

# Carbon-Aware VR

*Sustainable Performance Through Human-Centric Computing Continuum*

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# Context

## VR/XR USE: CASES, DEVICES, AND ENVIRONMENTAL CHALLENGES

**EDUCATION AND TRAINING**




**EDUCATION AND TRAINING**  
Virtual Classes / Medical Simulations

**ENTERTAINMENT AND GAMING**



**ENTERTAINMENT AND GAMING**  
Immersive Video Games / Virtual Events

**WORK AND COLLABORATION**



**WORK AND COLLABORATION**  
3D Design / Remote Work / Global Meetings

**HEALTH AND REHABILITATION**



**HEALTH AND REHABILITATION**  
Physical Therapy / Mental Health

### KEY CHALLENGES:

**ENERGY CONSUMPTION**




**ENERGY CONSUMPTION**  
High energy consumption (Batteries, Processing, Servers)  
-> Greater electricity demand.

**TEMPERATURE INCREASE**



**TEMPERATURE INCREASE**  
Device Heating (Discomfort) / Thermal Load in Data Centers (Cooling Need).

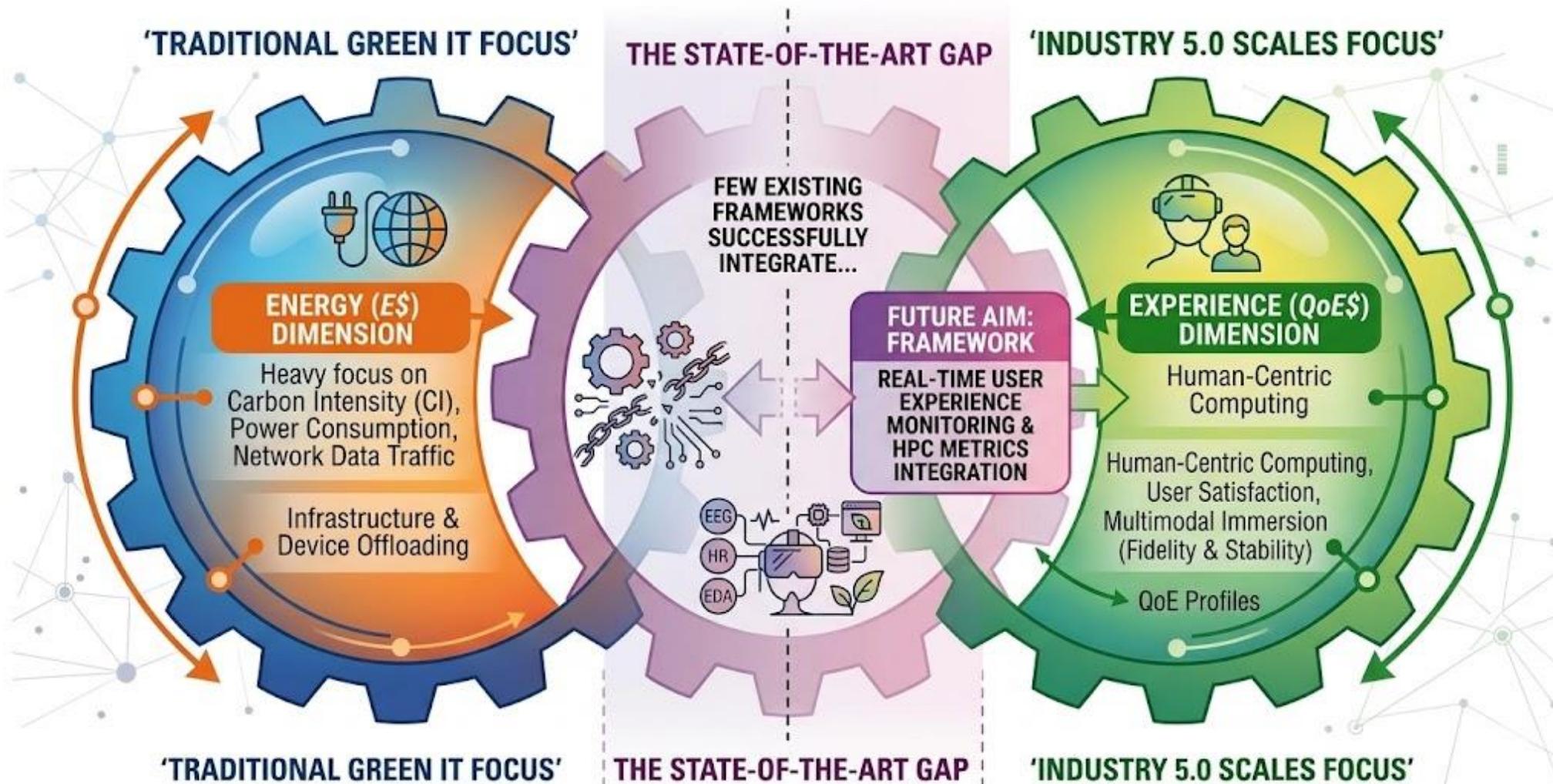
**CARBON COST**



**CARBON COST**  
Carbon Footprint (Energy production, Hardware manufacturing)  
> Impact on Climate Change.

# Background

FIGURE X: VISUALIZING THE STATE-OF-THE-ART GAP IN SUSTAINABLE XR



# Background

## EVOLUTION OF SUSTAINABLE XR RESEARCH

Research Domain	Key Contribution	Vertex	Core Computing Elements
Green Software	SCI Specification [13]	<b>E</b> (Energy)	Carbon-aware SDK frameworks
Carbon Network	Time/Location Shifting [21]	<b>E</b> (Energy)	Carbon-routing & telemetry APIs
Metaverse / Cloud	VE Footprint & Workload Shifting [14,20]	<b>P/E</b>	Operating system carbon daemons
XR 5.0 & Continuum	Human-Centric AI [15,17]	<b>QoE/E</b>	Biometric sensors & thermal offloading
Green HPC	DRL Placement [18]	<b>P/E</b>	Dynamic VM forecasting & scheduling

### The State-of-the-Art Gap

Traditional Green IT focuses heavily on the **Energy (E)** dimension, whereas Industry 5.0 scales prioritize **Experience (QoE)**. Very few existing frameworks successfully integrate real-time user-centric physiological telemetry with high-performance edge-to-cloud metrics.

2022



Green Foundations  
SCI Specification [13]  
Carbon Intensity APIs

2023



Infrastructure Shifting  
Time/Location Shifting [21]  
Carbon-Aware Networks

2024



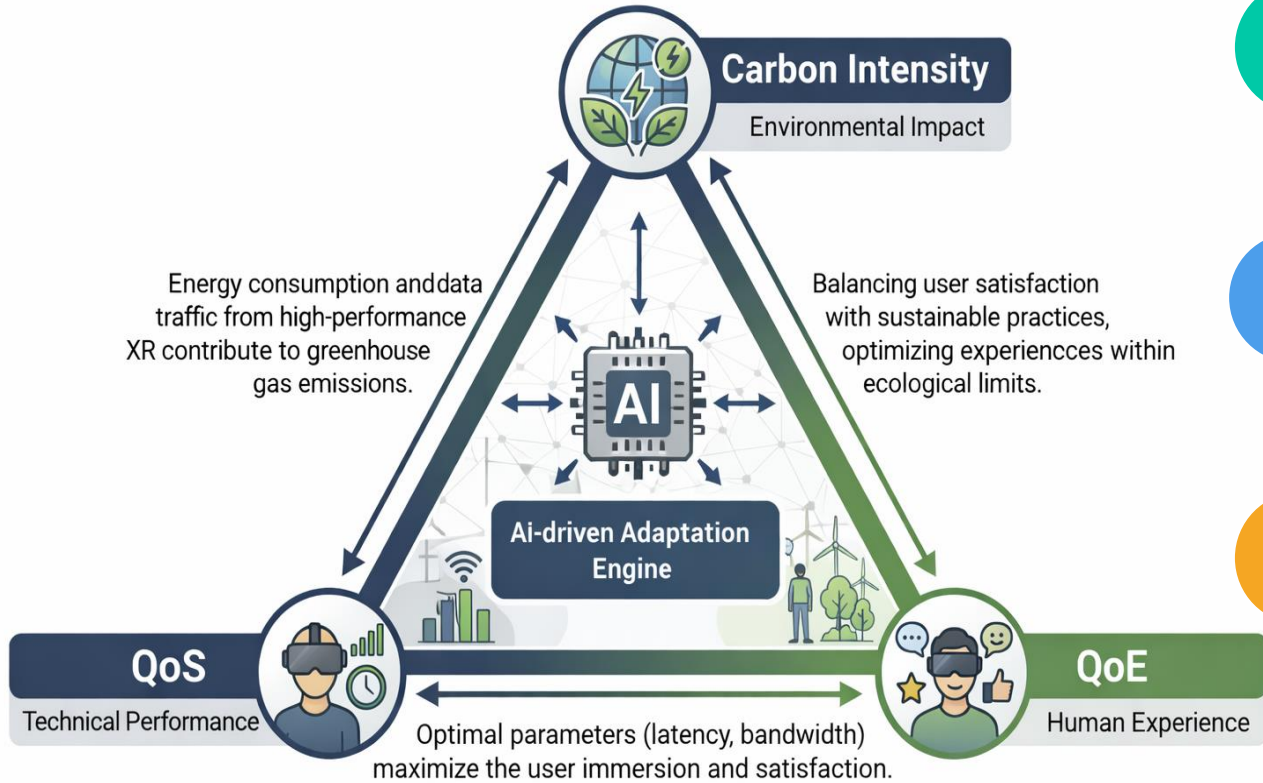
Software Adaptation  
VE Footprint [14]  
OS-level Daemon (Carbond) [20]

2025



Human-Centric Continuum  
XR5.0 Architectures [15]  
DRL Scheduling & TAO [17,18]

# Our Proposition: From the VR Triangle to the XR Triangle



## Sustainable VR Triangle

- CI Carbon Intensity**  
Environmental cost of computation — carbon emissions from VR device, edge nodes, and cloud infrastructure combined in real time.
- QoS Quality of Service**  
System technical performance: latency below 20ms, stable bandwidth, and smooth frame delivery across the compute continuum.
- QoE Quality of Experience**  
User immersion: presence, visual fidelity, and comfort measured via gaze tracking, EEG, and physiological signals.

# Our Proposition: From the VR Triangle to the XR Triangle

CE

## Computational Efficiency

The AI Software Vertex: Focuses on leveraging on-device AI for efficient local processing and thermal management.

HTE

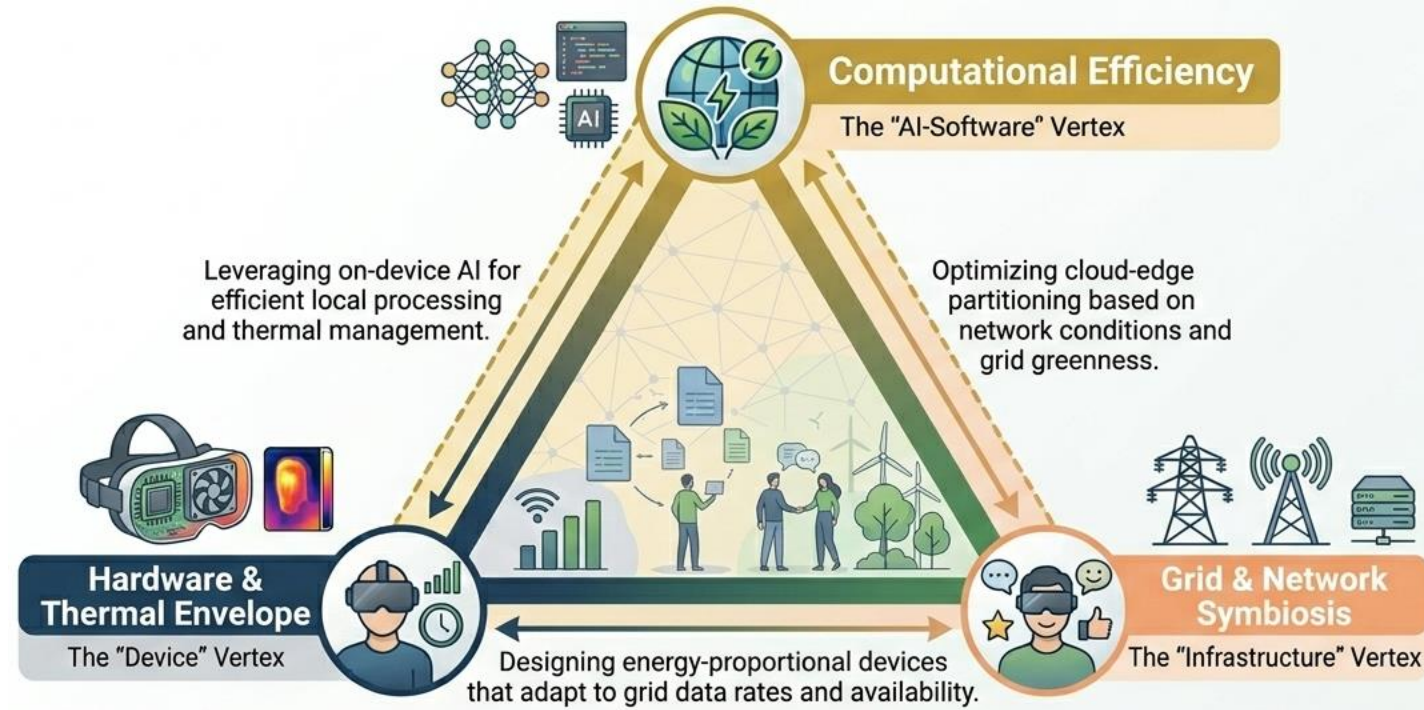
## Hardware and Thermal Envelope

The Device Vertex: Focuses on designing energy-proportional devices that dynamically adapt to grid data rates and availability.

GNS

## Grid and Network Symbiosis

The Infrastructure Vertex : Focuses on optimizing cloud-edge partitioning and resource offloading based on network conditions and grid greenness.



## Sustainable XR Triangle

# Resource Mapping and Sustainable Performance Metric



$$SPM = \frac{F * S}{E + \beta * CI}$$

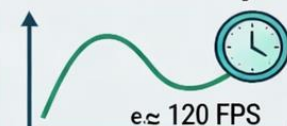
Scenario	Primary Vertex Priority	Trade-Off
High-End Gaming	Fidelity	High energy draw (active cooling)
Virtual Meetings	Infrastructure	High compression (cloud-side AI)
AR Navigation	Efficiency	Lower frame rate (battery saving)

**F - Perceived Fidelity**



Visually rich, sharp rendering

**S - Frame Stability**



Consistent frame rates, no lag



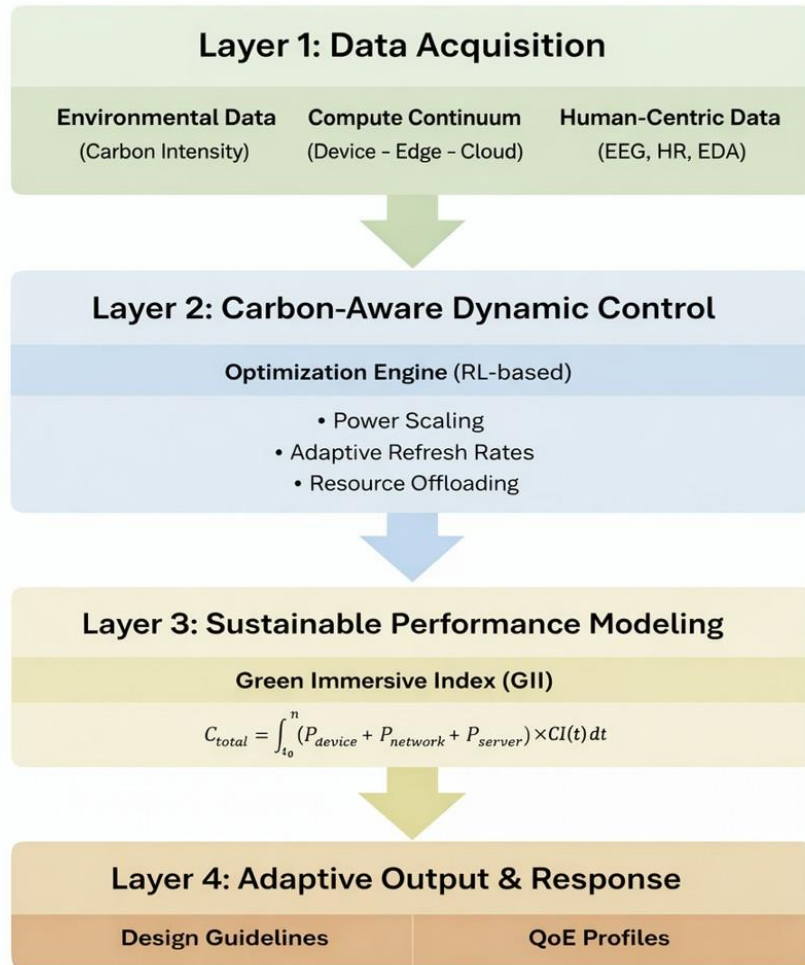
**E - Total Energy Consumption**  
Aggregated power use across continuum



**CI - Carbon Inttensity**  
Associated real-time carbon emissions

*Bridging Energy (E), Performance (P), and Experience (QoE)*






# Proposed carbon-aware VR framework



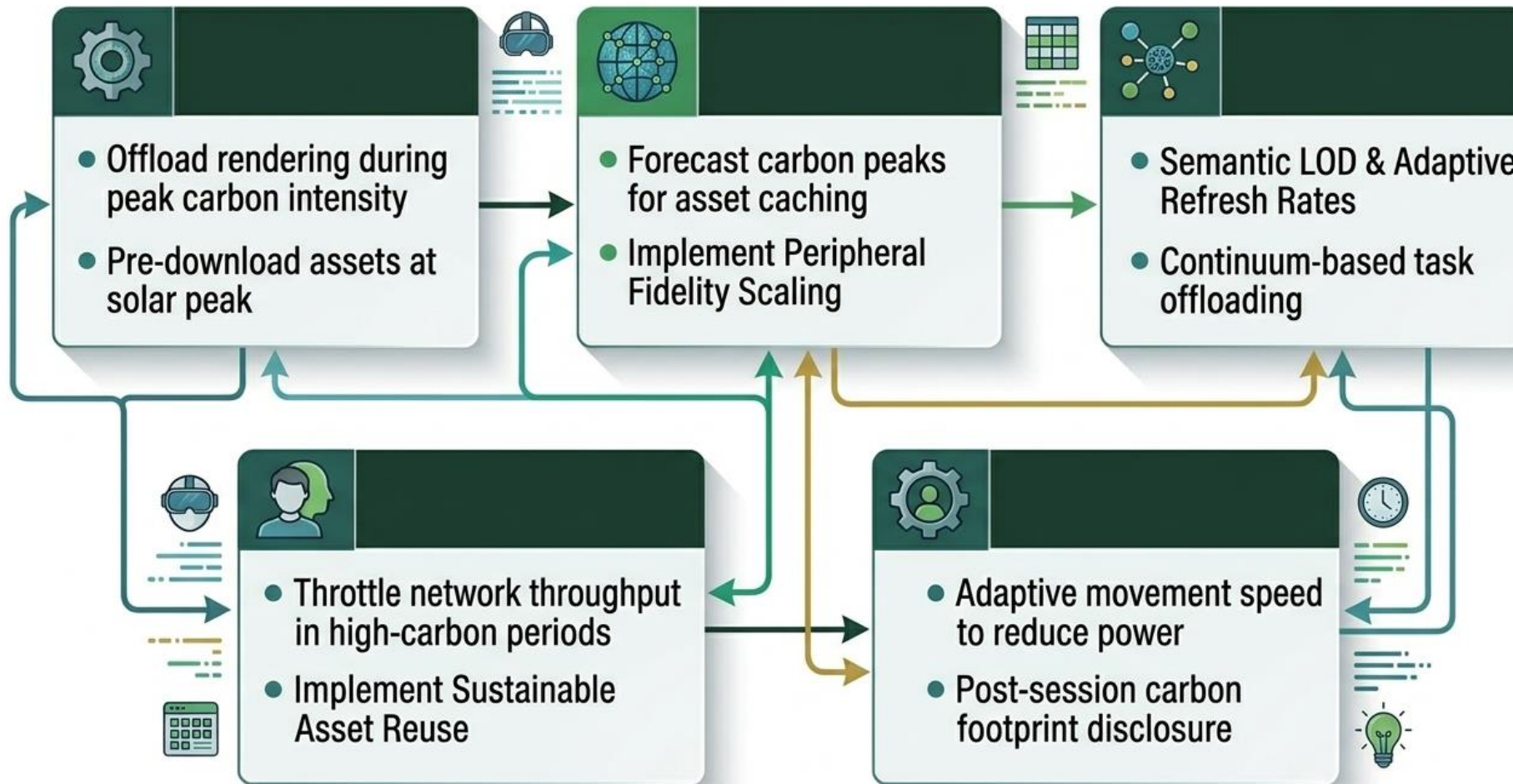
- **Layer 1:** Multi-Source Data Acquisition captures energy consumption across the compute continuum, including VR devices, edge/network infrastructure, HPC servers, and cloud-based carbon intensity sources.
- **Layer 2:** Carbon-Aware Dynamic Control leverages user-centric signals (e.g., gaze or physiological data) to adapt rendering strategies such as power scaling and refresh rate adjustment.
- **Layer 3:** Sustainable Performance Metrics introduces a Green Immersive Index to quantify the trade-off between energy consumption and QoE
- **Layer 4:** Output links system performance and QoE to derive carbon-fidelity trade-offs, enabling adaptive XR operation between eco-efficient and high-performance modes.

# Design Guidelines for Carbon-Aware XR

## Executive Summary of Strategic Adaptations across the Computing Continuum

CATEGORY	CORE GUIDELINE	PRACTICAL APPLICATION EXAMPLE
 <b>Intelligence</b>	Carbon-Aware Scheduling	Delay high-fidelity physics or offload rendering tasks to remote cloud instances when local grid intensity (\$CI\$) spikes.
 <b>Visuals</b>	Semantic LOD & Refresh Rate	Drop peripheral backgrounds to 720p using eye-tracking (Foveated Rendering) and dynamically adjust display rate from 120Hz to 72Hz.
 <b>Continuum</b>	Compute-Network Balancing	Shift heavy processing tasks seamlessly from headset to edge/cloud; throttle rendering bitrates during peak carbon hours.
 <b>Social</b>	Eco-Collaborative Spaces	Compress multiplayer avatar tracking packets; render distant players as 2D billboards; shift environments to "Eco-Amber" lighting.
 <b>User Experience</b>	Transparent Disclosure	Provide transparent post-session carbon footprints; lower sensor tracking rates or utilize teleport locomotion to preserve battery life.

# Methodological Implementation



# Discussion

- **Shift from Infrastructure to Human Experience:** Research has evolved from early energy-focused software specifications to human-centric architectures that prioritize the user's Quality of Experience (QoE).
- **The State-of-the-Art Integration Gap:** A persistent gap remains because traditional Green IT concentrates heavily on energy reduction ( $E$ ), whereas Industry 5.0 and so on emphasizes user experience.
- **Need for Multi-Metric Orchestration:** Few frameworks link real-time physiological data with edge-to-cloud performance metrics across the computing continuum.

# Conclusion and Further Work

- **Framework Validation:** The framework successfully maps the technical, environmental, and experiential trade-offs of XR systems using the Sustainable VR Triangle model.
- **Dynamic Optimization:** Future efforts will implement reinforcement learning agents to adaptively tune system parameters using real-time physiological and grid metrics.
- **Lifecycle Scope:** Upcoming research aims to incorporate embodied emissions and multi-stage lifecycle metrics across the entire compute continuum.



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