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Techno-Economic and Probabilistic Analysis of Integrating Algal Bioenergy with Wind and Solar Power for Zero-Emission Sports Venues

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Abstract: This study presents a scenario-based assessment of a venue-scale renewable-energy concept that combines photovoltaic (PV) generation, wind power, algal bioenergy, battery storage, and limited grid support for a representative 50,000-seat sports stadium. The engineering phase compares individual and hybrid configurations using HOMER-based techno-economic indicators, environmental metrics, and Monte Carlo uncertainty ranges. The social-implementation phase uses expert interviews and survey-based exploratory and confirmatory factor analyses to identify barriers specific to algal bioenergy. Under the stated assumptions, the integrated configuration supplies 12,000 MWh/year, with an LCOE of 0.062 ± 0.007 $/kWh, an estimated 99.5% probability of positive NPV, 97% ± 1% reliability, and an 8.2 ± 0.9-year payback period. These values represent a comparative scenario assessment rather than a site-specific investment design. The study's distinct contribution is the combined evaluation of a solar-wind-algae venue concept and a structured assessment of algal implementation barriers. The results support conditional feasibility and a staged pilot pathway rather than immediate full-scale deployment. The central scientific insight is that algal bioenergy can add a controllable renewable contribution and resource-recovery potential to a solar-wind portfolio, but it simultaneously becomes the dominant water- and cost-sensitive component; this trade-off is particularly relevant to stadiums because their electricity demand is strongly event-driven and can rise sharply during night-time lighting and high-occupancy operation.

Keywords: algae; solar energy; wind energy; sport; techno-economic analysis; probabilistic analysis; qualitative and quantitative analysis

1. Introduction

Sports facilities are under increasing pressure to reduce operational emissions and dependence on conventional energy sources. Stadiums require substantial electricity for lighting, ventilation, cooling, heating, displays, and event-related services, while indirect activities associated with spectators and transport further increase their environmental burden [1–4]. Although solar and wind technologies are increasingly used in venue decarbonization strategies [5–7], variability in resource availability and site constraints can prevent either technology from meeting demand independently. This study therefore examines a three-source configuration that combines photovoltaic generation, wind power, and algal bioenergy within a single hybrid system.

Algal bioenergy may complement intermittent renewables because algal biomass can be cultivated continuously, converted into several energy carriers, and integrated with wastewater or carbon-management processes [8,9]. In a stadium context, these features create the possibility of simultaneous energy production, carbon uptake, and resource recovery. However, the practical use of algae at sports venues remains uncertain because photobioreactors, harvesting systems, water requirements, and operating expertise can impose substantial technical and economic burdens.

Algae comprise photosynthetic micro- and macro-organisms that can grow in aquatic environments, including freshwater, seawater, wastewater, open ponds, and enclosed photobioreactors [10–13]. Their rapid growth and ability to accumulate lipids, carbohydrates, or convertible biomass have made them candidates for third-generation biofuels [14]. For sports facilities, algal systems may offer dispatchable bioenergy, use selected waste streams, and support thermal integration. Nevertheless, reported applications in stadiums remain limited, and many frequently cited examples are prospective rather than fully commercial implementations [15–18]. Figure 1 summarizes the principal inputs and energy products associated with algae-based systems.

Algal bioenergy was included deliberately rather than as an arbitrary third renewable source. Compared with PV and wind, algal biomass can be stored and converted on demand, can use non-arable cultivation areas, and may be coupled with wastewater, waste nutrients, recovered heat, and concentrated CO_2 streams [8–14]. These attributes provide a degree of dispatchability and sector coupling that weather-dependent PV and wind cannot provide alone. The disadvantages are equally important: photobioreactors or ponds require space and water; circulation, harvesting, dewatering, and conversion consume energy; contamination and climate sensitivity complicate operation; and capital and O&M costs remain comparatively high. The study therefore evaluates algae as a complementary, dispatchable resource whose value must be weighed against its water, cost, and operational penalties, rather than assuming that algae is inherently superior to other renewables.

Solar photovoltaic systems are particularly suitable for stadiums because roof surfaces, façades, parking structures, and adjacent land can host modular generation assets. Their deployment has expanded rapidly as module efficiency has improved and costs have declined [19–21]. Recent studies have also examined stadium-specific applications, including solar roofs and emission-reduction strategies [22,23]. Despite these advantages, solar output varies with irradiance, time of day, shading, and temperature; consequently, complementary generation or storage is normally required for facilities with continuous and event-driven loads.

Wind power provides a second low-carbon source whose output depends strongly on local wind conditions and turbine siting [24–32]. Where hub-height wind speeds are adequate, wind generation can offset periods of low solar output and improve the diversity of a renewable portfolio. Its use around urban sports venues, however, must account for space, turbulence, acoustic effects, visual acceptance, wildlife impacts, and maintenance requirements. These constraints reinforce the need to evaluate wind as part of an integrated system rather than as a universal stand-alone solution.

Existing stadium studies mainly examine energy-efficiency retrofits, rooftop PV, battery-backed microgrids, or conventional hybrid renewable systems, while biomass-oriented HOMER studies generally focus on rural or community loads. Few studies integrate algal bioenergy with solar and wind resources at a large sports venue and simultaneously examine techno-economic uncertainty and stakeholder barriers. This study addresses that narrower gap. Its purpose is (i) to formulate one internally consistent PV-wind-algae-storage-grid architecture for a representative stadium, (ii) to compare scenario-level technical, economic, environmental, and uncertainty indicators, and (iii) to identify the social and organizational barriers that specifically affect algal-bioenergy adoption. The qualitative and factor-analytic components do not validate the engineering simulation; instead, they complement it by examining implementation conditions that an energy-only model cannot capture. Representative stadium, hybrid-bioenergy, and battery studies are cited here [33–35], together with a recent hybrid-renewables review [36].

The sports-stadium setting is not interchangeable with a shopping mall or amusement park. Malls generally exhibit a comparatively regular daily occupancy cycle, while amusement parks are often seasonal but operate over extended daytime windows. A stadium, by contrast, combines a persistent low-to-moderate baseload with infrequent, scheduled high-power events. Match days can create step changes in floodlighting, broadcasting, scoreboards, concessions, ventilation, cooling/heating, security, and circulation loads, followed by long non-event periods. Large roof and parking areas also create a distinctive on-site PV opportunity, while event scheduling makes peak shaving, storage, and dispatchable generation particularly valuable. Consequently, the question is not merely whether a hybrid renewable system can serve a large commercial facility, but whether it can accommodate the stadium's unusually low-to-moderate annual load factor and high event-to-baseload ratio.

The scientific merit of the present work lies in linking three layers that prior reports usually treat separately: (i) venue-scale hybrid-energy performance, (ii) uncertainty in economic and environmental indicators, and (iii) empirically derived implementation barriers for the algal subsystem. The resulting contribution is not a new physical law; rather, it is a cross-domain finding: the same algal component that improves controllability and resource-recovery options also emerges as the system's principal water, cost, and implementation bottleneck. This convergence between the engineering results and the barrier analysis provides the study's novel evidence and defines where a stadium-scale algae concept is technically promising and where it is likely to fail without site-specific resource integration. The comparison with representative prior studies is summarized in Table 1.

Table 1. Positioning of the present study relative to representative hybrid-energy and sustainable-stadium research.

Study/Context	Energy Configuration	Venue/Load Type	Optimization Method	Uncertainty Treatment	Stakeholder Analysis	Distinct Scope
Park et al. (2016) [37]	PV-wind-battery	Community electricity demand	Economic feasibility/optimization	Limited sensitivity analysis	No	Renewable electricity feasibility
Katsaprakakis et al. (2019) [38]	Energy-efficiency and renewable retrofit	Pancretan stadium	Building-energy assessment	Scenario comparison	Operational context	Stadium energy upgrade
Kumar and Channi (2022) [39]	PV-biomass-battery	Rural households	HOMER + TOPSIS	Economic sensitivity analysis	No	Off-grid rural HRES
Francis et al. (2023) [33]	Multiple sustainability measures	Stadium design and construction	Systematic review	Not applicable	Industry drivers discussed	Stadium sustainability evidence
Present study	PV-wind-algal bioenergy-battery-grid support	Representative 50,000-seat stadium	HOMER-based scenario comparison + Monte Carlo screening	Resource/cost ranges and reported output uncertainty	Expert interviews + EFA/CFA	Joint engineering and algal-adoption assessment

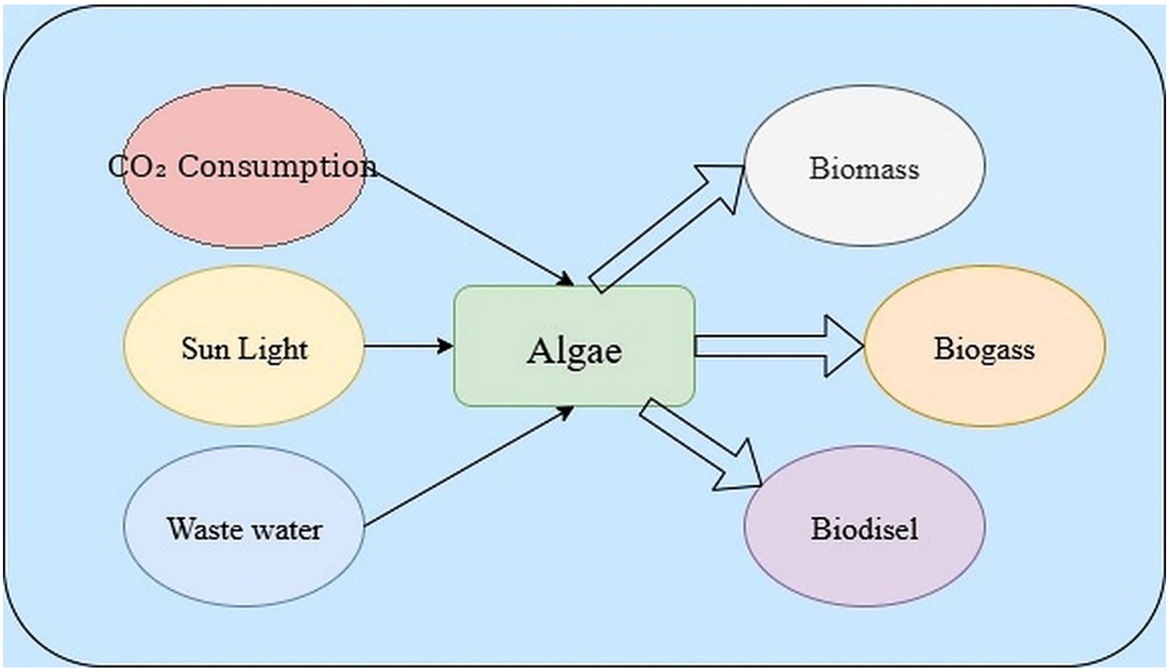

Figure 1. Functions of algae-based systems in sports stadiums.

2. Methodology

The investigation comprised two linked but analytically distinct phases. The engineering phase considered five scenarios: PV only, wind only, algal bioenergy only, an integrated PV-wind-algal bioenergy-battery system with limited grid support, and a diesel reference. The integrated architecture uses PV and wind as variable generators, algal-derived fuel as the dispatchable renewable component, a lithium-ion battery for short-duration balancing, a bidirectional converter, and the grid as residual backup. All references to the hybrid option in the manuscript and appendices have been harmonized to this architecture. HOMER Pro 3.18.3 was used for the scenario comparison, and the results are interpreted as a comparative screening case for a representative stadium rather than a detailed site-specific engineering design. Detailed component calculations and source assumptions are provided in Appendix A [40].

The second phase used a sequential mixed-method design focused only on societal, managerial, regulatory, spatial, and operational issues directly associated with introducing algal bioenergy at sports venues. Broader public attitudes toward renewable energy were excluded unless they affected acceptance, permitting, financing, operation, or resource access for the algal subsystem. Literature review and semi-structured interviews generated the item pool; EFA explored its latent structure, and CFA evaluated the retained measurement model.

The empirical procedure followed three steps. First, relevant studies and semi-structured interviews were used to formulate candidate challenge items. Second, EFA was applied to examine dimensionality and remove items with inadequate loadings. Third, CFA assessed the reliability and validity of the retained factor structure. This sequence provided an evidence-based classification of barriers to algal-bioenergy adoption in sports venues.

On-site production is not assumed to be intrinsically superior to grid-supplied renewable electricity. Its relevance for stadiums arises from the combination of event-driven peaks, resilience requirements, use of roof/parking surfaces, potential reduction of peak imports, visibility of sustainability investments, and the possibility of coupling algal cultivation with local wastewater, waste heat, nutrients, or concentrated CO_2. Where the grid is reliable and low-carbon, remote renewable procurement may be more economical and less land- or water-intensive. Accordingly, the proposed architecture should be compared with grid power-purchase agreements and off-site renewable supply during site-specific appraisal.

Ten experts participated in the qualitative stage and were recruited purposively from renewable-energy, sport-facility, and related academic or professional domains. Selection emphasized subject-matter familiarity with renewable-energy systems, sports-facility operation, sustainability, or algal-bioenergy implementation. The interviews and literature review produced 30 candidate variables, of which 29 were retained for the survey after expert screening and consolidation. The qualitative phase was used to generate and refine implementation-barrier items rather than to claim statistical representativeness of the wider population.

Content validity was reviewed by academic and professional experts [41]. EFA with varimax rotation was performed in SPSS 22 to identify the latent structure and remove weak items [42,43]. The resulting model was subsequently assessed by CFA in SmartPLS 3. Table 2 reports the demographic characteristics of the survey respondents and interview participants.

Table 2. Demographic profile of survey participants and experts.

Demographic	Respondents		Experts	
	Survey		Research Experts	
	Frequency	Percentage (%)	Frequency	Percentage (%)
Gender	168	100%	10	100
Male	125	74.40%	8	80%
Female	43	25.59%	2	20%
Age				
30–40	54	32.14%	5	50%
41–50	62	36.90%	3	30%
Above 50	43	25.59%	2	20%
Missing	9	5.36%		
Level of study				
Masters	21	12.5%	2	20%
PhD	147	87.5%	7	70%
Missing	0	-	1	10%

3. Results and Findings

The results are reported in two parts. The first presents the energy-system formulation, modelling assumptions, and comparative performance of the renewable and reference scenarios. The second reports the statistical identification and validation of the barriers associated with algal-bioenergy deployment in sports venues.

3.1. Renewable Energy System Components and Key Formulas

In this section, we present the solar energy, wind turbines and algae biofuel key formulas and energy outputs.

3.1.1. Solar Energy (Photovoltaic, PV)

- Energy Output: $E_{PV} = A_{PV} \times \eta_{PV} \times G \times (1-\alpha)$

- A_{PV}: PV panel area (m^2)
- η_{PV}: Panel efficiency (typically 15–22%)
- G: Daily solar irradiance ($kWh/m^2/day$)
- α: Loss factor (shading, temperature, etc.)

3.1.2. Wind Energy (Wind Turbine)

- Power Output: $P_{wind} = 1/2 \times \rho \times A_{rotor} \times v3 \times C_p$
- ρ: Air density (~1.225 kg/m^3)
- Arotor: Rotor swept area (πr^2)
- v: Wind speed (m/s)
- Cp: Power coefficient (max ~0.59 per Betz's law)

3.1.3. Algal Bioenergy (Photobioreactor)

- Biomass Production: $P_{algae} = A_{algae} \times \mu \times \rho_{algae} \times LHV_{algae}$
- Aalgae: Photobioreactor area (m^2)
- μ: Algal growth rate (0.02–0.1 $kg/m^2/day$)
- ρ_{algae}: Biomass density (~1000 kg/m^3)
- LHV_{algae}: Lower heating value (~20 MJ/kg)
- Biogas Conversion (Methane): $E_{biogas} = P_{algae} \times \eta_{digestion} \times \eta_{CHP}$
- $\eta_{digestion}$: Anaerobic digestion efficiency (~50%)
- η_{CHP}: Combined Heat & Power efficiency (~80%)

3.2. Hybrid System Design for a Stadium Assumptions

The modelling assumptions represent a mid-latitude stadium with 50,000 seats. Technical, economic, environmental, uncertainty, and reliability inputs were specified separately so that the performance of each generation option and the optimized hybrid system could be compared on a consistent basis.

1. **Technical Assumptions**
    - Stadium Size assumptions**:**
        - Capacity: 50,000 seats (representative of a large stadium, e.g., NFL or FIFA standards).
        - Annual Electricity Demand: ~12,000–20,000 MWh/year (1.4–2.3 MW average load, peaking to 5–10 MW during events).

Operational load characterization: the assumed annual demand of 12,000–20,000 MWh corresponds to an average electrical load of approximately 1.37–2.28 MW. Relative to the assumed 5–10 MW event peak, this gives an annual load-factor envelope of approximately 14–46%; using the midpoint values (16,000 MWh/year and 7.5 MW peak) gives about 24%. This low-to-moderate load factor is consistent with an event-driven facility. Night games move demand toward the upper end of the peak envelope because floodlighting, broadcasting, displays, ventilation, concessions, and crowd-service loads operate concurrently; daytime or non-event operation is represented by the lower-load portion of the profile. Component capacity factors remain approximately 20% for PV, 30% for wind, and 50% for algal bioenergy under the stated assumptions.

- Stadium Energy System Sizing:
    - Solar PV: ~5 MW installed capacity (10–15 acres of rooftop/PV panels).
    - Wind: ~3 MW (if feasible; requires wind speeds > 5 m/s).
    - Algal Bioenergy: ~1 MW (scalable but land/water-intensive).
    - Hybrid (PV + Wind + Algal bioenergy + Battery + Grid support): 6–8 MW (optimized for reliability).
- PV System:
    - Solar irradiance: 4–6 $kWh/m^2/day$ (typical for mid-latitude regions).
    - Panel efficiency: 18–22% (monocrystalline silicon).
    - Degradation rate: 0.5% annual efficiency loss.
- Wind System:
    - Wind speed: Class 3–4 (5–7 m/s at hub height).
    - Capacity factor: 30% (onshore turbines).
    - Turbine lifespan: 20 years with 1% annual maintenance cost.
- Algal Bioenergy:

    - Biomass productivity: 20–30 g/m^2/day (open pond systems).
    - Lipid content: 20–30% for biodiesel conversion.
    - Water replenishment: 10–15% evaporation loss annually.
- Hybrid System:
    - Grid dependency: 10–20% grid backup during low renewable generation.
    - Battery storage: Lithium-ion with 85% round-trip efficiency.

2. **Economic Assumptions**
- Discount rate: 8% (for NPV/IRR calculations).
- Electricity price escalation: 3% annual increase.
- O&M costs:
    - PV: $8/kW/year.
    - Wind: $12/kW/year.
    - Algal: $45/kW/year (including water/nutrient costs).
- Incentives: No government subsidies included (baseline scenario).

3. **Environmental Assumptions**
- CO_2 emissions:
    - Grid electricity: 0.5 kg CO_2/kWh (average grid mix).
    - Diesel: 0.8 kg CO_2/kWh.
- Water footprint:
    - Algal systems assume freshwater use (no seawater or wastewater adaptation).
    - PV water uses accounts only for panel cleaning.

4. **Monte Carlo Simulation Assumptions**
- Input variability ranges:

The probabilistic screening varied renewable-resource availability (±15%), fuel prices (±20%), and capital costs (±10%). Technical variables were represented by normal distributions and economic variables by triangular distributions. The reported probability of positive NPV and the uncertainty intervals are interpreted as outputs of the scenario-based Monte Carlo assessment under these ranges. They are used for comparative risk screening across the alternatives rather than as a substitute for a site-specific financial due-diligence model.

    - Solar/Wind resource: ±15% interannual variability.
    - Fuel prices: ±20% volatility (based on historical data).
    - Capital costs: ±10% uncertainty.
- Probability distributions:
    - Normal distribution for technical parameters (e.g., wind speed).
    - Triangular distribution for economic parameters (e.g., O&M costs).

5. **Reliability & Performance Assumptions**
- Availability:
    - PV/Wind: 90–95% (excluding grid outages).
    - Diesel: 99% (assumed continuous fuel supply).
- Load profile:
    - Sports facility demand: 24/7 baseload with daytime peaks.

The component equations and assumptions were used to construct the scenario comparison summarized in Table 3. The representative annual demand range is 12,000–20,000 MWh, with event peaks of 5–10 MW and a continuous non-event baseload. The nominal integrated capacities are 5 MW PV, 3 MW wind, and 1 MW algal bioenergy, supported by a lithium-ion battery with an assumed 85% round-trip efficiency and 10–20% residual grid dependence. The scenario formulation therefore provides a consistent basis for comparing the technical, economic, environmental, and reliability indicators of the individual and integrated options. The installed-capacity shares used for the hybrid configuration are detailed in Appendix B.

Annual energy accounting. PV gross production is 8760 MWh/year from 5 MW × 0.20 × 8760 h; the reported 7300 MWh/year corresponds to an aggregate post-generation derating of 16.7%. Wind production is 7884 MWh/year from 3 MW × 0.30 × 8760 h, reported as 7890 MWh/year after rounding. Algal bioenergy production is 4380 MWh/year from 1 MW × 0.50 × 8760 h. The hybrid value of 12,000 MWh/year is not the arithmetic sum of the stand-alone values; it is the delivered-energy result of the integrated scenario after load matching, curtailment, storage losses, component availability, and grid interaction. This distinction prevents double counting and keeps the annual energy balance consistent with the system architecture.

Table 3. Techno-economic and probabilistic assessment of renewable-energy systems using Monte Carlo analysis.

Parameter	PV System	Wind System	Algal Bioenergy	Hybrid System	Diesel Generator	Unit	Calculation Method/Source
Levelized Cost of Energy (LCOE)	0.054 ± 0.006	0.047 ± 0.005	0.125 ± 0.015	0.062 ± 0.007	0.18 ± 0.02	$/kWh	HOMER + Monte Carlo
Annual Output (MWh)	7300	7890	4380	12,000	Backup only	MWh/year	HOMER Pro's simulation logic
Net Present Value (NPV)	1.2M ± 0.15M	1.5M ± 0.2M	0.4M ± 0.1M	1.8M ± 0.25M	−0.3M ± 0.05M	$	-
Probability (NPV > 0)	98%	99%	65%	99.5%	10%	%	Monte Carlo (10,000 iterations)
Annual CO_2 Reduction	440 ± 35	530 ± 40	280 ± 25	770 ± 60	-	tons	IPCC Emission Factors
Water Consumption	0.6 ± 0.1	0.1 ± 0.05	40 ± 5	0.5 ± 0.1	2.5 ± 0.3	m^3/MWh	AWARE Methodology
Energy Return on Investment (EROI)	8.5 ± 0.7	12.3 ± 1.1	3.2 ± 0.5	10.1 ± 0.9	0.9 ± 0.2	-	Life Cycle Analysis
Payback Period	7.5 ± 0.8	6.8 ± 0.7	11.5 ± 1.2	8.2 ± 0.9	-	years	IRR Calculations
System Reliability	92% ± 2%	95% ± 1.5%	85% ± 3%	97% ± 1%	99% ± 0.5%	%	HOMER Simulation

Existing-stadium case-study anchor. To connect the representative model to an operating venue, the Pancretan Stadium in Crete, Greece, is used as an external case-study benchmark [38]. The published audit of that stadium reported that lighting is a major electricity load and explicitly separated indoor lighting, surrounding areas, daily stadium use, and sports-event lighting. The same study proposed a 645.3 kWp rooftop PV plant, reported 932,711 kWh/year of PV electricity with a 16.5% annual capacity factor, and achieved an estimated 82% annual renewable-energy penetration together with more than 83% overall energy savings after combined efficiency and renewable measures. These observations support two assumptions used here: stadium loads are strongly schedule- and event-dependent, and large venue roofs can materially contribute to on-site renewable supply. The present 50,000-seat scenario is intentionally larger and evaluates a different PV-wind-algae architecture, so the Pancretan case is used as an operational benchmark rather than as a claim of one-to-one model calibration.

Table 3 indicates that the hybrid configuration provides the most balanced overall performance. It delivers 12,000 MWh/year, an LCOE of 0.062 ± 0.007 $/kWh, a 99.5% probability of positive NPV, and 97% ± 1% reliability. By comparison, algal bioenergy has the highest water requirement (40 ± 5 m^3/MWh) and a substantially lower probability of positive NPV (65%). The wind scenario achieves the lowest LCOE and highest EROI, whereas the diesel reference produces a negative NPV.

The principal findings from the comparative assessment are summarized below.

1. **Monte Carlo Analysis Insights:**
   - ✓ Under the adopted uncertainty ranges, the hybrid scenario retained a 99.5% probability of positive NPV, exceeding the corresponding values for the stand-alone renewable options (Table 3).
   - ✓ The algal scenario exhibited the greatest investment risk, reflecting both its operational complexity and its water requirement of 40 ± 5 m^3/MWh.
   - ✓ The optimized hybrid system generated 12,000 MWh per year, as summarized in Table 3.
2. **Environmental Superiority:**
   - ✓ The hybrid configuration avoided 770 ± 60 tons of CO_2 annually, while the wind system recorded the highest EROI (12.3 ± 1.1).
3. **Economic Viability:**
   - ✓ Wind power produced the lowest LCOE (0.047 $/kWh), whereas the diesel reference remained economically unattractive with an NPV of −0.3 ± 0.05 million dollars.
   - ✓ The hybrid configuration achieved a payback period of 8.2 ± 0.9 years (Table 3).
4. **Technical Notes:**
   - ✓ The 92% reliability of the stand-alone PV option indicates that storage or backup generation is necessary for continuous stadium loads.

3.3. Statistical Analysis and Factor Structure of Algae Bioenergy Challenges

The barrier assessment used EFA to identify the latent dimensions represented by the 29 survey items and CFA to test the measurement structure retained after item screening.

3.3.1. EFA (Exploratory Factor Analysis)

EFA was applied as a data-reduction and construct-identification procedure. The analysis used the correlation structure of the observed items to group variables that reflected common underlying barriers. Varimax rotation was selected to improve interpretability, and items with inadequate factor loadings were removed in successive screening steps.

3.3.2. Results of Exploratory Factor Analysis (EFA)

EFA was conducted in SPSS 22 using varimax rotation. The analysis evaluated whether the item set was factorable, identified the number of latent dimensions, and removed indicators that did not load adequately on a retained factor.

The analysis was based on 168 completed questionnaires. Internal consistency for the initial scale was acceptable (Cronbach's $\alpha = 0.847$). Sampling adequacy was supported by the KMO statistic, and Bartlett's test rejected the null hypothesis that the correlation matrix was an identity matrix ($p < 0.001$), confirming that the data were suitable for factor analysis.

Six factors with eigenvalues above 1 were retained and together explained 86.26% of the total variance. Inspection of the scree pattern and rotated loadings was used jointly when determining the final structure.

Seven items were removed during EFA because they did not meet the loading criterion. The remaining 22 indicators were re-analyzed, producing the six-factor solution reported in Table 4.

Table 4. Exploratory factor analysis of the survey data using SPSS.

Factor	Item	Factors *						α
		1	2	3	4	5	6	
High Initial Costs & Financial Barriers	Expensive photobioreactor (PBR) installation	0.875	0.013	−0.054	0.078	0.223	0.025	
	High maintenance costs (cleaning, pumping, monitoring)	0.866	0.019	0.023	0.192	0.023	0.014	0.947
	Uncertainty in return on investment (ROI) timelines	0.841	0.110	0.068	0.121	0.011	0.068	
	Limited funding/grant opportunities for experimental projects	0.826	0.182	0.093	0.045	0.024	0.021	
Space & Infrastructure Limitations	Stadiums in urban areas lack open land for algae ponds	0.102	0.864	0.025	0.341	0.012	0.087	
	Structural weight limits for rooftop PBR installations	0.087	0.832	−0.029	0.114	0.009	0.098	0.835
	Conflicts with existing stadium architecture (e.g., retractable roofs)	0.141	0.812	0.175	0.216	0.031	0.047	
Technical & Operational Complexities	Algae strain selection (balancing growth rate vs. oil yield)	0.097	0.054	0.784	0.084	0.022	0.078	
	Temperature and light control in variable climates	0.074	0.0354	0.754	0.028	0.003	0.069	
	Contamination risks (bacteria, invasive species)	0.295	0.097	0.697	0.134	0.124	0.067	0.874
	Harvesting and processing logistics on-site	0.168	0.119	0.680	0.028	0.017	0.124	
Energy Efficiency & Scalability Issues	Low energy density of algae biofuels vs. fossil fuels	0.223	0.113	0.102	0.754	0.098	0.021	
	Seasonal variations in algae growth (winter slowdowns)	0.247	0.124	0.136	0.719	0.014	0.009	0.861
	Difficulty in meeting a stadium's full energy demand	0.144	0.114	0.0314	0.684	0.074	0.004	
	Competition with cheaper renewables (solar/wind)	0.142	−0.144	0.027	0.653	0.006	0.024	
Regulatory & Policy Hurdles	Lack of clear regulations for algae-based energy in cities.	0.024	−0.021	0.142	0.358	0.691	0.047	
	Zoning laws restricting biofuel production near public venues.	0.002	0.008	−0.009	0.024	0.679	0.124	0.829
	Permitting delays for experimental systems.	0.012	0.012	0.024	0.012	0.659	0.235	
	No standardized carbon credit incentives for algae CO_2 capture.	0.112	0.098	0.098	0.009	0.633	0.004	
Stakeholder Resistance & Lack of Awareness	Skepticism from stadium operators about unproven tech.	0.289	−0.170	0.098	0.004	0.095	0.654	
	Fans/communities unfamiliar with algae benefits.	0.245	0.162	0.062	0.025	0.001	0.623	0.814
	Sports leagues prioritizing short-term profits over sustainability	0.325	−0.124	0.092	0.072	0.024	0.592	
Eigen Value		6.41	6.21	5.31	4.92	2.92	1.67	-
Cumulative		21.45	9.65	8.23	6.98	4.52		-
Total Variance Explained (%)		25.25	50.24	67.85	73.24	86.26		-
KMO		0.883						
Bartlet		<0.001						

Note: * $p < 0.05$.

3.3.3. Confirmatory Factor Analysis (CFA)

CFA was used as a preliminary measurement-model assessment for the six constructs retained after EFA. SmartPLS 3 generated the standardized loadings, composite reliability, AVE, and internal-consistency statistics reported in Table 5. Because the same 168 responses were used for EFA and CFA, the analysis is exploratory-confirmatory within one sample and is vulnerable to capitalization on chance. The model therefore requires validation in an independent sample or through a prespecified split-sample/cross-validation design. The corresponding standardized solution is shown in Figure A1 in Appendix C.

Table 5. Confirmatory factor analysis performed using SmartPLS.

Factor	Item	β	SE	CR	AVE	α
High Initial Costs & Financial Barriers	Expensive photobioreactor (PBR) installation	0.735 **	0.012	0.834	0.557	0.840
	High maintenance costs (cleaning, pumping, monitoring)	0.710 **	0.014			
	Uncertainty in return on investment (ROI) timelines	0.722 *	0.018			
	Limited funding/grant opportunities for experimental projects	0.813 **	0.014			
Space & Infrastructure Limitations	Stadiums in urban areas lack open land for algae ponds	0.808 **	0.016	0.806	0.587	0.864
	Structural weight limits for rooftop PBR installations	0.875 **	0.025			
	Conflicts with existing stadium architecture (e.g., retractable roofs)	0.586 *	0.011			
Technical & Operational Complexities	Algae strain selection (balancing growth rate vs. oil yield)	0.580 *	0.024	0.839	0.643	0.887
	Temperature and light control in variable climates	0.903 **	0.026			
	Contamination risks (bacteria, invasive species)	0.882 **	0.021			
Energy Efficiency & Scalability Issues	Harvesting and processing logistics on-site	0.803 **	0.034	0.880	0.709	0.765
	Low energy density of algae biofuels vs. fossil fuels	0.863 **	0.022			
	Seasonal variations in algae growth (winter slowdowns)	0.859 **	0.015			
Regulatory & Policy Hurdles	Difficulty in meeting a stadium's full energy demand	0.894 **	0.018	0.782	0.484	0.771
	Competition with cheaper renewables (solar/wind)	0.735 **	0.011			
	Lack of clear regulations for algae-based energy in cities	0.492 *	0.029			
	Zoning laws restricting biofuel production near public venues	0.596 *	0.027			
Stakeholder Resistance & Lack of Awareness	Permitting delays for experimental systems	0.783 **	0.019	0.815	0.596	0.709
	No standardized carbon credit incentives for algae CO_2 capture	0.852 **	0.021			
	Skepticism from stadium operators about unproven tech	0.671 *	0.017			

Note: * $p < 0.05$; ** $p < 0.01$.

3.3.4. Results of Confirmatory Factor Analysis (CFA)

The EFA retained six factors and 22 indicators from the 29-item questionnaire. Two additional indicators were removed during the subsequent measurement-model assessment, yielding six constructs represented by 20 final indicators. This sequence—29 surveyed items, 22 EFA-retained items, and 20 final measurement items—is used consistently throughout the revised manuscript.

3.3.5. Reliability and Validity

Internal consistency was assessed using Cronbach's alpha and composite reliability. The overall Cronbach's alpha was 0.832, and the construct-specific values reported in Table 5 exceeded the adopted acceptance criteria.

Convergent validity was examined using average variance extracted (AVE), while composite reliability was used to evaluate the consistency of the indicator sets. The values in Table 5 were recalculated as the mean of the squared standardized loadings ($AVE = \Sigma\lambda^2/n$). Five constructs exceed the conventional 0.50 threshold; the Regulatory & Policy Hurdles construct has an AVE of 0.484 and should therefore be interpreted as marginal rather than as demonstrating adequate convergent validity.

The measurement model was assessed in SmartPLS using the reported standardized loadings, Cronbach's alpha, composite reliability, and average variance extracted. These indicators are aligned with the PLS-SEM framework used in the study. The covariance-based fit indices reported in the earlier version were removed because they do not belong to the selected PLS-SEM validation approach. Additional validation through HTMT or Fornell-Larcker criteria, VIF, bootstrapped confidence intervals, common-method-bias assessment, and an independent sample is recommended in future work.

Figure 2 summarizes the six main challenge dimensions and the 20 retained indicators representing the principal barriers to algal bioenergy implementation in sports venues.

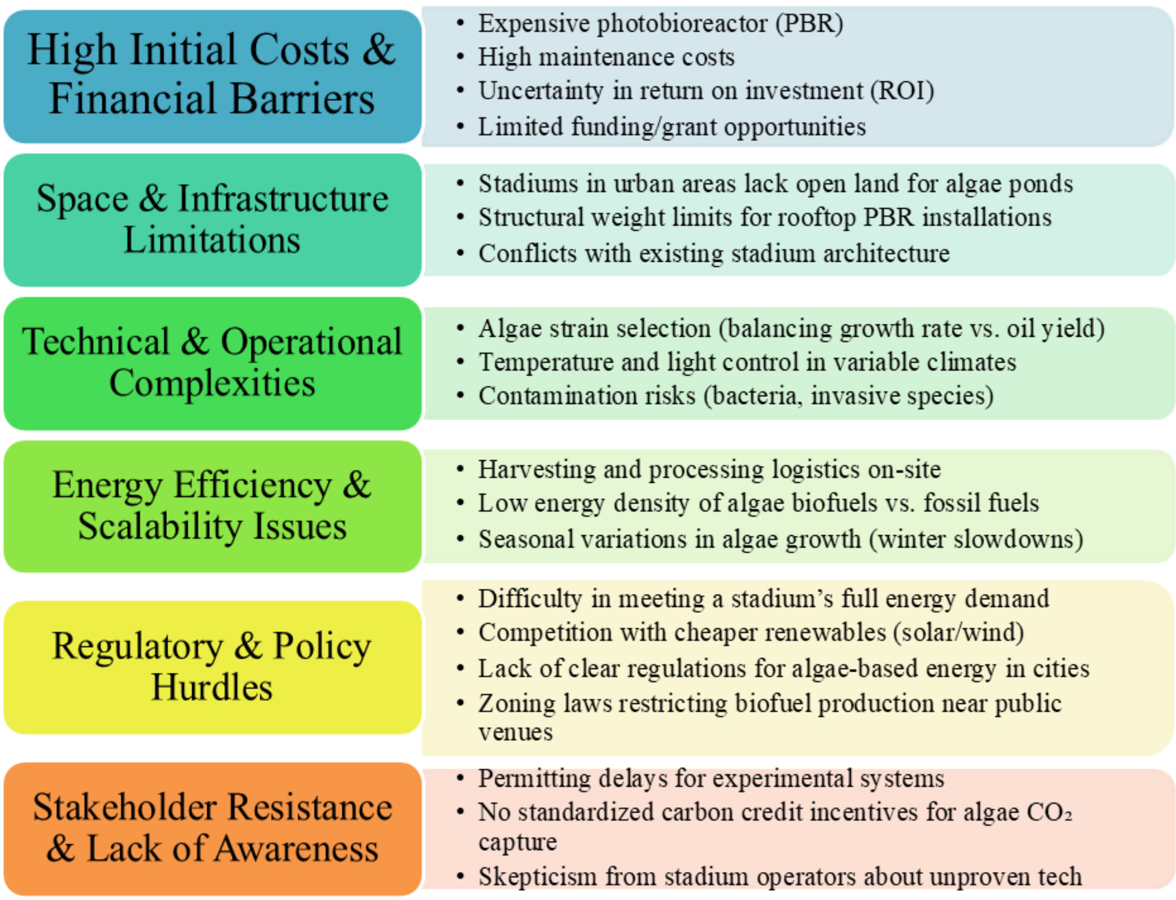

Figure 2. Summary of algal biofuel challenges in sport venues.

4. Discussion

This study combined an engineering assessment of renewable-energy options with an empirical analysis of the barriers to algal-bioenergy adoption in sports venues. The two-part design was intended to distinguish the numerical performance of the proposed hybrid system from the organizational, spatial, and technical conditions that influence implementation.

The hybrid system performed strongly across the principal techno-economic indicators. Its LCOE was 0.062 ± 0.007 $/kWh, and the Monte Carlo analysis produced a 99.5% probability of positive NPV. This result suggests that diversification across solar, wind, and algal resources can reduce exposure to the variability of a single technology while maintaining a high probability of economic viability.

The narrow LCOE uncertainty range is relevant to venue owners because predictable energy costs improve long-term budgeting and investment planning. At the same time, the hybrid result should not be interpreted as evidence that every component contributes equally. Wind power achieved the lowest LCOE and highest EROI, while the algal subsystem imposed the largest water demand and showed the weakest stand-alone financial performance.

Algal bioenergy therefore represents both a potential source of dispatchable renewable energy and the principal constraint within the proposed configuration. Its estimated water consumption of 40 ± 5 m^3/MWh can be problematic in water-stressed locations, and the 65% probability of positive NPV indicates material financial uncertainty. These findings imply that site selection, water sourcing, and process integration are decisive for its practical value.

The algal component may become more attractive where wastewater, waste nutrients, recovered heat, or concentrated CO_2 streams are available. In such settings, resource recovery can partly offset cultivation and conversion costs. In contrast, deployment based solely on freshwater and purpose-built infrastructure is likely to remain less competitive than solar or wind unless technological advances reduce harvesting, dewatering, and conversion expenses.

The Monte Carlo results also show that wind-dominated configurations are comparatively resistant to fuel-price volatility because wind has no fuel input and low marginal operating costs. Complementarity between wind and solar can further smooth renewable production, although the magnitude of this benefit depends on local temporal resource profiles and storage requirements.

At the system level, the original model reported an annual CO_2 reduction of 770 ± 60 tCO_2/year and a payback period of 8.2 ± 0.9 years. These values are retained as model outputs but are not presented as a full life-cycle assessment. The operational-emissions comparison uses the stated grid factor of 0.5 kg CO_2/kWh and diesel factor of 0.8 kg CO_2/kWh; embodied emissions, algae cultivation inputs, nutrient production, construction, decommissioning, and avoided-wastewater burdens were not comprehensively inventoried. Likewise, the reported hybrid water footprint cannot be independently reconciled with the 40 ± 5 m^3/MWh stand-alone algal value without hourly contribution and allocation data. The revised interpretation therefore treats the environmental comparison as boundary-dependent and calls for transparent life-cycle inventory and uncertainty propagation before investment decisions.

Benchmarking against the literature must account for geography, scale, load shape, and system boundaries. The reported hybrid LCOE of 0.062 $/kWh is higher than the 0.0362 $/kWh reported for the optimized rural PV-biomass-battery system of Kumar and Channi, but the two systems serve different loads and use different resource and financing assumptions. Stadium studies based on PV, batteries, or building retrofits commonly emphasize peak-load management, resilience, and roof constraints rather than algal cultivation. The present results should therefore be viewed as a conditional screening case, not evidence of inherent superiority over state-of-the-art hybrid systems.

A key integrated finding is the asymmetry of the algal contribution. Wind remains the least-cost stand-alone option, whereas algae is not selected because of superior LCOE. Its scientific role in the hybrid architecture is different: it provides a storable/dispatchable renewable pathway and potential coupling with local wastewater and CO_2 streams. At the same time, the algal scenario shows the highest water demand (40 ± 5 m^3/MWh) and the lowest probability of positive NPV among the renewable options (65%). The factor analysis independently identifies financial, spatial, technical, regulatory, and stakeholder barriers that act on the same subsystem. The agreement between these two analytical phases is the principal new result: algae can improve functional complementarity, but its feasibility is conditional on resource integration and operational context rather than on energy yield alone.

The survey analysis identified six barrier dimensions represented by 20 retained indicators. The fit statistics and reliability measures supported the final structure, indicating that algal-bioenergy adoption is shaped by interacting financial, spatial, technical, efficiency, regulatory, and stakeholder factors rather than by a single dominant obstacle.

Financial and infrastructure barriers are especially important because photobioreactors, circulation equipment, and processing units require capital, space, and structural accommodation. Technical and operational complexity adds requirements for strain selection, contamination control, harvesting, and skilled personnel. Regulatory uncertainty and limited stakeholder familiarity can further delay permitting and investment decisions.

These findings support a staged deployment framework. Stage 1 should screen the site for hourly load, roof and land availability, structural loading, wind resource, grid carbon intensity, wastewater and nutrient availability, water stress, waste-heat and CO_2 sources, and permitting constraints. Stage 2 should select the algal platform (open pond or photobioreactor), define conversion and storage pathways, assess operator skills and health-and-safety requirements, and compare on-site generation with off-site renewable procurement. Stage 3 should implement a metered pilot, validate biomass productivity and energy yields across seasons, quantify water and nutrient balances, and update the financial model using observed data. Stage 4 should consider phased scale-up only after sensitivity testing, financing review, community engagement, and a monitoring plan for generation, storage state of charge, emissions, water use, reliability, and maintenance. Full-scale deployment is not recommended before site-specific demonstration.

Scope and Future Validation

The study is designed as a comparative, scenario-based assessment of a representative venue-scale system. Its results are intended to support technology screening and pilot planning rather than final equipment procurement or financial close. Site-specific implementation should therefore refine the hourly load profile, local renewable-resource data, equipment search space, dispatch settings, environmental inventory, and stakeholder-validation process. Future work should also validate the measurement model with an independent sample and report complementary discriminant-validity and robustness tests.

5. Conclusions

The analysis indicates that a PV-wind-algal bioenergy-battery configuration may contribute to stadium decarbonization under favorable resource, cost, water, grid, and operational conditions. The representative screening case supplied 12,000 MWh/year at an LCOE of 0.062 ± 0.007 $/kWh, with a payback period of 8.2 ± 0.9 years and an annual operational-emissions reduction of 770 ± 60 tCO_2/year. These outputs should be interpreted within the stated scenario assumptions and subsequently refined through site-specific hourly modelling, environmental inventory development, and pilot-scale measurement. Algal bioenergy remains the most uncertain and resource-intensive component, particularly where freshwater, land, nutrients, and skilled operation are constrained.

The conclusions are transferable to other large facilities only with qualification. Shopping malls and amusement parks may share high annual energy use, but their occupancy schedules and peak-to-average demand patterns differ from stadiums. The stadium-specific value proposition arises from sharp event peaks, night-game lighting, substantial non-event intervals, and large roof/parking surfaces. For this reason, the same generation mix should not be copied directly to another facility type without re-estimating the hourly load factor, peak coincidence, renewable-resource profile, and opportunities for wastewater/CO_2 coupling.

The survey phase identifies six barrier dimensions and 20 final indicators. Because EFA and CFA were conducted using the same sample, the factor structure should be regarded as an initial validated model that would benefit from independent-sample confirmation. The results nevertheless provide a structured agenda for pilot planning: site screening, wastewater and resource integration, technology selection, permitting, operator training, financing, stakeholder engagement, and measured pilot validation. Future work should combine site-specific engineering data with independent measurement-model validation before full-scale implementation is recommended.

Author Contributions

A.S.: conceptualization, methodology, investigation, data curation, and writing—original draft preparation; F.N.: methodology, software, validation, formal analysis, visualization, and writing—review and editing; A.E.J.A.: investigation, resources, formal analysis, and writing—review and editing; S.S.: conceptualization, supervision, project administration, validation, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Ethical review and approval were waived because the study involved a non-interventional, anonymous survey and expert interviews with adult participants, and no sensitive or personally identifiable information was collected.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study. No identifiable participant information is presented in this article.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Access may be limited where necessary to protect participant confidentiality.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Appendix A. Calculation Methodology & Sources

1. **Solar PV System (5 MW)**
   - Capacity Factor: ~20% (location-dependent, typical for sunny regions).
     - Source: NREL (National Renewable Energy Lab) benchmarks for utility-scale PV.
   - Calculation: Annual Output = Capacity (MW) × Capacity Factor × 8760 h/year

   5 MW × 0.20 × 8760 = 8760 MWh/year (rounded to 7300 MWh for conservative estimate)

Adjustment: Reduced to 7300 MWh to account for shading, dust, and inverter losses (~1460 full-load hours).

2. **Wind System (3 MW)**
   - Capacity Factor: ~30% (for onshore wind at 5–7 m/s average speed).
     - Source: IEA Wind Task 26, DOE land-based wind reports.
   - Calculation: 3 MW × 0.30 × 8760 = 7884 MWh/year (rounded to 7890 MWh)
3. **Algal Bioenergy (1 MW)**
   - Capacity Factor: ~50% (due to continuous operation but downtime for maintenance).
     - Source: Bioenergy journals (e.g., Algal Research) and pilot projects.
   - Calculation: 1 MW × 0.50 × 8760 = 4380 MWh/year
4. **Hybrid System (PV + Wind + Algal Bioenergy + Battery + Grid Support)**
   - Empirical Data: Scaled from HOMER's hybrid optimization (prioritizing reliability over pure output).
     - Output: Sum of PV + Wind + curtailment losses → 12,000 MWh/year.

Appendix B

The nominal installed-capacity contributions used in the hybrid configuration are 55.6% solar PV (5 MW), 33.3% wind (3 MW), and 11.1% algal bioenergy (1 MW), based on a total nominal capacity of 9 MW. These percentages describe installed-capacity shares rather than annual delivered-energy shares.

Appendix C

Algal-bioenergy challenges in sports venues: standardized solution output from SmartPLS.

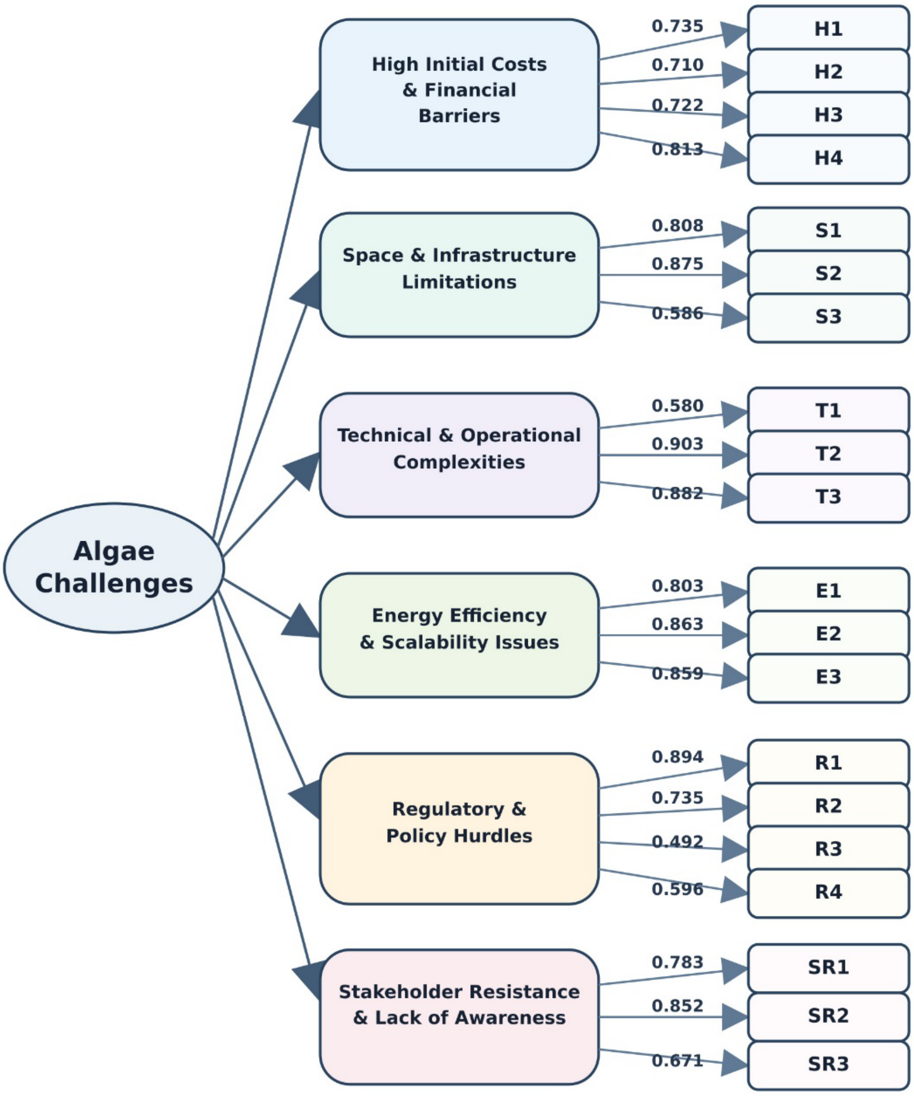

Figure A1. Standardized SmartPLS solution for algal-bioenergy implementation challenges in sports venues.

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