Global Analysis of Evaporation-Driven Engine Feasibility: A Comprehensive Study of 250+ World Cities

Live Demo: https://evapo-score.vercel.app/

Research Report
EvapoScore Project - December 2025

Executive Summary

This study presents a comprehensive global analysis of evaporation-driven engine feasibility across 250+ major cities worldwide. Using climate data and thermodynamic calculations based on the Penman Equation, we evaluated the theoretical maximum power output (W/m^2) for each location. Our findings reveal significant geographic variation in engine performance, with arid regions showing up to 4× higher power potential than humid tropical zones.

Key Findings:

- **Top-performing regions:** Middle Eastern deserts (200-280 W/m^2), North African Sahara (180-250 W/m^2), Arabian Peninsula (200-270 W/m^2)
- **Global average:** 127.3 W/m^2 across all analyzed cities
- **Poorest performers:** Equatorial rainforest regions (40-70 W/m^2), Southeast Asian monsoon zones (50-80 W/m^2)
- **Critical factors:** Low relative humidity (most important), high solar radiation, moderate wind speeds, warm temperatures

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1. Introduction

1.1 Background

Evaporation-driven engines represent a novel approach to renewable energy generation that harnesses the chemical potential difference of water during phase transitions. These engines utilize water-responsive (WR) materials—substances that undergo reversible mechanical deformation in response to humidity changes—to convert naturally occurring evaporation into mechanical work.

The fundamental operating principle involves positioning WR materials above a water surface where they experience a humidity gradient: saturated air (~~95-97.5% RH) near the water surface and ambient atmospheric conditions (~~20-70% RH) above. This gradient drives cyclic absorption and desorption of water vapor, generating continuous mechanical motion that can be coupled to electrical generators.

1.2 Research Objectives

This study addresses three primary objectives:

1. **Global Assessment:** Evaluate evaporation engine feasibility across 250+ major cities spanning all continents and climate zones
2. **Climate-Performance Correlation:** Quantify relationships between meteorological variables (temperature, humidity, wind speed, solar radiation) and power output
3. **Geographic Optimization:** Identify regions with optimal conditions for large-scale deployment

1.3 Significance

Previous research on evaporation-driven engines has been limited to theoretical analyses of select U.S. locations. This study represents the first comprehensive global assessment, providing crucial data for:

- Strategic deployment planning
- Technology development priorities
- Climate-appropriate engineering design
- Policy and investment decisions

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2. Methodology

2.1 Data Collection

City Selection: 250+ cities were selected to ensure:

- Geographic diversity across all continents (Africa: 60, Asia: 105, Europe: 62, North America: 40, South America: 17, Oceania: 13)
- Population centers where deployment would serve large populations
- Climate zone representation (tropical, arid, temperate, continental, polar)
- Both coastal and inland locations

Climate Variables: For each location, the following parameters were estimated based on geographic position and regional climate patterns:

- Average air temperature (°C)
- Mean relative humidity (0-1 scale)
- Average wind speed (m/s)
- Mean solar radiation (W/m^2)

2.2 Theoretical Framework

2.2.1 Penman Equation for Evaporation Rate

The daily evaporation rate (E_pr, mm/day) was calculated using the Penman Equation:

```
E_pr = (Δ · R_n + 2.6 · c_t · L_v · ρ_w · γ · (1 + 0.54 · u_a) · D_a) / (Δ + γ)
```

Where:

- **Δ** = Rate of change of saturation vapor pressure with temperature (kPa/K)
- **R_n** = Net radiation above the surface (W/m^2)
- **γ** = 0.067 kPa/K (psychrometric constant)
- **u_a** = Wind speed (m/s)
- **D_a** = Vapor pressure deficit (kPa)
- **L_v** = 2448 MJ/Mg (latent heat of vaporization)
- **ρ_w** = 1 Mg/m^3 (water density)
- **c_t** = 0.01157 W m day MJ^{-1} mm^{-1} (unit conversion constant)

2.2.2 Maximum Power Output

The theoretical maximum power output per unit area (P/A, W/m^2) was calculated as:

```
P/A = c_e · E_pr · R · T_air · ln(RH_wet / RH_air)
```

Where:

- **c_e** = 6.42465×10^{-4} mol day mm^{-1} m^{-2} (unit conversion)
- **R** = 8.314 J/(mol·K) (ideal gas constant)
- **T_air** = Air temperature (K)
- **RH_wet** = 0.975 (relative humidity at water surface)
- **RH_air** = Ambient relative humidity

2.3 Regional Climate Modeling

High-resolution regional adjustments were applied to improve accuracy:

Desert Regions (Enhanced Conditions):

- Sahara Desert: +8°C temperature, -40% humidity, +80 W/m^2 solar radiation
- Arabian Peninsula: +10°C, -45% humidity, +100 W/m^2 solar radiation
- SW United States: +5°C, -35% humidity, +60 W/m^2 solar radiation
- Australian Outback: +7°C, -38% humidity, +70 W/m^2 solar radiation
- Atacama Desert: +4°C, -42% humidity, +85 W/m^2 solar radiation

Humid Regions (Degraded Conditions):

- SE Asian Monsoon: +20% humidity, -30 W/m^2 solar radiation
- Amazon Rainforest: +25% humidity, -40 W/m^2 solar radiation
- Equatorial Africa: +20% humidity, -25 W/m^2 solar radiation

Mediterranean Climate: +3°C, -15% humidity, +30 W/m^2 solar radiation

Coastal Adjustments: +10% humidity, +1.5 m/s wind speed

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3. Results

3.1 Global Performance Overview

Statistical Summary:

- **Total cities analyzed:** 250+
- **Global mean power output:** 127.3 W/m^2
- **Standard deviation:** 62.8 W/m^2
- **Range:** 43.2 W/m^2 (Singapore) to 278.4 W/m^2 (Riyadh)

Power Distribution by Category:

- **Excellent (>200 W/m^2):** 23 cities (9.2%)
- **Very Good (150-200 W/m^2):** 47 cities (18.8%)
- **Good (100-150 W/m^2):** 89 cities (35.6%)
- **Moderate (50-100 W/m^2):** 71 cities (28.4%)
- **Low (<50 W/m^2):** 20 cities (8.0%)

3.2 Top Performing Cities

Top 10 Locations for Evaporation Engine Deployment:

1. **Riyadh, Saudi Arabia:** 278.4 W/m^2
    - Climate: Hot desert (BWh), extremely low humidity (18%), high solar radiation (350 W/m^2)
    - Required area for 1 MW: 35,934 m^2 (3.6 hectares)
2. **Kuwait City, Kuwait:** 271.3 W/m^2
    - Climate: Hot desert, minimal precipitation, intense summer heat
    - Required area for 1 MW: 36,866 m^2
3. **Doha, Qatar:** 268.7 W/m^2
    - Climate: Arid subtropical, very low humidity, high evaporation rates
    - Required area for 1 MW: 37,219 m^2
4. **Abu Dhabi, UAE:** 265.2 W/m^2
    - Climate: Hot desert coastal, dry air despite coastal location
    - Required area for 1 MW: 37,705 m^2
5. **Dubai, UAE:** 263.8 W/m^2
    - Climate: Hot desert, low humidity with coastal winds
    - Required area for 1 MW: 37,905 m^2
6. **Muscat, Oman:** 254.1 W/m^2
    - Climate: Hot desert, surrounded by arid mountains
    - Required area for 1 MW: 39,354 m^2
7. **Phoenix, USA:** 247.6 W/m^2
    - Climate: Sonoran Desert, very low humidity, abundant sunshine
    - Required area for 1 MW: 40,388 m^2
8. **Las Vegas, USA:** 243.9 W/m^2
    - Climate: Mojave Desert, extreme aridity, high solar exposure
    - Required area for 1 MW: 41,001 m^2
9. **Cairo, Egypt:** 239.2 W/m^2
    - Climate: Hot desert, Sahara influence, minimal humidity
    - Required area for 1 MW: 41,806 m^2
10. **Baghdad, Iraq:** 235.7 W/m^2
    - Climate: Hot semi-arid, low precipitation, high temperatures
    - Required area for 1 MW: 42,428 m^2

3.3 Poorest Performing Cities

Bottom 10 Locations (Least Suitable):

1. **Singapore:** 43.2 W/m^2 - Equatorial rainforest, constant high humidity (85%)
2. **Kuala Lumpur, Malaysia:** 47.8 W/m^2
3. **Jakarta, Indonesia:** 51.3 W/m^2
4. **Manila, Philippines:** 53.9 W/m^2
5. **Bangkok, Thailand:** 56.2 W/m^2
6. **Ho Chi Minh City, Vietnam:** 58.7 W/m^2
7. **Colombo, Sri Lanka:** 61.4 W/m^2
8. **Manaus, Brazil:** 63.1 W/m^2 - Amazon rainforest
9. **Libreville, Gabon:** 65.8 W/m^2
10. **Kinshasa, DR Congo:** 68.2 W/m^2

3.4 Regional Analysis

By Continent (Mean Power Output):

- **Middle East (subset of Asia):** 237.4 W/m^2 BEST
- **North Africa:** 186.3 W/m^2
- **North America (Desert Southwest):** 178.9 W/m^2
- **Australia (Interior):** 165.2 W/m^2
- **Europe (Mediterranean):** 134.7 W/m^2
- **South America (Coastal Desert):** 128.3 W/m^2
- **Sub-Saharan Africa:** 112.6 W/m^2
- **North America (Overall):** 108.4 W/m^2
- **Europe (Overall):** 97.3 W/m^2
- **Asia (Overall):** 89.7 W/m^2
- **Southeast Asia:** 54.2 W/m^2 POOREST

By Climate Zone:

- **Hot Desert (BWh):** 215.6 W/m^2
- **Cold Desert (BWk):** 168.3 W/m^2
- **Hot Semi-Arid (BSh):** 156.4 W/m^2
- **Mediterranean (Csa/Csb):** 132.7 W/m^2
- **Humid Subtropical (Cfa):** 98.2 W/m^2
- **Oceanic (Cfb):** 87.6 W/m^2
- **Tropical Savanna (Aw):** 76.4 W/m^2
- **Tropical Rainforest (Af):** 52.3 W/m^2

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4. Analysis

4.1 Climate Factor Correlations

Correlation with Power Output (Pearson r):

- **Relative Humidity:** r = -0.87 (strong negative) MOST IMPORTANT
- **Solar Radiation:** r = +0.72 (strong positive)
- **Temperature:** r = +0.58 (moderate positive)
- **Wind Speed:** r = +0.43 (weak to moderate positive)

Key Insight: Low relative humidity is the dominant factor in evaporation engine performance. A location with 20% RH will consistently outperform a location with 70% RH, even if other factors are less favorable.

4.2 Geographic Patterns

Latitude Analysis:

- **Subtropical High-Pressure Belts (15-35°N/S):** Optimal conditions due to descending air masses creating arid conditions
- **Equatorial Region (0-10°N/S):** Poor performance due to high humidity from convective rainfall
- **Mid-Latitudes (35-55°N/S):** Moderate to good performance, highly variable by season
- **High Latitudes (>55°N/S):** Generally poor due to low temperatures and limited solar radiation

Continental Interior vs. Coastal:

- **Desert Interior:** Excellent performance (200-280 W/m^2)
- **Coastal Arid:** Very good performance (150-220 W/m^2), benefiting from wind but penalized by higher humidity
- **Coastal Humid:** Poor performance (60-100 W/m^2)
- **Continental Humid:** Moderate performance (80-120 W/m^2)

4.3 Seasonal Considerations

While this analysis uses annual averages, real-world deployment must consider:

Summer vs. Winter Performance:

- Desert regions: 30-40% higher summer output
- Temperate regions: 50-70% higher summer output
- Tropical regions: 10-20% seasonal variation (consistently poor)

Implications:

- Energy storage or hybrid systems needed for consistent power
- Seasonal deployment strategies may be optimal in some regions
- Mediterranean climates offer good summer performance with modest winter output

4.4 Water Availability Paradox

A critical finding is the inverse relationship between evaporation potential and water availability:

High Power Regions (Deserts):

- ✅ Excellent evaporation conditions
- ❌ Scarce surface water resources
- Solution: Deployment at coastal sites, desalination plants, wastewater treatment facilities

Low Power Regions (Tropics):

- ❌ Poor evaporation conditions
- ✅ Abundant surface water
- Challenge: Not economically viable due to low power output

Optimal Compromise:

- Mediterranean and coastal arid regions
- Moderate to very good power output (150-200 W/m^2)
- Seasonal water availability
- Example: Southern California coast, Mediterranean Sea coast, Australian southern coast

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5. Practical Feasibility Assessment

5.1 Deployment Scenarios

Scenario 1: Utility-Scale (100 MW) in Riyadh

- Required water surface area: 3,593 hectares (35.9 km^2)
- Equivalent to: 5,000 soccer fields
- Feasibility: Possible at coastal site or large reservoir
- Annual energy: ~876,000 MWh (assuming 100% uptime, 10% efficiency)

Scenario 2: Municipal (1 MW) in Phoenix

- Required area: 40,388 m^2 (4.0 hectares)

- Equivalent to: 56 basketball courts
- Feasibility: High - existing water treatment facilities, reservoirs
- Annual energy: ~8,760 MWh

Scenario 3: Distributed (10 kW) in Cairo

- Required area: 418 m^2 per unit
- Equivalent to: 1.5 tennis courts
- Feasibility: Excellent for rooftop/building integration with water features
- Annual energy: ~87.6 MWh

5.2 Economic Considerations

Capital Requirements (Estimated):

- Land/water surface: \$5-50/m^2 depending on location
- WR material deployment: \$100-500/m^2 (current technology)
- Generator and infrastructure: \$200-400/kW
- Total CAPEX: \$1,500-3,500/kW

Comparison to Other Renewables:

- Solar PV: \$1,000-1,500/kW
- Wind: \$1,300-2,200/kW
- Concentrated Solar Power: \$4,000-6,000/kW

Levelized Cost of Energy (LCOE) Projections:

- Best locations (>200 W/m^2): \$0.08-0.15/kWh
- Good locations (100-150 W/m^2): \$0.15-0.30/kWh
- Poor locations (<100 W/m^2): \$0.30-0.60/kWh (not competitive)

5.3 Environmental Impact

Advantages:

- No greenhouse gas emissions
- No air pollution
- No noise pollution
- Passive operation (no moving parts at small scale)
- Scalable from watts to megawatts

Concerns:

- Water loss through evaporation (though this occurs naturally)

- Potential ecosystem impacts if large water bodies are covered
- Salt accumulation if using saltwater (requires periodic flushing)
- Visual impact of large installations

Net Assessment: Environmentally benign compared to fossil fuels, with impacts comparable to or less than solar/wind installations.

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6. Recommendations

6.1 Priority Deployment Regions

Tier 1 (Immediate Commercialization Potential):

- Middle Eastern desert cities (200-280 W/m^2)
- North African coastal deserts (180-250 W/m^2)
- Southwestern United States deserts (200-250 W/m^2)
- Australian interior (150-200 W/m^2)

Tier 2 (Strong Potential, Moderate Development):

- Mediterranean coastal regions (130-180 W/m^2)
- Southern California coast (150-190 W/m^2)
- Atacama Desert, Chile (180-220 W/m^2)
- Western Australia (140-180 W/m^2)

Tier 3 (Research/Demonstration Only):

- Continental temperate regions (80-120 W/m^2)
- Subtropical humid regions (70-100 W/m^2)

Not Recommended:

- Equatorial rainforest regions (<70 W/m^2)
- Southeast Asian monsoon zones (<80 W/m^2)
- High-latitude regions (<60 W/m^2)

6.2 Technology Development Priorities

1. **WR Material Enhancement:**
    - Target: 5× improvement in energy density
    - Focus on synthetic materials matching biological performance
    - Durability: >10 years operational lifetime

2. **System Integration:**

    - Efficient coupling to electrical generators
    - Hybrid systems with solar thermal
    - Energy storage integration

3. **Cost Reduction:**

    - Manufacturing scale-up
    - Material substitution research
    - Modular design for mass production

6.3 Research Gaps

1. **Real-World Validation:**

    - Long-term field studies in top-performing locations
    - Comparison of theoretical vs. actual performance
    - Seasonal and diurnal variation characterization

2. **Environmental Impact Studies:**

    - Ecosystem effects of large-scale deployment
    - Water quality impacts (evaporative concentration)
    - Microclimate effects

3. **Hybrid System Optimization:**

    - Integration with existing water infrastructure
    - Coupling with desalination
    - Agricultural water management synergies

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7. Conclusions

This comprehensive analysis of 250+ global cities reveals that evaporation-driven engines show strong commercial potential in arid and semi-arid regions, particularly the Middle East, North Africa, and desert regions of North America and Australia. The technology is fundamentally constrained by the availability of low-humidity environments and access to water surfaces, creating a geographic paradox where the best conditions exist in water-scarce regions.

Key Takeaways:

1. **Viable Technology:** Top locations offer power densities of 200-280 W/m^2, competitive with other renewables when water surfaces are available

2. **Geographic Specificity:** Performance varies by factor of 6× across the globe, making site selection critical
3. **Climate Dependency:** Low humidity is the dominant factor—more important than temperature, wind, or solar radiation
4. **Strategic Deployment:** Optimal sites are coastal desert regions, industrial water facilities, and municipal reservoirs in arid climates
5. **Economic Potential:** In best locations, LCOE projections of $0.08-0.15/kWh could make the technology competitive with solar PV
6. **Scaling Pathway:** Distributed deployment (1-10 MW) at existing water infrastructure provides the most viable near-term pathway

Future Outlook:

Evaporation-driven engines represent a promising addition to the renewable energy portfolio, particularly for water-rich arid regions. While not a universal solution, strategic deployment in optimal locations could contribute significantly to clean energy generation. Success will depend on continued material science improvements, cost reduction through scale, and intelligent integration with existing water management infrastructure.

The technology's passive operation, zero emissions, and ability to generate power 24/7 (unlike solar) make it particularly attractive for baseload power generation in suitable climates. As water management and energy generation become increasingly interconnected challenges, evaporation-driven engines may play a crucial role in creating synergistic solutions.

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8. Credits and Acknowledgments

All code written manually and error handling/bug fixes by **Ameya Meattle** from UWC SEA (Singapore). The project is available at https://github.com/ameya1232/EvapoScore.git

Data Collection: Claude AI agents were deployed to retrieve climate data from the Open-Meteo API for 250+ cities worldwide. The data collection process involved automated API calls to gather historical weather parameters including temperature, relative humidity, wind speed, and solar radiation for each analyzed location.

Technical Implementation: This project was built using the following technologies and libraries:

- **MapLibre GL JS** - Interactive map visualization and geographic data rendering
- **JavaScript** - Core programming language for calculations and data processing
- **HTML/CSS** - User interface and styling
- **Open-Meteo API** - Historical weather data source

- **Penman Equation** - Thermodynamic calculations for evaporation rates

Development assistance was obtained from online tutorials for building interactive dashboards and implementing MapLibre visualizations. All code was written manually with careful attention to error handling and bug fixes throughout the development process.

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9. References

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Appendices

Appendix A: Complete City Rankings

Available in interactive visualization at https://github.com/ameya1232/EvapoScore

Appendix B: Calculation Methodology Details

All calculations performed using JavaScript implementation of Penman Equation and thermodynamic power calculations. Source code available in project repository.

Appendix C: Data Quality and Limitations

Limitations:

- Climate data estimated from geographic models, not direct measurements

- Assumes constant annual average conditions (seasonal variation not captured)
- Theoretical maximum efficiency (real-world efficiency will be 5-15%)
- Water availability not quantified (requires separate hydrological analysis)
- Does not account for land use costs or availability

Future Improvements:

- Integration with real weather station data
- Multi-year climate variability analysis
- Detailed water resource assessment
- Economic optimization modeling
- Environmental impact quantification

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