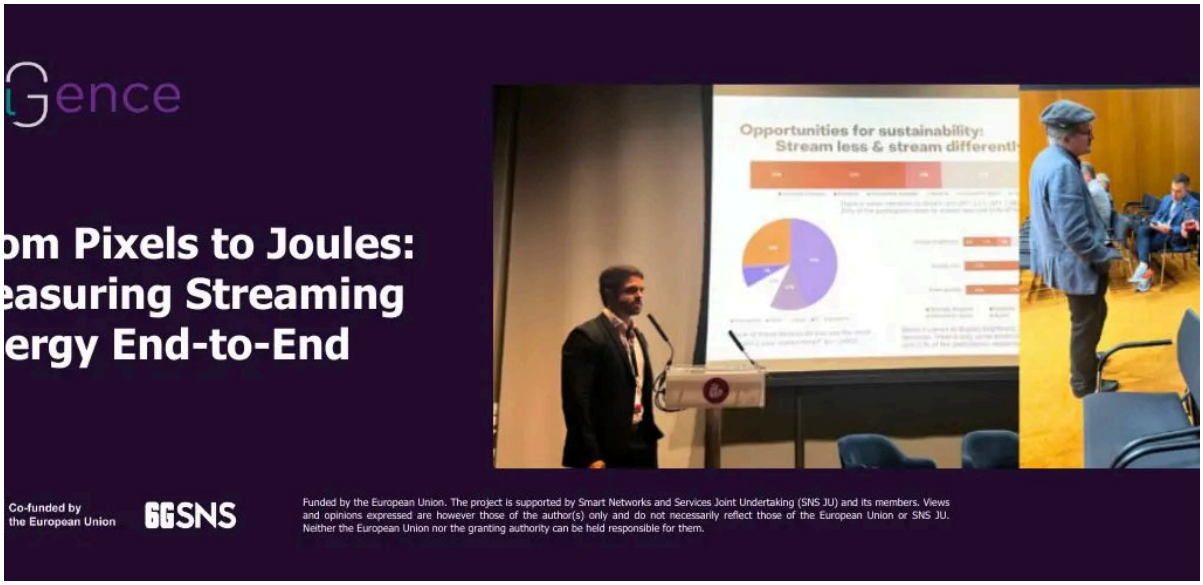
From Pixels to Joules: Measuring Streaming Energy End-to-End

Data Collection, Energy Measurements, Energy Metrics December 14, 2025



Video streaming has become a very common way to relax, learn and connect. From short clips on our phones to full-length series on smart TVs, video is now a central part of the digital experience. But this convenience comes with a hidden cost: energy consumption across a complex chain of devices and networks that most of us never see.

At TNO, we believe that making this energy visible, in a credible, understandable and transparent way, is a key step toward reducing the environmental footprint of digital media. On Sunday 14 September at IBC (RAI Amsterdam), Jesús Martínez de Juan (TNO Networks) presented "End-to-End Energy Monitoring during Video Streaming" during a session organized by Greening of Streaming (GoS), an industry organization of which TNO is an active member. IBC (International Broadcasting Convention) is one of the world's leading events for the media, entertainment and technology industry, attracting more than 40,000 visitors annually.

The presentation brought together results and insights from two complementary TNO efforts: ERP Sustainable ICT and EXIGENCE. This blog post expands on that story. Instead of focusing only on the conference moment, we explore the larger topic: how combining behavioural insights with real measurement technology can help both industry and consumers make streaming more sustainable.

Why End-to-End Energy Monitoring Matters

If you ask someone how much electricity is used when they press play on a video, the most honest answer is: "it depends" and "we usually don't know". The energy impact of a single viewing session is distributed across multiple parts of the delivery chain:

1. **End-user device:** A smartphone, tablet, laptop or TV must decode and display the content. Screen size, brightness, video codec and hardware acceleration can significantly change the energy required to play the same video.
2. **Network:** Whether content travels over Wi-Fi, 4G/5G or fixed broadband, the network performs transmission, routing and control functions, each with its own energy footprint. In a mobile setting, both the Radio Access Network (RAN) and 5G Core play a role.
3. **Server/CDN:** Content is stored, transcoded and delivered from servers and CDNs that also consume energy depending on traffic volume and compute demand.

Because the footprint is spread across these layers, focusing on only one component risks missing the real story. A "greener device" does not guarantee greener streaming if network energy dominates in a given scenario. Similarly, improving network efficiency may not have the expected effect if device playback settings remain the main driver.

That's why end-to-end monitoring is a key step for credible sustainability claims: it helps answer not only "how much energy is used?" but also "where is it used?" and "what choices reduce it?"

What ERP Sustainable ICT Tells Us About Behaviour

Technology alone won't solve the problem. People's habits like what they watch, how often, on which devices and at which quality settings, can materially shape energy demand.

Within ERP Sustainable ICT, TNO has been exploring consumer behaviour and the potential for change. The key message shared at IBC was optimistic and pragmatic: **There is clear potential to shift certain Dutch user streaming habits toward lower energy consumption, if the right incentives, information and user-friendly choices exist.**

This is important because it suggests that sustainability interventions don't have to feel punitive. The most promising approaches are likely to be:

- **Low-friction** (small changes, easy choices)
- **Benefit-driven** (better battery life, fewer data costs, smoother playback)
- **Visible** (showing users the impact of what they do)

In other words: **if people can see what a choice costs, they can decide when the higher-impact option is worth it and when it isn't**.

EXIGENCE: Turning Theory into Measurable Practice

While ERP Sustainable ICT helps identify behavioural levers, EXIGENCE focuses on the technical foundation needed to measure energy credibly across the chain. A recurring challenge in sustainability discussions about streaming is that energy estimates are often:

- too high-level to be actionable
- too fragmented to be credible outside a lab.

EXIGENCE addresses this by building a multi-layer measurement approach that combines:

- on-chip energy counters (where available)
- software attribution tools
- external metering for ground-truth and components that are otherwise "black boxes".

This combination helps bridge the gap between scientific accuracy and real-world feasibility.

A Simple Use Case that Makes the Point

The IBC presentation used a relatable example to show why end-to-end perspectives matter:

A user watches a short cat video on a smartphone via 5G. Even in this small scenario, measurement has to consider:

1. Video server/CDN
2. 5G network functions: Core + RAN
3. End user device

This is a deliberately simple framing, but the implications are important: multiply a small per-session footprint by millions of daily sessions and small improvements become meaningful at scale.

How the Measurement Approach Works

To avoid measuring only one piece of the puzzle, TNO's approach combines complementary tools that each cover part of the chain:

- **At the server: RAPL (hardware counters)**

On x86 servers, modern CPUs provide built-in energy telemetry. RAPL (Running Average Power Limit) exposes estimates of CPU and memory energy use. While RAPL does not cover an entire server's power draw (it focuses on silicon domains), it is valuable for tracking how compute intensity changes with different workloads or streaming configurations.

- **In the 5G Core: Kepler (workload attribution)**

In cloud-native environments, it's not enough to know that a server consumed energy: we need to know which workload drove it. Kepler is a Kubernetes-based exporter that helps attribute energy consumption to containers and pods using hardware counters and system metrics. This creates a pathway to link energy to specific network functions.

In the context of streaming, a key point is that the User Plane Function (UPF) is typically the most relevant 5G Core component for energy during active video traffic, because it carries the actual user data.

- **In the RAN: smart plugs (system-level reality)**

Some network components are not easily instrumented internally, especially when using commercial stacks. For these, external power metering remains a pragmatic and reliable choice.

Using a smart plug allows measurement of whole-device energy of RAN-related hardware. While this doesn't automatically provide per-user attribution, it gives a trustworthy system-level baseline that can be combined with controlled experiments and traffic correlation.

Why this Matters to Everyday Users?

A central idea in the talk (and one that resonates beyond the engineering audience) is that measurement can be turned into a clear cause-and-effect message.

In other words: **We aim to show the additional electricity YOU cause by playing that cat video.** That causal link is powerful. It moves the conversation from abstract sustainability targets to something tangible:

- "If I lower resolution, do I save energy?"
- "Does using Wi-Fi instead of 5G help?"
- "Is this choice worth it when I'm on the go?"

This doesn't mean the burden should fall entirely on users. But it does mean that transparent information gives everyone a lever, including platform designers, telecom operators and content providers.

What the IBC Audience Reacted to

One reason this work drew attention at IBC is that it connects multiple stakeholder perspectives:

- **Media and production** want credible sustainability stories.
- **Platform and CDN providers** want efficiency without hurting user satisfaction.
- **Telecoms** need tools to understand how traffic profiles translate into energy costs.
- **Researchers and standardisation communities** want methods that can be replicated and compared.

After the session, interest came from different sides of the streaming delivery chain: from production industry to satellite TV, with several parties expressing interest in follow-up discussions and potential collaboration.

Where this Goes Next

The current approach establishes a credible foundation, but the most exciting work lies ahead in making per-session energy attribution more scalable and more automated.

Key next steps include:

1) Scaling beyond single-user scenarios

Controlled single-user experiments allow clean subtraction of idle baselines. But real-world networks serve many users simultaneously. Moving forward, we aim to improve attribution by linking dynamic RAN power changes to traffic and radio load indicators so that per-session energy contributions can be estimated in multi-user settings.

2) Strengthening cross-layer alignment

An end-to-end view depends on synchronised data across device, network and server. Improving time alignment, session identification and traffic correlation will help quantify how changes in one part of the chain shift energy elsewhere.

3) Turning measurement into practical interventions

Ultimately, measurements are valuable only if it supports action. This will likely lead to:

- user-facing awareness concepts;
- platform-level optimisations;
- operator dashboards for energy-aware traffic management;
- evidence-based recommendations that can be embedded in product design.

Conclusion

Making streaming more sustainable requires a combination of human insight and technical measurement. ERP Sustainable ICT highlights that behavioural change is realistic when the right signals and incentives exist. EXIGENCE builds the technical backbone that can turn those insights into measurable, scalable and actionable approaches.

The key takeaway from the work presented at IBC is simple:

- We can measure energy across device → network → server.
- We can increasingly attribute energy to specific streaming sessions.
- And by making the impact visible, we open the door to meaningful change without compromising user experience.

In short: **if we want to reduce the footprint of streaming, we first need to understand where the watts really go and how to connect them to the choices that people and platforms make every day.**

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