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Assessing Environmental Sustainability of Sport Mega-Events: A State-Pressure-Impact-Response Framework with Application to Super Bowl and Olympics

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Abstract. Sport mega-events generate substantial economic benefits but impose significant environmental pressures on host cities. This study develops a comprehensive State-Pressure-Impact-Response (SPIR) framework to quantitatively assess environmental sustainability across carbon, water, waste, and energy dimensions. The model integrates a city's baseline environmental capacity (State) with event-driven pressures (on-site and of-site) through a nonlinear logistic response function, yielding a Sustainable Event Impact Score (SEIS). Nine weighted indicators are determined via Analytic Hierarchy Process (AHP), emphasizing grid carbon emissions and spectator travel as dominant factors. Applied to 22 potential Super Bowl host cities, Indianapo- lis emerges as optimal (SEIS = 0.1788), followed by Minneapolis and Pittsburgh. Model exten- sion to Summer Olympics accounts for multi-venue configurations and extended event duration through temporal integration; Toronto (SEIS = 0.17) outperforms Singapore and Madrid due to cleaner energy infrastructure. Sensitivity analysis confirms robustness to parameter variations except on-site/of-site pressure weighting. An economic externality optimization framework demonstrates integration of environmental costs into venue selection. Results provide decision support for sustainable mega-event planning.

Keywords: Sport Mega-Events; Environmental Sustainability; SPIR Model; Analytic Hierarchy Process; Super Bowl; Olympic Games; Venue Selection

1. Introduction

Sport mega-events such as the Super Bowl and Olympic Games attract millions of spectators globally, generating substantial economic activity but imposing considerable environmental stress on host cities. The Super Bowl, as the National Football League's annual championship, assembles over 70,000 attendees in a single location, intensifying carbon emissions, waste generation, and resource consumption [1]. Despite economic prioritization in venue selection, environmental externalities—including air pollution spikes during Super Bowl Sunday—demand systematic quantification [2].

Current sustainability evaluations often lack comprehensive frameworks integrating both baseline urban environmental capacity and event-specific pressures. While individual impact assessments exist for waste management or energy consumption [5], holistic models accounting for multi-dimensional environmental carrying capacity remain underexplored. This study addresses this gap by developing the SPIR framework, which operationalizes ecological synergy theory through nonlinear stress-capacity relationships [6].

Our contributions include: (1) a structured SPIR model quantifying nine environmental indicators across State and Pressure dimensions; (2) AHP-based weighting reflecting relative importance of carbon intensity, water risk, and waste diversion; (3) application to 22 U.S. cities for Super Bowl 2029 venue selection; (4) model extension to multi-venue, multi-day Olympics with temporal integration; and (5) economic externality optimization integrating environmental costs into decision frameworks.

2. Methodology

2.1. The SPIR Framework

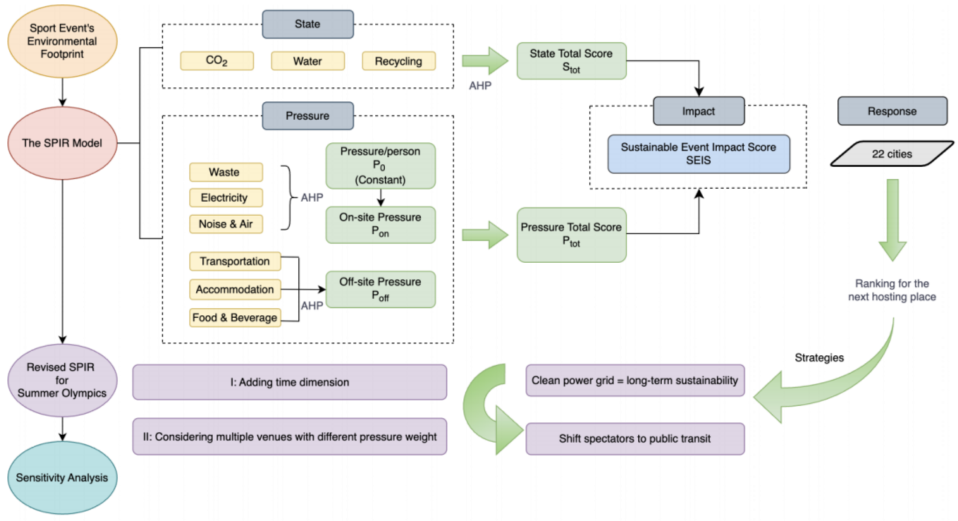

Figure 1: Conceptual structure of the SPIR framework. Environmental sustainability evaluation pro- ceeds through four chronological stages: State (baseline capacity), Pressure (event-driven impacts), Impact (nonlinear response), and Response (policy interventions).

The SPIR framework (Figure 1) divides sustainability assessment into four stages:

State (S): Baseline environmental carrying capacity before event hosting, reflecting self-regulation ability and vulnerability to sudden pressure loads. Three indicators quantify State: Grid Carbon Emission Rate (E_g, lb/MWh), Overall Water Risk Index (W_r, scale 0–5), and Recycling Rate (R_c, %). State score:

$$S_{tot} = \sum_{i=1}^{3} w_i S_i \quad (1)$$

Where w_i are AHP-derived weights.

Pressure (P): Event-induced environmental loads, bifurcated into on-site and of-site compo- nents. On-site pressure (P_{on}) encompasses stadium operations: Event Waste Generation (W_e, ton), Venue Electricity Consumption (E_v, kWh), and Noise & Air Disturbance Index (N_i, normalized 0–1). Of-site pressure (P_{off}) captures spectator impacts: Travel Emissions (P_t, t CO_2 e), Accommodation Carbon Footprint (E_h, MtCO_2e), and Food & Beverage Service Density (F_r, establishments/10,000 residents). Individual pressure scores follow Eq. (1) structure; total pressure employs geometric aggregation to prevent compensatory efects:

$$P_{tot} = P_{on}^{\alpha} \cdot P_{off}^{1-\alpha} \quad (2)$$

Where α balances on-site/of-site importance (baseline α = 0.5).

Impact (I): Nonlinear environmental response quantified via Sustainable Event Impact Score (SEIS). The stress ratio ($x = P_{tot}/S_{tot}$) measures pressure relative to capacity. A logistic function models impact:

$$\mathrm{SEIS} = \frac{1}{1 + e^{-k(x-1)}} \tag{3}$$

Where k controls response steepness (baseline k = 2). Lower SEIS indicates higher sustainability. The logistic form reflects ecological synergy theory: impacts grow slowly under low stress, accelerate near capacity thresholds, and saturate at extreme stress [6].

Response: Policy interventions alter State or Pressure components, modifying SEIS trajectories. Future predictions employ diferential equations; economic optimization integrates environmental costs as negative externalities.

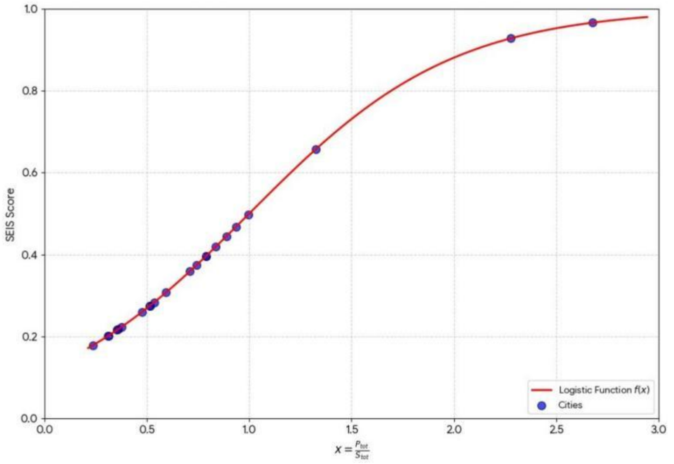

Figure 2: Logistic response function for SEIS. Environmental impact grows nonlinearly with stress ratio (P_{tot}/S_{tot}), reflecting threshold dynamics observed in ecosystem responses.

2.2. Indicator Selection and Quantification

Nine indicators (Table 1) were selected to comprehensively represent environmental dimensions:

Table 1: Environmental Indicators in the SPIR Model

Indicator	Symbol	Unit
State		
Grid Carbon Emission Rate	E_g	lb/MWh
Overall Water Risk	W_r	Index (0–5)
Recycling Rate	R_c	%
Pressure (On-site)		
Event Waste Generation	W_e	ton
Venue Electricity Consumption	E_v	kWh
Noise & Air Disturbance	N_i	Normalized (0–1)
Pressure (Of-site)		
Spectator Travel Emissions	P_t	t CO_2e
Accommodation Footprint	E_h	$MtCO_2e$
Food & Beverage Density	F_r	per 10,000 residents

Grid Carbon Emission Rate (E_g): State-level average CO_2 emissions per electricity unit, reflecting energy infrastructure sustainability [7].

Overall Water Risk (W_r): Composite index aggregating drought risk, untreated wastewater, and access to improved drinking water [8].

Recycling Rate (R_c): Municipal solid waste diversion percentage [9].

Event Waste Generation (W_e): Net stadium waste after subtracting recyclables, calculated from Super Bowl LIX (New Orleans) baseline data [10].

Venue Electricity Consumption (E_v): Stadium operational energy for lighting, broadcasting, and HVAC during event period [11].

Noise & Air Disturbance (N_i): Composite index integrating auditory and atmospheric pollution:

$$N_i = 0.5N_{noise} + 0.5N_{air} \tag{4}$$

Where $N_{noise} = (10^{\Delta L/10} - 1)/(10^{3/10} - 1)$ models logarithmic sound energy increase (ΔL = 1.5–3 dB during Super Bowl [12]), and $N_{air} = \min(1, 0.003A/300)$ reflects AQI degradation per 10,000 spectators (A) [13].

Spectator Travel Emissions **(P_t):** Total GHG from non-local attendee transportation, esti- mated via modal split data (air/car/coach), average distances, and emission factors:

$$P_t = N_{nl} \sum_m s_m \cdot d_m \cdot \frac{EF_m}{1000} \tag{5}$$

Where N_{nl} = non-local attendees, s_m = mode share, d_m = distance, EF_m = emission factor [15].

Accommodation Footprint (E_h): Hotel-related emissions calculated from estimated room- nights. Assuming 60% attendees travel overnight, 60% use hotels, and 2 persons/room: Rooms = 0.18S (where S = total attendance). Carbon footprint obtained via Greenview Hotel Footprint Calculator [16].

Food & Beverage Density (F_r): Establishments per 10,000 residents, inversely representing service strain capacity [18].

2.3. Analytic Hierarchy Process for Weighting

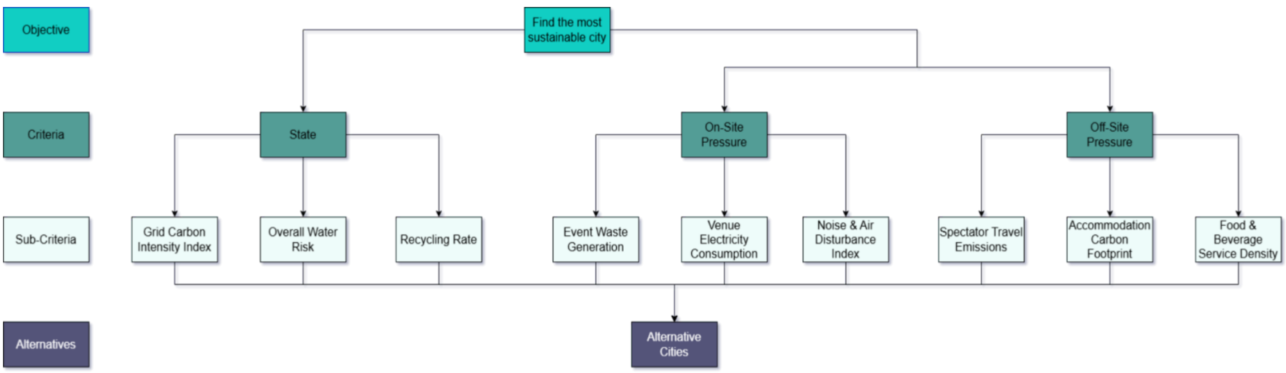

Figure 3: AHP hierarchy structure. The goal (optimal host city) branches into three criteria (State, On-site Pressure, Of-site Pressure), each containing three sub-criteria weighted independently.

Indicator weights derive from pairwise comparisons using Saaty's 1–9 scale (Figure 3). For each criterion group, a reciprocal matrix C is constructed where element C_{ij} represents factor i's importance relative to factor j. Priority vector **w** (principal eigenvector) satisfies:

$$\mathbf{Cw} = \lambda_{max}\mathbf{w} \tag{6}$$

Weights are approximated via column normalization and row averaging:

$$w_i = \frac{1}{3}\sum_{j=1}^{3}\frac{C_{ij}}{\sum_{k=1}^{3} C_{kj}} \tag{7}$$

Consistency is verified using Consistency Ratio CR = CI/RI, where CI = $(\lambda_{max} - 3)/2$ and RI = 0.58 for 3 × 3 matrices. All matrices satisfy CR < 0.10.

Expert judgments prioritize climate change and energy efficiency: Grid Carbon Emission Rate receives highest State weight (0.637), Venue Electricity Consumption leads On-site (0.637), and Spectator Travel Emissions dominates Of-site (0.714). Figure 4displays the complete weight distribution.

3. Application for Super Bowl Venue Selection

3.1. Data Collection and Normalization

Data for 22 U.S. cities (19 previous hosts, 3 potentials with NFL teams) were compiled from EPA eGRID [7], WRI Aqueduct [8], Ball Corporation recycling reports [9], census commuting data [14],

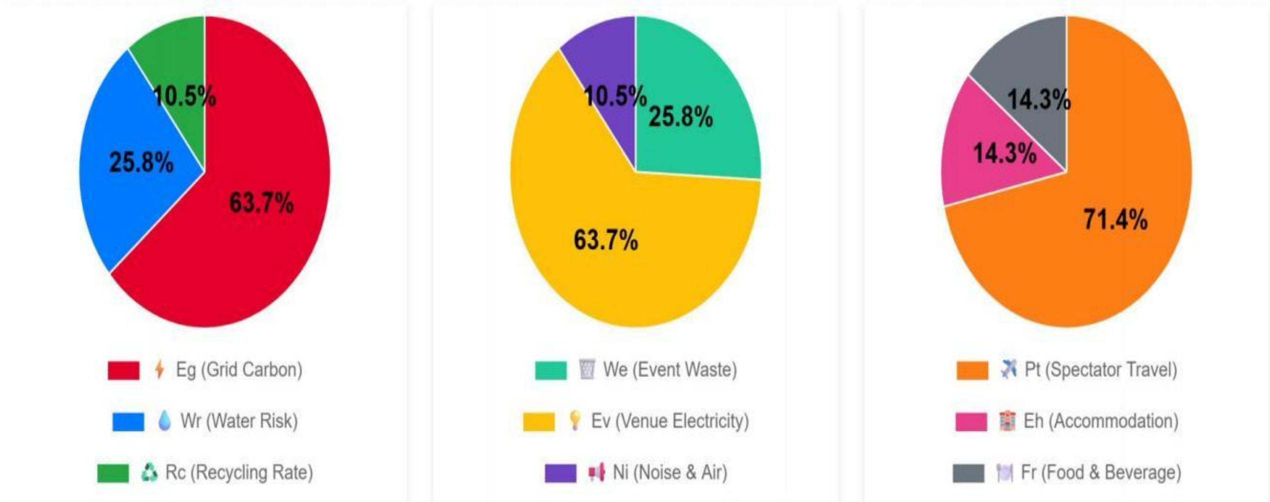

Figure 4: Final weight distribution. Grid carbon emissions (63.7%) and spectator travel (71.4%) dominate State and Of-site Pressure respectively, reflecting energy infrastructure and transportation as primary sustainability determinants.

And event studies [15,17]. All indicators were min-max normalized to [0,1] with appropriate directional adjustments (e.g., higher R_c = better performance = lower score).

On-site pressure per capita (P_0) was held constant using New Orleans (Super Bowl LIX) as baseline, justified by OECD guidelines on normalized indicator comparability [4]. Total on-site pressure scales with stadium capacity: $P_{on} = nP_0$, where n rescales normalized seat count to [0.1, 1] to avoid zero-multiplication artifacts.

3.2. Results and Ranking

Table 2: Top 10 Cities by SEIS Score (Descending Sustainability).

City	Type	SEIS	Ptot /Stot	Stot	Pon	Poff
Indianapolis	Host	0.1788	0.2376	0.6936	0.0899	0.3022
Minneapolis	Host	0.2016	0.3117	0.5400	0.1280	0.2215
Pittsburgh	Potential	0.2017	0.3123	0.3912	0.0500	0.2985
Detroit	Host	0.2159	0.3552	0.6624	0.1099	0.5038
Santa Clara	Host	0.2177	0.3603	0.2890	0.2097	0.0517
San Diego	Host	0.2234	0.3771	0.3307	0.1654	0.0940
Las Vegas	Host	0.2598	0.4765	0.4226	0.1099	0.3690
Atlanta	Host	0.2741	0.5131	0.4205	0.1598	0.2912
Stanford	Host	0.2753	0.5162	0.3157	0.2596	0.1023
Arlington	Host	0.2834	0.5363	0.3279	0.2596	0.1191

Note: Full 22-city ranking available in supplementary materials.

Indianapolis achieves the lowest SEIS (0.1788), driven by favorable Grid Carbon Emission Rate and low water risk yielding superior State score (0.6936). Pittsburgh, best among non-hosts, benefits from minimal Spectator Travel Emissions due to regional accessibility and high Recycling Rate. Conversely, Tempe (0.9662) and Pasadena (0.9280) score poorly due to high stress ratios exceeding 2.0—Tempe sufers from extreme of-site pressure (0.8488), while Pasadena's maximal stadium capacity (100,000 seats) generates unsustainable on-site pressure (0.5000).

The results validate prioritizing State improvements: cities with $S_{tot} > 0.50$ consistently rank top-10 regardless of moderate pressure variations, confirming that baseline infrastructure quality dominates sustainability outcomes.

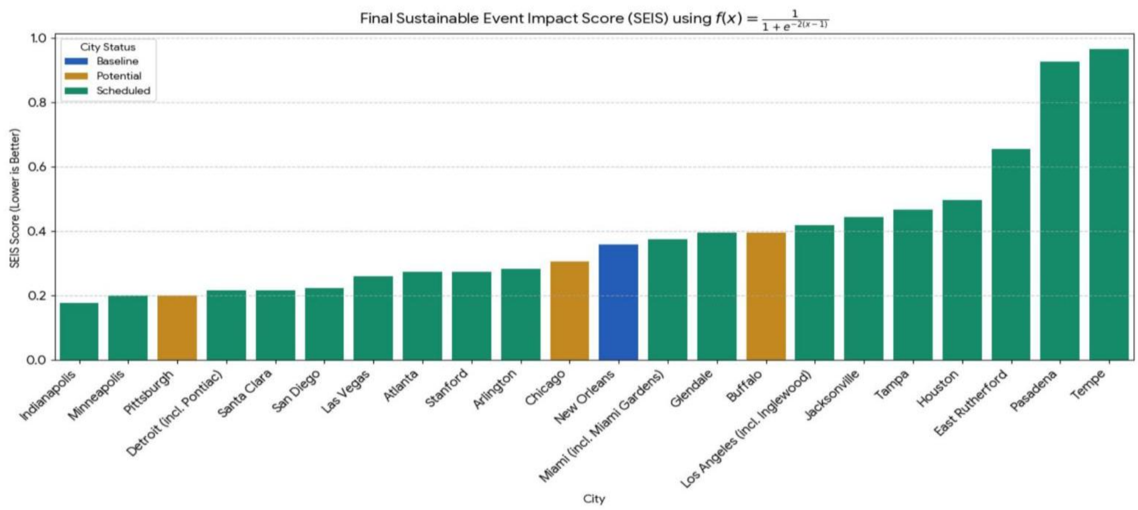

Figure 5: SEIS scores for all 22 candidate cities. Indianapolis (0.1788) and Pittsburgh (0.2017) emerge as optimal choices among hosted and potential venues respectively. Lower scores indicate superior environmental sustainability.

4. Model Extension to Olympic Games

4.1. Temporal-Venue Integration

Olympic Games difer from Super Bowl through extended duration (17 days) and multiple venues. The revised SPIR incorporates time-dependent pressure and venue-weighted aggregation:

$$\text{SEIS}_{\text{city}} = \sum_{v} \pi_v \frac{1}{T} \int_0^T g\left(\frac{P_v(t)}{S_v}\right) dt \tag{8}$$

Where π_v = venue popularity weight (derived from IOC broadcast hours and viewership [19]), $T = 17$ days, $P_V(t)$ = time-varying pressure reflecting daily event schedules, and $S_V = S_{tot}\,\theta_V$ distributes city capacity across venues by physical size ($\Sigma_V\, \theta_V = 1$).

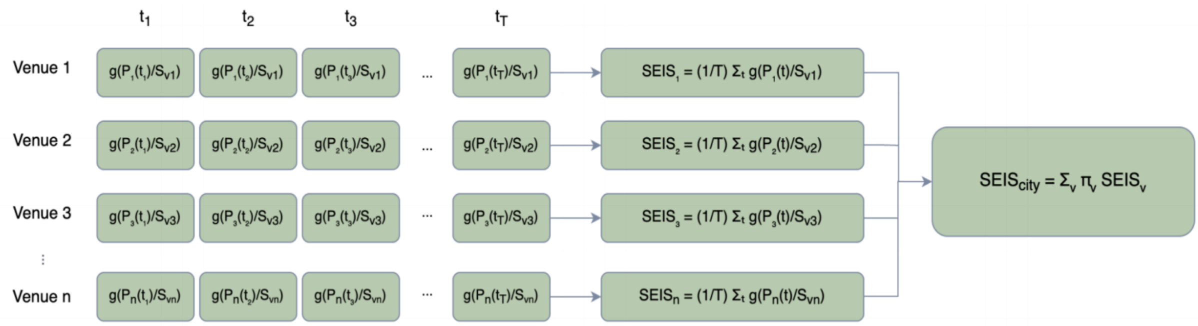

Figure 6: Revised SPIR framework for Olympics. Time-averaged SEIS across multiple venues ac- counts for event duration and spatial distribution of environmental pressure.

This formulation (Figure 6) enables fair comparison across cities with diferent venue configurations by normalizing for temporal and spatial factors.

4.2. Case Study: Toronto, Singapore, Madrid

Three candidate cities were evaluated using Olympic-specific parameters (Table 3).

Table 3: Olympic Games SEIS Results.

City	SEIS	Key Strength	Key Weakness
Toronto	0.17	Low E_g (clean grid)	Moderate travel distance
Madrid	0.31	Low P_t (regional access)	Higher E_g than Toronto
Singapore	0.50	High F_r (service capacity)	High E_g, P_t, E_h

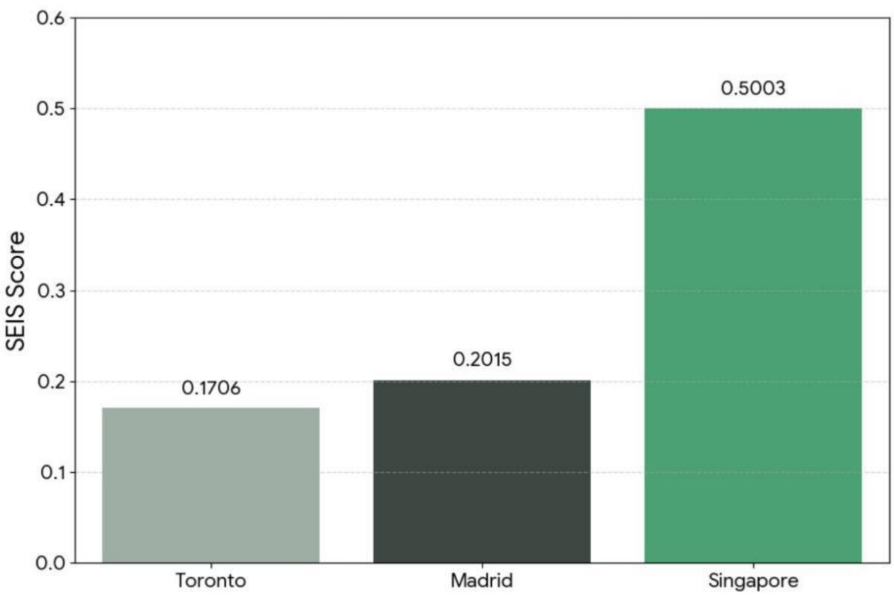

Figure 7: Olympic SEIS comparison. Toronto's clean energy infrastructure (low Grid Carbon Emis- sion Rate) provides decisive advantage despite moderate spectator travel pressures.

Toronto (SEIS = 0.17) outperforms competitors primarily through renewable energy penetration (hydroelectric and nuclear), reducing E_g by 60% versus Singapore. Madrid achieves intermediate performance (0.31) via superior P_t score—centralized European location minimizes long-haul flights. Singapore's fossil-fuel-dependent grid (highest E_g) and intercontinental travel requirements impose insurmountable pressure.

The results underscore that State improvements (especially energy decarbonization) yield greater sustainability gains than event-specific pressure mitigations, aligning with Super Bowl findings.

5. Policy Implications and Extensions

5.1. Sustainability Strategies

Two evidence-based strategies emerge from model insights:

Strategy 1: Grid Decarbonization. Cities aiming to host future events should prioritize long-term renewable energy investments. Toronto's advantage stems from decades of hydroelectric development. A 50% reduction in E_g (feasible via solar/wind expansion) can decrease SEIS by 20–30%, permanently enhancing competitiveness.

Strategy 2: Transportation Demand Management. Short-term pressure reduction focuses on spectator travel—the dominant of-site factor (71.4% weight). Policies include: (i) free public transit for ticket holders, (ii) regional marketing to reduce long-haul air travel, and (iii) shuttle services from proximate cities. Reducing average travel distance by 30% lowers P_t by equivalent margin, improving SEIS by 10–15%.

5.2. Future Trend Prediction

Environmental score evolution follows policy-driven improvement modeled via diferential equations:

$$\frac{d(\mathrm{SEIS})}{dt} = -\gamma(\mathrm{SEIS}(t) - \mathrm{SEIS}_{\mathrm{target}}) \quad (9)$$

Where γ = green transition rate (0.03 for moderate policy, 0.10 for aggressive). Solution:

$$\mathrm{SEIS}(t) = \mathrm{SEIS}_{\mathrm{target}} + (\mathrm{SEIS}_0 - \mathrm{SEIS}_{\mathrm{target}})e^{-\gamma t} \quad (10)$$

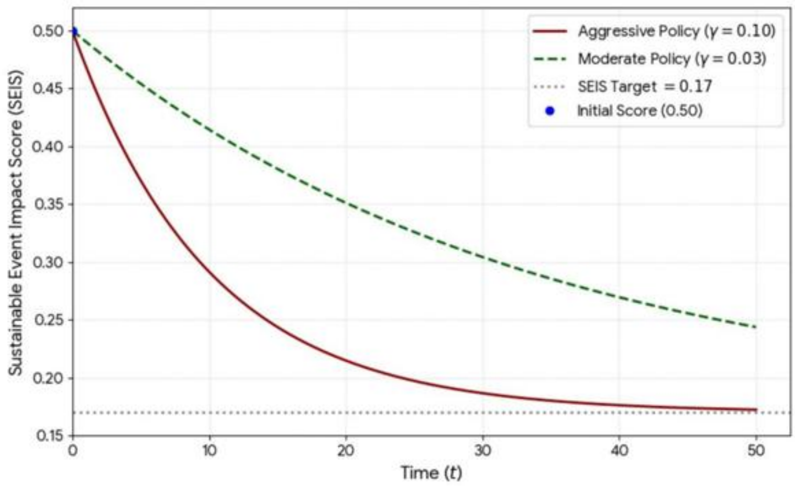

Figure 8: Predicted SEIS trajectory for Singapore under aggressive (γ = 0.10) and moderate (γ = 0.03) policies. Aggressive decarbonization enables convergence to Toronto's level (0.17) within 15 years; moderate policy requires 35+ years.

Figure 8 demonstrates that Singapore could match Toronto's sustainability through aggressive grid transition ($\gamma = 0.10$) in 15 years, but moderate eforts prolong improvement to 35+ years, highlighting policy urgency.

5.3. Economic-Environmental Optimization

Integrating environmental externalities into economic frameworks treats SEIS as negative utility. The optimization problem:

$$\max Z = \sum_{i=1}^{N} (B_i - \lambda \cdot \text{SEIS}_i) \cdot x_i \tag{11}$$

Subject to $\sum_{i=1}^{N} x_i = 1$, where B_i = economic benefit, λ = environmental monetization coefficient, $x_i \in \{0, 1\}$ = selection binary.

The monetization coefficient λ quantifies organizational environmental priority (Figure 9). For $\lambda = 0$, selection maximizes economic benefit only; for $\lambda > 10^4$, environmental performance dominates. This framework enables transparent valuation of sustainability goals.

6. Sensitivity Analysis

Model robustness was tested through parameter perturbations:

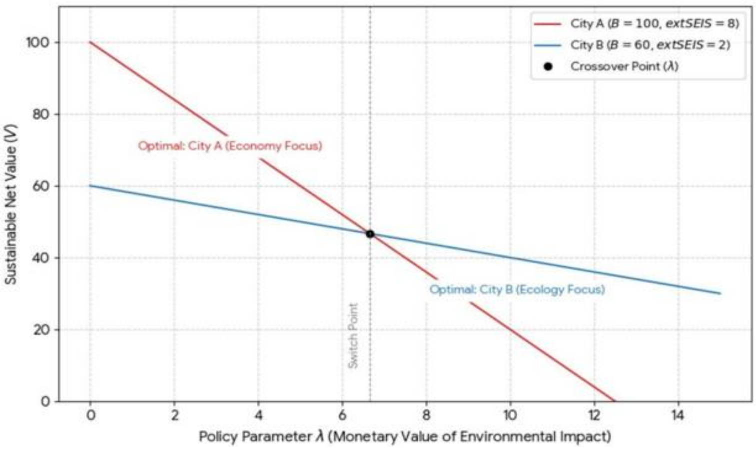

Figure 9: Economic-environmental trade-of for two hypothetical cities. Higher monetization coef- ficient (λ) shifts selection toward environmentally superior City B despite lower economic benefit, operationalizing organizational sustainability commitment.

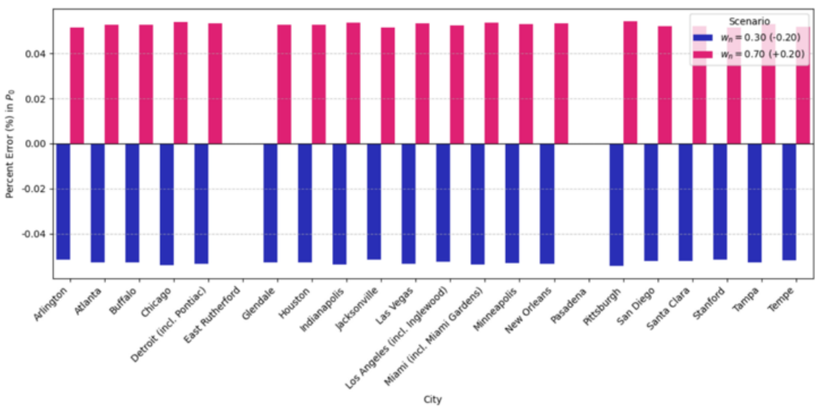

Figure 10: Sensitivity of on-site pressure baseline (P_0) to noise disturbance weight. Percentage error remains within 5% across $w_n \in [0.3, 0.7]$, validating composite index robustness.

Noise Weight (w_n in N_i): Varying $w_n \in [0.3, 0.7]$ produces ¡5% change in P_0, confirming sub-index stability.

On-site/Of-site Balance (α): Moderate sensitivity observed—rankings shift ±3 positions for mid-tier cities (Figure 11). At α = 0.7, high-stadium-capacity venues (Pasadena, East Rutherford) drop; at α = 0.3, high-travel-distance cities (Tempe, Houston) decline. Top-tier (Indianapolis, Minneapolis) and bottom-tier (Tempe, Pasadena) remain stable, indicating ranking endpoints are insensitive to weighting assumptions.

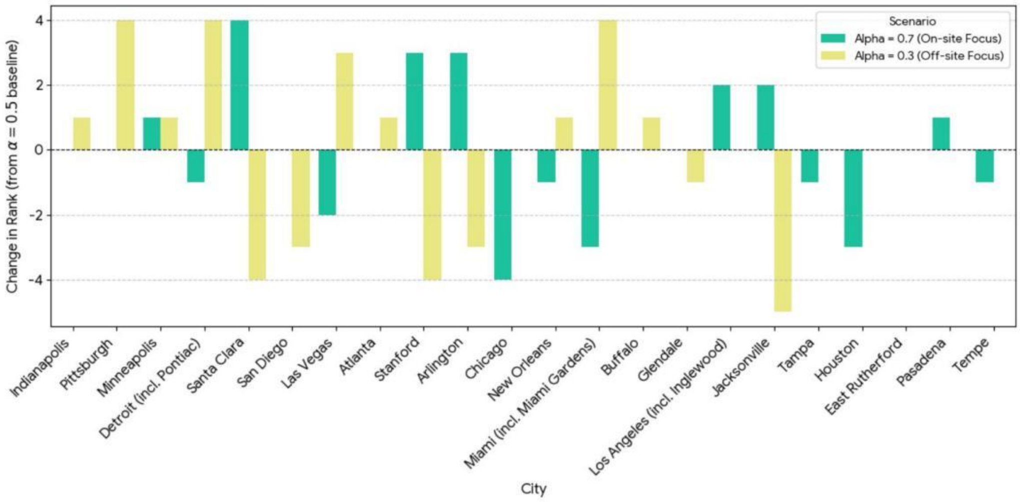

Figure 11: Ranking sensitivity to on-site pressure weight (α). While mid-ranked cities shift moder- ately, top and bottom tiers remain stable, confirming model validity for extreme-case identification.

Logistic Steepness (k): Varying k ∈ [1, 5] alters absolute SEIS values but preserves ranking order (Figure 12), demonstrating that nonlinear function choice does not afect comparative city assessment.

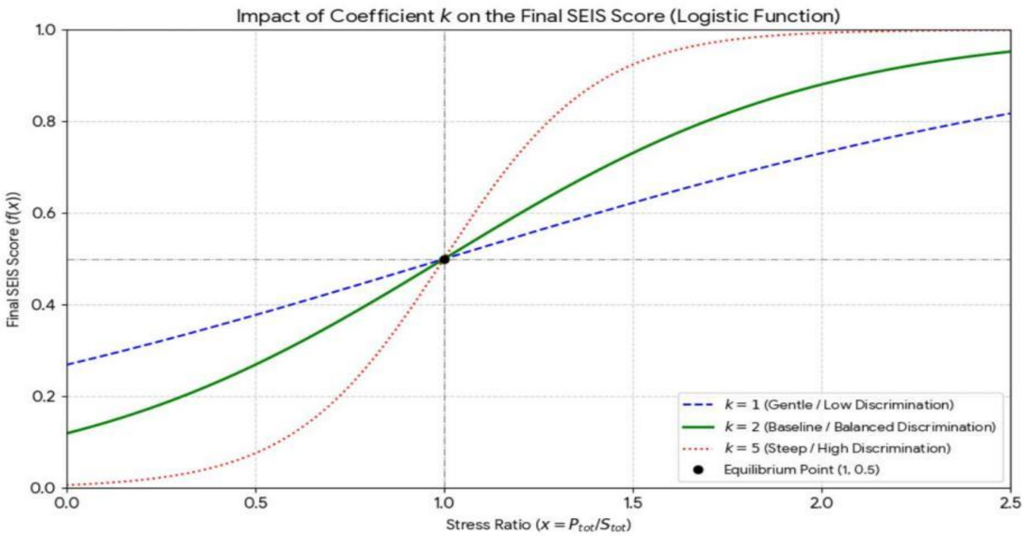

Figure 12: Logistic function variations with steepness parameter k. Diferent k values shift SEIS magnitudes but maintain monotonic stress-response relationship, preserving ranking stability.

7. Discussion

7.1. Model Advantages

The SPIR framework ofers several methodological contributions:

1. Holistic Multi-Dimensional Assessment. By integrating carbon, water, waste, and energy indicators across State and Pressure dimensions, the model captures environmental complexity beyond single-metric approaches. The nine-indicator structure aligns with international sustainability standards [3] while remaining computationally tractable.

2. Nonlinear Stress-Capacity Mechanism. The logistic response function operationalizes ecological synergy theory [6], reflecting observed environmental system behavior: gradual degradation under low stress, accelerated collapse near capacity thresholds, and saturation at extreme loads. This realism improves predictive validity compared to linear aggregation methods.

3. Transferability Across Event Types. Successful application to both single-day (Su- per Bowl) and multi-day, multi-venue (Olympics) events demonstrates framework generalizability. The temporal-venue integration (Eq. 8) provides systematic methodology for extending single-event models to complex configurations.

4. Decision-Support Utility. Clear ranking outputs (SEIS scores) enable transparent venue selection, while sensitivity analysis identifies critical parameters (α) requiring careful calibration. The economic-environmental optimization (Eq. 10) bridges sustainability science and operational decision-making.

7.2. Limitations and Future Work

Several constraints warrant acknowledgment:

Data Dependency. Sub-models for E_h , P_t , and N_i rely on estimations due to limited direct mea- surements, introducing uncertainty. Future iterations should incorporate real-time sensor networks (IoT-based energy monitoring, GPS travel tracking) for empirical validation.

Subjective Weighting. AHP pairwise comparisons embed expert judgment. While consistency ratios validated coherence ($CR < 0.10$), stakeholder consultations could refine weights to reflect diverse priorities (e.g., community health vs. carbon targets).

Static Capacity Assumption. The model treats State as time-invariant during event plan- ning horizon (5+ years). Long-term infrastructure changes (renewable energy installations, waste facility upgrades) could dynamically update S_{tot}, requiring Markov-chain or dynamic programming extensions.

Interaction Efects. Current formulation assumes indicator independence. However, grid de- carbonization reduces both E_g (State) and E_v impacts (Pressure), creating covariance. Structural equation modeling could capture these synergies.

Future research directions include: (i) machine learning integration for predictive analytics using historical event data; (ii) life-cycle assessment expansion incorporating construction/decommissioning phases; (iii) social equity metrics (environmental justice indicators) to complement physical sustain- ability measures; and (iv) real-time adaptive frameworks enabling in-event adjustments based on monitored conditions.

7.3. Practical Recommendations

For event organizers and city planners:

Pre-Event Phase: Prioritize cities with $S_{tot} > 0.50$ (strong baseline capacity). Mandate re- newable energy contracts for venues. Establish travel demand management plans (public transit subsidies, carpool incentives).

During Event: Deploy real-time monitoring for W_e, E_v , and N_i to enable adaptive interventions. Communicate sustainability metrics to attendees via mobile apps to encourage pro-environmental behavior.

Post-Event: Conduct comprehensive environmental audits comparing predicted vs. observed impacts. Feed lessons learned into iterative model refinement for subsequent events.

For policy-makers:

Long-Term Infrastructure: Accelerate grid decarbonization through renewable portfolio standards. Invest in high-capacity public transit connecting venues to population centers.

Regulatory Frameworks: Require SEIS disclosure in bid proposals. Establish minimum sustainability thresholds (e.g., SEIS ¡ 0.30) for hosting eligibility.

Incentive Structures: Ofer tax credits or subsidies to cities achieving SEIS improvements year-over-year, creating competitive sustainability markets.

8. Conclusion

This study developed and validated the SPIR framework for quantitative environmental sustainability assessment of sport mega-events. Integrating baseline urban capacity with event-driven pressures through a nonlinear logistic function, the model produces Sustainable Event Impact Scores enabling evidence-based venue selection. Applied to 22 U.S. cities for Super Bowl 2029, Indianapolis emerged as optimal (SEIS = 0.1788), leveraging low grid carbon emissions and water risk. Extension to Olympic Games demonstrated model transferability, with Toronto (SEIS = 0.17) outperforming Singapore and Madrid through renewable energy infrastructure.

Sensitivity analysis confirmed robustness to most parameters, with moderate dependence on on-site/of-site pressure weighting. Policy simulations indicated that aggressive grid decarbonization (transition rate 0.10) enables convergence to top-tier sustainability within 15 years, while transportation demand management provides near-term SEIS reductions of 10–15%.

The framework bridges environmental science and operational decision-making, ofering transpar- ent, replicable methodology for sustainable mega-event planning. As global sporting events confront intensifying climate accountability, the SPIR model provides essential infrastructure for balancing economic benefits with ecological responsibilities. Future iterations integrating real-time monitoring and social equity dimensions will further enhance decision support for the sporting industry's sustainability transition.

Acknowledgments

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