent removal (range 1.0–2.0). Complementary pathways include composting of wet streams for soil-carbon benefit and the diversion of food waste from landfill, which avoids approximately 2.2 million tonnes of carbon-dioxide equivalent (range 1.5–2.9); compost adds a small, slowly decaying soil-carbon benefit of about 0.2 million tonnes. The total climate benefit is therefore on the order of 3.9 million tonnes of carbon-dioxide equivalent per year (range 2.6–5.2), of which 1.5 million is permanent removal. The surplus pyrolysis gas not needed for drying and process heat yields a small electricity output of approximately 0.36 terawatt-hours (range 0.28–0.44), about 0.2–0.3% of national demand.

7.1 The Carbon-Credit Market and Unit Value

The economic significance of the carbon scenario rests on the price commanded by durable carbon-removal credits, which is an order of magnitude above the price of conventional avoidance offsets. Biochar carbon-removal credits, certified under methodologies such as the Puro Standard, traded in 2025 in a band of roughly EUR 125 to 145 per tonne of carbon dioxide, with a representative index value near EUR 125 in late 2025; biochar accounted for 86% of all durable removals delivered in 2024 and its prices rose while most other pathways fell (Puro.earth, 2025; CDR.fyi, 2025). At the central price of US$140 per tonne (approximately EUR 130), the biochar removal of 1.5 million tonnes per year is worth approximately US$208 million per year (range US$101–345 million), to which the small electricity surplus and disposal fees add roughly US$114 million, for a total direct revenue near US$322 million. The annualised cost of the pyrolysis and composting capacity, on a capital base of about US$1.8 billion, is approximately US$350 million per year, so the carbon-only scenario is close to breakeven in the central case: its breakeven biochar credit price is approximately US$159 per tonne, slightly above the prevailing index and close to the US$143 per tonne that biochar suppliers themselves report as breakeven (CDR.fyi & OPIS, 2025); it is profitable in the high case and loss-making in the low case. This is the central economic finding of the carbon scenario: a residue stream that is currently a disposal cost can be transformed into a product whose unit value is set by an international market for permanent carbon removal, and at current prices that product roughly covers the full cost of producing it before any value is assigned to the biochar as a soil amendment.

7.2 A New In-Country Value and Export Revenue Stream

Carbon-removal credits possess an economic property that distinguishes them sharply from electricity: they are an internationally tradable, foreign-exchange-earning product. Whereas power generated from biomass substitutes for domestic gas and is consumed within the national grid, a verified carbon-removal credit can be sold to an international buyer—a corporation meeting a net-zero commitment, for example—bringing external

revenue into the country. In the framework of the UAE's ICV programme, which seeks to retain and grow the share of economic activity captured domestically (ADNOC, 2018), biochar and engineered-removal credits represent an almost ideal new vertical: the feedstock is domestic, the conversion and the measurement, reporting, and verification activity are performed domestically, the soil-amendment co-product can substitute for imported fertiliser inputs, and the credit itself is exported for hard currency. The carbon scenario thus contributes to GDP not only through the magnitude of credit revenue but through its quality as a net export and as a high-skill, high-retention domestic value chain. Its limitation is symmetrical to that of Scenario 1: by optimising for carbon storage, it forgoes most of the dispatchable electricity that the energy scenario captures, and the maximisation of biochar yield reduces the energy recoverable from the pyrolysis volatiles.

7.3 Biochar as an Agronomic Asset in Arid Soils

The economic value of biochar is not confined to the carbon credit it earns; the material itself is a saleable soil amendment, and its agronomic properties are especially valuable in the UAE's context. The country's soils are predominantly sandy, low in organic matter, and poor at retaining water and nutrients, and its agriculture is constrained above all by water scarcity. Biochar improves water-holding capacity, cation-exchange capacity, and nutrient retention in exactly such soils, an effect confirmed both by meta-analysis across coarse-textured soils and by UAE-specific trials using date-palm-waste biochar (Razzaghi et al., 2020; Edeh et al., 2020; Khan et al., 2023). This means domestically produced biochar can raise the efficiency of scarce irrigation water and reduce the quantity of fertiliser required per unit of output. Both effects carry direct economic value in a country that imports a large share of its food and much of its fertiliser and that treats food security as a strategic priority. A domestic biochar industry therefore substitutes for imports at two points—reducing fertiliser purchases and improving the productivity of water-limited cultivation—while supporting national food-security and sustainable-agriculture objectives. This dual role, as both a carbon-removal vehicle and an agricultural input, is what makes biochar economically distinctive: the same tonne of material is simultaneously a sequestration asset earning a credit and a soil product earning a sale. The central revenue figures deliberately exclude the product value; were the 0.68 million tonnes of biochar to realise even US$100 per tonne as a soil amendment, the carbon scenario's revenue would rise by roughly US$68 million per year and its breakeven credit price would fall by about US$45 per tonne to roughly US$115—below the prevailing index—a margin of safety that is noted here but not relied upon.

8. Scenario 3: The Hybrid Pathway—Stacked Revenue and Dual Contribution

The two preceding scenarios present a false choice. The defining insight of the hybrid pathway, which follows directly from the joint-production framework of Section 2.1, is that energy and carbon removal are not mutually exclusive products of a residue stream but joint products that can be co-produced from the same feedstock through complementary, integrated technologies. Pyrolysis inherently yields both a stable carbon solid and combustible gases; the only decision is the split between them, governed largely by temperature, and across a wide range of configurations an operator can deliberately balance carbon yield against energy yield (Woolf et al., 2014). Anaerobic digestion yields biogas for energy and leaves a digestate that can itself be pyrolysed into additional biochar. And the biogenic carbon dioxide released when biogas, biomethane, pyrolysis gas, or residue is combusted can be captured and routed to geological storage, delivering negative emissions alongside the energy. The hybrid pathway assembles these into a single polygeneration system, allocating each stream to its comparative-advantage route as described in Section 5.4.

8.1 Combined Physical Output

In the central case the hybrid yields approximately 1.9 terawatt-hours of net electricity per year (range 1.3–2.4), composed of roughly 0.7 terawatt-hours from pyrolysis gas, 0.5 from combustion of crop residue, and 0.6 from biomethane, after a 15% parasitic deduction for capture; this corresponds to an installed-capacity equivalent of roughly 250 megawatts (range 175–330). Permanent carbon-dioxide removal totals approximately 3.4 million tonnes per year (range 2.4–4.5), of which about 0.9 million tonnes (range 0.6–1.3) is biochar from date-palm residue and digestate and about 2.5 million tonnes is captured biogenic carbon dioxide—roughly 0.3 million tonnes from the near-pure biogas-upgrading stream and 2.2 million tonnes from flue gas. Avoided emissions add approximately 2.9 million tonnes of carbon-dioxide equivalent, so the total climate benefit reaches approximately 6.3 million tonnes per year (range 4.4–8.3). The hybrid therefore retains roughly two-thirds of the energy-only scenario's electricity (67%; range 62–

ISSN: 2791-3171 - https://doi.org/10.54878/dwob8r57

70%) while more than doubling the carbon-only scenario's permanent removal. The electricity forgone relative to Scenario 1 is the direct consequence of diverting carbon into biochar and of the capture parasitic load; the gain in permanent removal is possible because every biogenic carbon-dioxide stream in the system, including the cheapest to capture, is captured rather than vented, and because the UAE's existing storage infrastructure provides a destination for it.

8.2 Stacked Revenue and Its Composition

The economic case for the hybrid pathway is that it books several revenue streams from one feedstock and one integrated asset base. The first is electricity sales of approximately US$131 million per year (range US$72–207 million). The second is carbon-removal credits, themselves of two kinds: biochar credits of approximately US$131 million per year (range US$64–215 million) at the central biochar price, and engineered removal credits on the captured biogenic carbon dioxide of approximately US$742 million per year (range US$351–1,300 million). The pricing of the latter is anchored in disclosed transactions for permanent, geologically stored carbon removal: contracts in the range of US$300 to US$400 per tonne have been reported for engineered removals, the weighted-average price across all durable removals purchased in 2024 was about US$320 per tonne, and bioenergy-with-carbon-capture suppliers report an expected breakeven of about US$212 per tonne by 2030 (CDR.fyi, 2025; CDR.fyi & OPIS, 2025; Drax, 2024; Abegg et al., 2024). Disposal fees on the wet streams add approximately US$89 million. Summing the four components yields a stacked direct revenue of approximately US$1.09 billion per year in the central case (range US$0.51–1.91 billion). Critically, the carbon-credit revenue—US$873 million—exceeds the power revenue by a factor of roughly six to seven, which is the central economic reason to pursue the more complex hybrid rather than the simpler energy-only plant: the value of the residue base is unlocked principally through carbon, and only secondarily through electricity. Table 3 sets out the stacked revenue composition.

Table 3

Estimated Annual Stacked Revenue of the Hybrid Pathway

Revenue stream	Physical basis (central)	Unit price (central)	Annual revenue, central (US$ m)	Range, low–high (US$ m)
Electricity sales	1.87 TWh	US$70/MWh	131	72–207
Biochar carbon-removal credits	0.94 Mt CO_2	US$140/t	131	64–215
Engineered (BECCS) removal credits	2.47 Mt CO_2	US$300/t	742	351–1,300
Disposal fees on wet streams	3.56 Mt wet	US$25/t	89	23–191
Total direct revenue	—	—	1,093	510–1,912

Note. BECCS = bioenergy with carbon capture and storage. Components are computed from Table 2 and sum exactly to the total. Credit prices follow Puro.earth (2025) and CDR.fyi and OPIS (2025) for biochar and CDR.fyi (2025), Drax (2024), and Abegg et al. (2024) for engineered removals. Figures are indicative ranges, not contracted prices, and carbon-credit prices are volatile and index-dependent. m = million; Mt = million tonnes; TWh = terawatt-hours.

8.3 Contribution to Energy, GDP, and Net Zero

The hybrid pathway's contribution can now be expressed against each of the three national aggregates that frame this article. In energy terms, its 1.9 terawatt-hours per year correspond to approximately 1.2% of national electricity consumption (range 0.9–1.6%)—below the energy-only maximum, the difference being the carbon locked into biochar and the parasitic load of capture, but delivered as dispatchable, carbon-negative power. In GDP terms, the direct stacked revenue of US$1.09 billion is equivalent to roughly 0.21% of the UAE's nominal GDP of approximately US$510 billion in

2023 (World Bank, 2024), with a range of 0.10 to 0.37%. This direct share is modest, and it would be a mistake to oversell it; the strategic value lies less in the headline percentage than in the quality and novelty of the revenue. When the broader economic footprint is included—the value of roughly 0.35 billion cubic metres of gas freed for export, the substitution of imported fertiliser by biochar and digestate, avoided landfill costs, and the indirect and induced output of a new domestic industry at a conventional output multiplier of around 1.5—the total economic contribution plausibly reaches US$1.5 to 2.5 billion per year, or roughly 0.3 to 0.5% of GDP; this footprint is an author estimate and is not used in any of the comparative tables. The contribution to the Net Zero objective is examined in detail in the comparative section that follows, but in summary the hybrid's permanent removal of 3.4 million tonnes per year and total mitigation of 6.3 million tonnes per year represent a material share of the UAE's declared engineered-removal ambition.

9. Comparative Economic Analysis

Bringing the three scenarios together allows the central trade-offs to be seen clearly. The energy-only scenario maximises dispatchable electricity but generates no permanent carbon removal, captures none of the high-value carbon-credit revenue, and does not cover its cost of capital at prevailing power prices. The carbon-only scenario maximises biochar removal and the associated credit revenue, is approximately at breakeven at current biochar prices, but forgoes most of the dispatchable electricity. The hybrid pathway captures two-thirds of the electricity and more than twice the permanent removal, at the cost of higher capital intensity and greater integration complexity, and it is the only scenario with a substantial positive net margin in the central case. Because the carbon-credit revenue so substantially exceeds the electricity revenue, the hybrid generates by far the highest combined economic and climate return of the three, and it does so by exploiting the same residue base and, crucially, the same pre-existing collection and storage infrastructure. Table 4 consolidates the physical and revenue comparison and Table 5 the cost comparison.

Table 4

Comparative Economic and Decarbonisation Profile of the Three Scenarios (Central Case, With Low–High Range)

Dimension	Scenario 1: Energy	Scenario 2: Carbon	Scenario 3: Hybrid
Net electricity (TWh/yr)	2.8 (2.1–3.5)	0.36 (0.28–0.44)	1.9 (1.3–2.4)
Share of national consumption	1.8% (1.4–2.3%)	0.2% (0.2–0.3%)	1.2% (0.9–1.6%)
Installed-capacity equivalent (MW)	~375 (280–470)	~50	~250 (175–330)
Permanent CO_2 removal (Mt/yr)	0	1.5 (1.0–2.0)	3.4 (2.4–4.5)
Avoided emissions (Mt CO_2e/yr)	3.3 (2.3–4.2)	2.4 (1.6–3.1)	2.9 (2.0–3.8)
Total mitigation (Mt CO_2e/yr)	3.3 (2.3–4.2)	3.9 (2.6–5.2)	6.3 (4.4–8.3)
Direct revenue (US$ m/yr)	285 (139–488)	322 (139–573)	1,093 (510–1,912)
Direct GDP share	~0.06%	~0.06%	~0.21% (0.10–0.37%)
Capital intensity	moderate	moderate	high

Note. National benchmarks: final electricity consumption ≈ 153 TWh (2023) (EIA, 2025) and record gross generation ≈ 177 TWh (2024) (MEES, 2025); nominal GDP ≈ US$510 bn (2023) (World Bank, 2024). Direct revenue includes disposal fees on the wet streams in all scenarios. GDP shares reflect direct revenue only and exclude the indirect economic footprint. Avoided emissions for Scenario 2 include the compost soil-carbon benefit. Figures are first-order estimates from the model in Section 5. bn = billion; Mt = million tonnes; MW = megawatts; TWh = terawatt-hours.

9.1 Costs, Margins, and Breakeven Prices

Table 5 reports the cost side, which the revenue comparison alone would obscure. The energy-only scenario carries the lowest annualised cost but, lacking any carbon revenue, is marginally loss-making at a

US$70 per megawatt-hour power price; it would require a realised price of about US$80 per megawatt-hour, or a disposal fee above roughly US$33 per tonne, to break even. The carbon-only scenario's annualised cost is of similar magnitude and is almost covered by biochar credits, surplus electricity, and disposal fees at current prices, with a shortfall of under US$30 million per year. The hybrid's annualised cost is roughly twice that of either single-product scenario—approximately US$660 million per year, of which about US$230 million is capture, transport, and storage—but its revenue is more than three times higher, giving a central net margin of approximately US$434 million per year and a margin on revenue of about 40%. The all-in cost per tonne of permanent removal under the hybrid is approximately US$193 (range US$145–273), which sits within the published cost ranges for bioenergy with carbon capture and storage and biochar (Fuss et al., 2018; Abegg et al., 2024) and well below the central engineered-removal price. The breakeven engineered-removal credit price—the price at which the hybrid's net margin is zero with all other parameters central—is approximately US$124 per tonne; it rises to about US$151 if biochar credits fall to US$70 per tonne and falls to about US$98 if they rise to US$210 per tonne. Equivalently, the capture leg considered on its own costs about US$94 per tonne captured all-in and earns US$300, so it is strongly accretive at central prices and remains accretive down to roughly US$100 per tonne before the parasitic electricity loss is counted.

Table 5

Indicative Cost, Net Margin, and Breakeven Prices by Scenario (Central Case)

Metric	Scenario 1: Energy	Scenario 2: Carbon	Scenario 3: Hybrid
Capital base (US$ bn)	1.9	1.8	2.7 (conversion) + capture charged per tonne
Annualised cost (US$ m/yr)	312	350	658 (426 conversion; 232 capture, transport and storage)
Direct revenue (US$ m/yr)	285	322	1,093
Net annual margin (US$ m/yr)	−27 (−185 to +167)	−28 (−186 to +210)	+434 (−144 to +1,258)
Levelised cost of electricity (US$/MWh)	111 (92–154)	—	—
Gross cost per tonne of permanent removal (US$/t CO_2)	—	~235	193 (145–273)
Breakeven biochar credit price (US$/t CO_2)	—	159 (67–285)	covered by engineered credits at central price
Breakeven engineered-removal credit price (US$/t CO_2)	—	—	124 (13–282)

Note. Costs are pre-tax, pre-incentive, first-order figures built from the unit costs in Table 2 with a capital recovery factor of 0.102. Ranges in parentheses are the low and high cases of Section 10. Breakeven prices are

the credit prices at which net annual margin equals zero with all other parameters at central values. bn = billion; m = million; MWh = megawatt-hour.

9.2 Energy Production Potential as a Percentage

Across the scenarios the contribution to national electricity supply ranges from about 0.2% (carbon-only) through 1.2% (hybrid) to 1.8% (energy-only) of consumption. This spread reflects a physical reality: the energy content of the recoverable residue base is finite—about 37 petajoules of primary energy—and the scenarios differ in how much of that energy is converted to electricity versus locked into biochar or consumed by capture. A contribution of one to two percent should be interpreted in context rather than dismissed as small. It is comparable in scale to the contribution of a mid-sized conventional power station, it is dispatchable in a system increasingly dominated by intermittent solar, and it is delivered from a fuel that would otherwise impose a disposal cost. For an economy seeking both supply diversification and the productive use of waste, a reliable low-carbon one to two percent that pays for itself through stacked carbon revenue is a sound proposition, particularly because the marginal cost of the fuel is suppressed by the pre-existing collection infrastructure.

9.3 Net-Zero Contribution as a Percentage

The contribution to the UAE's climate commitments can be framed against three different denominators, each illuminating a different aspect of the value. Measured against total national greenhouse-gas emissions—the official 2019 baseline of 196.3 million tonnes of carbon-dioxide equivalent including land use, with third-party gross estimates running higher (Government of the UAE, 2024a; Climate Analytics, 2024)—the hybrid pathway's 6.3 million tonnes of annual mitigation represents approximately 3.2% (range 2.2–4.2%). Measured against the emissions-reduction task implied by the third Nationally Determined Contribution—the roughly 93 million tonne gap between 2019 emissions and the 2035 target of 103.5 million tonnes—the same mitigation represents on the order of 7% of the required reduction (Climate Action Tracker, 2024). And measured against the UAE's explicit engineered-removal ambition, which the long-term strategy frames in terms of 9.5 million tonnes of engineered carbon-dioxide removal by 2050, alongside 3.5 million tonnes of nature-based sinks (Government of the UAE, 2024c; Climate Action Tracker, 2024), the hybrid's 3.4 million tonnes of permanent removal could supply approximately 36% of the declared engineered-removal target (range 25–47%). This last framing is the most economically consequential, because permanent removal is the scarcest and most expensive form of climate mitigation, and the capacity to supply more than a third of a national removal target from a domestic residue base, using domestic storage, at a cost per tonne below the price of direct air capture, is a strategic asset whose value exceeds its share of gross emissions. It is in the permanent-removal column, not the energy column, that biomass valorisation makes its most distinctive contribution to Net Zero 2050.

9.4 In-Country Value and the Quality of the Revenue

A recurring theme across the scenarios is that the headline GDP share understates the strategic economic value, because it does not capture the quality of the revenue created. Three qualitative features are decisive. First, the carbon-credit revenue—80% of the hybrid's direct revenue—is a net export, earning foreign exchange from international buyers rather than recirculating domestic spend, which is precisely the kind of new tradable sector that diversification policy seeks. Second, the value chain is highly retentive: with collection already domestic, and with conversion, measurement and verification, biochar production, and soil-amendment manufacturing all performed in country, the share of revenue captured domestically—the essence of ICV—is high relative to import-dependent industries. Third, the industry substitutes for imports at two points, displacing imported natural gas at the margin and imported fertiliser through biochar and digestate, each of which improves the trade balance independently of the credit export. When these features are weighed alongside the direct revenue, the biomass-valorisation sector emerges as a small but high-quality addition to the non-oil economy: modest in gross magnitude, but disproportionately aligned with national objectives of diversification, import substitution, export earning, and decarbonisation.

9.5 Employment, Skills, and Domestic Capability

An economic assessment focused solely on revenue and emissions would omit one of the most policy-relevant dimensions of biomass valorisation: its labour intensity and its capacity to build domestic skills. Bioenergy and biochar value chains are, per unit of energy or carbon, more labour-intensive than the capital-intensive gas-fired generation they partly displace, because they involve feedstock aggregation and handling, plant operation and maintenance, laboratory analysis, and the

specialised work of carbon measurement, reporting, and verification. For an economy pursuing the employment of nationals in productive private-sector roles, a new industry that spans agricultural logistics, process engineering, environmental science, and carbon-market analytics offers a breadth of skilled and semi-skilled positions that a comparable investment in imported, automated generation capacity would not. The measurement and verification function is particularly significant from a capability standpoint, because it is a high-skill, exportable service: expertise in quantifying and certifying carbon removal can be applied beyond the domestic industry to the wider regional carbon market in which the UAE seeks a leading role. These capabilities are transferable to other sectors and to other markets, and they position the UAE to export not only carbon-removal credits but the services and know-how associated with producing them. In this sense the sector's contribution to the economy is partly an investment in future competitiveness, the returns to which are not captured in the annual revenue figures but are nonetheless real.

10. Sensitivity Analysis

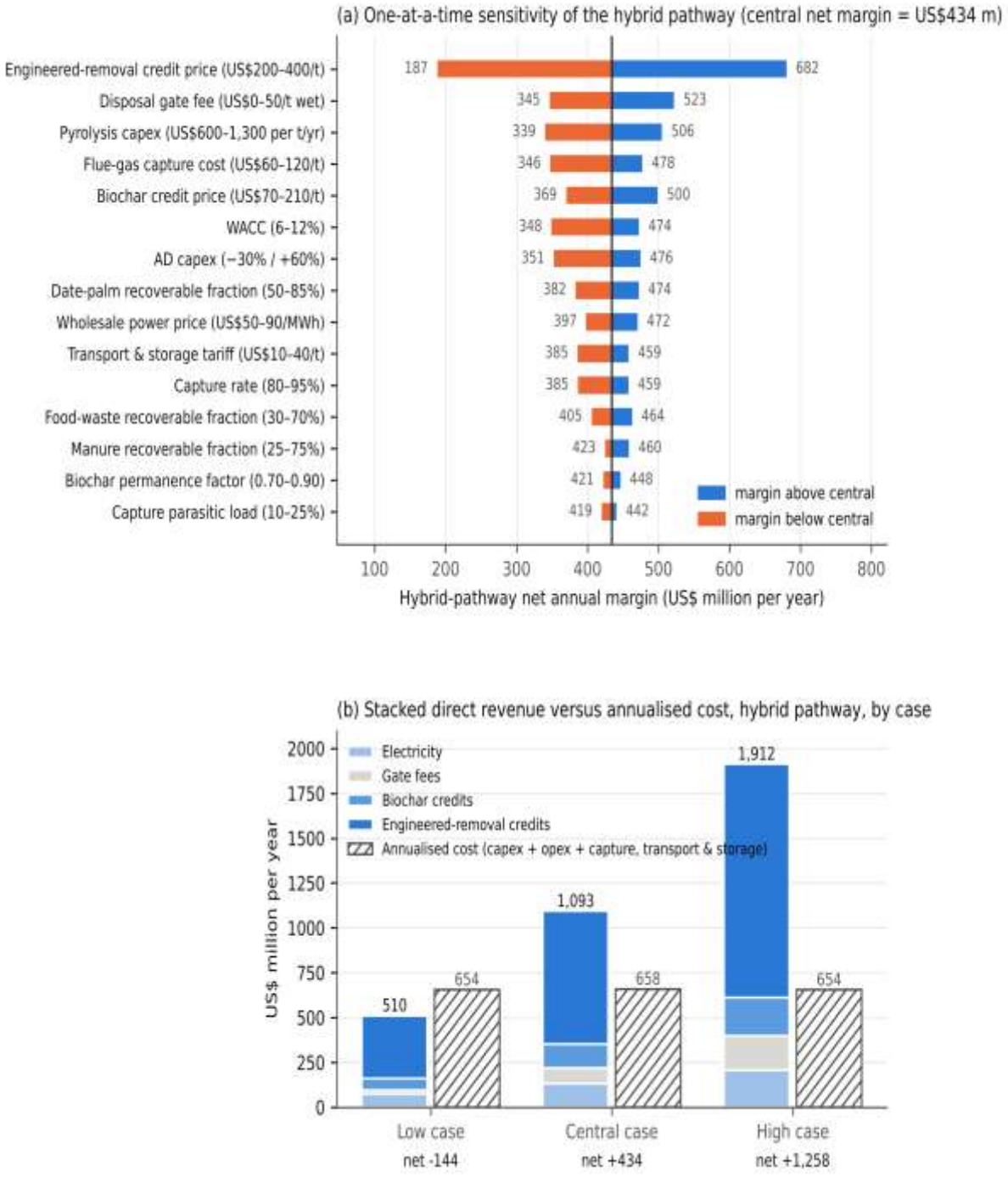
Figure 1 and Table 6 report the two sensitivity exercises described in Section 5.6. The one-at-a-time analysis (Figure 1a) ranks the fifteen varied parameters by the swing they induce in the hybrid's net annual margin around its central value of US$434 million. One parameter dominates: the engineered-removal credit price, which across its US$200–400 per tonne range moves the margin from US$187 million to US$682 million, a swing of nearly US$500 million. No other single parameter moves the margin by more than US$180 million. The second tier comprises the disposal fee received on wet streams, the capital cost of pyrolysis, the flue-gas capture cost, the biochar credit price, the cost of capital, and the capital cost of digestion, each with a swing of US$125–180 million. The recoverable fractions of the date-palm and food-waste streams, the wholesale power price, the transport-and-storage tariff, and the capture rate each move the margin by US$60–90 million. The biochar permanence factor, the capture parasitic load, and—notably—the manure recoverable fraction are the least influential parameters, each with a swing below US$40 million, because manure contributes little energy and little captured carbon per tonne; the manure uncertainty flagged in Section 3 therefore matters more for the design of digestion capacity than for the economic conclusion.

Three features of the ranking are worth drawing out. First, the hybrid's margin remains positive—at or above US$187 million—at every single-parameter extreme tested, including an engineered-removal price of US$200 per tonne, a disposal fee of zero, and a cost of capital of 12%; the conclusion that the hybrid clears its cost of capital is therefore robust to any one adverse assumption. Second, the cost-side parameters collectively matter about as much as the price-side parameters, which argues for the same analytical attention to engineering, procurement, and construction cost calibration as to carbon-market forecasting. Third, the storage tariff—the parameter most specific to the UAE's infrastructural advantage—ranks low, because even at US$40 per tonne it is small relative to a US$300 credit; the value of pre-existing storage lies less in the tariff saved than in the avoided capital, permitting, and timeline risk of developing dedicated storage, which the model does not attempt to price.

The coherent cases (Table 6; Figure 1b) show the joint effect of moving all uncertain parameters together. In the low case—low recovery, low prices, high unit costs, a 10% cost of capital—the hybrid's revenue falls to US$510 million against a cost of US$654 million, a loss of US$144 million per year; permanent removal falls to 2.4 million tonnes and electricity to 1.3 terawatt-hours. In the high case revenue rises to US$1.9 billion against a cost of US$654 million, a margin of US$1.26 billion. The asymmetry is informative: because costs are dominated by capital that scales with throughput, and lower throughput offsets higher unit costs in the low case, total cost is almost invariant across the cases (US$654–658 million), whereas revenue varies almost fourfold; the investment case is therefore essentially a view on carbon-removal prices and on feedstock recovery. The low case is a conjunction of adverse outcomes rather than a probable one, but it establishes that the hybrid is not unconditionally profitable; it is profitable conditional on engineered-removal prices holding above roughly US$125–150 per tonne at central costs, or above roughly US$280 per tonne if every cost and recovery assumption simultaneously disappoints. These thresholds are the quantitative basis for the price gates recommended in Section 12.

Figure 1

Sensitivity of the Hybrid Pathway's Net Annual Margin



Note. Panel (a): one-at-a-time sensitivity of the hybrid pathway's net annual margin (revenue less annualised cost) to each parameter varied across the range shown, all other parameters at central values; the vertical line marks the central margin of US$434 million per year and the figures at the bar ends are the margins at the low and high parameter values. Panel (b): stacked direct revenue by component and annualised cost for the low, central, and high cases of Table 6. AD = anaerobic digestion; WACC = weighted average cost of capital.

Table 6

Low, Central, and High Cases for the Hybrid Pathway

Output	Low case	Central case	High case
Recoverable feedstock (Mt wet/yr)	4.3	6.0	7.8
Net electricity (TWh/yr); share of consumption	1.3; 0.9%	1.9; 1.2%	2.4; 1.6%
Biochar removal (Mt CO_2/yr)	0.64	0.94	1.26
Captured biogenic CO_2 (Mt/yr)	1.76	2.47	3.25
Permanent removal (Mt CO_2/yr); share of 9.5 Mt target	2.4; 25%	3.4; 36%	4.5; 47%
Total mitigation incl. avoided (Mt CO_2e/yr)	4.4	6.3	8.3
Direct revenue (US$ m/yr)	510	1,093	1,912
Annualised cost (US$ m/yr)	654	658	654
Net annual margin (US$ m/yr)	−144	+434	+1,258
Gross cost per tonne of permanent removal (US$/t CO_2)	273	193	145
Breakeven engineered-removal price (US$/t CO_2)	282	124	13
Direct GDP share	0.10%	0.21%	0.37%

Note. Case definitions: the low case sets recoverable fractions to 55/45/35/25% (date palm/other agricultural/food/manure), the power price to US$55/MWh, biochar and engineered credits to US$100 and US$200/t, the disposal fee to US$10/t, capture cost to US$100/t, transport and storage to US$30/t, pyrolysis capital to US$1,100 per t/yr and digestion capital to 150% of central, combustion capital to US$4,200/kW, the cost of capital to 10%, permanence to 0.70, capture rate to 85%, and parasitic load to 20%; the high case sets the converse values (85/75/65/55%; US$85/MWh; US$170 and US$400/t; US$40/t; US$65/t; US$12/t; US$700 per t/yr and 80% of central; US$3,000/kW; 7%; 0.89; 95%; 12%). The central case uses the values in Table 2. m = million; Mt = million tonnes; TWh = terawatt-hours.

11. Alternative Biomass-Utilisation Pathways

The waste hierarchy and the cascading-use principle (Section 2.2) oblige an assessment of whether energy and carbon conversion are in fact the highest-value use

of the residue, or whether higher-hierarchy alternatives should take precedence for some or all of the streams. Table 7 compares the three scenarios of this article with six alternative pathways on four criteria: indicative revenue per tonne of feedstock, climate benefit per tonne and whether it constitutes permanent removal, technological and commercial maturity, and the principal constraint on deployment in the UAE. The per-tonne revenue figures for the alternatives are author estimates anchored in the cited literature and are intended for ordering, not for project appraisal.

Three conclusions follow. First, for the food-waste stream, redirection to animal feed ranks above digestion on both the hierarchy and life-cycle grounds, because displacing conventional feed production avoids more emissions per tonne than generating biogas (Salemdeeb et al., 2017); but it is applicable only to the segregated, pre-consumer, biosecurity-compliant fraction—plausibly a tenth to a fifth of the stream in the UAE's hospitality- and retail-dominated food-waste profile—and it yields no permanent removal. It is therefore a complement that should take the suitable fraction, not a substitute for digestion of the remainder. Second, for the dry lignocellulosic streams, cement-kiln co-processing and material uses compete with pyrolysis. Co-processing is mature and the UAE has substantial clinker capacity, but it pays little or nothing for feedstock, returns the biogenic carbon to the atmosphere, and its climate benefit is an avoidance that depends on the fuel displaced (Chatziaras et al., 2016); it is the appropriate route for contaminated or off-specification residue that cannot meet biochar feedstock standards. Bio-based materials from date-palm fibre—particleboard, composites, packaging—can command the highest product value per tonne and store carbon for the life of the product (Al-Oqla & Sapuan, 2014), but their market is limited to perhaps a few hundred thousand tonnes per year and the carbon storage is not credit-eligible under current removal standards. Third, biomethane upgrading and grid injection shares the digestion front end with Scenarios 1 and 3 and is attractive where gas prices are high (IEA, 2020), but in the UAE, where gas is domestically abundant and electricity dispatchability is the scarcer service, the biogas is better used for power—and, in the hybrid, the upgrading step is retained for its near-pure carbon-dioxide stream rather than for the biomethane itself. Composting is the mature low-value fallback for wet streams where digestion capacity is lacking; its revenue and climate benefit per tonne are an order of magnitude below the alternatives, lignin-rich and nitrogen-poor date-palm residue composts slowly unless co-composted with manure, and salinity is a recurring concern in arid conditions (Kavvadias et al., 2024); it is retained in Scenario 2 only to make that scenario internally complete. Landfill with gas capture is the counterfactual, not an alternative: it recovers at best half to three-quarters of the methane and earns no product revenue. The hybrid pathway therefore ranks first on revenue per tonne and on permanent climate benefit per tonne across the whole residue base, and the policy design should route the small feed-eligible and material-eligible fractions to those higher-hierarchy uses while committing the bulk of the base to the hybrid.

Table 7

Comparison of the Three Scenarios With Alternative Biomass-Utilisation Pathways

Pathway	Applicable streams	Indicative revenue (US$ per t feedstock)	Climate benefit per tonne; permanence	Maturity	Principal constraint in the UAE
Scenario 1: combustion + AD to power	all	~33 (wet) + disposal fee	~0.54 t CO_2e avoided per wet t; none permanent	commercial	LCOE above wholesale price without capacity premium
Scenario 2: biochar pyrolysis + compost	dry → pyrolysis; wet → compost	~117 (dry) via credits; + product value	~0.84 t CO_2 permanent per dry t	commercial (credits since 2019)	credit-price exposure; breakeven slightly above current price
Scenario 3: hybrid with capture	all	~180 (wet basis, all streams)	~0.57 t CO_2 permanent + 0.48 avoided per wet t	components commercial; integration early-commercial	engineered-removal price; storage access
Composting only	wet; date-palm residue only with manure co-composting	10–30	~0.05–0.2 t CO_2e; none permanent	mature	low value; slow for lignin-rich palm residue; salinity; market absorption
Animal feed (processed food waste)	segregated pre-consumer food waste	50–150	highest avoided per tonne via displaced feed; none permanent	mature where regulated	biosecurity and halal rules; ≤10–20% of stream eligible
Cement-kiln co-processing (RDF / biomass fuel)	dry, incl. contaminated	0–20 (sometimes negative)	~1.0–1.5 t CO_2 avoided per dry t if coal/petcoke displaced; none permanent	mature	no removal; feedstock paid little or nothing
Biomethane upgrading and grid injection	wet	35–55 (energy value) + disposal fee	~0.9–1.1 t CO_2e avoided; none permanent	mature	low domestic gas price; dispatchable power scarcer than gas
Bio-based materials (date-palm fibre boards, composites)	date-palm fibre, fronds	100–300	product carbon storage for product life; not credit-eligible	pilot to early-commercial	market size (≈0.1–0.3 Mt/yr); competition with wood imports
Landfill with gas capture (counterfactual)	wet	none (cost)	50–75% of methane captured at best	mature	no product; residual methane

Note. Revenue and climate-benefit figures for the three scenarios are central-case model outputs divided by feedstock processed; figures for the alternatives are author estimates (class A) anchored in Salemdeeb et al. (2017), Chatziaras et al. (2016), IEA (2020), Al-Oqla and

Sapuan (2014), Kavvadias et al. (2024), and Papargyropoulou et al. (2014). AD = anaerobic digestion; LCOE = levelised cost of electricity; RDF = refuse-derived fuel.

12. Discussion: Investment Sequencing and Policy Implications

The analysis supports a clear conclusion and a cautious implementation path. The conclusion is that the hybrid pathway is the optimal long-term strategy for the UAE biomass-residue base, because it captures two-thirds of the energy and more than twice the permanent removal of the single-product alternatives, because the carbon value dominates and is best realised through the hybrid's capture component, because it is the only scenario with a robust positive margin at central assumptions, and because the enabling infrastructure—collection at the front end and carbon storage at the back end—already exists. The cautious path concerns sequencing, because the hybrid is also the most capital-intensive and integration-dependent option, and because the sensitivity analysis shows its economics to rest overwhelmingly on a single market price that, while currently supportive, is volatile.

A staged deployment manages this risk, consistent with the option framing of Section 2.5. The first stage should capture the mature value: anaerobic digestion of the wet food-waste and manure streams, which is technologically proven and delivers immediate methane-avoidance, disposal-fee, and dispatchable-power value, deployed in parallel with intermediate-pyrolysis biochar production on the date-palm residue, which can sell carbon-removal credits from the outset. The second stage should add the carbon-capture overlay, beginning with the near-pure carbon-dioxide stream from biogas upgrading—the lowest-cost and lowest-energy-penalty capture in the system—then extending to the pyrolysis-gas and combustion flue streams, tied to a commercial agreement for access to national storage. Each stage should be gated on explicit economic thresholds derived from Section 9.1 and Table 6: the biochar stage on a durable-credit price holding at or above roughly US$160 per tonne—the carbon-only breakeven, slightly above the prevailing index—or on a realised biochar product value of about US$70 per tonne that closes the same gap; and the capture stage on an engineered-removal price contracted at or above roughly US$200 per tonne—comfortably above the US$124 central breakeven, in line with the breakeven that bioenergy-with-carbon-capture suppliers themselves report, and sufficient to absorb moderate cost overruns—together with a confirmed storage tariff at or below US$40 per tonne. Should prices fall below these thresholds, the system can be operated as energy plus biochar without the capture leg; the sensitivity analysis shows that configuration to be close to breakeven rather than strongly profitable, so the fallback preserves the asset and the option rather than guaranteeing a return. From a policy standpoint, four measures would materially improve the investment case: the extension and enforcement of source-segregation rules to raise feedstock quality and recoverable fractions, which the sensitivity analysis shows to be worth up to US$90 million per year for the date-palm stream alone; a disposal-fee regime that passes the full social cost of landfill to the generator, which is worth a further US$90 million per year per US$25 per tonne; the development of a domestic measurement, reporting, and verification capability and a clear regulatory treatment of carbon-removal credits to reduce market risk; and the provision of transparent, non-discriminatory access to national carbon storage for third-party biogenic carbon dioxide at a published tariff. None of these requires new physical infrastructure; each builds on assets and institutions the UAE already possesses.

Three cautions temper the conclusion. The first is that the manure tonnage, and therefore a share of the digestion capacity, rests on an estimate rather than a measured inventory; although the sensitivity analysis shows the economic conclusion to be insensitive to it, the sizing of digestion plant is not, and a national manure survey should precede any large commitment. The second is that the unit capital and operating costs are international literature values; a UAE-specific engineering cost estimate could move the hybrid's margin by the US$125–170 million swings shown for the capital-cost parameters in Figure 1, in either direction. The third is that the carbon-credit prices underpinning the revenue case are set in an evolving voluntary market whose depth and pricing for engineered removals remain uncertain; the staged structure and the price gates are the appropriate response to this uncertainty, and the low case of Table 6 shows what a conjunction of adverse outcomes would mean. None of these cautions overturns the central finding, but all three argue for disciplined, evidence-led implementation rather than rapid, undifferentiated scaling.

13. Conclusion

The United Arab Emirates produces close to 12 million tonnes of agricultural and food-related organic residue

ISSN: 2791-3171 - https://doi.org/10.54878/dwob8r57

each year, of which roughly half is practically recoverable for conversion, and currently realises a small fraction of its economic value. This article has argued that the conditions for capturing that value are unusually favourable, because the collection infrastructure that ordinarily dominates biomass project costs already exists, and because the carbon storage that enables carbon-negative conversion is operational and permitted. Using a transparent model in which every parameter is tabulated and classified by evidential status, and testing the results with one-at-a-time sensitivity analysis and coherent low, central, and high cases, the article finds that the energy-only pathway can supply roughly 1.4 to 2.3% of national electricity consumption but does not cover its cost of capital at prevailing power prices without a dispatchability premium; that the carbon-only pathway delivers about 1.5 million tonnes of permanent removal per year at approximately breakeven; and that the hybrid pathway delivers approximately 1.9 terawatt-hours of dispatchable, carbon-negative electricity together with approximately 3.4 million tonnes of permanent carbon removal per year—on the order of a third of the country's declared engineered-removal ambition—at a central direct revenue of US$1.1 billion per year against an annualised cost of US$0.65 billion. The hybrid's economics rest principally on the engineered-removal credit price, with a breakeven near US$125 per tonne at central costs, and it outperforms composting, animal-feed, cement co-processing, biomethane, and material alternatives on revenue and permanent climate benefit per tonne across the residue base as a whole, while leaving room for the small feed- and material-eligible fractions to be routed to those higher-hierarchy uses. The direct contribution to GDP is modest in magnitude—about 0.2%—but high in quality, mapping precisely onto the national priorities of diversification, export earning, import substitution, and decarbonisation. The recommended path is a staged deployment that captures mature biochar and biogas value first and adds carbon capture as prices and storage access confirm, converting a standing waste liability into a durable contribution to the UAE's economy and to its Net Zero 2050 commitment.

Acknowledgements

The author, Mohamed Alnuaimi (University of Reading), gratefully acknowledges the public availability of data and reports from the UAE Ministry of Climate Change and Environment, the Abu Dhabi Agriculture and Food Safety Authority, the Abu Dhabi National Oil Company, the BEEAH Group, Masdar, the Food and Agriculture Organization of the United Nations, the International Energy Agency, the International Renewable Energy Agency, the U.S. Energy Information Administration, CDR.fyi, and the Climate Action Tracker consortium, which together made this independent assessment possible. The author also thanks colleagues at the University of Reading and the anonymous reviewer at Emirates Scholar for constructive comments that materially improved the manuscript. No external funding was received for this work, and the author declares no conflict of interest. Responsibility for any remaining errors rests with the author alone.

Data Availability Statement

All inputs to the scenario model are listed in Tables 1 and 2 with their sources, and all outputs in Tables 3 to 6 and Figure 1 can be reproduced from them. The model is deterministic and contains no proprietary data.

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