Carbon-Aware VR

Sustainable Performance Through Human-Centric Computing Continuum

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Context

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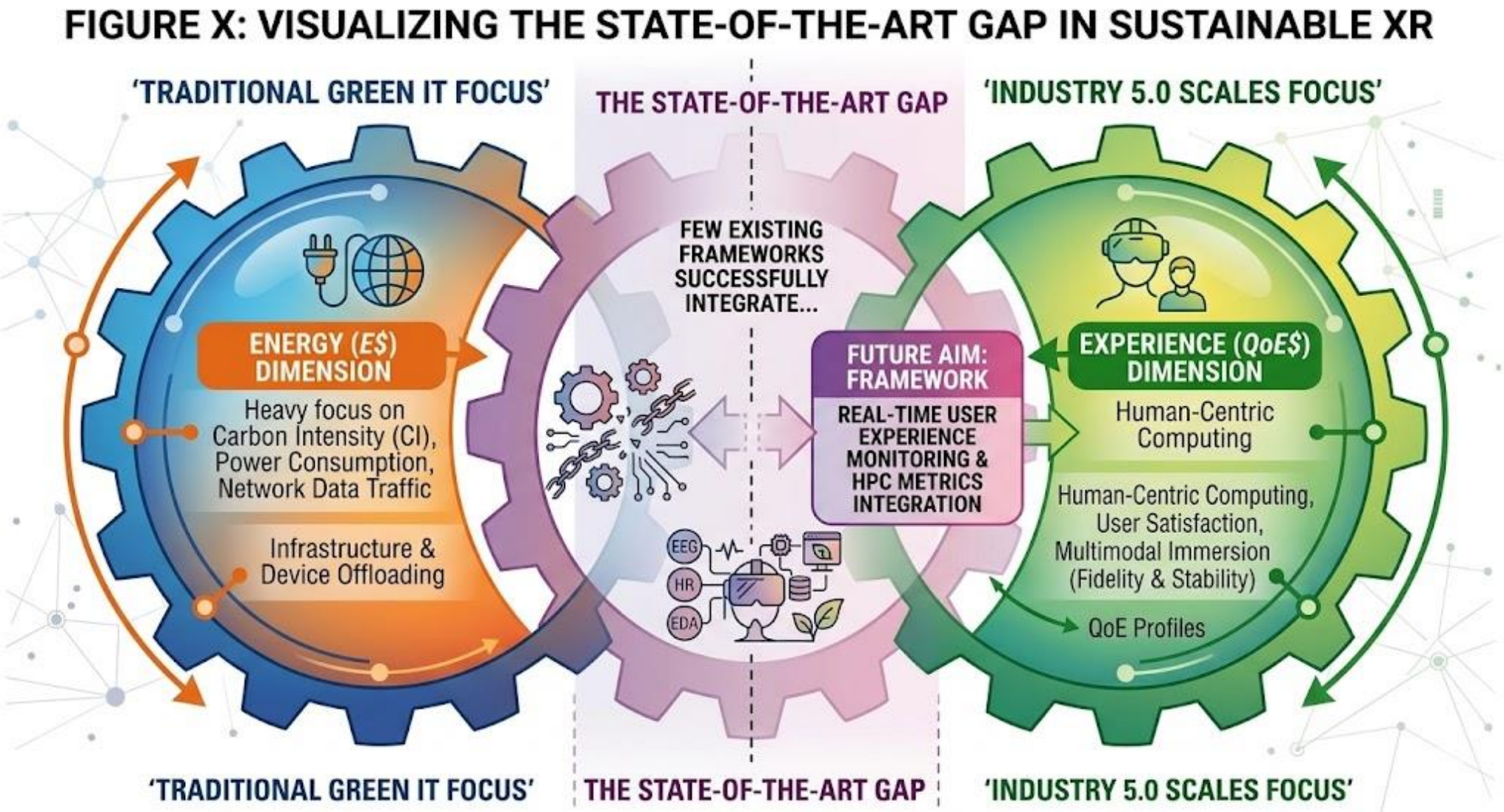
Background



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Background

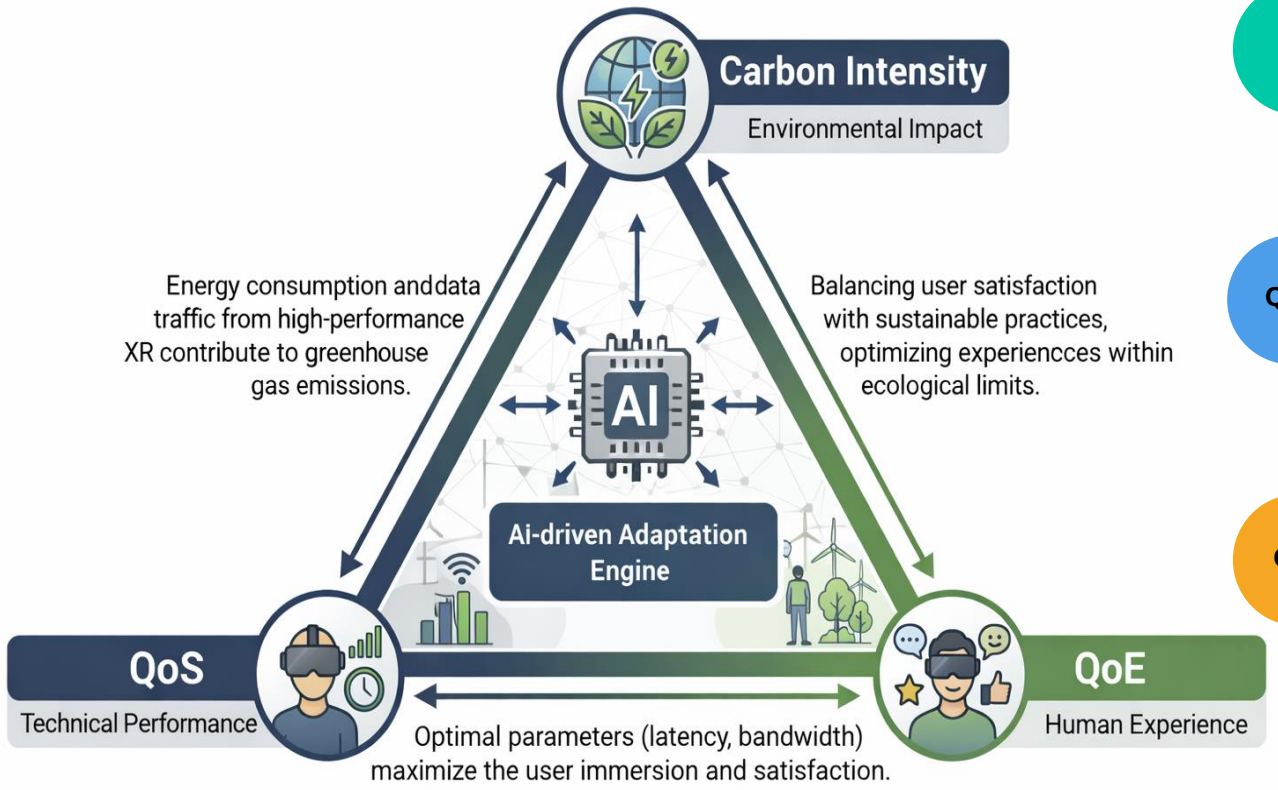
EVOLUTION OF SUSTAINABLE XR RESEARCH

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

Our Proposition:
From the VR Triangle to the XR Triangle



Soustainable 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

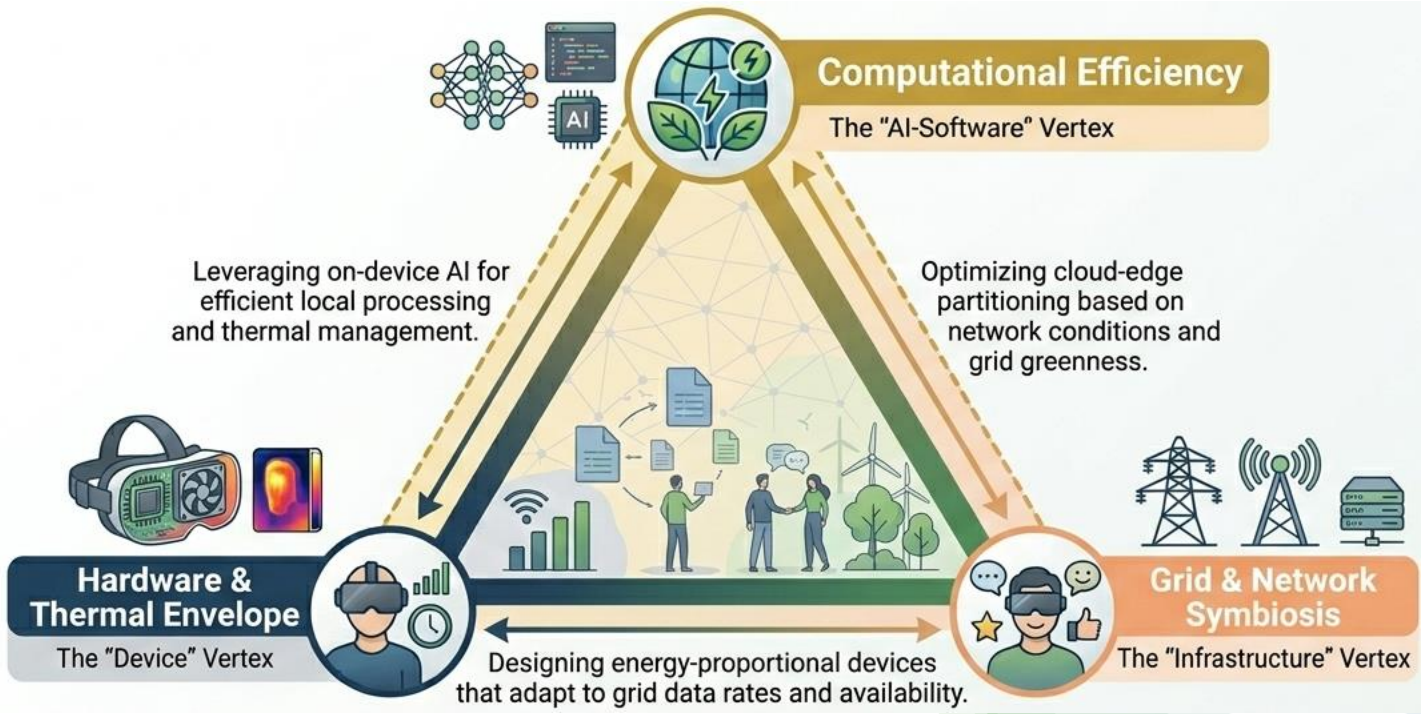
Hardware and Thermal Envelope

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

GNS

Grid and Netwrok Symbiosis

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



Soustainable 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

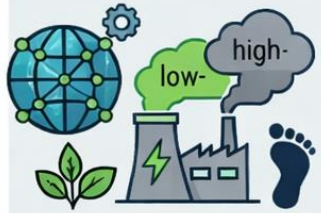
Visually rich, sharp rendering

S - Frame Stability

Consistent frame rates, no lag

E - Total Energy Consumption

Aggregated power use across continuum

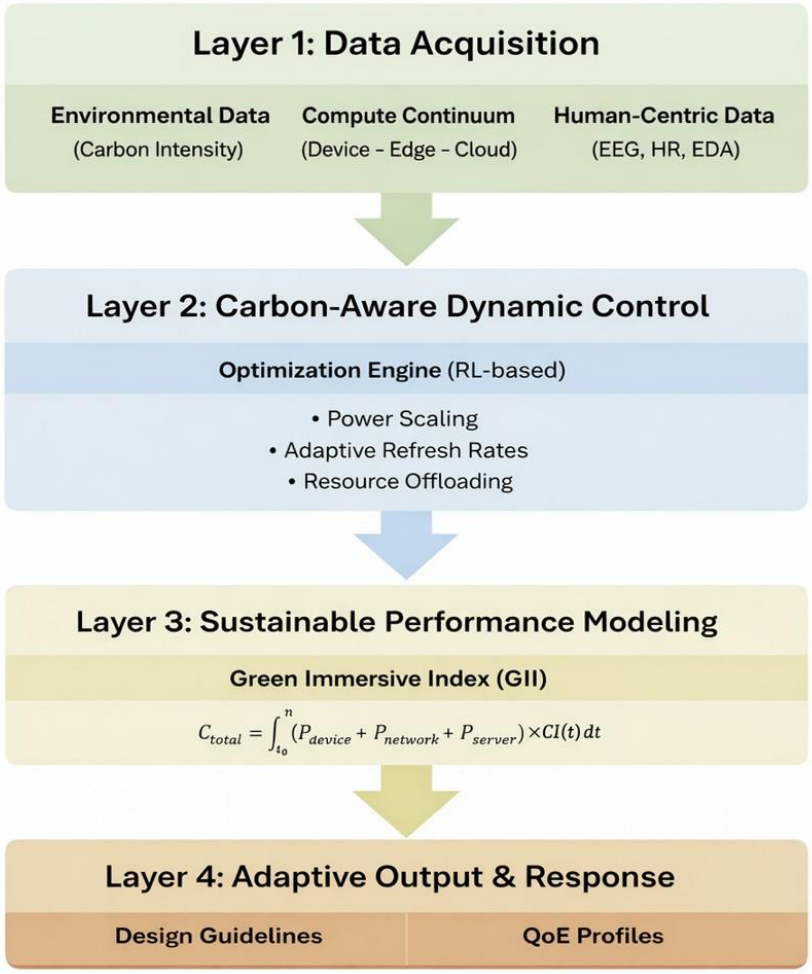


CI - Carbon Inttensity

Associated real-time carbon emissions

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

Proposed carbon-aware VR framework



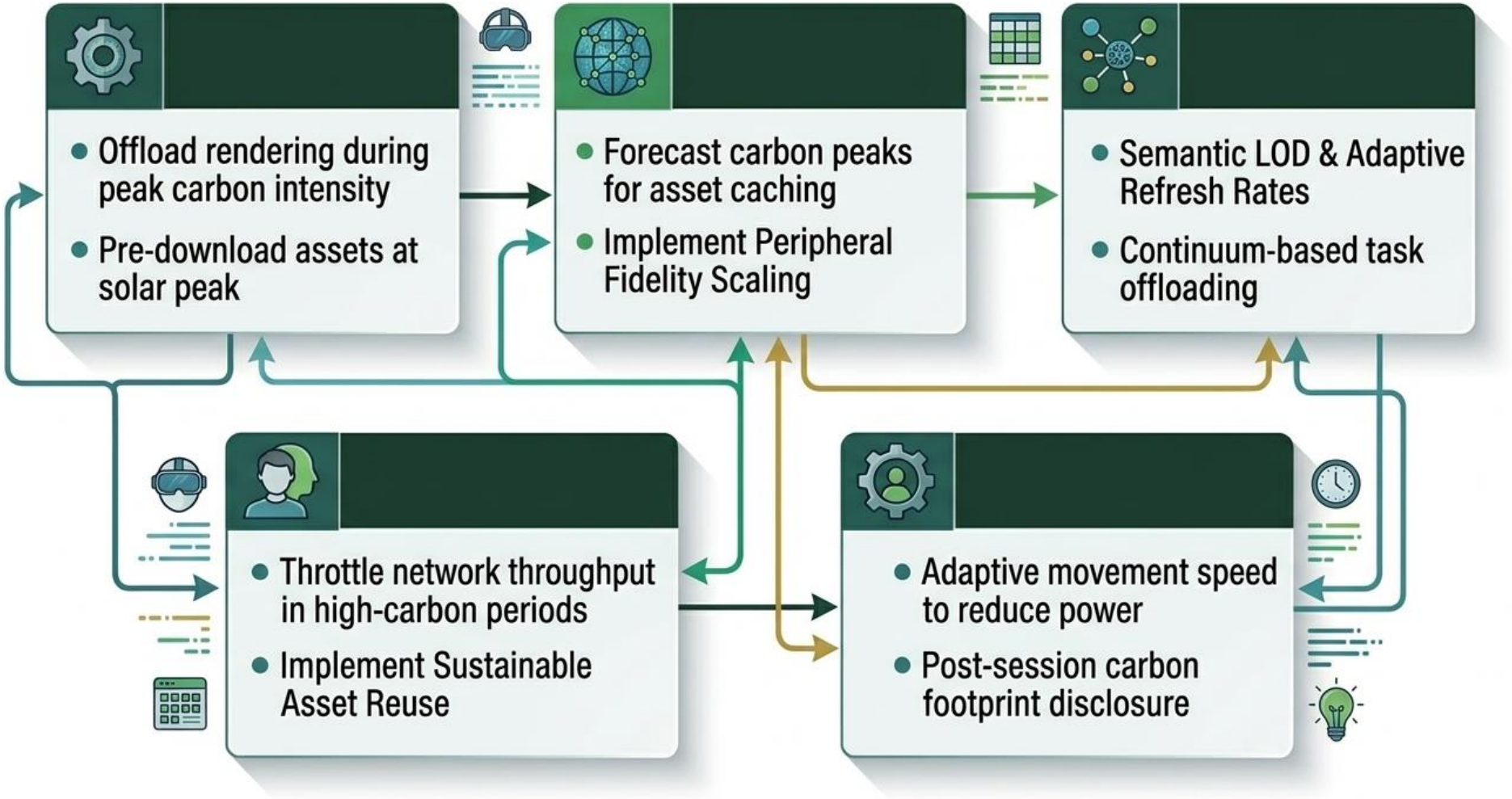
- **Layer 1**: Multi-Source Data Acquisition captures energy consumption across the compute continuum, including VR devices, edge/network infrastructure, HPC servers, and cloud-based carbon intensity sources.
- **Layer 2**: Carbon-Aware Dynamic Control leverages user-centric signals (e.g., gaze or physiological 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
Intelligence	Carbon-Aware Scheduling	Delay high-fidelity physics or offload rendering tasks to remote cloud instances when local grid intensity (CI) spikes.
Visuals	Semantic LOD & Refresh Rate	Drop peripheral backgrounds to 720p using eye-tracking (Foveated Rendering) and dynamically adjust display rate from 120Hz to 72Hz.
Continuum	Compute-Network Balancing	Shift heavy processing tasks seamlessly from headset to edge/cloud; throttle rendering bitrates during peak carbon hours.
Social	Eco-Collaborative Spaces	Compress multiplayer avatar tracking packets; render distant players as 2D billboards; shift environments to "Eco-Amber" lighting.
User Experience	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.

sighpc computing continuum

https://sighpc-continuum.acm.org/

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