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A SYSTEMATIC REVIEW OF ENERGY EXERGY AND ECONOMIC ASSESSMENTS OF BREWERY ENERGY SOURCING PATTERNS

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Abstract

Breweries combine low- and medium-temperature process heat with refrigeration, electricity, compressed air, water treatment and batch scheduling, so energy-source decisions must be evaluated jointly. This systematic review synthesised 33 brewery-specific studies using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement, the PRISMA extension for searches (PRISMA-S) and Synthesis Without Meta-analysis (SWiM) guidance. Searches of Scopus, Web of Science, ScienceDirect and Google Scholar covered records through 25 July 2026. The evidence comprised 19 audit, process-integration and exergy studies and 14 renewable, electrification, waste-to-energy and digital-control studies. Steam generation, brewhouse heating, wort boiling, refrigeration and packaging were the recurrent hotspots. Reported case-study results included 21.5% heat-recovery potential, overall exergy efficiency as low as 3.33%, and a dual-source heat-pump case with 60% lower modelled carbon emissions and 10% lower energy cost. Results were heterogeneous because boundaries, brewery scale, production schedules, tariffs, discount rates and validation methods differed. The proposed efficiency-first hierarchy requires breweries to meter utilities, correct avoidable losses and recover heat before sizing heat pumps, renewable supply or waste-to-energy systems for residual demand. This sequence reduces retrofit capacity and financial exposure. Practitioners should require transparent boundaries, life-cycle cash-flow assumptions and sensitivity analysis, while policymakers should prioritise metering standards, audit support and performance-linked incentives. Figure 1 summarises the evidence pathway and decision sequence.

Keywords
brewery energy; energy efficiency; exergy heat integration; industrial heat pumps; techno-economic analysis

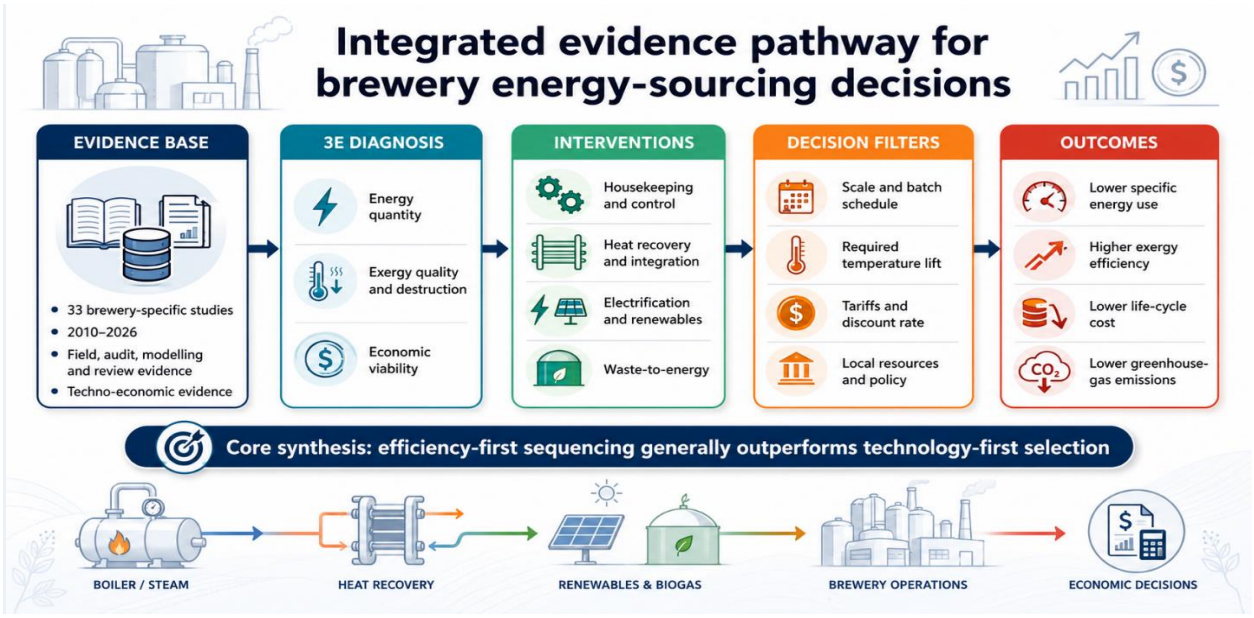


Figure 1. Graphical abstract of the integrated evidence pathway and efficiency-first decision sequence used in this review

1. INTRODUCTION

Beer production is a batch-oriented food process in which heating and cooling duties occur at different temperatures and times. Thermal energy supports mashing, vessel heating, wort boiling, cleaning in place, pasteurisation and hot-water preparation, whereas electricity supports milling, pumping, refrigeration, packaging, compressed air, carbon dioxide (CO_2) handling and wastewater treatment. Heat recovery, water storage, refrigeration, process scheduling and utility control therefore interact with fuel and conversion-technology choices [1]-[4]. Energy intensity varies with brewery scale, product and packaging mix, plant age, utilisation, climate and system boundary. Small breweries often have higher specific energy consumption because intermittent batches and fixed utility loads are spread over less product. Large breweries may achieve lower energy intensity but still incur high exergy destruction through combustion, steam throttling, large heat-transfer temperature differences, wort boiling and refrigeration. Benchmarks are therefore meaningful only when they use a stated functional unit, production basis and boundary [5]-[8].

The energy source changes both thermodynamic and economic performance. Diesel generators and boilers can provide autonomy but typically impose high fuel cost, local emissions and combustion irreversibility. Natural gas may reduce cost and emissions relative to diesel but remains fossil dependent. Heat recovery and industrial heat pumps reduce the quantity and quality of external energy required. Solar thermal, photovoltaic (PV), photovoltaic-thermal (PVT), biogas, combined heat and power (CHP) and thermal storage may further reduce fossil demand, but their value depends on local resources, tariffs, temperature requirements, utilisation and financing [9]-[13]. Figure 2 maps the main brewery utilities, process duties and intervention points.

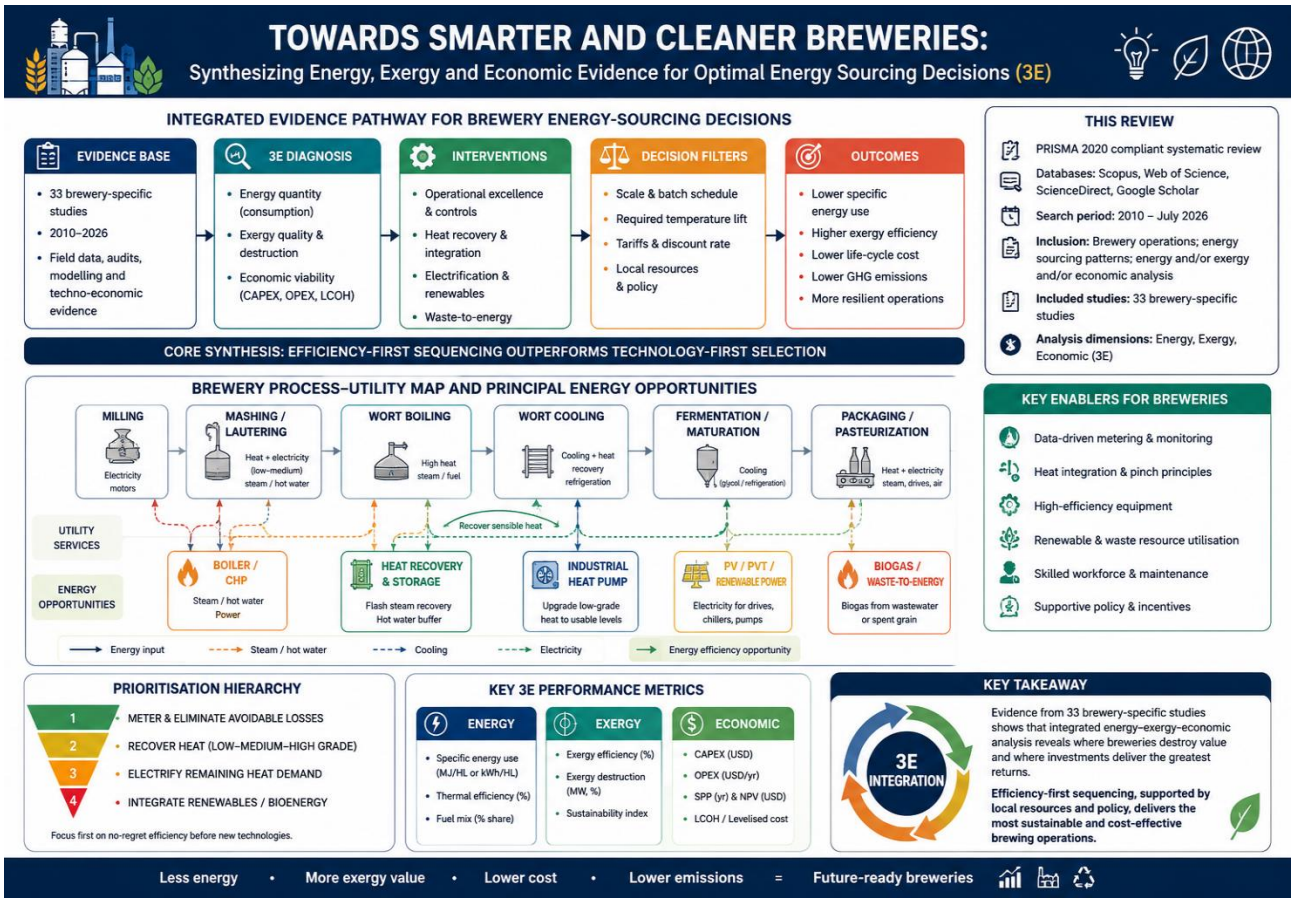


Figure 2. Brewery process-utility map showing principal energy duties and intervention opportunities.

First-law analysis accounts for energy quantity but not its capacity to perform useful work. One megajoule of electricity and one megajoule of low-temperature hot water are energetically equal, although their work potentials differ. Exergy analysis quantifies this difference and locates irreversibility in combustion, heat transfer, throttling and mixing. It therefore identifies whether high-grade resources are being used for low-grade duties and whether the principal improvement opportunity lies in the boiler, heat exchanger, refrigeration system or process [14]-[17].

Economic analysis is required because thermodynamic superiority does not guarantee investability. A heat pump may reduce primary energy and exergy destruction but remain unattractive under low gas prices, high electricity tariffs, limited annual operating hours or expensive finance. Conversely, low-capital measures may deliver modest energy savings with rapid payback and improved reliability. Integrated energy, exergy and

economic (3E) analysis links resource quantity, resource quality and life-cycle cost, while exergoeconomics identifies components that combine high destruction with high cost consequence [18]-[20].

The brewery evidence remains fragmented in four specific ways. First, energy audits often omit second-law analysis. Second, exergy studies may quantify irreversibility without capital or operating costs. Third, renewable and electrification studies frequently rely on simulated production profiles with limited field validation. Fourth, system boundaries and functional units differ across boilers, brewhouses, whole plants, packaging, wastewater and district-energy systems. Values reported in megajoules per hectolitre (MJ/hL), kilowatt-hours per hectolitre (kWh/hL), kilograms of standard-coal equivalent per kilolitre or component efficiency cannot be pooled without harmonisation [21]-[24].
Earlier reviews explain brewery sustainability, environmental pressures and by-product valorisation, but they do not systematically compare energy quantity, exergy quality and life-cycle economics across energy-sourcing patterns [25]-[26]. The present review narrows the main synthesis to brewery-specific evidence and compares boundary, metric, validation status and economic assumptions before drawing cross-study conclusions.
This review addresses five questions:

(i) Which brewery processes and utilities consistently dominate energy use and exergy destruction?
(ii) How do conventional, process-integrated, renewable, electrified, and waste-derived sourcing patterns compare across energy, exergy, and economic criteria?
(iii) Which contextual variables explain differences in reported technical and economic performance?
(iv) What methodological weaknesses limit comparability and implementation?
(v) What minimum framework should future brewery 3E studies report?

This review is the first brewery-focused synthesis in the assessed literature to combine conventional fuels, process integration, exergy, renewable heat and power, heat pumps, storage and waste-to-energy within one 3E decision framework. It separates measured industrial evidence from modelling, links each technology claim to boundary and validation conditions, and converts the synthesis into an efficiency-first investment hierarchy and minimum reporting standard.
The primary audiences are brewery operators, energy managers, engineering researchers, technology developers and policymakers. Review questions 1 and 2 are answered in Sections 4.4-4.9; question 3 in Section 5.2; question 4 in Sections 3.6, 4.1-4.3 and 5.7; and question 5 in Table 5 and Appendix B.

2. METHODOLOGY

2.1 Analytical Foundations and Performance Equations

2.1.1 System boundary and functional unit

A defensible brewery assessment begins by defining the product basis and system boundary. The preferred functional unit is one hectolitre (hL) of saleable beer at the packaging gate. Wort-only results should be reported per hL of wort and should not be compared directly with whole-brewery values. The boundary should state whether malting, onsite power generation, water treatment, refrigeration, compressed air, CO_2 recovery, wastewater treatment, packaging and distribution are included [1], [4].
Equation (1) defines specific energy consumption (SEC) as the sum of measured or modelled carrier inputs divided by saleable beer or wort volume:

$$SEC = \frac{\sum_{i=1}^{n} E_i}{V_b} \qquad (1)$$

where E_i is energy input from carrier i and V_β is saleable beer or wort volume. Electricity and fuels should first be reported separately because primary-energy factors and exergy qualities differ. Equation (1) follows standard brewery energy-intensity practice [1], [7].

2.1.2 First-law energy analysis

For a steady control volume, with kinetic and potential terms neglected only when demonstrably small, the first-law balance is given by (2) [15]:

$$\dot{Q} - \dot{W} + \sum_{in} \dot{m}\, h - \sum_{out} \dot{m}\, h = 0 \qquad (2)$$

Equation (3) expresses useful-product energy efficiency. The numerator and denominator must be stated for the specific component or process [15]:

$$\eta_{en} = \frac{\dot{E}_{useful}}{\dot{E}_{input}} \times 100\% \qquad (3)$$

Boiler studies should state the heating-value basis, stack temperature, excess air, blowdown, radiation loss, condensate return and load factor. For heat pumps, the heating coefficient of performance (COP) is defined

by (4). Reported high-temperature heat-pump COP values span approximately 2.4-5.8 as temperature lift decreases from about 95 K to 40 K, so a COP without source and sink temperatures is not comparable [27]-[28]:

$$COP_h = \frac{\dot{Q}_{hot}}{\dot{W}_{comp}} \qquad (4)$$

Equation (4) is a steady or quasi-steady performance measure. Brewery batches require time-resolved source and sink profiles, part-load behaviour, auxiliary power, defrost or cleaning downtime and annual operating hours before a seasonal COP or economic conclusion is drawn.

2.1.3 Exergy analysis

The specific physical exergy of a stream relative to a reference environment is calculated with (5) [14]-[15]:

$$ex_{ph} = (h - h_0) - T_0(s - s_0) \qquad (5)$$

For a steady control volume, the exergy balance is written as (6) [14], [16]:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \dot{E}x_D \qquad (6)$$

where exergy destruction, ĖxD = T₀Ṡgen, quantifies irreversibility. Equation (7) defines component or system exergy efficiency, provided that fuel and product exergy are identified explicitly [18]:

$$\eta_{ex} = \frac{\dot{E}x_{product}}{\dot{E}x_{fuel}} \times 100\% \qquad (7)$$

Equation (8) gives the share of total exergy destruction attributable to component k:

$$y_{D,k} = \frac{\dot{E}x_{D,k}}{\sum_j \dot{E}x_{D,j}} \times 100\% \qquad (8)$$

Fuel and product definitions must be component specific. Studies should report the dead-state temperature T_0 and pressure p_0, chemical-exergy source, steam properties and treatment of mixing, pressure drops and non-ideal combustion. Ambient reference temperatures of 293.15-298.15 K are reasonable sensitivity bounds for many brewery locations, but the measured site condition should be the base case. Symbols and units used in (1)-(12) are defined in Table B1.

2.1.4 Economic and exergoeconomic analysis

Simple payback period (SPP) is useful for screening but ignores the time value of money; it is calculated with (9) [23]:

$$SPP = \frac{I_0}{S_{annual}} \qquad (9)$$

Net present value (NPV), defined by (10), is the preferred life-cycle decision metric when annual cash flows and discounting are available [23], [29]:

$$NPV = -I_0 + \sum_{t=1}^{N} \frac{CF_t}{(1+r)^t} \qquad (10)$$

For heat technologies, the levelised cost of useful heat (LCOH) can be calculated with (11). The heat boundary and delivered-temperature level must accompany the value:

$$LCOH = \frac{I_0 + \sum_{t=1}^{N} \frac{C_{O\&M,t} + C_{energy,t}}{(1+r)^t}}{\sum_{t=1}^{N} \frac{Q_{useful,t}}{(1+r)^t}} \qquad (11)$$

In exergoeconomic analysis, the component cost-rate balance is given by (12) under the specific exergy costing (SPECO) framework [18]:

$$\sum \dot{C}_{out} = \sum \dot{C}_{in} + \dot{Z} \qquad (12)$$

where Ċ = cĖx and Ż is the levelised capital and operation-and-maintenance cost rate. Economic studies should state currency and base year, exchange rate, project life, residual value, tariffs, fuel escalation, maintenance, replacement and incentives. The brewery solar studies used a 3% real discount rate [23], [29]; future studies should also test wider locally justified rates and report the break-even tariff or discount rate.

2.1.5 Dynamic application uncertainty and integrated decision logic

Equations (1)-(12) are most reliable for steady components or time slices. Annual averages can hide the temporal mismatch between wort cooling, hot-water demand, refrigeration, renewable output and tariffs. Batch studies should therefore apply the balances to representative time intervals and couple them to storage and production schedules [21]-[22]. Measurement uncertainty in flow, temperature, pressure, fuel use, electricity and production volume should be propagated through derived indicators by first-order uncertainty analysis or Monte Carlo simulation. A complete 3E assessment should report central estimates and sensitivity ranges, then prioritise measurement and low-cost loss reduction, heat recovery and storage, electrification of residual heat, and finally low-carbon supply.

2.2 Review Design and Reporting Guidance

The reporting plan followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement, the PRISMA extension for searches (PRISMA-S), and Synthesis Without Meta-analysis (SWiM) guidance [30]-[32]. Quantitative pooling was not attempted because boundaries, functional units, process configurations and economic assumptions were heterogeneous. The protocol was not prospectively registered because registration was not incorporated when the review commenced; the eligibility criteria, extraction fields and synthesis rules were nevertheless fixed before full-text assessment.

2.3 Eligibility Criteria

Studies were eligible when they (i) evaluated an operating brewery, brewery process or brewery-specific model; (ii) quantified at least one energy, exergy, exergoeconomic or techno-economic outcome; (iii) examined an energy source, utility configuration, process-integration measure, renewable technology, heat pump, storage or waste-to-energy pathway; and (iv) were peer-reviewed journal articles or full conference papers in English. Malt-drink studies were retained only when their thermal and utility operations were materially comparable with brewing.

Records were excluded when they were unrelated to breweries, lacked a quantitative energy or economic dimension, were editorials, abstracts, theses, patents, vendor brochures or non-peer-reviewed preprints, or duplicated a more complete publication. Duplicate control occurred twice: bibliographic duplicates were removed before screening, and full texts using the same plant, dataset or experiment were linked so that the most complete report represented the evidence unit. Generic process studies were used only as methodological background and were not counted among the 33 brewery-specific studies.

2.4 Information Sources and Search Strategy

The review team maintained a search log for Scopus, Web of Science, ScienceDirect and Google Scholar. The core Boolean logic was: (brewery OR brewing OR brewhouse OR beer production) AND (energy OR fuel OR steam OR electricity OR refrigeration) AND (exergy OR exergoeconomic OR economic OR techno-economic OR efficiency OR heat recovery OR pinch OR heat pump OR solar OR photovoltaic OR biogas OR cogeneration)

Backward and forward citation checking and targeted publisher and digital object identifier (DOI) searches supplemented the database queries. The final search date was 25 July 2026, with no lower publication-date restriction. Appendix A provides database-specific strings. The database exports were not independently re-run during peer-review revision, and this constraint is reported in Section 5.7.

2.5 Study Selection

Titles and abstracts were screened against the predefined criteria. The search log contained 421 records. After 193 bibliographic duplicates were removed, 228 unique records remained. Of the 186 records excluded at title and abstract screening, 120 were not brewery related, 35 lacked the required energy or 3E outcome, 20 were ineligible publication types, and 11 represented duplicate or overlapping datasets identified after record linkage. Forty-two reports were sought, nine could not be retrieved, and 33 full texts met the eligibility criteria. Figure 3 presents the complete selection flow.

2.6 Data Extraction

The extraction framework captured author and year, country, brewery scale, process boundary, study design, empirical or simulated data source, energy carrier or intervention, analytical dimensions, equations and reference environment, functional unit, energy and exergy outcomes, capital and operating costs, discount rate, project life, emissions, uncertainty and stated limitations. For multi-scenario studies, the baseline and the authors' preferred or optimal scenario were recorded. Table B2 provides the reusable extraction form.

2.7 Reporting-Completeness Appraisal

Each study was appraised against six reporting domains: boundary and functional unit, data provenance, method transparency, normalised quantitative outcomes, economic assumptions where applicable, and limitations or uncertainty. Table 1 defines full, partial and absent reporting. The appraisal measured reporting completeness rather than penalising a study for omitting an analysis outside its stated purpose.

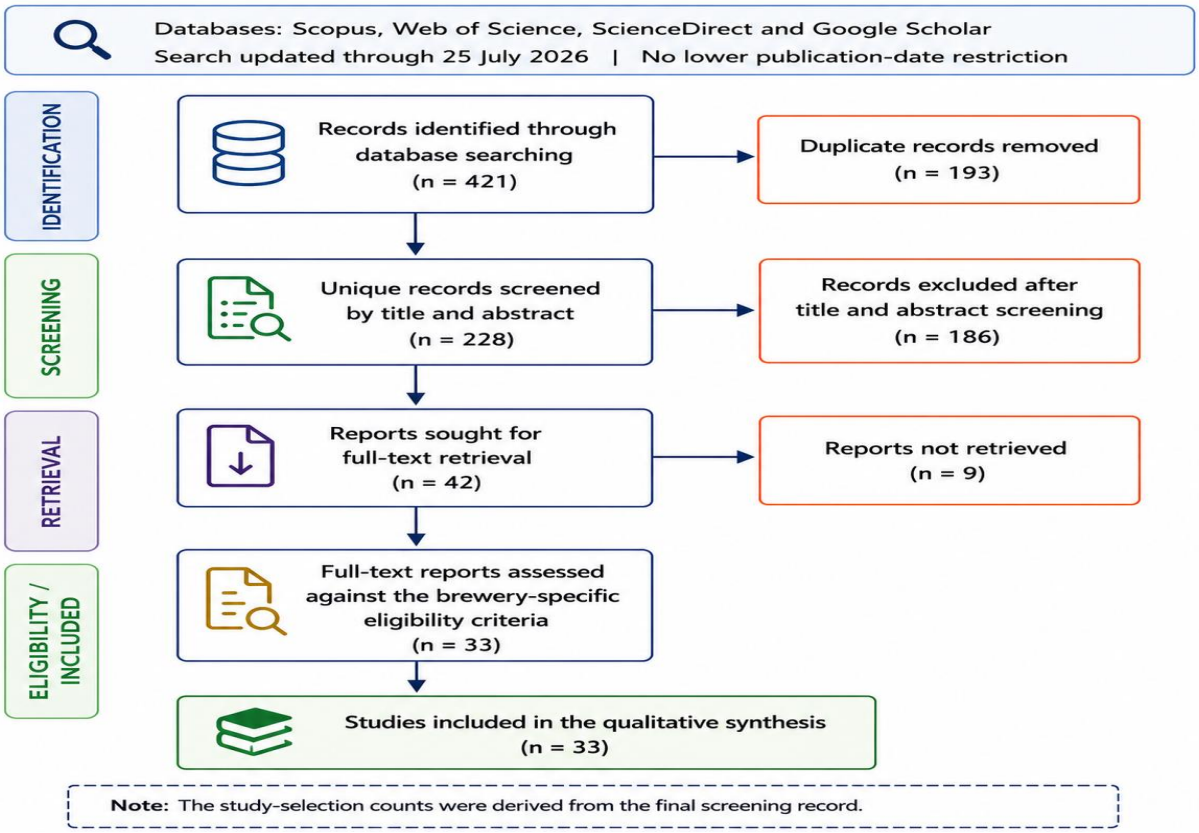


Figure 3. PRISMA 2020 flow diagram showing the identification, screening, retrieval and inclusion of studies in the systematic review of energy, exergy and economic assessments of brewery energy-sourcing patterns.

Table 1. Reporting-completeness appraisal criteria applied to each included study.

Domain	Full reporting	Partial reporting	Not reported
Boundary and functional unit	Brewery/process boundary and normalisation basis explicit	Boundary implied or incomplete	No defensible boundary
Data provenance	Measured industrial data or validated model described	Mixed or limited validation	Unclear data source
Energy/exergy method	Equations, properties, assumptions, reference state reported	Some assumptions omitted	Method not reproducible
Quantitative outcomes	Baseline and intervention metrics reported	Only selected metrics	Qualitative claims only
Economic assumptions	Currency year, tariffs, life, discount rate and costs reported	Some assumptions omitted	No reproducible economics
Uncertainty/limitations	Sensitivity, uncertainty or limitations discussed	Limited discussion	Not reported

2.8 Synthesis Method

Studies were grouped into six intervention themes: baseline audits and benchmarking; heat integration and process optimisation; exergy and exergoeconomics; solar and renewable integration; heat pumps and electrification; and waste-to-energy, digital control and flexibility. Direction and magnitude were synthesised narratively. Numerical values were retained only when their boundary and unit were clear and were not pooled as a common effect size.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Publication and geographical characteristics

The 33 included studies were published between 2010 and 2026. Figure 4 reports both annual and cumulative counts. Output increased after 2019, reaching a cumulative total of 33 by 2026, but the trend is descriptive because the evidence base remains small and heterogeneous. Europe and Asia were overrepresented, although African cases provided distinct evidence on diesel dependence, boiler performance, unstable power supply and locally constrained heat integration.

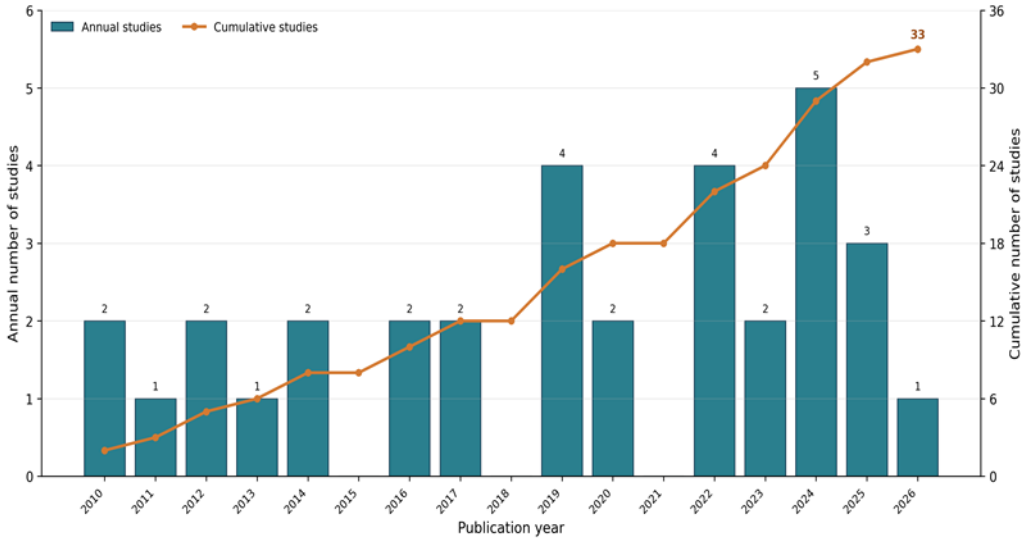


Figure 4. Annual and cumulative distribution of the 33 brewery-specific studies included in the qualitative synthesis.

3.1.2 Characteristics of studies: audits, process integration, and exergy

The evidence comprised 19 studies of audits, process integration or exergy (Table 2) and 14 studies of renewables, electrification, waste-to-energy or digital control (Table 3). Field measurements dominated conventional audits, whereas simulation and optimisation dominated technology sizing. The general beverage-model study [33] informed the methodological discussion but was not counted in the 33-study brewery synthesis.

Table 2. Characteristics of audit, process-integration and exergy studies.

Reference	Brewery context	Intervention or focus	Analysis	Principal contribution
[34]	Nigerian malt-drink plants	Whole-process performance	Energy and exergy	Demonstrated the difference between first- and second-law performance in beverage production.
[35]	Industrial brewery model	Pinch, CHP, heat pumps, refrigeration, biomethane	Energy and thermo-economic optimisation	Reported large heating-cost and emissions reductions from integrated utility design.
[2]	Multiple brewery cases	Green brewery concept	Energy integration and renewable screening	Showed that process integration can materially reduce thermal demand before renewable sizing.
[9]	Nigerian brewery	Diesel generator and boiler sourcing	Energy, exergy, economic	Revealed different sensitivity of energy and exergy performance to generator and boiler diesel use.

Reference	Brewery context	Intervention or focus	Analysis	Principal contribution
[36]	Small UK brewery	Biogas from brewery wastes	Energy audit, modelling, economics	Evaluated site-specific energy self-supply from brewery residues.
[5]	Medium UK brewery	Operational and retrofit measures	Audit and economic screening	Identified technical opportunities and organisational/financial barriers; low-cost measures offered short payback.
[21]	Brewery process model	Technology evaluation and demand profiles	Process modelling	Demonstrated the importance of batch scheduling, equipment area, and supply management.
[37]	Malt and beer production	Low-temperature solar process heat	Energy and demonstration assessment	Established the technical fit between solar process heat and brewery temperature levels.
[22]	Small/medium breweries	Stochastic cooling demand	Data-driven simulation	Quantified temporal uncertainty in refrigeration demand and production schedules.
[6]	Small brewery	Departmental energy monitoring	Energy audit and barriers	Added detailed packaging and sub-process data and tracked implementation barriers.
[38]	Ugandan brewery process	Pinch targeting	Energy analysis	Identified 1.806 MW recoverable heat and approximately 21.5% saving potential at the selected ΔT_{min}.
[10]	Medium Scottish brewery	Heat recovery then solar thermal	Pinch and economic analysis	Showed that prior heat recovery constrains and improves solar-system design.
[39]	Nigerian brewery	Heat-exchanger-network retrofit	Pinch and cost optimisation	Reported heating and cooling utility reductions and improved annualised cost.
[8]	Tanzanian brewery	Whole-plant audit and boiler performance	Energy and emissions	Located major demand in packaging, brewing, utilities, and an underperforming boiler.
[7]	California craft brewery	Material and energy flow	Empirical flow analysis	Reported electrical and thermal intensity and identified scale-sensitive inefficiencies.
[40]	Ethiopian brewery	Energy audit and carbon footprint	Energy, cost, emissions	Reported boiler efficiencies near 80% and a quantified portfolio of saving measures.

Reference	Brewery context	Intervention or focus	Analysis	Principal contribution
[19]	Tier-1 brewery wort production	Component performance	Energy, exergy, exergoeconomic	Identified the brewhouse and wort kettle as dominant sources of destruction and cost increase.
[20]	Large industrial brewery	Whole-process component analysis	Exergy and exergoeconomic	Reported a very low overall exergy efficiency and concentrated losses in brewhouse and packaging.
[41]	Large Chinese brewery	Field-tested thermal retrofits	Energy, exergy, economics, emissions	Quantified thermal loss, exergy destruction, and a short-payback heat-pump retrofit for wort cooling.

3.1.3 Characteristics of studies: renewables, electrification, waste-to-energy, and digitalisation

Table 3. Characteristics of renewable, electrification, waste-to-energy and digital-control studies.

Reference	Brewery context	Intervention or focus	Analysis	Principal contribution
[42]	Small Italian breweries	Anaerobic digestion of residues	Methane yield and techno-economics	Evaluated scale-dependent feasibility and enhancement using carbonaceous additives.
[43]	South African microbrewery	Efficiency measures	Audit and economic assessment	Demonstrated the importance of scale, operating practice, and local tariffs.
[44]	Brewery refrigeration	Decarbonised wastewater biogas	Primary-energy comparison	Found direct-fired absorption cooling advantageous for biogas utilisation under the study assumptions.
[23]	Spanish microbrewery	PV, solar thermal, and heat recovery	Dynamic simulation and economics	PV was financially stronger than solar thermal under low gas prices; heat recovery was competitive.
[11]	South African microbrewery	Grid-connected PV and battery	Optimisation and life-cycle economics	Demonstrated demand-response and tariff dependence of PV-storage value.
[45]	Model brewery process	Dual-source heat pump	Experimental/model energy and cost analysis	Reported lower emissions and energy cost when simultaneous heating and cooling were exploited.
[46]	239 Danish breweries	Demand flexibility	Multi-agent simulation	Estimated sector-level electricity cost and emissions benefits from flexible operation.
[47]	Brewery and district energy	Solar, digestion, heat pumps, power-to-gas	Mixed-integer techno-economic optimisation	Showed the value of cross-system integration and flexible technology portfolios.

Reference	Brewery context	Intervention or focus	Analysis	Principal contribution
[48]	Craft breweries	Anaerobic digestion and CO_2 recovery	Experimental and economic model	Found combined recovery increasingly feasible above a production threshold.
[24]	UK microbrewery	Integrated retrofit portfolio	MINLP techno-economic optimisation	Optimal PV, wind, digestion and heat storage reduced annual cost and emissions in the case study.
[29]	Small-scale brewing	PVT polygeneration	Technical and economic simulation	Evaluated simultaneous electricity, heat, and cooling integration for microbreweries.
[49]	Microbrewery	ANN forecasting and thermal storage	Prediction and optimisation	Linked short-term demand forecasting with storage dispatch and sustainability improvement.
[12]	Global brewing sector	Industrial heat-pump roadmap	Technical, policy, and decarbonisation synthesis	Proposed phased electrification according to temperature and regional context.
[13]	Generalised brewery	Multi-heat-pump and MVR solutions	Pinch and techno-economic analysis	Compared centralised and deeply integrated electrification; lower electricity use required higher complexity and capital.

3.1.4 Baseline audits and process hotspots

Across plant scales, thermal energy generally exceeded electricity on a final-energy basis, although refrigeration and packaging could dominate electricity. Boiler loss, steam leakage, poor condensate return, vessel heat loss, compressed-air leakage and weak refrigeration control repeatedly appeared as avoidable burdens. Departmental sub-metering is therefore required to separate production-volume effects from packaging mix, cleaning, idle operation and deterioration [5]-[6], [8], [40].

Small breweries were especially sensitive to batch size and utilisation. A California craft-brewery case [7] reported about 1.6 MJ/L of electricity and 4.2 MJ/L of thermal energy. This point estimate should not be treated as a universal benchmark because vessel surface-to-volume ratio, cleaning load, idle time and boundary selection differ across plants.

Plant-wide totals are insufficient for action; scale-stratified, departmental and production-normalised data are the minimum diagnostic basis.

3.1.5 Heat integration and thermal optimisation

Pinch and process-integration studies identified heat recovery between wort cooling, hot-water preparation, mashing and cleaning. A multi-brewery assessment [2] showed that internal integration should precede renewable sizing. A Ugandan case [38] estimated 21.5% recovery potential at a minimum temperature difference, ΔT_{min}, of 10 °C. A Nigerian heat-exchanger-network study [39] also reported lower hot and cold utility requirements. These values are study-specific rather than a pooled 20-30% range.

Savings depend on time as well as temperature. A feasible heat match may not be available simultaneously in a batch brewery. Storage, production scheduling, indirect recovery and heat pumps can bridge this mismatch. Time-average pinch models may overestimate direct recovery when stream availability is omitted, whereas time-slice and dynamic models better represent operation [10], [21]-[22].

Heat recovery should be quantified with both temperature and time constraints before renewable or heat-pump capacity is selected.

3.1.6 Exergy and exergoeconomic evidence

Exergy analysis consistently gave a more severe diagnosis than energy efficiency. A malt-drink study [34] showed that first- and second-law indicators ranked beverage-process components differently. A Nigerian

brewery study [9] found that boiler diesel use exerted greater influence on exergy performance, while generator diesel use exerted greater influence on energy performance. Combustion and steam generation can therefore destroy a large fraction of chemical exergy even when the energy balance appears acceptable.
A high-gravity wort study [19] reported 86 ± 1 MJ/hL, 30.35% operational energy efficiency, 3.2737 MW cumulative exergy destruction, and 89.25% of system inefficiency in the brewhouse. A large industrial brewery study [20] reported 3.33% overall exergy efficiency and 5.54 MW total exergy destruction. The uncertainty reported for the first estimate is retained; the two studies cannot be directly pooled because their products and boundaries differ.
A field-tested large-brewery study [41] reported that 37.2% of steam input was dissipated as thermal loss, while brewhouse exergy efficiency was 72.4% and exergy destruction represented 23.4% of input exergy. Equipment performance differed substantially, and a wort-cooling heat-pump retrofit saved about 3.62 kg standard-coal equivalent per kL with a dynamic payback near 1.1 years under the reported tariffs and operating schedule.
Energy efficiency alone can conceal severe irreversibility; component exergy and cost rates are needed to rank interventions.

3.1.7 Solar and renewable integration

Many brewery heating duties occur below about 120 °C and can accept solar process heat. Low-temperature solar applications have been documented [37], while a heat-integration case [10] showed that heat-recovery targeting should precede solar sizing. The latter case also demonstrated that capacity constraints and policy incentives can materially change solar fraction and payback.
A Spanish microbrewery study [23] found a positive NPV and 8.3-year discounted payback for PV under net billing, whereas solar thermal was unattractive because gas was inexpensive. Cooling-water heat recovery also achieved a positive NPV with similar payback and lower capital. PVT can improve land-use efficiency by producing electricity and useful heat, but performance remains climate-, control- and load-dependent [29].
Renewable economics depend on the displaced carrier, utilisation and policy; solar sizing should follow demand reduction and heat recovery.

3.1.8 Heat pumps, electrification, and storage

Breweries offer simultaneous heating and cooling loads that can support heat pumping. A dual-source heat-pump case [45] reported 60% lower modelled carbon emissions and 10% lower energy cost when demands were effectively matched. A sectoral roadmap [12] positioned industrial heat pumps within phased brewery electrification but emphasised temperature lift, refrigerant, electricity carbon intensity and grid readiness.
A generalised brewery electrification study [13] defined a heat demand of 21.4 kWh/hL and reduced it to about 10 kWh/hL through heat recovery. Electricity demand declined from about 5 to 3.6 kWh/hL as integration progressed from a central heat pump to a CO_2 heat pump, high-temperature booster and mechanical vapour recompression (MVR). The more integrated systems required greater complexity and capital but improved longer-horizon NPV.
Thermal storage and predictive control can shift electricity use and decouple heat availability from batches. A PV-battery optimisation study [11] demonstrated tariff-sensitive dispatch. A sector-level simulation of 239 Danish breweries [46] estimated that coordinated flexibility could reduce electricity cost by 1.56% and avoid about 1,745 t CO_2 annually. A forecasting-and-storage study [49] combined artificial neural network (ANN) forecasting with thermal storage, although long-term field validation remains limited.
Heat pumps and storage are most attractive when heating and cooling are matched dynamically and electricity price, carbon intensity and grid capacity are included.

3.1.9 Brewery wastes as energy and carbon resources

Brewery wastewater, spent yeast, spent grain and other residues can support anaerobic digestion, but feasibility depends on quantity, composition, logistics, digester loading and end use. Studies of brewery bio-waste supply, anaerobic digestion and spent-grain biorefineries [36], [42], [50] showed that scale and coproduct assumptions materially affect bioenergy economics.
Electricity generation is not always the highest-value biogas route. A biogas-refrigeration study [44] reported a primary-energy-efficiency coefficient of 126.2% for a direct-fired absorption chiller in the analysed decarbonised-biogas case. A craft-brewery recovery study [48] found that coupling anaerobic digestion with fermentation-CO_2 recovery improved economics and became feasible above roughly 50,000 barrels per year under its assumptions. Figure 5 maps the analytical coverage of all intervention themes.

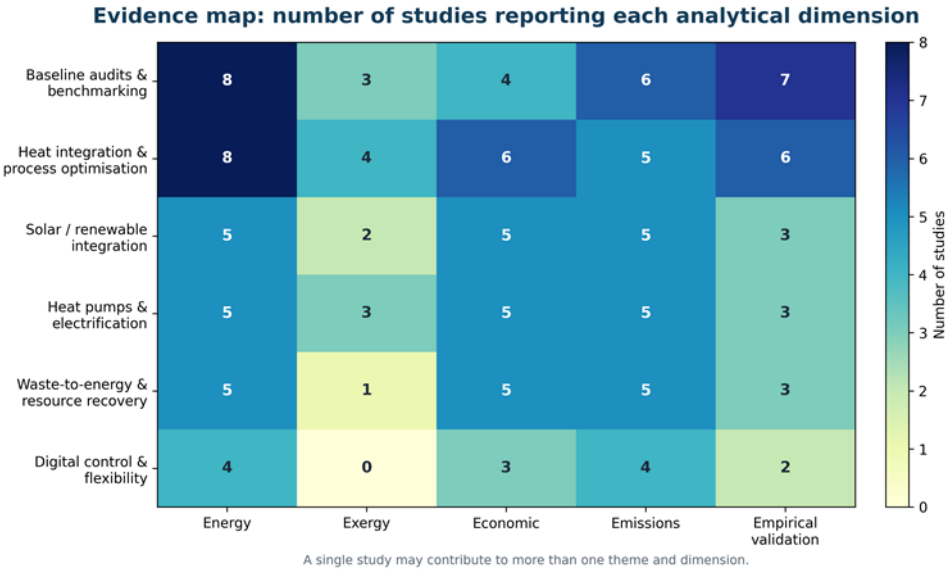


Figure 5. Evidence coverage by brewery intervention theme and analytical dimension. A study may contribute to more than one cell.

Figure 5 shows that energy analysis was most frequent in baseline audits and heat integration, with eight studies in each theme. Exergy coverage was sparse: no digital-control study and only one waste-to-energy study reported it. Empirical validation was strongest for baseline audits (seven studies) but weakest for digital control (two studies). Economic and emissions analyses appeared across most technology themes, although assumptions and uncertainty were often incompletely reported. Table 4 consolidates the principal numerical findings without treating unlike boundaries as a pooled range.

Brewery residues have value as a portfolio of heat, cooling, gas, fertiliser and CO_2 services; the best route depends on scale and coproduct demand.

Table 4. Key numerical findings retained from the included studies.

Reference	Context	Reported numerical finding	Transferability caution
[38]	Ugandan pinch case	21.5% recovery potential at ΔTmin = 10 °C	Depends on stream timing, baseline and ΔTmin
[7]	California craft brewery	1.6 MJ/L electrical and 4.2 MJ/L thermal energy	Small-plant boundary and utilisation
[19]	High-gravity wort	86 ± 1 MJ/hL; 30.35% energy efficiency; 3.2737 MW exergy destruction	Wort-only boundary
[20]	Large industrial brewery	3.33% overall exergy efficiency; 5.54 MW destruction	Different product and process boundary
[41]	Large Chinese brewery	37.2% steam loss; 72.4% brewhouse exergy efficiency; about 1.1-year retrofit payback	Tariff and operating-schedule dependent
[45]	Dual-source heat-pump model	60% lower carbon emissions and 10% lower energy cost	Modelled matched heating and cooling
[46]	239 Danish breweries	1.56% lower electricity cost and about 1,745 t CO_2/year avoided	Sector simulation and Danish market conditions
[13]	Generalised brewery	Heat demand reduced	Modelled integration and

Reference	Context	Reported numerical finding	Transferability caution
		from 21.4 to about 10 kWh/hL; electricity 5.0-3.6 kWh/hL	capital trade-off
[48]	Craft brewery waste recovery	Combined pathway feasible above about 50,000 barrels/year	Scale, coproduct price and waste assumptions

3.2 Discussion

3.2.1 Principal synthesis: diagnose before selecting technology

The strongest cross-study conclusion is that brewery decarbonisation should begin with diagnosis. Technology-first selection can oversize renewable or electrified equipment to serve avoidable losses. Metering, steam maintenance, boiler tuning, insulation, condensate return, heat-exchanger cleaning, refrigeration control and production scheduling reduce both demand and required retrofit capacity. Heat integration then lowers the residual load and heat-pump temperature lift, improving COP and renewable utilisation [2], [5], [38], [41]. Figure 6 presents this efficiency-first hierarchy.

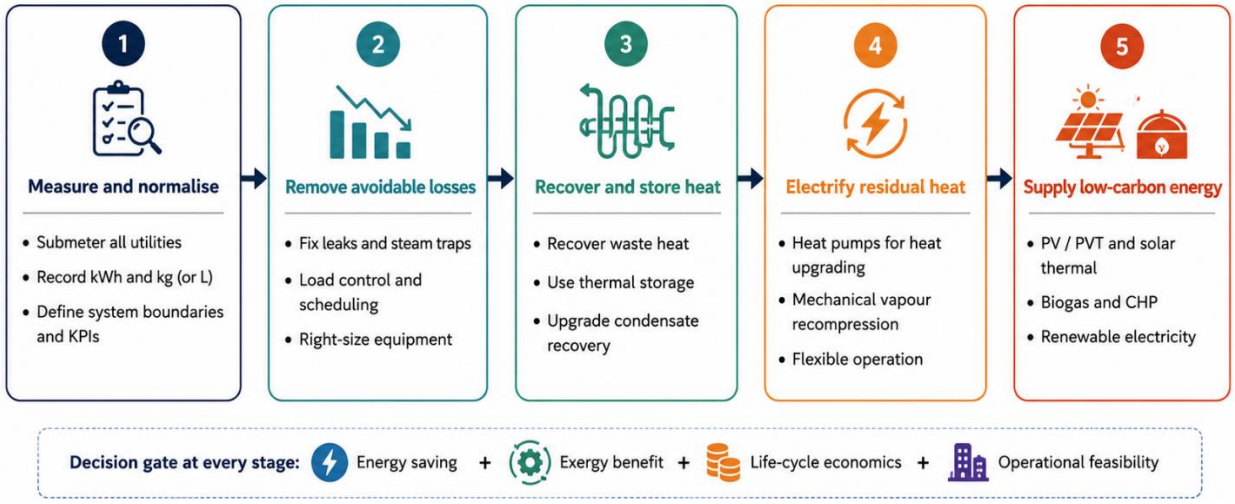


Figure 6. Efficiency-first hierarchy for brewery energy-system improvement.

1. Steam generation, brewhouse heating, wort boiling, refrigeration and packaging are the recurrent energy and exergy hotspots.
2. Low-cost control and heat recovery are the most transferable first actions; heat pumps, renewables and waste-to-energy perform well only when temperature, timing, scale and tariffs are favourable.
3. Brewery scale, production schedule, boundary, energy price, capacity factor, discount rate, climate, grid carbon intensity and policy explain most variation in reported performance.
4. Inconsistent functional units, incomplete economic assumptions, weak uncertainty reporting and limited empirical validation prevent direct technology ranking.
5. Future studies should report the production basis, full boundary, data provenance, energy and exergy assumptions, intervention design, cash-flow model, emissions method, validation and uncertainty specified in Table 5.

3.2.2 Why study results appear contradictory

Apparent contradictions largely reflect boundaries and local conditions. Solar thermal can be technically suitable but financially weak where gas is cheap; PV can perform better when electricity prices and export terms are favourable. Biogas may be more valuable for direct heating or absorption cooling than power generation. Heat pumps perform best when waste heat and demand coincide and temperature lift is moderate [23], [44]-[45].

Scale and production schedule are equally important. Design-point efficiency can understate losses at low utilisation, whereas storage and flexible operation can convert low-price or intermittent electricity into useful heat. Economic conclusions should therefore be reported as functions of tariffs, annual hours, capacity factor, discount rate, escalation and policy, not as universally transferable payback values.

3.2.3 Implications for brewery operators

Operators should develop a utility balance by production department and product or packaging format. Steam or thermal energy, electricity, refrigeration, compressed air and hot-water production should be sub-metered. Indicators should be normalised per hL of saleable beer and interpreted against production volume, ambient condition and idle hours. Anomalies should be investigated before capital projects are selected.

The first investment portfolio should normally include steam-trap and leak management, combustion tuning, insulation, condensate return, set-point control, refrigeration optimisation and wort-cooling heat recovery. Pinch analysis and dynamic batch modelling should then determine direct recovery and storage. Only the residual demand should size heat pumps, solar systems, biomass or biogas systems and CHP. This sequence lowers capital exposure and protects the economics of later technologies.

3.2.4 Implications for researchers and engineers

Future studies should not report an isolated efficiency without a complete numerator, denominator and boundary. Energy studies should separate electricity and fuels and report final and, where relevant, primary energy. Exergy studies should define the dead state and component fuel or product exergy. Economic studies should disclose cash-flow assumptions. Emissions studies should identify the factor source, electricity accounting method and treatment of biogenic carbon.

Measured studies should report sampling interval, calibration, missing-data treatment and production normalisation. Simulation studies should report calibration and prediction error. Optimisation studies should state constraints, objective functions, solver settings and sensitivity. These requirements directly support the research agenda in Section 6 because comparable evidence is a prerequisite for multi-site validation and transferable technology design.

3.2.5 African and emerging-economy relevance

African evidence shows why local context changes technology ranking. Diesel self-generation, power interruptions, boiler maintenance, foreign-exchange exposure and biomass availability can dominate thermodynamic advantages. Nigerian, Ugandan, Tanzanian, Ethiopian and South African studies identified diesel burdens, heat-integration potential, boiler and departmental losses, and tariff-sensitive PV and storage [8]-[9], [11], [38]-[40], [43], [49].

European paybacks cannot be transferred directly to African plants. Future work should model grid unreliability, generator part-load efficiency, fuel logistics, inflation, exchange-rate risk, finance, water constraints and local maintenance capacity. Table 5 defines the minimum reporting framework required to make future 3E studies comparable.

Table 5. Minimum reporting framework for comparable brewery 3E studies.

Reporting block	Minimum information required
Brewery and production	Country, plant scale, annual production, product mix, packaging mix, operating days and shifts
System boundary	Included processes and utilities; gate definition; whether malting, wastewater, CO_2, and packaging are included
Energy data	Meter type, interval, fuel LHV/HHV, conversion factors, uncertainty, final and primary energy
Functional unit	MJ/hL or kWh/hL of saleable beer; separate wort-only results
Exergy	T_0, p_0, chemical-exergy source, steam properties, component fuel/product definitions
Intervention	Baseline, equipment size, source/sink temperatures, storage capacity, annual utilisation, control strategy
Economics	Currency/base year, CAPEX, OPEX, project life, discount rate, tariffs, escalation, replacement, incentives
Environment	Emission factors, grid basis, biogenic-carbon treatment, avoided-emission method
Validation	Measured baseline, model calibration, error statistics, sensitivity/uncertainty
Results	SEC, η_{en}, η_{ex}, $\dot{E}x_D$, NPV, payback, LCOH, emissions, confidence/sensitivity ranges

3.2.6 Policy implications implementation barriers and sector comparison

Policy should make verified demand reduction financially preferable to equipment installation alone. Useful instruments include minimum sub-metering requirements, subsidised audits for small breweries, concessional finance, accelerated depreciation, carbon pricing or fuel-tax reform, and performance-linked grants. Incentives should require measured baselines and post-installation verification so that heat recovery and control are not displaced by oversized supply technologies.

Non-economic barriers are equally important. Limited staff time, weak data ownership, production-risk concerns, maintenance capability, fragmented capital approval and permitting can delay measures with attractive payback. Training, clear responsibility for utility performance, standard measurement and verification, and staged pilots address these organisational, behavioural and regulatory constraints [3], [5].

The brewery pattern is consistent with other food and beverage processes, where batch scheduling, cleaning, refrigeration and low- to medium-temperature heat create integration opportunities [3], [33]. Breweries are distinguished by wort boiling, fermentation cooling and recoverable fermentation CO_2. Policy and research should therefore combine cross-sector heat-pump and efficiency standards with brewery-specific guidance on batch integration, residues and CO_2 recovery. These requirements motivate the field-validation and uncertainty agenda in Section 6.

3.2.7 Limitations of this review

This review is limited by heterogeneity in terminology, boundary, functional unit and reporting. Search counts were taken from the review team's screening log; the original database exports were not available for an independent rerun during revision. Non-English and inaccessible reports may have been missed. The appraisal measured reporting completeness and did not reanalyse raw data. Some recent studies were assessed mainly from publisher-accessible summaries, and publication bias may favour successful retrofits or positive economics. Exact numerical values should therefore be interpreted within their reported boundaries, although the recurring directions of effect remain consistent.

3.3 Research Gaps and Future Directions

3.3.1 Truly integrated and comparable 3E studies

The most important gap is the scarcity of before-and-after field studies that report energy, exergy, life-cycle economics and emissions within one boundary. Future work should compare boiler, heat-recovery, heat-pump, renewable and biogas configurations under identical production schedules and assumptions.

3.3.2 Advanced exergy and avoidable irreversibility

Conventional exergy analysis identifies destruction but not the portion that is avoidable or created by component interactions. Advanced analysis should separate avoidable from unavoidable and endogenous from exogenous destruction so that redesign opportunities can be distinguished from losses imposed by process temperatures or external systems.

3.3.3 Dynamic batch integration and storage

Annual balances cannot represent mismatches among wort cooling, hot-water demand, refrigeration, renewable output and tariffs. Dynamic simulation should combine pinch analysis, thermal storage, production scheduling and model-predictive control, followed by validation under real brew schedules.

3.3.4 Standardised techno-economic uncertainty

Economic studies should move beyond deterministic payback. Scenario or Monte Carlo analysis should include capital uncertainty, discount rate, fuel and electricity escalation, carbon price, equipment degradation, production growth and downtime. Results should report the probability of positive NPV and break-even conditions.

3.3.5 Circular-energy and carbon-dioxide integration

Anaerobic digestion, spent-grain conversion, wastewater heat recovery and fermentation-CO_2 capture are often assessed separately. Integrated biorefinery studies should compare competing residue uses, nutrient recovery, CO_2 purification, heat and power, and water treatment within one mass-energy-exergy-cost boundary.

3.3.6 Regional empirical evidence

Longitudinal field studies are needed in Africa, Latin America and other underrepresented regions. Priorities include hybrid grid-diesel-renewable systems, local biomass and biogas, maintainable heat recovery, financing constraints, and the interaction between water scarcity and energy use. Table 6 converts these gaps into recommended study designs and outputs.

Table 6. Research gaps, recommended study designs and priority outputs.

Gap	Recommended research design	Priority output
Fragmented 3E evidence	Before-after field study with a common boundary	Comparable energy, exergy, NPV and emissions
Static batch models	Dynamic scheduling + pinch + storage optimisation	Hourly utility and flexibility profiles
Weak economic transparency	Probabilistic life-cycle cost model	NPV distribution and break-even tariffs
Limited advanced exergy	Avoidable/endogenous decomposition	Prioritised irreversibility reduction
Sparse regional data	Multi-site African and Latin American audits	Scale- and context-specific benchmarks
Separate waste/CO_2 studies	Integrated circular-resource model	Optimal allocation of residues, biogas and CO_2
Limited implementation evidence	Long-term monitoring after retrofit	Persistence, degradation and maintenance effects

4. CONCLUSION

This review synthesised 33 brewery-specific studies and found recurring hotspots in steam generation, mashing, wort boiling, wort cooling, refrigeration and packaging. Case-study results included 21.5% heat-recovery potential, exergy efficiency as low as 3.33%, and a dual-source heat-pump case with 60% lower modelled carbon emissions and 10% lower energy cost. These values are boundary-specific and should guide diagnosis rather than serve as universal benchmarks.

The economic case for an efficiency-first sequence is that every avoided kilowatt or recovered unit of heat reduces the capacity, capital cost and operating risk of downstream electrification and renewable supply. Breweries should therefore meter and repair first, recover and store heat second, electrify suitable residual duties third, and add locally appropriate renewable or waste-derived supply last.

Operators should implement sub-metering, loss-control plans and staged investment screening. Researchers should conduct before-and-after field studies using common 3E boundaries, uncertainty analysis and transparent cash-flow models. Policymakers should support energy audits, metering standards, concessional finance, carbon- or performance-linked incentives and technical training, with safeguards that reward verified savings rather than installed capacity alone.

These conclusions are limited by heterogeneous system boundaries, incomplete economic reporting, uneven regional coverage and limited independent validation. The priority is therefore not a universal technology winner, but reproducible evidence that identifies the least-cost and least-destructive configuration for each brewery's scale, schedule, resource base and policy environment.

Appendix A Reproducible Search Strategy

A1. Scopus

TITLE-ABS-KEY ((brewery OR brewing OR brewhouse OR "beer production") AND (energy OR fuel OR steam OR electricity OR refrigeration) AND (exergy OR exergoeconomic OR economic OR "techno-economic" OR efficiency OR "heat recovery" OR pinch OR "heat pump" OR solar OR photovoltaic OR biogas OR cogeneration))

A2. Web of Science Core Collection

TS=((brewery OR brewing OR brewhouse OR "beer production") AND (energy OR fuel OR steam OR electricity OR refrigeration) AND (exergy OR exergoeconomic OR economic OR "techno-economic" OR efficiency OR "heat recovery" OR pinch OR "heat pump" OR solar OR photovoltaic OR biogas OR cogeneration))

A3. ScienceDirect

(brewery OR brewing OR brewhouse OR "beer production") AND (energy OR exergy OR exergoeconomic OR "techno-economic" OR "heat recovery" OR pinch OR "heat pump" OR solar OR photovoltaic OR biogas OR cogeneration)

A4 Google Scholar and Citation Checking

Exact-title and phrase searches combined brewery terms with energy audit, exergy, exergoeconomic, pinch analysis, heat recovery, industrial heat pump, solar thermal, photovoltaic, PVT, biogas, anaerobic digestion, thermal storage, demand response and energy flexibility.

Appendix B Nomenclature and Data Extraction

Table B1. Nomenclature used in the review equations and reporting framework.

Symbol	Definition	Typical unit
E	Energy quantity	MJ, kWh
$\dot{E}$	Energy rate	kW
Ex	Exergy quantity	MJ
$\dot{E}x$	Exergy rate	kW
SEC	Specific energy consumption	MJ/hL or kWh/hL
V_b	Saleable beer or wort volume	hL
η_{en}	First-law energy efficiency	%
η_{ex}	Exergy efficiency	%
T_0	Dead-state temperature	K
h, s	Specific enthalpy and entropy	kJ/kg, kJ/(kg K)
NPV	Net present value	currency
I_0	Initial capital investment	currency
CF_t	Net cash flow in year t	currency/year
r	Discount rate	fraction/year
$LCOH$	Levelised cost of heat	currency/MWh_{th}
CHP	Combined heat and power	-
COP	Coefficient of performance	-
HEN	Heat-exchanger network	-
HTHP	High-temperature heat pump	-
MVR	Mechanical vapour recompression	-
PV/PVT	Photovoltaic / photovoltaic-thermal	-

Table B2. Recommended data-extraction form for future brewery 3E studies.

Field	Entry to record
Bibliographic information	Author, year, title, journal, DOI
Location and scale	Country, annual production, craft/medium/large
Boundary	Processes and utilities included
Data basis	Measured, simulated, mixed; duration and resolution
Baseline energy	Fuel, electricity, thermal and cooling demand
Intervention	Technology, capacity, operating temperature and schedule
Energy results	SEC and efficiency before/after
Exergy results	Reference state, efficiencies, destruction by component
Economic results	CAPEX, OPEX, NPV, IRR/payback, LCOH and assumptions
Emissions	Factors, scope and avoided emissions
Validation	Calibration method and errors
Sensitivity	Variables and ranges
Limitations	Boundary, data, implementation and transferability

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