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OTEX: An open-source software for ocean thermal energy conversion modeling

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ABSTRACT

OTEX (Ocean Thermal Energy eXchange) is an open-source Python package for the design, simulation, and techno-economic assessment of Ocean Thermal Energy Conversion (OTEC) power plants. It implements three cycle architectures, closed Rankine (with simple, Kalina, and Uehara variants), open Rankine, and hybrid, realized as five configurations with pure and ammonia-water working fluids, coupled to heat-exchanger sizing, seawater hydraulics, and off-design operation. Integration with global ocean reanalysis data (CMEMS, HYCOM) enables site-specific resource assessment, while levelized cost of electricity and Monte Carlo and Sobol uncertainty analysis support comparative evaluation. A spatially resolved case study of Cuban waters demonstrates multi-configuration optimization of net power and cost.

Metadata

Nr	Code metadata description	Metadata
C1	Current code version	v0.5.3
C2	Permanent link to code/ repository used for this code version	https://github.com/Net-Zero-Horizon/OTEX
C3	Legal code license	MPL 2.0
C4	Code versioning system used	git
C5	Software code languages, tools and services used	Python, pyOTEC
C6	Compilation requirements, operating environments and dependencies	Python ≥ 3.9; NumPy, Pandas, SciPy, Matplotlib, xarray, netCDF4, tqdm; optional CoolProp (working fluids) and SALib (Sobol indices). OS-agnostic (Linux, macOS, Windows).
C7	If available, link to developer documentation/manual	https://otex.readthedocs.io
C8	Support email for questions	msotocalvo@hiroshima-u.ac.jp

1. Motivation and significance

The global energy landscape stands at a critical juncture. With atmospheric CO_2 concentrations surpassing 420 ppm and global temperatures rising 1.1 °C above pre-industrial levels, the imperative for rapid decarbonization has never been more urgent [1]. The International Energy Agency projects that achieving net-zero emissions by 2050 requires renewable energy to constitute approximately 90 % of total electricity generation, up from <30 % today [2]. However, this ambitious transition faces a fundamental challenge: the inherent intermittency of dominant renewable sources such as solar and wind energy, which limits their capacity to provide the stable baseload power essential for grid reliability and industrial operations [3].

Ocean thermal energy conversion (OTEC) presents a compelling solution to this baseload challenge. Unlike intermittent renewables, OTEC harnesses the temperature differential between warm surface waters and cold deep ocean waters to generate continuous, predictable power [4–6]. This temperature gradient, typically 20 °C or greater in tropical and subtropical regions, remains remarkably stable throughout day-night cycles and seasonal variations, enabling capacity factors exceeding 90 %, comparable to conventional fossil fuel and nuclear plants, and far surpassing the 20–40 % typical of solar and wind installations [7–10]. The International Renewable Energy Agency (IRENA) has identified OTEC as possessing the highest potential among all ocean energy technologies, with an estimated theoretical resource of

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300 exajoules per year, representing approximately 90 % of total global ocean energy potential and equivalent to multiple times current global electricity demand [11].

Despite this extraordinary potential and a development history spanning over a century, OTEC has struggled to transition from experimental demonstration to commercial deployment [12]. Multiple factors have constrained development, including high capital costs estimated at $50,000–100,000 per installed kilowatt, technical challenges associated with construction and maintenance, efficiency limitations, and insufficient policy support mechanisms to offset these economic barriers during technology maturation [13,14]. Recent techno-economic assessments have explored polygeneration configurations that couple OTEC with hydrogen production, freshwater desalination, and cold-energy recovery [15–17], broadening the economic value proposition beyond electricity alone.

Paradoxically, climate change is projected to enhance OTEC resource availability by approximately 46 % by the end of this century under high emission scenarios [18]. This counterintuitive benefit positions OTEC as one of the few renewable technologies that becomes increasingly viable as climate impacts intensify, particularly in tropical island nations and coastal regions where stable baseload power is most critically needed [19].

A significant impediment to OTEC advancement has been the scarcity of comprehensive, accessible modeling tools for system design, performance analysis, and technoeconomic assessment [9,12]. Existing analytical frameworks have typically been proprietary, limited in scope to specific cycle configurations, or implemented in platforms that restrict accessibility for researchers and developers in resource-constrained settings. This software gap has hindered systematic exploration of design space, comparative evaluation of thermodynamic cycles and working fluids, sensitivity analysis of key operational parameters, and rigorous site-specific feasibility studies incorporating actual oceanographic conditions.

OTEX (Ocean Thermal Energy eXchange) addresses this critical gap by providing an open-source, Python-based computational framework specifically designed for OTEC plant design, simulation, and technoeconomic analysis. Built upon established thermodynamic principles, OTEX implements three cycle architectures, closed, open, and hybrid Rankine, as five configurations, with Kalina and Uehara as closed-cycle variants using ammonia-water zeotropic mixtures, with support for various working fluids such as ammonia, R134a, R245fa, propane, and isobutane. The software integrates with global oceanographic databases, specifically the Copernicus Marine Environment Monitoring Service (CMEMS), enabling spatially and temporally resolved resource assessments that account for actual ocean temperature profiles, seasonal variability, and long-term climatic trends. This integration facilitates site-specific feasibility analysis for any location within the global OTEC resource zone. This development represents a logical and necessary step in supporting OTEC technology evolution and facilitating its contribution to the global energy transition.

OTEX substantially extends pyOTEC [5] beyond its single closed-cycle Rankine/ammonia baseline to three cycle architectures, adding Kalina and Uehara as zeotropic NH_3-H_2O closed-cycle variants, with six working fluids and both offshore and onshore facility types. Moreover, it adds multisource resource data, multi-criteria site screening, integrated uncertainty stacks, per-site optimization, and couples with climatic scenarios, enabling prospective assessment of OTEC viability under climate change.

2. Software description

2.1. Software architecture

OTEX implements a thermodynamic and technoeconomic framework for OTEC system analysis. The software architecture consists of five principal modules: (1) thermodynamic cycle modeling, (2) heat exchanger design and off-design performance, (3) seawater system hydraulics, (4) economic evaluation, and (5) uncertainty quantification.

Fig. 1 presents the overall computational workflow implemented in OTEX. The framework systematically evaluates OTEC system configurations by combining facility type, thermal cycle architecture, and working fluid selection. For each configuration and spatial grid point, site-specific datasets (including coastline geometry, ocean temperature profiles, bathymetry, and environmental constraints) are integrated to define boundary conditions and feasibility limits. The thermodynamic performance is computed through the determination of evaporator and condenser operating conditions, component sizing, and seawater system requirements, accounting for both warm and cold-water circuits and working fluid pumping. Gross power output is prescribed, while parasitic losses are explicitly modeled to obtain net power production. In parallel, capital and operational expenditures are estimated from component-level scaling relationships, including structures, equipment, cabling, and auxiliary systems. The workflow links physical performance and economic assessment to derive net power output and levelized cost of electricity (LCOE) for each location and configuration, enabling systematic comparisons across technologies and spatial domains.

At each grid point, the framework integrates six spatial datasets: coastline geometry, ocean temperature profiles (HYCOM [20], CMEMS [21]), bathymetry (GEBCO [22]), hazards (GEM Global Seismic Hazard Map [23], NOAA IBTrACS v04 [24]), shipping routes (World Bank Global Vessel Density [25]), and marine protected area (WDPA, April 2026 snapshot) [26] designations. These define boundary conditions and feasibility constraints.

OTEX is implemented in Python 3.9+ leveraging NumPy [27] and SciPy [28] for numerical computations, Pandas [29] for data manipulation, and Matplotlib [30] for visualization. The thermodynamic properties are computed via either polynomial correlations (for ammonia baseline calculations) or CoolProp when installed, providing access to REFPROP-quality equations of state for diverse working fluids. The modular architecture separates thermodynamic core functions (cycle analysis, heat exchanger sizing), plant-level integration (parasitic loads, off-design performance), economic calculations, and uncertainty modules, facilitating extension and validation.

Regional analysis scripts automate the workflow: oceanographic data retrieval, plant optimization across multiple design configurations, LCOE mapping, and capacity factor calculation. Global analysis capabilities enable screening-level assessment of OTEC potential across all tropical and subtropical waters. Results are exported in standard formats (CSV, HDF5, NetCDF, GeoJSON) compatible with geographic information systems and visualization platforms.

2.2. Software functionalities

OTEX models three cycle architectures, closed, open, and hybrid Rankine, as five configurations selectable at configuration time: closed Rankine in a simple variant (ammonia, R134a, R245fa, propane, isobutane) and in the Kalina and Uehara variants using ammonia-water zeotropic mixtures to exploit temperature glide; open Rankine (Claude cycle, seawater flash evaporation); and hybrid Rankine. Thermophysical properties are obtained from internal polynomial correlations or, when installed, CoolProp. For each cycle the package sizes evaporator and condenser areas, seawater flow rates, and cold-water pipe geometry, then evaluates parasitic loads to obtain net power.

OTEX interfaces with the Copernicus Marine Environment Monitoring Service (CMEMS) [21] global ocean reanalysis dataset, providing monthly-averaged temperature profiles with 0.083° spatial resolution from 1993 to present. The software automatically retrieves temperature data at specified geographic coordinates and depths via the Copernicus Marine Python API.

For every configuration and grid point, OTEX computes net power output as gross turbine power minus pumping and auxiliary parasitic

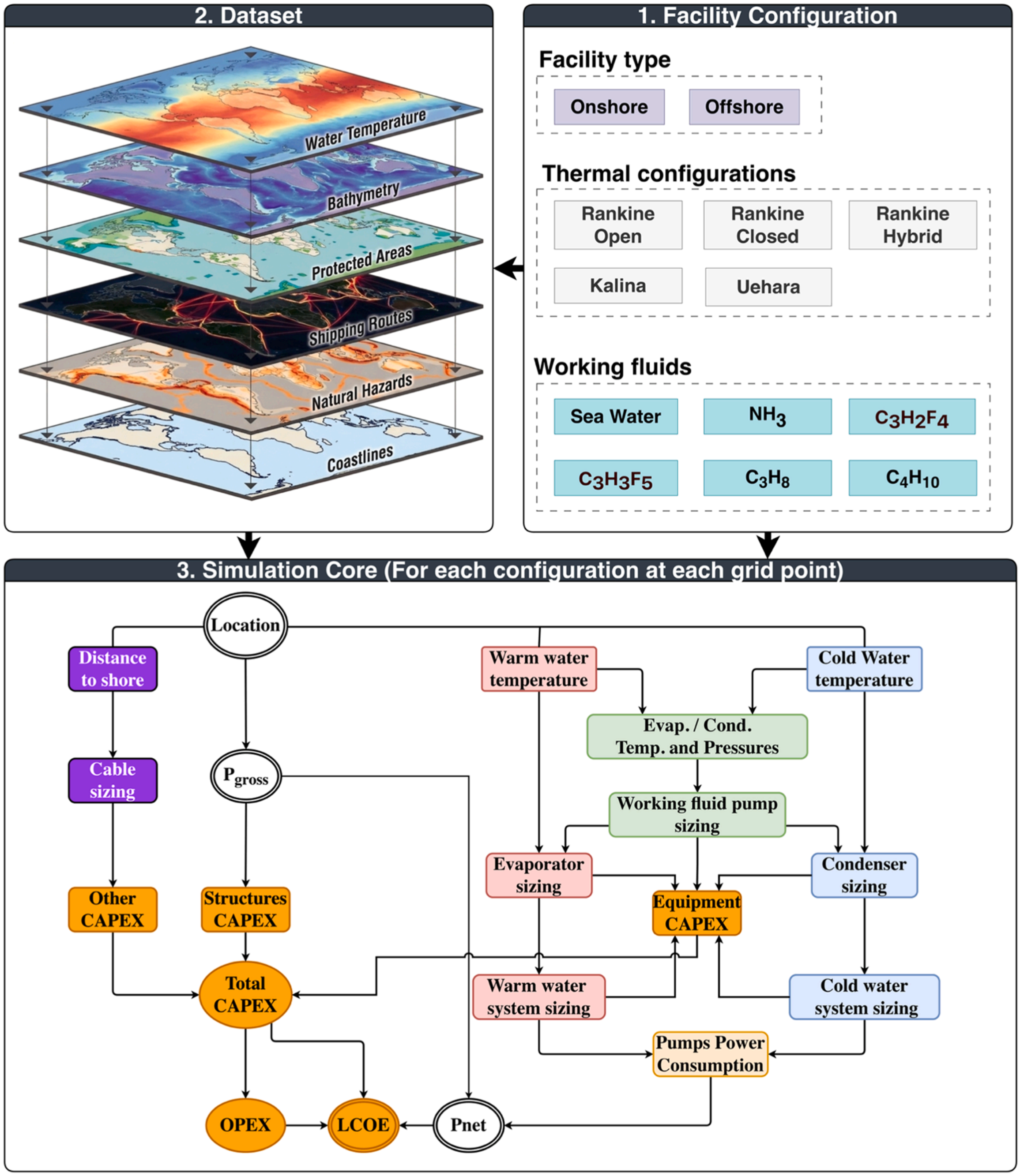

Fig. 1. General process flowchart of the OTEX computational framework for OTEC plant design, simulation, and technoeconomic assessment.

loads, and the resulting capacity factor:

$$W_{net} = W_{turb} - W_{pump} - W_{CWP} - W_{WWP} - W_{aux} \quad (1)$$

$$CF = E_{annual} / (W_{net} \times 8760\ h) \quad (2)$$

The levelized cost of electricity (LCOE) serves as the primary economic metric, representing the break-even electricity price required over the project lifetime. OTEX implements the standard discounted cash flow formulation (Eq. (3)):

$$LCOE = \frac{[CAPEX \times CRF + C_{O\&M,\ annual}]}{E_{annual}} \quad (3)$$

where CAPEX is the total capital expenditure, $C_{O\&M,annual}$ is the annual operation and maintenance cost, E_{annual} is the net annual electricity generation (Eq. (2)), and $CRF = i(1+i)n / [(1+i)n - 1]$ is the capital recovery factor with discount rate i and project lifetime n. Multiplication by 100 converts \$/kWh to ¢/kWh. OTEX also exposes an explicit discounted-cashflow variant (*lcoe_npv*) supporting configurable degradation and OPEX escalation as an optional alternative to the CRF formulation.

OTEX implements three complementary uncertainty quantification methodologies: Monte Carlo simulation with Latin Hypercube Sampling (LHS) [31], Sobol global sensitivity analysis [32], and tornado diagram construction for local sensitivity assessment.

3. Illustrative examples

Having established the theoretical framework and computational methodology in the previous section, this section demonstrates the practical capabilities of OTEX through a comprehensive case study of OTEC's potential in Cuban waters. Cuba represents an ideal demonstration case for several compelling reasons: (i) as a Caribbean island nation with year-round tropical conditions, it possesses consistently favorable thermal gradients between warm surface waters (26–29 °C) and deep cold waters (4–6 °C at 1000 m depth); (ii) its significant energy demand coupled with limited domestic fossil fuel resources creates strong economic incentives for renewable ocean energy development; (iii) the surrounding waters exhibit oceanographic stability with relatively low seasonal variability, enabling high-capacity factor operation; and (iv) adequate bathymetric conditions exist along multiple coastal regions where the 1000 m isobath lies within reasonable distance from shore. This section systematically applies OTEX's multi-configuration optimization framework to evaluate five configurations across three cycle architectures, closed Rankine (with simple, Kalina, and Uehara variants), open Rankine, and hybrid Rankine across both onshore and offshore installation scenarios, demonstrating the software's capacity to identify optimal configurations, quantify regional performance variations, assess technoeconomic viability through LCOE analysis, and provide actionable insights for OTEC project development. The analyses presented herein utilize 30 years of oceanographic reanalysis data (1993–2022) and consider dual-cost scenarios to bound the solution space for decision-makers.

To illustrate the spatial variability in OTEC performance across Cuban waters, OTEX was applied to multiple grid points within the domain, incorporating monthly-averaged temperature profiles from the Copernicus Marine Environment Monitoring Service (CMEMS) reanalysis dataset (1993–2022). For each location, the software performed multi-configuration optimization, component sizing, and off-design evaluation to determine annual energy production and economic metrics for a nominal 100 MW gross power plant.

Fig. 2 summarizes the statistical distributions of the net electrical power output (Fig. 2a) and LCOE (Fig. 2b) obtained from all evaluated configurations within the predefined spatial and technoeconomic domain. For each thermodynamic cycle and working fluid, kernel density estimates (KDEs) are constructed from the full ensemble of simulated locations and operating conditions. Solid curves correspond to offshore configurations, while dashed curves represent onshore installations. The distributions therefore reflect combined effects of oceanographic variability, design-point selection, off-design operation, parasitic loads, and cost scaling.

Fig. 3 synthesizes the aggregated performance metrics of the evaluated OTEC configurations by cycle type and working fluid and places these results in a joint technoeconomic context through a median-based Pareto representation. Figs. 3a-3d report median values of net power output and LCOE across the full ensemble of simulated locations and operating conditions, whereas Fig. 3e combines these metrics to identify nondominated trade-offs between power generation and cost.

Fig. 4 illustrates the spatial distribution of median net power output and median LCOE across Cuban waters. The figure shows the configuration that dominates the Pareto frontier: the Uehara cycle with ammonia-water mixture. The median values are computed from the full ensemble of simulated operating conditions at each spatial location, accounting for long-term oceanographic variability and off-design operation.

A comparison of the net power and LCOE patterns reveals a clear spatial coupling between thermodynamic performance and economic outcome. Regions with elevated net power consistently correspond to lower LCOE, confirming the dominant influence of annual energy production on cost metrics under the low-cost scenario.

4. Software validation

To assess model fidelity beyond internal consistency checks, OTEX was benchmarked against three independent techno-economic OTEC studies covering closed Rankine and Kalina architectures. For each

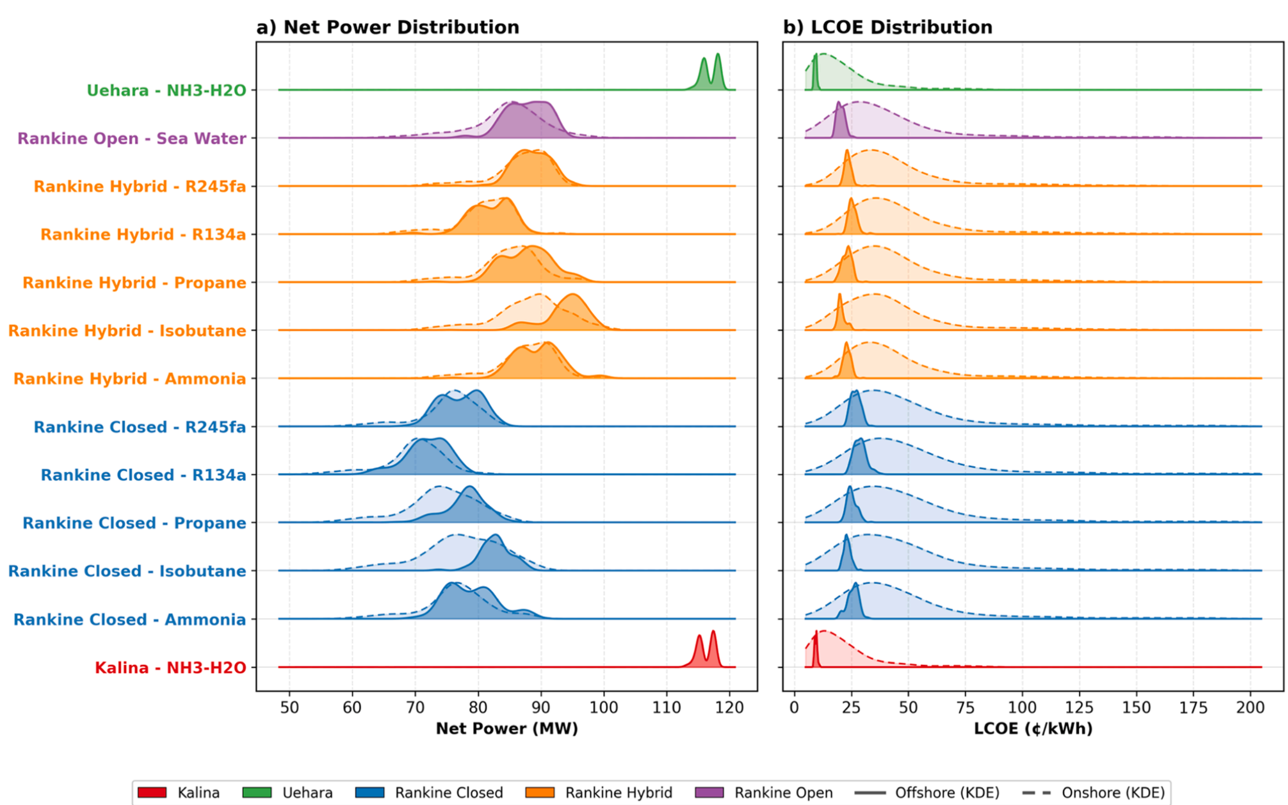

Fig. 2. Kernel density estimate (KDE) distributions of (a) net power output and (b) levelized cost of electricity (LCOE) for nominal 100 MW gross power OTEC plants across the evaluated domain in Cuban waters.

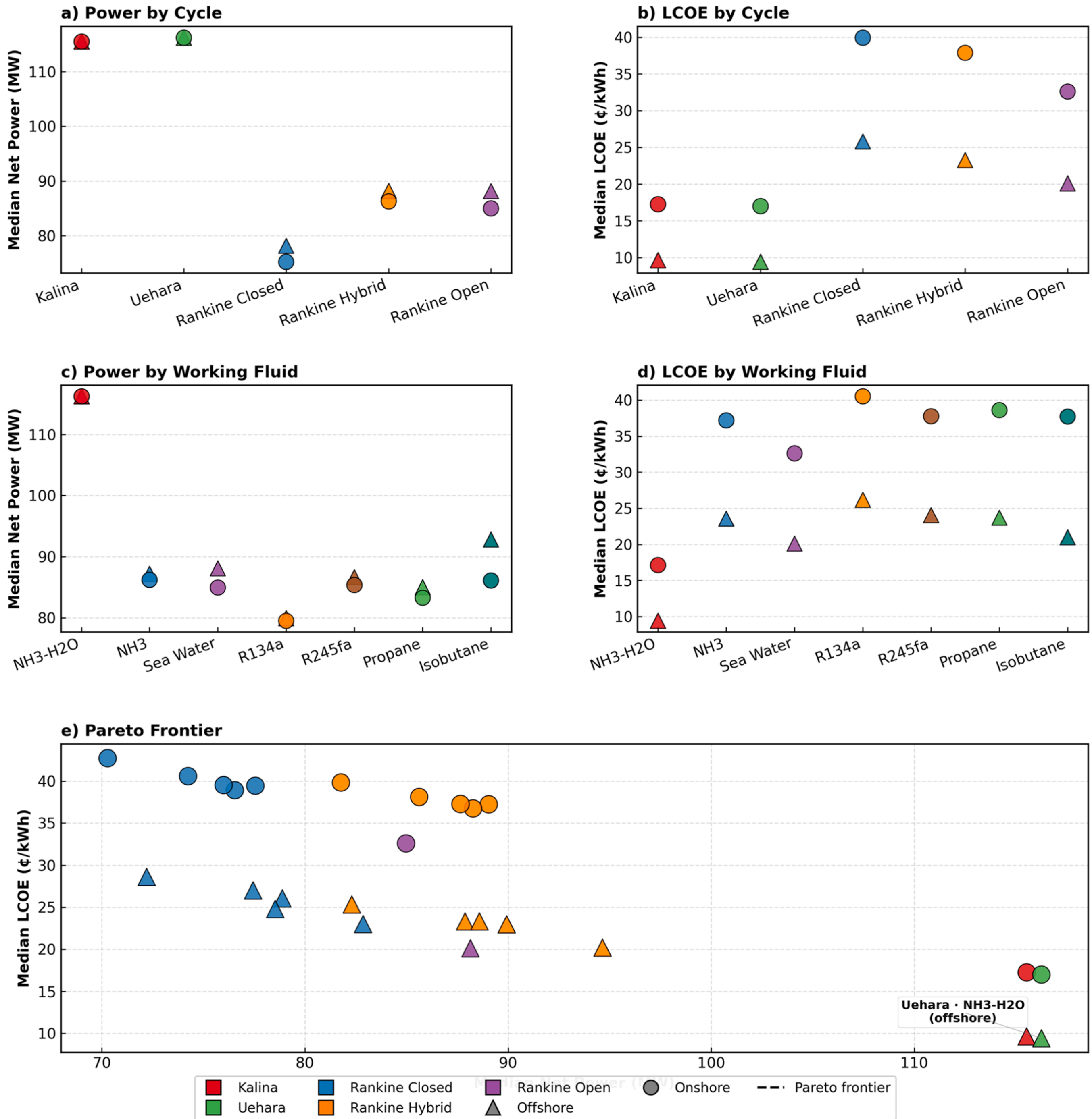

Fig. 3. Median net power output and LCOE across Cuban waters for nominal 100 MW gross OTEC plants (low-cost scenario), grouped by thermodynamic cycle (a-b), working fluid (c-d), and Pareto frontier (e) identifying optimal configurations.

reference, OTEX was executed in single-site mode with the paper's own physical parameters (temperatures, ΔT, pinch, K_L, component efficiencies) and, where reported, cost coefficients.

OTEX reproduces each reference within 3 % across net power, capital expenditure, and levelized cost of electricity when the paper-specified inputs are supplied, as shown in Table 1.

The validation covers the thermodynamic core (cycle states, heat-exchanger sizing, mass and energy balances), plant-level parasitic-load accounting, and single-year LCOE. Multi-year NPV degradation dynamics, uncertainty-propagation calibration, and off-design transient response remain calibrated internally and have not yet been benchmarked against independent published data.

5. Reproducibility and performance

OTEX installs from PyPI (‘pip install otex’) with all dependencies pinned by release tag. Fig. 5 characterizes single-node performance across five case studies spanning 511 to 4155 valid sites and all five implemented configurations. Compute time scales near-linearly with the number of sites; NH_3-H_2O mixture cycles (Kalina, Uehara) are ∼60–75 × slower than pure-fluid Rankine variants owing to per-timestep CoolProp binary-mixture lookups, so the largest Uehara case (Cuba) takes ∼11 h single-threaded. Peak resident memory tracks site count almost linearly (∼0.6–0.7 MB per site) and is cycle-independent. Download time is dominated by the CMEMS bounding-box size rather than by site count.

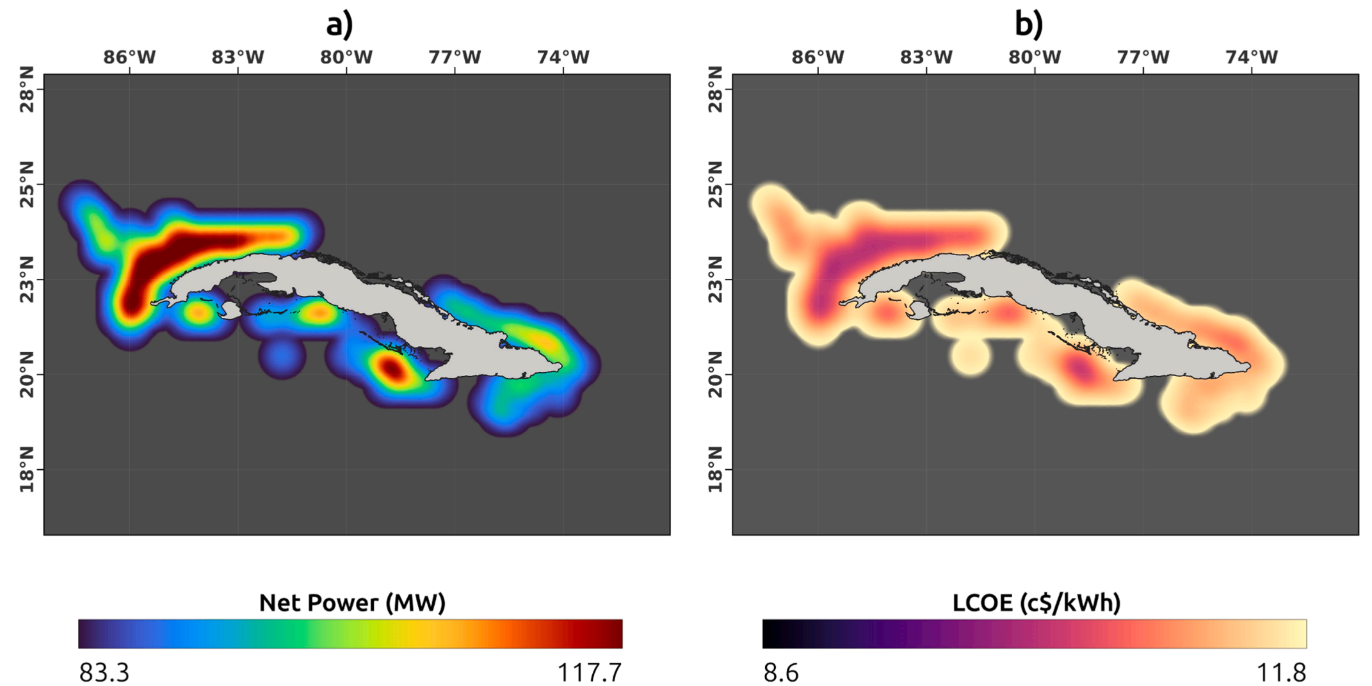

Fig. 4. Spatial distribution of median net power output (MW) and levelized cost of electricity (LCOE, ¢/kWh) across Cuban waters for nominal 100 MW gross OTEC plants under the low-cost scenario, comparing (a-b) Uehara cycle with ammonia-water mixture offshore.

Table 1
OTEX vs literature benchmark results.

Reference	Cycle-fluid	Metric	Reported	OTEX	Δ
Bernardoni et al. (2019) [33]	Closed Rankine-NH_3	P_net (MW)	2.345	2.345	0.0 %
		CAPEX (M $)	40.6	39.9	−1.9 %
		LCOE ($/MWh)	289	296	+2.5 %
Ciappi et al. (2024) [16]	Closed Rankine-NH_3	P_net (MW)	1.000	0.988	−1.2 %
Ciappi et al. (2024) [16]	Kalina-NH_3-H_2O 82 %	P_net (MW)	1.000	0.999	−0.1 %

Cycle × fluid × installation combinations are parallel: the 26-configuration Cuban sweep completes in ∼12 h wall-clock on 30 cores.

6. Impact

OTEX lowers the barrier to rigorous OTEC feasibility analysis. Prior assessments relied on proprietary or single-cycle tools, which prevented systematic comparison of cycle architectures, working fluids, and sites under consistent assumptions. By exposing a unified, scriptable interface over global ocean reanalysis data, OTEX enables reproducible studies that were previously impractical: spatially resolved LCOE mapping, multi-cycle Pareto analysis, and uncertainty propagation across thousands of configurations.

The package supports new research questions on how climate-driven changes in ocean thermal structure affect OTEC viability, and on the trade-off between thermodynamic performance and economic robustness across cycle types. Distributed through PyPI, GitHub, and Zenodo with continuous integration and documentation, OTEX is intended for academic research, early-stage project screening, and teaching of ocean-energy systems.

7. Conclusions

This work introduces OTEX, an open-source, Python-based framework for the integrated thermodynamic, technoeconomic, and uncertainty analysis of Ocean Thermal Energy Conversion (OTEC) systems. OTEX addresses a longstanding gap in OTEC research by providing a transparent, extensible, and reproducible modeling environment capable of representing multiple cycle architectures, working fluids, design philosophies, and off-design operating conditions within a unified computational framework.

The open-source nature of OTEX is central to its intended impact. By making the full codebase, documentation, and example workflows publicly available, the framework supports reproducibility, community-driven validation, and methodological transparency: elements that have been largely absent in prior OTEC modeling efforts. The modular architecture facilitates reuse and extension, enabling adaptation to alternative cost assumptions, new cycle configurations, additional working fluids, or integration within broader energy system models.

While the case study presented focuses on Cuban waters, the underlying methodology is fully general and directly applicable to any tropical or subtropical region with suitable thermal gradients. As such, OTEX provides a scalable platform for comparative site assessment, technology benchmarking, and exploratory design studies, supporting both academic research and early-stage project development.

Data availability

All data used is open source, and their sources have been properly attributed. The results presented will be made available on request.

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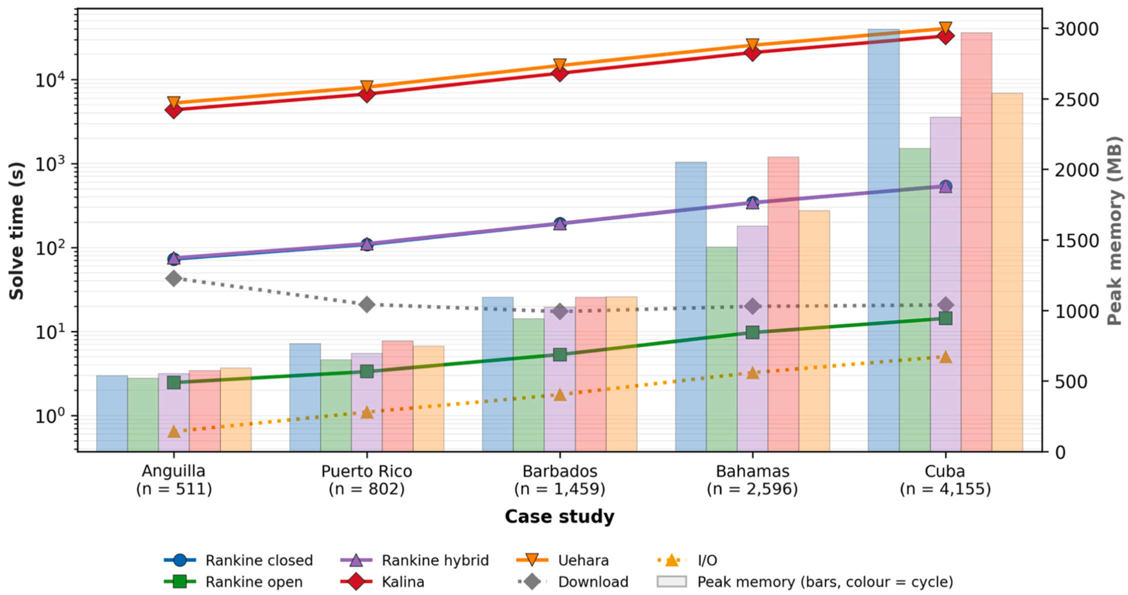

Fig. 5. OTEX regional-run performance across five case studies spanning 511 to 4155 valid ocean sites. Solid lines: per-cycle compute time (left axis, log). Dotted lines: shared Download and I/O times. Bars: peak resident memory per cycle × region (right axis).

CRediT authorship contribution statement

Manuel Soto Calvo: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Han Soo Lee:** Software, Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Zachary Williams:** Software, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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