EVALUATING THE ENERGY IMPACT OF DIFFERENT DIMENSIONS OF UHD

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ABSTRACT

The UHD standard introduces improvements in video quality across several dimensions. Although the first to be adopted commercially was the increase in resolution, features such as high framerate and dynamic range, wide color gamut and increased bit-depth offer important gains in the quality of experience of the end user. Nevertheless, each of these improvements comes with an associated cost in terms of storage, bandwidth and energy consumption. In this paper, we first present key studies for evaluating the energy impact of streaming video as well associated models. We then aim to quantify this cost for each UHD dimension, considering the distinct elements of an example streaming video chain. Through the use of concrete scenarios combining different UHD features, an end-to-end model is employed to provide a comparative analysis, allowing us to evaluate the impact of each characteristic of the UHD format and aid in guiding workflow choices for UHD content production and distribution.

INTRODUCTION

The Ultra High Definition (UHD) format, today in its second phase of deployment, brings about many improvements to video quality relative to HD. Starting with the spatial resolution of images, the most recognized feature of the new format, UHD also includes improvements in the framerate, bit-depth, color gamut and dynamic range.

Nevertheless, these additions come at the cost of increased storage, bandwidth and energy requirements. For instance, moving from 1080p to 2160p means a 4x increase in the number of pixels, and therefore storage in an uncompressed form. Bitrate requirements also increase with UHD, albeit not to the same degree – we might find a 2 to 3-fold increase when considering compressed content relative to HD. The less obvious cost when moving to UHD resolution is in the energy required to encode, decode and display content. The increased resolution leads to a more computationally-intensive encoding process, while UHD TVs are more energy-hungry than equivalent displays limited to HD resolutions, with studies suggesting up to a 30% increase (1).

Although the impact of the increase in resolution has been relatively well studied, the same cannot be said for the other dimensions of the UHD format. For example, depending on the production workflow, content may be encoded in 8 or 10 (or even 12) bits. Similarly, different framerates may be encountered going from 25 fps up to 120 fps for high framerate content.

Intuitively, we might expect each improvement to introduce a similar increase in resource demands. However, the answer not so clear. Certain dimensions have a significant impact on the quantity of data produced, while others influence power consumption more on the display side. Finally, depending on the compression technology used, different characteristics, as we will see, might have a negligible impact in terms of energy, all the while offering a better quality of experience to viewers.

In the following, we will discuss certain key studies that evaluate the energy and carbon impact of video streaming. We will then present the different characteristics of the UHD format considered here, defining a number of scenarios representing combinations that are currently employed. Using an end-to-end, state-of-the art model, we will analyze the energy consumption associated with 1 hour of streaming video for each of the defined scenarios.

BACKGROUND

The energy and carbon impact of the ICT sector, and of video technologies more specifically, has been widely studied in recent years, with varying findings. Most existing studies aim at providing an overall estimate of the impact of certain consumption behaviors. Notably, with the growing adoption of video streaming technologies, the consumption of video content has significantly increased, and is estimated to contribute anywhere from 1% to 4% of global greenhouse emissions, depending on the study considered and its underlying assumptions.

One of the key studies was published by The Shift Project, a French think tank founded in 2010 with the aim of mitigating climate change and reducing the economy's dependence on fossil fuels, particularly oil (2). In their 2019 analysis, they report that digital technologies are responsible for 4% of greenhouse gas emissions, estimating a rise to 8% by 2025. They also state that 80% of all data flow is due to videos. Finally, the study concludes that one hour of online video streaming consumes around 0.77 kWh after correcting for bitrate error.

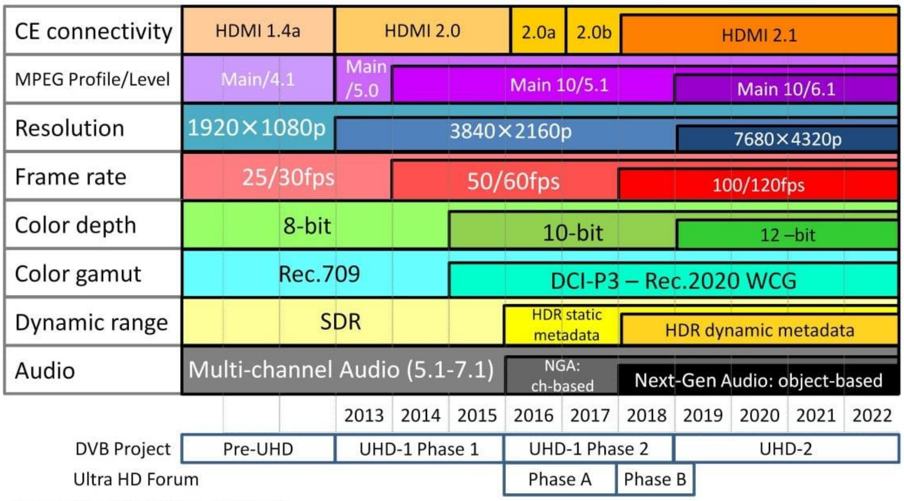
In the study conducted by Greenspector and EVEA the aim was to optimize the energy efficiency of the ICT industry, focusing in particular on France (3). They estimate that several factors come into play in energy consumption, such as viewing quality, streaming technology or the type of broadcast or the means of connection at the user's end. Their analysis gives an average consumption of 214 Wh per hour of video, and suggests that the Shift Project overestimates network consumption.

The study launched by Carbon Trust and the DIMPACT collaborative project (4) assessed the electrical energy consumed by data centers, networks, and user devices, during one hour of video streaming. The study used direct measurement and a time-based energy allocation method to estimate data center energy consumption. As for the consumption of transmission networks, two approaches were considered: the conventional approach and the time-based approach. The former suggests that a network's energy consumption varies in proportion to the amount of data transiting over it. An average allocation is used to represent the amount of energy consumed per GigaByte of data transferred without considering the network's idle state. The time-based method is a power model approach that uses a marginal allocation methodology considering the network's idle state. The basic network power is allocated per user/subscriber, and a marginal network energy component is allocated according to the volume of data used.

In (5), Makonin and al. propose a holistic end-to-end model to calculate the environmental impact of watching one hour of video streaming service. This study evaluates the carbon footprint of a stream and the impact of unused energy in data centers. This model results from the combination of high-level sub-models and highly detailed sub-models. The model has different main sub-models: data center, internet, and user device, and takes into consideration the time of day. This study aimed to adopt a more neutral approach to avoid possible underlying motives or bias. Our analysis in this work relies on this model, as it allows to easily integrate the influence of video characteristics, as well as viewing devices.

UHD FEATURES

The adoption of UHD has introduced improvements in video quality along several dimensions. The different UHD features and their adoption timeline are highlighted in Figure 1. In this study we focus only on ones likely to have an impact on storage, bandwidth and energy consumption across the whole video chain.



Source: Yoeri Geutskens, @UHD4k

Figure 1: UHD features and their adoption timeline

Resolution: moving from HD, to 4K and eventually to 8K brings about a 4-fold increase in the number of pixels each time. The impact of this increase in terms of storage, especially for uncompressed content, is evident and remains important even after compression. Resolution increases also put higher demands on distribution infrastructure. On the display side, we can observe two confounding factors related to increased resolution: more pixels require more processing power and electronics necessary to address the panel, in turn leading to both higher manufacturing and operation cost. Simultaneously, the better image quality pushes consumers towards larger panel sizes, with a compounding effect.

Framerate: similar to resolution, a higher framerate directly multiplies the data volume when considering uncompressed video. However, in contrast to resolution, we find more data redundancy between subsequent frames at higher framerates, a characteristic that modern encoding solutions take advantage of, leading to a less significant impact after compression relative to increases in resolution. Nevertheless, on the display side, as more frames need to be decoded, we might expect an increase in resource use.

Color gamut: refers to the volume of colors that can be represented by an image or display. The full gamut defined by Rec.2020 is not currently achievable by any display, however the majority of modern TVs are able to display significantly more colors than Rec.709. The impact of this improvement is noticeable visually, allowing for more vivid colors that better correspond to reality, arguably without requiring any additional resources in terms of data volume and energy, with the exception of device manufacturing, where more complex technologies are necessary to achieve a wider color gamut.

Dynamic range: the Ultra HD format introduces high dynamic range (HDR), which essentially allows images to represent a wider range of illumination. To achieve this, improved acquisition technologies are necessary (cameras, sensors…), as well as different transfer functions to translate light to digital values. HDR content may be accompanied by static metadata defining global characteristics of the content, or dynamic metadata offering information about each scene or frame and allowing the display to better preserve the artistic intent. Overall, HDR displays offer a higher peak luminance than SDR displays, which can have an impact on power consumption.

Bit-depth: refers to the number of bits used to encode pixel values and therefore how many distinct values are available for each color channel. A higher number of bits allows for smoother color transitions, minimizing quantization artifacts. The transition to HDR necessitates an increase in bit-depth as the contrast between adjacent quantization steps when using an 8-bit encoding exceeds the visible threshold on brighter displays.

Coding: the transition towards UHD coincides with the transition from AVC (h.264) compression towards HEVC (h.265). The HEVC compression offers a better performance, leading to more than 50% bitrate savings for the same perceived quality (6). Nevertheless, despite its lower performance, AVC is still used in several scenarios, particularly to address older devices, even though the installed base of HEVC covers the majority of consumer devices (7).

Although the format supports the features listed in Figure 1, in practice only certain combinations have been adopted and implemented for different workflows as they have been found to offer better tradeoffs in terms of bandwidth requirements and the quality of experience they offer.

Video parameter scenarios

As seen in the previous section, UHD allows for several levels for each of its different features. In practice, different combinations have been adopted for different use-cases and workflows. In the context of streaming, we first consider a baseline profile with a 1080p resolution, 30fps framerate and a Rec.709 color gamut, as might be encountered in the free offers of different streaming platforms for example. Moving to UHD in the same context, we might encounter an increase to 2160p resolution, 60fps framerate and 10-bit color depth, following the BT.2020 recommendation. However, in this case, the transition to HDR and therefore BT.2100 might not be present in all cases, as this larger color gamut is typically associated with HDR. If we move even further, we might envisage a cinema-oriented production, with an 8K resolution at 120fps, encoded at a 12-bit color depth and HDR with improved luminance.

Another aspect to consider is the encoding employed in each case. DVB specifications rely on HEVC (H.265) encoding for all the above-mentioned scenarios, albeit with different profiles used in each case. Despite the important gains that HEVC offers, streaming platforms still use AVC encoding depending on the user device and network capabilities, especially to target older devices. As such, we consider both compression solutions. To provide a valid comparison between configurations, we encoded the same source sequence as a ProRes HD or UHD file, forcing the specified characteristics using the appropriate encoding profile through ffmpeg. In all cases, the constant rate factor (CRF) option[1] was used, therefore automatically choosing the appropriate bitrate for the content, while maintaining a comparable visual quality in each case.

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[1] https://trac.ffmpeg.org/wiki/Encode/H.265

As the focus of this paper is on broadcast and streaming related workflows, cinema-oriented use cases are not considered in our analysis. As such, based on the above discussion, we identify the configurations outlined in Table 1. The bitrate column results from the encoded videos as described above.

Resolution	Frame rate	Bit depth	Color gamut	Dynamic Range	Encoding	Bitrate (kb/s)
1080p	30	8	Rec.709	SDR	H.264 Main	7 568
1080p	30	8	Rec.709	SDR	HEVC Main	2 578
1080p	30	10	Rec.709	SDR	HEVC Main10	2 711
1080p	30	10	Rec.2020	HDR	HEVC Main10	2 711
2160p	30	10	Rec.709	SDR	HEVC Main10	8 520
2160p	30	10	Rec.2020	HDR	HEVC Main10	8 520
2160p	60	10	Rec.709	SDR	HEVC Main10	8 359
2160p	60	10	Rec.2020	HDR	HEVC Main10	8 359

Table 1: Configurations of (U)HD features corresponding to existing workflows

METHODOLOGY

To compare the impact of the different parameters relating to the UHD format, we rely on the methodology of Makonin et al. (5). This work combines elements from several existing models to calculate the impact of streaming video. The provided estimates depend on four aspects, namely the data center where content originates, the network technologies and infrastructure involved in its distribution from the data center to the user, user devices and finally the time of the day when video is consumed.

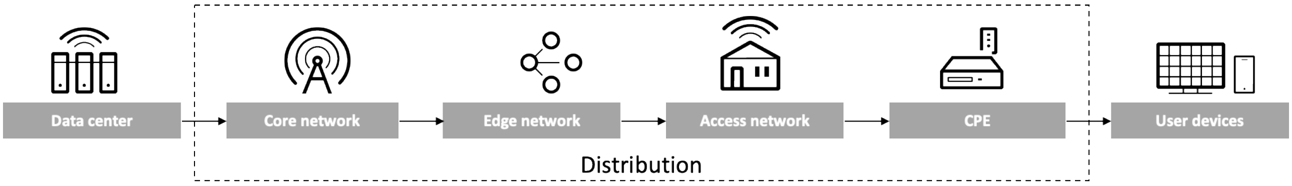

Figure 2: the components of the model proposed by Makonin et al. (5)

Although the impact of the time-of-day parameter is found to be important in the original study, we do not consider it in this work as our goal is to provide a comparative evaluation of the different video related parameters, which should remain valid irrespective of the time when videos are consumed. The energy impact in kWh for a stream can be computed as:

$$E_{total} = E_{DC} + E_{network} + E_{device} + E_{man}$$

where E_{DC} corresponds to the energy attributed to the data center, $E_{network}$ to the total energy for the distribution of the video from the data center up to the user's device, E_{device} corresponds to the final device used to view the video and E_{man} to the energy required in manufacturing the user device.

Data center

The energy (in kWh) for the data center component of the video workflow can be summarized as:

$$E_{DC} = \frac{DC_{demand} * V_{time}}{V_{streams}}$$

where $V_{streams}$ refers to the number of times the considered video is streamed simultaneously, V_{time} indicated the duration of the video in hours, and DC_{demand} reflects the energy demand of a data center relative to its size given in kW (8). Specifically, Schoemaker et al. (8) estimate this intensity at 50 kW, 240 kW and 2500 kW for small, medium and large data centers respectively.

Network

The network component of the model, as illustrated in Figure 2, encompasses the core network used for data transfer (long-haul and metro network), the edge network, the access network which is responsible for reaching the end user, and finally any customer premises equipment (CPE) that may be employed, such as routers. Makonin et al. compute the energy of the network in two parts.

First, the large-scale network energy is computed, including the core and edge network components:

$$E_{core} = (V_{time} * 3600) * V_{bitrate} * N_{core\_int}$$

where V_{time} as before corresponds to the video duration (multiplied by 3600 to obtain the duration in seconds), $V_{bitrate}$ represents the bitrate of the video and allows us to incorporate the impact of video quality/compression in the model, and finally, N_{core_int} represents the energy intensity of each network component (long-haul, metro, edge) and amounts to 0.0523 kWh/GB according to Schien et al. (9).

The access network component is computed as:

$$E_{access} = \frac{N_{access\_int} * V_{time}}{1000}$$

where $N_{access_{int}}$is estimated to be 52W according to the study of Coroama et al. (10), V_{time} is the video duration in hours and the division by 1000 transforms the computation to kWh.

User Devices

User devices might include TVs, smart phones or computers used to consume video content, each with a different energy impact. Further, when considering consumer devices, the manufacturing cost has been found to have a significant impact on the lifecycle energy footprint of the device. As such, both the energy during the use of the device, and the energy of manufacturing are considered at this step.

The device energy is computed as:

$$E_{device} = D_{demand} * V_{time}$$

where D_{demand} is the power demand of the device, in kW and V_{time} the video duration as mentioned previously.

The manufacturing energy is estimated according to Belkhir et al. (11) to be equal to 85-95% of the annual energy footprint of the device. As such, the manufacturing energy is simply taken as $E_{man} = 0.9 * E_{device}$.

In Makonin et al. (5), the model allows for the choice of device type, however average estimates are taken in each case, both for the energy demand and the lifespan. Although the precise lifecycle of a given device cannot be known, average estimates exist, showing for example that smart phone lifecycles are considerably shorter than those of a TV. In our analysis, we only consider smart TV and smart phone devices, which according to Makonin et al. have an average lifespan of 7-10 and 2-4 years respectively. For a smart phone, an average demand of 7.4 W and average energy of 1.35 kWh/year are reported, while for an average smart TV, Makonin et al. suggest an average demand of 43 W and energy of 15.7 kWh/year, considering a use of 1 hour per day.

TV Characteristics

As our goal is to evaluate the impact of different features of UHD, for the demand and consumption of each device we opt for a more accurate representation instead of considering a single average value. Considering that the majority of TVs on the market today are 4K, we might expect that a difference in video resolution will not have a significant impact – HD resolution images will be upscaled by the TV to 4K. However, the same cannot be said when comparing SDR and HDR display modes. Energy labels accompanying TVs and electronic displays within the EU are required to mention energy consumption in both normal (SDR) operating mode and HDR on the label[2] , as shown in Figure 3.

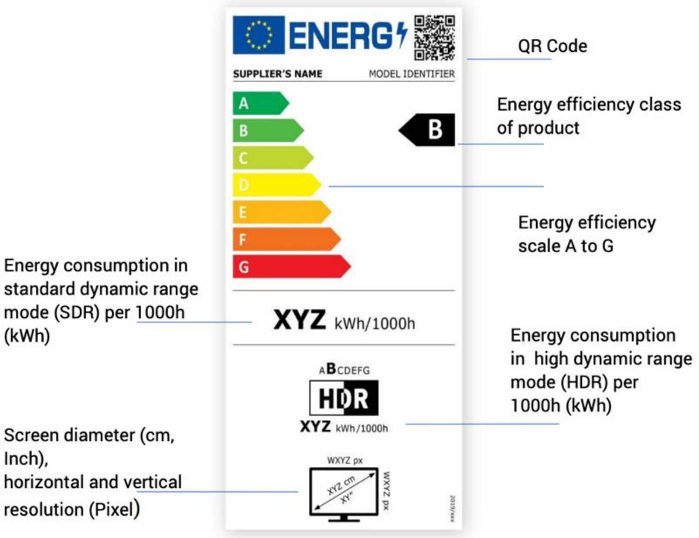

Figure 3: New energy label for TVs and electronic displays showing both SDR and HDR energy consumption.

To provide an estimate of the SDR and HDR energy consumption of TVs we consider 10 different 55'' TVs mixing both OLED and LED based technologies. All models considered are available for sale in mainstream electronic stores at the time of writing this paper. SDR consumption is reported according to the energy labels between 61 and 91 kWh/1000h, with an average of 79.3, while for the HDR mode energy consumption ranges between 74 and 236 kWh/1000h, with an average of 146. A similar analysis considering TVs at 75-77'' leads to an SDR average of 126 kWh/1000h and HDR average of 264.6 kWh/1000h.

Two key observations arise from the above. First, with very few exceptions encountered, the HDR mode of current TVs is reported to have a more significant energy impact relative to the SDR mode. This is intuitively not surprising as generally HDR content tends to have both a higher peak luminance and average brightness levels than equivalent SDR content. Nevertheless, it should be

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[2] https://www.label2020.eu/fileadmin/eu/documents/factsheet-televisions-label2020.pdf

noted that the relative energy consumption between SDR and HDR modes will be highly dependent on the content characteristics, and in realistic conditions differences might be less pronounced or even reversed (12). Further, we note that larger TV panels generally lead to a higher energy consumption, irrespective of display technology used. The push towards 4K and even 8K resolutions however (among other market and social reasons) (13) has the tendency to push consumers towards larger TV screens, compounding the energy impact of the video format advances may have in the first place.

EVALUATION OF ENERGY IMPACT

Using the methodology presented in the previous section, we estimate the energy consumption for 1 hour of video for each of the identified scenarios. As mentioned previously, to determine the bitrate for each configuration, the same source sequence initially encoded in ProRes in either HD or UHD and with different framerates was re-encoded using AVC or HEVC encoding, using the CRF option of ffmpeg. In the Makonin et al. model, to limit the dimensions studied, certain parameters were set as shown in Table 2.

Parameter	**Description**	**Value**
V_{time}	Video duration in hours	1
$V_{streams}$	Number of times the same video is streamed simultaneously from the data center	1000
DC_{demand}	The energy demand of the data center depending on its size. We consider a **medium** DC in this study.	240

Table 2: Constants used in our calculations

We perform our analysis considering three different devices: 55-inch TVs, 75-inch TVs and smartphones. Figure 4 shows the estimated energy consumption for one hour of streaming under different considered scenarios for the two TV sizes. The stacked bars show the relative contribution of each component of the model.

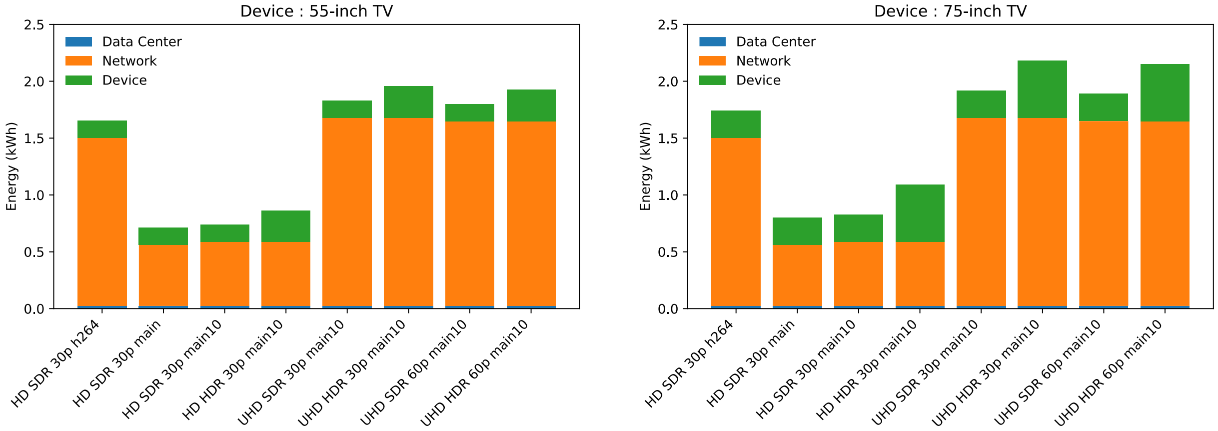

Figure 4: Energy consumption for 1h of streaming under different conditions. Left - 55-inch TV, right - 75-inch TV

Several observations can be made from these results. As would be expected from previous findings, when comparing the first two conditions (HD SDR 30p 8bits AVC vs HEVC) we observe that the bitrate gains afforded by HEVC lead to a significantly lower energy consumption. Interestingly, encoding the sequence using 8 or 10 bits using HEVC leads to very minor differences.

Video resolution is the characteristic leading to the most significant impact in energy consumption. In our analysis, moving from HD to UHD led to a 2-fold increase, which was the case for both SDR and HDR conditions.

Comparing SDR and HDR viewing conditions, if we refer to Table 1, we observe that the dynamic range has no influence on the bitrate of the video. Nevertheless, due to the increased power consumption of the display, HDR leads to an overall increase in energy requirements relative to SDR content with the same characteristics, which is more pronounced for the larger screen size – 10% and 14% respectively for the 55 and 75-inch TV conditions.

Framerate interestingly has a minimal impact both in bitrate and power consumption, however this is likely to depend on the characteristics of the considered sequence. For the purposes of this study, a single sequence was analyzed, with relatively slow-moving scenes, where the additional frames were likely redundant. As such, we can expect modern codecs such as HEVC to make use of this redundancy. In faster moving sequences, where additional frames carry more information, we might expect an increase in bitrate when moving from 30 fps to 60.

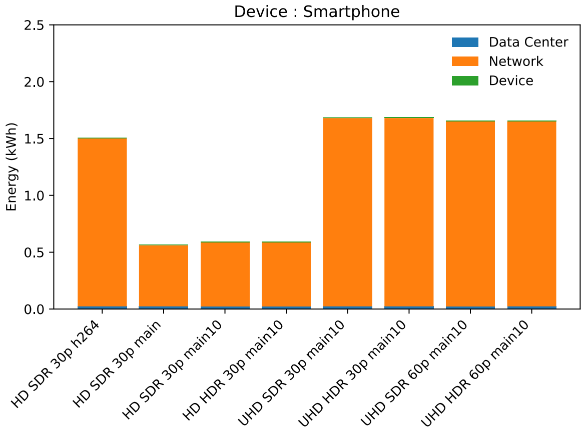

Figure 5: Energy consumption for different conditions on a smartphone.

Considering a smartphone as a viewing device, shown in Figure 5, it is not possible to distinguish between SDR and HDR condition, as no specific data was available. Overall, similar conclusions may be made, however we note that, globally, the energy consumption for each condition is somewhat lower than for the TV scenarios, with an average of 1.65 kWh for the 55-inch TV scenario, 1.79 kWh for the 75-inch TV and 1.46 kWh for the smartphone.

In all cases, we can observe the relative contribution of each component of the energy consumption model. Overall, the network and distribution aspects are responsible for the vast majority of the energy requirements for video. Nevertheless, the choice of device used for viewing can have a significant impact as well, which is not necessarily correlated with the network component.

Discussion

Our findings, consistent with previous studies, suggest that the impact of viewing device is relatively minor. Nevertheless, the same cannot be said for the characteristics of the video. Resolution was found to have a significant impact both in energy and bitrate, unlike framerate, while the dynamic range of the content affected the overall energy consumption only relative to the viewing device, with no impact on the video bitrate.

Framerate and resolution have been compared in previous studies in terms of their perceived quality of experience (14), finding that framerate has a much stronger influence. Combined with our findings, this suggests that framerate increases might offer a more interesting trade-off than resolution.

Although similar studies are lacking comparing HDR to other dimensions of the UHD format, empirical evidence through different production tests suggest that the transition to HDR brings a significant gain in perceived visual quality, which is visible independent of resolution. As the energy increase for HDR is quite limited relative to SDR, we can conclude that this feature too provides a better trade-off between energy cost and quality of experience relative to resolution.

We note that the present study has certain limitations that should be taken into consideration. A single video sequence was considered as an example for our analysis. Although we expect the conclusions drawn to be similar qualitatively for different sequence, the influence that certain content characteristics might have in both bitrate and energy consumption should be assessed in future work. For instance, scenes containing more motion might require a higher bitrate to encode in higher framerates relative to their lower framerate versions.

To limit the scope of our analysis we have also opted for a rather simplified model for the distribution component of the video chain. Smartphone viewing likely suggests that video is distributed through a mobile network, while TV viewing is more likely to rely on broadband networks, each with different components and therefore energy requirements. Although including a more detailed network and distribution model would be important for a more precise estimate in future studies, our goal in this work is not to evaluate the impact of different devices, but rather different characteristics relating to the video itself.

CONCLUSIONS

In this study, we evaluated the energy cost for different scenarios combining features of the UHD format. Using the end-to-end model proposed by Makonin et al. (5), we estimated the power consumption corresponding to each scenario, considering different resolutions, framerates, dynamic range and viewing device among others. Although the adoption of the 4K resolution both for production and distribution is becoming more widespread, our findings suggest that from an energy perspective, better compromises might be possible, leading to a better quality of experience for the end user but with a lower power consumption, considering notably a higher frame rate and HDR imaging.

In future work, to provide targeted guidelines on optimal configurations among the options offered by the UHD format, the impact of each option on the quality of viewers' experience should be assessed. Combining energy consumption measures as produced in this study, with assessments of visual quality can help guide decisions for broadcasters and content producers, providing a more comprehensive view of the impact different video characteristics might offer, and showing that perhaps more is not always better.

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