Consequential and Attributional Life Cycle Assessment in Streaming Media Sustainability

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Greening of Streaming's WG1 explores standard industry terms related to sustainability.

Abstract

This paper examines the critical distinction between Attributional (ALCA) and Consequential (CLCA) Life Cycle Assessment approaches in the context of streaming media sustainability.

While both approaches aim to assess environmental impact, they serve fundamentally different purposes and can lead to dramatically different conclusions. ALCA provides a static snapshot of how environmental impacts are distributed among current activities, while CLCA examines how systems respond to changes.

We demonstrate why this distinction matters for streaming media sustainability through industry examples, mathematical models, and practical case studies. We explore how conflating these approaches can lead to misleading conclusions and ineffective actions, particularly in complex systems like content delivery networks and telecommunications infrastructure.

Our analysis reveals that while ALCA remains useful for regulatory compliance and reporting, CLCA becomes essential for driving meaningful environmental improvements in streaming media systems. This understanding is crucial for network engineers, system architects, and sustainability teams working to reduce the environmental impact of streaming services.

The paper concludes with practical recommendations for moving the industry toward more effective environmental assessment and improvement strategies.

Keywords: Sustainability, Streaming Media, Life Cycle Assessment, Environmental Impact, Network Infrastructure, Content Delivery Networks

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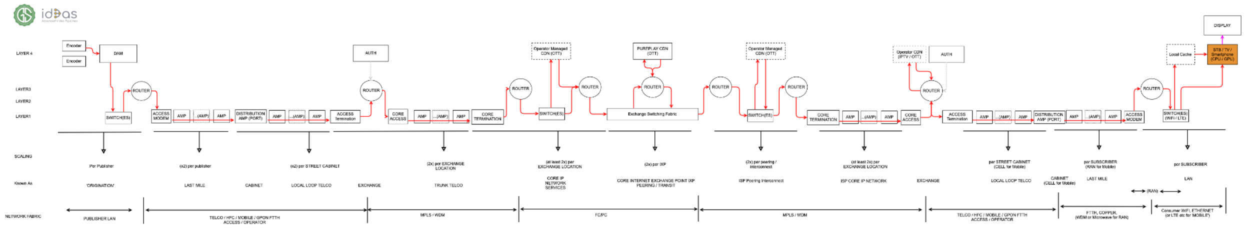
1. Introduction

As the streaming media industry confronts its environmental impact, a crucial distinction has emerged in assessing and understanding our environmental footprint. Two approaches to life cycle assessment (LCA) have come to the forefront: attributional LCA (ALCA) and Consequential LCA (CLCA). The difference between these approaches isn't merely academic—it fundamentally shapes how we measure, communicate, and address environmental challenges in our industry.

The history of these approaches offers essential context. ALCA emerged as the dominant framework partly through major energy companies' efforts to shift environmental responsibility to consumers. This mirrors BP's promotion of the "carbon footprint" concept—a strategy that effectively individualised fundamentally systemic challenges. Understanding this history is crucial as our industry develops its approach to sustainability assessment.

This document represents the culmination of a year's worth of monthly discussions within Working Group 1 of Greening of Streaming. Through purposefully unstructured conversations, we've explored how these terms are used, misused, and often conflated within our industry. We aim to develop a more precise understanding that can guide engineers and decision-makers in integrating sustainability into streaming media systems.

The following diagram illustrates the scope of streaming infrastructure that Greening of Streaming is attempting to measure. It incorporates the multiple layers of networking, routing and streaming applications (including encoding, caching and decoding) that underpin the delivery of a streaming service.



2. Understanding ALCA and CLCA

The distinction between Attributional and CLCA lies at the heart of how we approach environmental impact measurement in streaming media. These two methodologies serve different purposes and lead to varying insights about our industry's environmental impact.

ALCA provides what might be considered a snapshot—a static picture of environmental impacts at a particular moment. When applied to streaming media, ALCA examines the energy consumption and emissions associated with delivering specific content, considering everything from data centre operations to transmission infrastructure and end-user devices.

This approach appeals to our desire for clear, quantifiable metrics and straightforward accountability. However, ALCA's simplicity comes with significant limitations. By focusing on direct attribution of impacts, it can miss the complex ways our systems operate and evolve. Think of it as trying to understand a city's traffic patterns by counting cars at a single intersection—useful information but far from the complete picture.

CLCA takes a fundamentally different approach. Rather than attempting to divide existing impacts among current activities, CLCA asks a different question: "What changes in environmental impact will result from our actions?" This approach considers system-wide effects, technological evolution, and behavioural changes. In the streaming context, this means examining how changes in streaming patterns affect infrastructure needs, drive technology adoption, and influence user behaviour.

The relationship between these approaches is complex and often misunderstood. While both might use similar data sources, they serve fundamentally different purposes. ALCA helps us understand where we are and supports regulatory compliance and standardised reporting. CLCA, on the other hand, helps us understand where we're going and what actions will truly make a difference.

Furthermore, CLCA itself can be understood in two timeframes. Short-term consequential analysis examines immediate effects within existing infrastructure—similar to understanding how traffic patterns might change if we adjust traffic light timing. Long-term consequential analysis considers broader systemic changes—like understanding how new transportation technologies might reshape city planning. Both perspectives are valuable, but they answer different questions.

The streaming industry's challenge lies in understanding when and how to apply each approach. ALCA's simplicity makes it attractive for reporting and communication, but the limitations of extrapolation based on estimation and lack of broader context and view over time can lead us astray if we rely on it exclusively for decision-making. CLCA's complexity makes it harder to communicate and implement, but its accurate insights are essential for making meaningful - consequential - progress toward sustainability goals. The industry needs feedback data based on measured information to avoid steering by guesswork and estimation.

3. The Mathematics Behind Impact Assessment

While mathematical models can help clarify the relationship between ALCA and CLCA, it's crucial to understand that numbers should follow, not lead, our understanding of environmental impacts. Through our discussions with environmental scientists, we've learned that starting with qualitative mapping of consequences often yields better insights than immediate quantification.

Nevertheless, mathematical expressions can help illustrate how these approaches differ.

In its simplest form, ALCA can be expressed as a sum of inventory data, I (such as energy consumption, hardware resources, or network capacity) multiplied by allocation factors, A (the proportion of shared resources attributed to a specific activity, like the percentage of a server's total capacity used by a particular stream). This straightforward calculation reflects ALCA's focus on dividing existing impacts among current activities. The maths looks deceptively simple: multiply what exists by who's responsible for what share:

$$\text{ALCA}_{\text{impact}} = \sum_{i=1}^{n} (I_i \cdot A_i)$$

CLCA's mathematical expression builds on this foundation but adds crucial elements that capture system dynamics. Beyond the basic allocation of current impacts, it incorporates changes in inventory and allocation factors as well as external influences such as policy changes and technological advancements. This more complex formula reflects CLCA's attempt to capture the full scope of how systems respond to changes:

$$\text{CLCA}_{\text{impact}} = \sum_{i=1}^{n} (I_i \cdot A_i) + \sum_{j=1}^{m} (\Delta I_j \cdot \Delta A_j) + \sum_{k=1}^{p} E_k$$

However, these mathematical models come with important caveats. Real-world data often needs more granularity than neat equations suggest. Complex feedback loops resist simple quantification. Economic and behavioural factors introduce variables that don't fit neatly into mathematical expressions. The models serve best as frameworks for thinking rather than precise predictive tools.

You can look at this paper for a more comprehensive approach: Heijungs, R. (2015). Some fundamentals on ALCA and CLCA. In I. Blanc (Ed.), EcoSD Annual Workshop. Consequential LCA 2013 (pp. 41-48). Presses des Mines, which you can read here (from page 41).

4. The Bus Analogy: Making It Real

To understand the practical difference between ALCA and CLCA, consider a simple example: commuting by bus. Through an attributional lens, if you typically take the bus five days a week and decide to work from home for two of those days, you might claim a 40% reduction in your transportation-related emissions. The math seems straightforward—you're using the bus 40% less, so surely your impact has decreased by that amount.

But the consequential perspective reveals a different story. The bus continues its route whether you're on it or not. The driver still drives, the engine runs, and the fuel burns. Your decision to stay home two days a week creates no meaningful reduction in emissions unless enough other people make similar changes to affect the bus schedule or route planning.

This analogy illuminates several crucial points about assessing the environmental impact of streaming media. First, it demonstrates how individual actions that appear significant through an attributional lens might have minimal real-world implications. Second, it shows how meaningful change often requires coordinated action at a system level. Finally, it highlights the importance of understanding our choices' immediate and long-term consequences.

The bus analogy also reveals why ALCA, while easier to communicate and calculate, can lead to misconceptions about the effectiveness of individual actions. When we tell people they can reduce their carbon footprint by 40% by working from home two days a week, we're not technically wrong—but we're not telling the whole truth either. The same challenge appears in streaming media when we suggest that individual viewers can significantly reduce their environmental impact by lowering their streaming quality or watching less content.

For policymakers, corporate strategists, ESG leaders, and broader economic modelling purposes, ALCA can provide early indication and guidance about where to conduct deeper research, focus efforts and explore engineering efforts. However, ALCA only includes part of the picture to measure impact. All too often, estimation becomes treated as an ‘actual’ measurement of CLCA. Estimating is not actionable feedback data for engineers attempting to implement demonstrable changes.

Despite this essential requirement for real data, the network industry, somewhat ironically, lacks any network energy telemetry at all today!

5. Streaming Media: Where Theory Meets Practice

The streaming media industry presents a unique laboratory for understanding these concepts in practice. Our infrastructure combines long-term fixed assets with dynamic resource allocation, shared resources with individual consumption, and global scale with local delivery. This complexity makes both attribution and consequential assessment challenging but also illuminating.

Consider the rollout of 5G networks. The industry promotes 5G as a more efficient technology, offering ten times the traffic capacity of 4G while using only four to five times more power. Through this lens, once fully utilised, 5G should deliver better efficiency per stream. However, a broader analysis reveals a more concerning story. Current 5G networks show significant underutilisation (around 89%) compared to 4G networks (which operated at about 80% utilisation).

This means that while 4G networks efficiently serve 80Mbps using one unit of power, 5G networks currently deliver only about 110Mbps using four to five units of power. The networks have been dimensioned for anticipated traffic growth that has yet to materialise, leading to significant inefficiencies in current operations. While we've seen positive patterns of technology improvement in other areas (from 2012 to 2022, optical router capacity increased tenfold while power consumption halved), the 5G rollout demonstrates how focusing solely on theoretical efficiency can mask real-world energy implications when systems are underutilised.

The Content Delivery Network (CDN) landscape offers another illuminating example of how ALCA and CLCA perspectives lead to different insights. Through an attributional lens, reducing video bitrates creates direct energy savings. Lower-quality streams mean less data transferred, which should mean less energy consumed. This straightforward relationship makes for compelling sustainability messaging but misses crucial system dynamics.

A consequential analysis reveals that base load—the energy required to keep systems running regardless of traffic—typically accounts for most total power consumption. The difference between idle and full load might be as little as a few percent. This means that reducing individual stream quality often has little actual effect on energy consumption unless the changes are substantial enough to affect infrastructure deployment decisions over time, illustrating the difference between short and long-term CLCA.

Furthermore, the relationship between traffic and power consumption isn't linear. CDNs can employ sophisticated load concentration strategies, shifting traffic between servers to optimise efficiency. Successfully implemented, these strategies can maintain high efficiency even with varying traffic levels. However, this sophistication makes it harder to attribute specific energy consumption to individual streams or users.

The Challenge of Data Quality

Underlying both approaches is a fundamental challenge: the quality and availability of data. Most current models rely on secondary data sources, with real-time energy measurements being rare and CDN/infrastructure data challenging to access. What might appear as precise figures in sustainability reports often derive from laboratory measurements or theoretical calculations and extrapolation rather than real-world operations.

This data challenge affects different stakeholders in different ways:

- Network engineers need detailed, real-time data to optimise operations.
- System architects need reliable benchmarks to guide design decisions.
- Sustainability teams need verifiable metrics to report progress.

Greening of Streaming has begun addressing these gaps, starting with live streaming measurements where the synchronised nature of the delivery stack makes measurement more straightforward.

6. The Communication Challenge

Where do the differences between attributional and consequential approaches become more apparent than in sustainability messaging? The streaming industry faces a complex challenge: communicating environmental impact and progress in accurate and actionable ways.

The Attribution Trap

The attributional approach leads naturally to simple, compelling messages: "Reducing your streaming quality saves X amount of carbon" or "Your one-hour video stream equals driving Y kilometres." These comparisons make for effective headlines and seem to offer clear paths for individual action. However, they often oversimplify complex relationships and can promote actions that have minimal real-world impact.

This oversimplification mirrors historical corporate strategies to shift environmental responsibility to consumers. Just as oil companies promoted individual carbon footprints to deflect attention from systemic issues, there's a risk that focusing on individual streaming habits could distract from more meaningful industry-wide improvements.

The Complexity of Consequence

While more accurate, consequential thinking presents significant communication challenges. System interactions are more challenging to explain. Benefits may materialise over the years rather than immediately. Individual actions matter only when aggregated at scale. These nuances make for less compelling headlines but better decision-making.

The key lies in communicating complex systems thinking without overwhelming audiences. This might mean starting with qualitative consequence mapping, using visual representations of system relationships, and clearly distinguishing between individual and collective action.

The Utilisation Paradox

One of the most challenging concepts to communicate is the relationship between utilisation and efficiency. Higher system utilisation often means better efficiency, but this counterintuitive reality doesn't fit neatly into simple sustainability messages. Similarly, reduced usage doesn't necessarily save energy if infrastructure remains powered on. Infrastructure upgrades might increase immediate power use while improving long-term efficiency, but only if the projected utilisation materialises. This is particularly evident in streaming infrastructure, where new technologies are often deployed based on anticipated growth that may not emerge.

The 5G example demonstrates this clearly - while the technology promises better efficiency at full utilisation, the reality of significant underutilisation means we often use more energy to deliver similar services. This challenges the common industry narrative that newer infrastructure leads to better environmental outcomes and highlights the importance of accurate capacity planning and utilisation forecasting when making infrastructure decisions. The reality is that overprovisioning of capacity, even with theoretically more efficient technology, can result in worse environmental outcomes than maintaining well-utilised legacy systems.

7. Time, Technology, and Trends

The temporal dimension adds another layer of complexity to environmental impact assessment in streaming media. While attributional approaches provide useful snapshots, understanding trends and temporal relationships becomes crucial for meaningful environmental improvement.

The technology improvement cycle in streaming infrastructure tells a compelling story about the importance of temporal context. Consider that in 2012, a one-terabit optical router consumed approximately 800 watts of power. By 2022, a ten-terabit router used only 400 watts. This represents not just an improvement in efficiency but a fundamental transformation in the relationship between capacity and energy consumption. Such dramatic improvements complicate attributional and consequential assessments, as today's measurements might poorly predict tomorrow's impacts.

The industry also experiences various tipping points—moments when quantitative changes in one aspect of the system lead to qualitative changes in behaviour. These might be technical, such as when traffic growth necessitates infrastructure upgrades, or market-driven, such as mass adoption of new streaming formats. Identifying and anticipating these tipping points becomes crucial for environmental planning.

8. Stakeholder Implications

For network engineers, the priority becomes understanding and optimising baseline efficiency. This means looking beyond simple traffic-to-energy ratios to understand system dynamics under varying conditions. It means implementing sophisticated load concentration capabilities and developing more nuanced approaches to capacity planning. Real-time energy monitoring becomes crucial, not just for reporting but for active system optimisation.

Architects face the challenge of designing efficient systems across varying load conditions in streaming media systems. This requires moving beyond simple quality adaptation strategies to consider the impact of architectural decisions on the whole system. Load distribution, caching hierarchies, and failover mechanisms need to be evaluated for their operational effectiveness and environmental impact.

Sustainability and ESG teams perhaps face the most significant challenge in bridging the gap between attributional and consequential approaches. They must develop frameworks that satisfy reporting requirements while driving meaningful improvement. This means maintaining clear distinctions between different types of metrics, ensuring transparent methodology, and developing stakeholder-specific communication strategies.

Business leaders need to understand how environmental considerations affect both short-term operations and long-term strategy. This means looking beyond simple efficiency metrics to understand how investment decisions affect system-wide environmental impact. It means considering how economic factors influence environmental outcomes and how environmental considerations affect competitive position.

9. The Path Forward

As the streaming media industry evolves, the distinction between attributional and consequential approaches becomes increasingly essential. While attribution provides valuable metrics for reporting and compliance, consequential thinking becomes essential for driving meaningful improvement.

Several key actions can help the industry move forward effectively:

First, we need better measurement. This means installing real-time energy monitoring across infrastructure, developing standardised measurement methodologies, and creating frameworks for industry-wide data sharing. It means moving beyond laboratory measurements to understand real-world system behaviour.

Second, we need a better understanding. This means developing comprehensive consequence maps for streaming systems, understanding system interactions, and building better models of how changes affect outcomes. It means considering both the short-term and long-term impacts of decisions.

Third, we need better collaboration. The challenges we face transcend individual organisations. Sharing data, developing common standards, and working together on solutions becomes crucial for meaningful progress.

The streaming media industry is at a crucial juncture in its sustainability journey. While attributional thinking has dominated environmental reporting, moving toward consequential understanding becomes essential for meaningful improvement. This shift requires new tools, metrics, and ways of thinking about environmental impact.

Success will require unprecedented collaboration across the industry, transparent sharing of data and insights, and a commitment to long-term systemic improvement rather than short-term individual actions. The path forward is complex but necessary to ensure sustainable growth of streaming media services.

As we move forward, we must remember that neither attributional nor consequential approaches alone provide complete answers. Instead, they offer complementary perspectives that can help guide the industry toward genuine environmental improvement when properly understood and applied. The challenge lies not in choosing between them but in understanding how to use each appropriately to pursue meaningful sustainability goals.