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Using Behavioural Data to Assess the Environmental Impact of Electricity Consumption of Alternate Television Service Distribution Platforms

Keywords: Broadcasting, Digital, Energy Efficiency, Environmental Impact Assessment, Life Cycle Assessment, Streaming, User Analytics

Introduction

Digital technology and entertainment is a significant driver of electricity use (Andrae and Edler, 2015; Malmmodin et al., 2010) and service use is both growing and changing in nature, resulting in an anticipated increase in electricity consumption (Andrae, 2020).

As part of wider environmental and climate change strategies, digital and media companies are increasingly wanting to understand the electricity involved in media distribution and consumption, and to find ways of mitigating the associated greenhouse gas emissions. Many now wish to integrate quantification into their corporate greenhouse gas reporting (specifically Scope 3, indirect emissions) (Carnstone Partners Ltd., 2021). They also wish to incorporate considerations of electricity consumption and associated emissions in decision making: both strategic decisions regarding the services provided, and technical decisions regarding the design of the transmission and distribution systems which deliver them.

To do this, a methodology is required which:

1. Allows integration and comparison of both broadcast and digital media distribution methods.
2. Allows modelling at a sufficiently fine granularity to identify specific electricity hotspots as a guide to decision making.
3. Allows modelling of the heterogenous behaviours of the user population.

In this paper, we present the first methodology which satisfies all three of these requirements. We show how it can be used to analyse the distribution and viewing of television services provided by a large media company. The analysis incorporates a variety of distribution platforms, from traditional terrestrial broadcast to on-demand streaming over the internet, and allows both reporting on the overall electricity footprint and comparison of the electricity demanded per viewer-hour of each. Our method combines impact assessment techniques with models of the diversity of actual user behaviour, derived from detailed audience monitoring and online behaviour analytics data. The process model and secondary data we present are general, and can be applied to any large media company.

We identify hotspots in this system which would enable electricity use reductions in the short term, and provide guidance for large broadcasting organisations, media providers and policymakers as to where it is most

appropriate to focus reduction efforts currently. We also provide insights as to how such hotspots might change in the future as a result of changing service usage patterns.

Related Work

Research has been conducted on understanding and quantifying residential electricity use, including that associated with home entertainment equipment (Drysdale et al., 2015; Stankovic et al., 2016; Yohanis, 2012)(Sekar et al., 2016)(Sekar et al., 2019) and (Marsden et al., 2020). However, such studies do not account for electricity use beyond the home to deliver the entertainment services provided.

There has also been research on methods to characterise electricity use and greenhouse gas emissions associated with certain digital services. These include Electronic Software Distribution (Daniel R. Williams, 2011), web media (Schien et al., 2013a), internet advertising (Pärssinen et al., 2018) and telecoms network services (Chan et al., 2013)(Yan et al., 2019). However, these do not extend to media broadcast services, and so do not allow quantification and comparison between traditional and more recent distribution methods.

Life Cycle Assessment (LCA) has been identified as a key methodology in assisting in the understanding of the environmental impacts of industrial processes and the products they produce. Such approaches have been widely used to assess the environmental impacts of both consumer electronics (Subramanian and Yung, 2016), and ICT products (Arushanyan et al., 2014).

LCA methods are often used in reduced scope and modified form to estimate greenhouse gas emissions ('carbon footprint') associated with a given product, and to calculate corporate emissions for climate reporting. This approach has been used to assess digital services and the greenhouse gas (GHG) emissions associated with the electricity used to provide those services (Hischier et al., 2014; Moberg et al., 2011, 2010); (Schien et al., 2013b); (Weber et al., 2010); (Mayers et al., 2015) (Shehabi et al., 2014); (Coroama et al., 2012). Often, this is in comparison with alternative traditional forms of services such as a printed paper vs. digital, critically reviewed in (Bull and Kozak, 2014)), or a physical vs. virtual conference (Toniolo et al., 2017). It can also be for specific classes of services, such as internet advertising (Pärssinen et al., 2018). Most relevant to our work is that of that of (Chandaria et al., 2011) who conducted a scoping greenhouse gas impact assessment for emissions associated with electricity use for one hour of BBC viewing on terrestrial broadcast and digital platforms of a typical viewer.

Such studies often focus on a functional unit of a single service (e.g. an hour's worth of reading or viewing) to a customer. In doing this, they often identify that user practices and choices can make a significant difference to the actual impact, therefore making general conclusions difficult to draw. To apply such techniques to calculate electricity use (and associated Scope 3 greenhouse gas emissions) of an organisation's services requires understanding the impact of an entire community of service customers. To do so requires a model of behaviour for such customers. One approach is to model the "typical" customer and their choices, an approach adopted by Achachlouei et al (2015). Yet, as they

observe in their section on limitations and follow-on work, such an approach may miss important subtleties – it may be that a small number of “atypical” customers might have a disproportionately large impact. As Schien et al. (2013b) demonstrate, such variability can have a significant effect on the impact associated with digital services. In order to reduce uncertainty of an assessment, the inherent variability in the behaviour of users and the characteristics of the system infrastructure need to be adequately taken into account.

There are two ways of doing this, both of which we use. Firstly, digital systems provide detailed user analytics data which can be used to identify the behavioural choices made by each user. This, combined with an impact model that is parameterised according to such choices, can give a more detailed and nuanced picture of the overall footprint of a service than assuming a “typical” average user does. This approach has been used by Schien et al. (2013a) to calculate the carbon footprint of a News and Media website over a period of a month, and to estimate the global footprint of major video streaming service using publicly available aggregate data (Preist et al., 2019). However, broadcast distribution and viewing cannot be monitored in this way. Hence, we augment this by using detailed survey data of viewer behaviour to build a model of the audience clustered according to different equipment used, tv size, and viewing times. This can be considered an extension of the approach used in (Sekar et al., 2016), which clustered US TV viewers according to hours watched, to increase accuracy of electricity usage estimates for policy assessments. Such an approach can also be combined with machine learning techniques (Raihanian Mashhadi and Behdad, 2018), to identify which household behaviours impact domestic electricity usage.

Using these two approaches, the methodology presented below can assess electricity used by services provided by large media organisations with heterogeneous methods of distribution. It can use information such as user analytics, audience monitoring data, and sales data to help build a model of heterogeneous behaviour for a given media organisation. In turn, this allows for the creation of a bottom-up model of the impacts of viewing by summing the consequences of each individual consumer decision across the whole of the customer population. As Chan et al. (2013) demonstrate in the context of mobile networks, this bottom-up approach can avoid errors that result from dealing with aggregate data in models.

Methodology

LCA is a methodological framework that allows the estimation of the environmental burden associated with the production and use of a product or service, and which has been standardised for specific applications. We adopt the GHG Protocol Life Cycle Reporting standard (Greenhouse Gas Protocol, 2011) and more specifically we work within the guidelines of the GHG Protocol ICT Sector Guidance (Greenhouse Gas Protocol, 2012) Chapter 4 ‘Guide for assessing GHG emissions of Cloud Computing and Data Center Services’ in relevant areas of our system. We go beyond it in our use of detailed behavioural data, obtained from online and in-home audience monitoring, to produce a model of the

heterogeneous behaviour of users. We use this to parameterise the LCA to allow the total electricity usage (and associated GHG emissions) to be calculated for a given service.

In the following sections, we present the methodology we have used. Firstly, we provide a summary of the steps involved, focusing on the novel aspects of our approach;

1. Develop a detailed process model of the system under study, ensuring that the multiple processes involved in different patterns of user behaviour are captured within it. Ensure it is parameterizable to allow user differences to be captured within it. In our case, the process model includes terrestrial, cable and satellite broadcast, and internet-based video on demand (VOD) access both in the home and over mobile networks. Parameters allow variation in such factors as TV screen size, network access technology, time of viewing, image bit rate, etc.
2. Collect user behaviour data and from this identify the different configurations of the system they use – in other words, different ‘pathways’ through the process model. In our case, the data we use comes from two sources. For internet access, we use detailed user analytics data available for all users. From this, it is possible to determine different devices used, how long they were used for and their data bit rate, and the type of connection (cellular or wired access network). For broadcast viewing, we use detailed data extracted from surveys conducted by the Broadcasters Audience Research Board (BARB). This survey monitors in real-time the viewing behaviours of a representative sample of UK households, and is used to produce authoritative and independent audience viewing figures. The more detailed data behind this allowed tailored reports to be provided to us, giving data on the different viewing configurations used, and parameters such as distribution of TV size, viewing hours, etc. Similar such surveys are conducted in other countries.
3. Cluster the user data for each of these configurations, and aggregate the data to give a total system usage for all users in the given configuration. In our case, this consists of the total viewer-hours for the population using a given configuration, together with other parameters such as the distribution of screen size, video stream bitrate, etc in that configuration.
4. Use the process model to calculate the total material flow (or, in our case, electricity usage) for each configuration and sum these.
5. Processes that are shared by all users can be assessed independently, and added to the user device configuration result. In our case, these are datacenter processes such as coding and multiplexing which are unaffected by user choice of device configuration.

The carbon footprint from the generation of electricity consumed is calculated with the standard emission factors, applying GHG protocol rules, including scope 2 and 3 (DEFRA, 2019).

Having provided an overview of the approach taken in this assessment, we now give a description of the method and document the choices made within it. Further detailed regarding the methodology can be found in (Schien et al., 2020).

Goal, Functional Unit, Scope and System Boundaries

The goal of this study is to calculate the electricity consumption and associated carbon emissions (electricity footprint) from the distribution and use (i.e. broadcast and viewing) of a national-scale television service, identify hotspots within this, and determine the current energy intensity of different distribution platforms. As noted above, we use the British Broadcasting

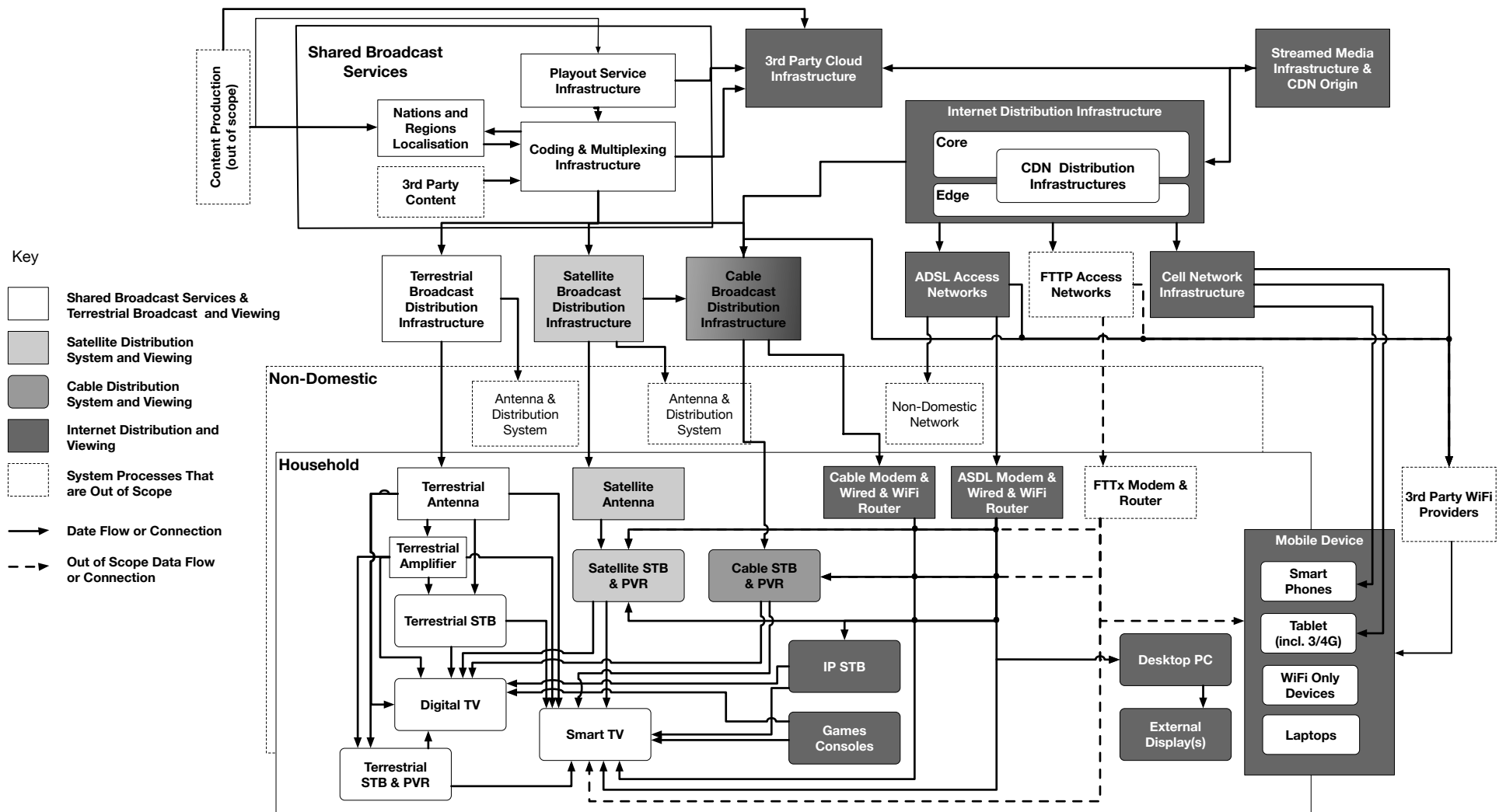


Figure 1: Processes involved in Television Distribution and Viewing

Corporation as a representative case study. In presenting our results, we adopt two functional units. To assess the demand placed on the UK electricity system, our functional unit is the delivery and viewing of one year's worth of BBC television to the population of the UK. To assess the energy intensity of different distribution platforms, our functional unit is the provision of one hour's worth of video content to a viewer at given typical bitrate quality (see appendix).

The scope of the study aims to include all mainstream means of distribution and viewing. Distribution includes digital terrestrial broadcast (via Freeview), cable TV multicast, satellite broadcast (via Freesat or Sky) and distribution via the Internet "over the top" (via the BBC iPlayer service). Each of these involves different delivery platforms that lead to different infrastructure and reception equipment in a viewer's home. Viewing can be on a television set or on a portable consumer electronics device such as a laptop or smartphone.

As our goal is to understand the electricity consumption associated with distribution and viewing technologies, we do not consider energy usage resulting from the production of TV content, manufacturing and use of DVDs, or the manufacture of the infrastructure and devices used, or launching of broadcast satellites.

Process Description

The process model (Figure 1) provides a simplified view of the activities involved in the delivery of the service. Processes with solid borders are within the system boundaries and the scope of assessment. It consists of three stages: **preparation, distribution, and consumption.**

Preparation

Firstly, live or pre-recorded content is sequenced as needed for transmission through digital equipment responsible for *layout*. This is then converted (through a process of *encoding and multiplexing*) into forms appropriate for broadcast. Encoding reduces the bit rate of the content through the use of audio and video compression techniques. Multiplexing is the process that bundles together multiple encoded streams of video, audio and data prior to distribution. The final multiplexes are then sent to the appropriate broadcast distribution infrastructure. A high-quality feed is also sent to digital storage for Internet distribution. In the case of the BBC, this is cloud storage hosted by Amazon Web Services.

Broadcast Distribution

Distribution of content for broadcast takes place in three main ways.

1. Digital terrestrial television (DTT) distribution consists of relaying the signal to a network of transmission stations over the area to be served. In the case of the BBC, there are one thousand transmission stations across the UK. Relaying is carried out by a dedicated high-performance distribution network carrying a number of bundled streams of video signal (multiplexes), each of which is associated with a specific antenna at each transmission station. This network of transmitters is managed by a third-party company, Arqiva. Some homes will have aerial amplifiers to boost the DTT signal.

2. Satellite distribution consists of relaying the signal to an Earth Station Uplink, which transmits the signal to the satellite for broadcast. At the BBC (and most other broadcasters), there are two of these with one acting as a hot backup (i.e. working and ready to take over in case of failure of the primary).
3. Content for cable distribution is fed to the cable providers via two routes depending on the content type:
 - a. High Definition (HD) channels are provided via a fibre link of uncompressed audio, video and subtitle streams that are then encoded and multiplexed centrally by the cable network operator.
 - b. Standard Definition (SD) channels are received from the direct-to-home satellite feed described above.

In both cases, the channel feeds are transmitted over the cable operator's private fibre data network to a number of regional cable head-end sites across the area served, and thence to local cable hubs on street corners, which, in turn, relay the signals on to individual subscriber homes via a co-axial final drop cable.

Internet Preparation and Distribution

Internet distribution can take place for both live and on-demand viewing, such as the BBC's online iPlayer service. Unlike broadcast distribution, Internet distribution today occurs through unicast Internet Protocol packet switching, which means an individual stream of data packets is generated for each viewer.

BBC content served across the Internet in the UK shares the initial playout process with the other delivery modes, but, other than this, is an entirely separate set of processes.

Both storage of master content and video encoding of this content for streaming are carried out using datacentre facilities. In the case of the BBC, this is cloud-based and presently provided by Amazon Web Services. The elastic nature of cloud services – meaning they can be scaled up at times of higher demand and reduced at other times – is helpful in dealing with peak periods such as the preparation of multiple early-evening regional news bulletins, and reduces overall energy consumption for encoding.

Prepared content is transferred and stored temporarily in a set of caching servers which act as the origin for online content. In the case of the BBC, as with most large media providers, these are in-house within the BBC's datacentres. This, in turn, is distributed using *Content Delivery Networks* (CDNs). These are effectively distributed datacentres allowing the storage ("caching") of copies of the origin content at a number of locations around the country. The effect of this is that customer requests are satisfied by more local servers, reducing the demand on the core network and the latency in serving a customer request. The BBC uses several such CDNs, one of which (BIDI) they operate themselves.

CDNs acquire content across the *core* and *edge* network segments of the Internet for both fixed and mobile Internet Service Providers. It is then served from a CDN edge cache to the user's receiver device via the Internet Service Provider's local *access network* equipment. For domestic installations, the access network is terminated at a home modem/router with in-home distribution to receiver devices typically over Wi-Fi. Outside the home, a mobile cellular

network (3G/4G) provides access directly to the user's terminal equipment (e.g. smartphone). A simplifying assumption made is that all Wi-Fi reception is within home network environments rather than third party out-of-home Wi-Fi providers (e.g. cafés and transport companies).

Consumption

Viewing content can take place on a number of different devices, most commonly a traditional *television set*, which encompasses a number of different screen sizes and resolutions, and which may have other features such as High Dynamic Range. Often, the TV set is fed from a set-top box that decodes broadcast (terrestrial, satellite and/or cable) or Internet signals. In some cases, the set-top box also acts as a personal video recorder (PVR). In modern TV sets, some of this functionality may be built in: for example, most sets these days include at least one terrestrial receiver, some can be extended to add in recording capabilities, and a few include an integrated satellite (Freesat) receiver. Furthermore, new smart TVs also allow direct reception of Internet services such as BBC iPlayer. In some cases, games consoles are used to access such services and display them on a TV set.

Although the traditional TV set is the most commonly used device to view TV services, other types of consumer electronics device are also being used to access Internet streaming services such as iPlayer. These devices can be personal computers (desktops and laptops), which may have external displays attached to them, or mobile devices such as smart phones and tablets. Although viewing often takes place at home, with the use of streaming over mobile networks it can also take place outside of the home.

Modelling User Access Configurations

The majority of UK households view BBC TV services through at least one of the delivery modes available, but how this is done can vary widely. These differences can impact energy consumption. Past assessments of digital services have estimated energy consumption by user devices by assuming a homogeneous distribution of devices across the population. To illustrate, typically an average value for the power draw of television sets is used across the entire population. Yet, it might be that those in the population with larger, more energy-intensive sets watch more TV than those with smaller ones, meaning an estimate of energy consumption using a simple mean power value for the whole population would underestimate the overall energy. For this reason, we avoid adopting an approach where we model a statistically "average" household as representative, and instead aim to capture this diversity in our estimate. We represent populations of devices and demographics at a much finer granularity than in previous work. This unique and novel approach to modelling makes our estimate more robust.

We identify a number of different *configurations* of equipment a customer can have when viewing BBC services. Each configuration consists of a choice of viewing device, and equipment associated with reception or access. To illustrate, we provide a few example configurations. The complete set of configurations are presented in the supplemental materials.

- A TV and a set-top box recording from a satellite broadcast and viewed later;
- A laptop connected to iPlayer through a home cable modem and Wi-Fi router;
- An integrated TV set including a built-in Freeview receiver receiving terrestrial television;
- A tablet device using the BBC iPlayer app over the cellular mobile network.

To determine the energy used by a given configuration, we need detail of the equipment involved, and an estimate of the number of *device viewing hours* (i.e. hours that devices are actively receiving, displaying or recording content as distinct from viewer or “eyeball” hours) using it. This is done using two main sources of data.

For configurations using one of the three main broadcast distribution platforms, detailed demographic and TV viewing device population data is provided to us by the Broadcasters Audience Research Board (BARB). This is obtained through in-home continuous monitoring of viewing behaviours of a representative sample of the UK domestic population. The BARB Establishment Survey (BARB, 2018) provides data on population profiles and access to TV viewing platforms (including households using multiple platforms). It also provides data on the ownership of television reception equipment, including distribution of screen sizes and the use of secondary televisions in different household types. We combine this with a BARB commissioned report of total *viewing hours* (including recorded content viewed within 28 days) and proportion of BBC viewing by device type, and estimates of shared screen viewing from BARB household profile data.

For configurations using internet streaming over iPlayer consumption, the BBC user analytics data from this service provides rich data. It can tell us the distribution of devices used, how long viewing took place for, the mean bit rate by device type, and estimates of numbers of Internet connections via Wi-Fi and cellular mobile networks. This can be used to estimate how many device-hours took place in any given configuration and how much data was transferred.

Account also needs taken of *digital waste* (Preist and Shabajee, 2010), where a service is provided but not used. This takes two forms: *uncovered viewing* where a TV set is left playing with no viewer, and *over-recording*, where a set-top box records content that is never viewed. The former is estimated from BARB’s quality control reports for “uncovered viewing”. The latter is modelled via an “over recording ratio”, which is a ratio of total duration of recorded content viewed to duration of content viewed. Currently, this is modelled as a mean value of two based on expert opinion via BBC R&D.

For each configuration, we calculate the typical power consumption of all equipment involved in the process model, and combine this with the calculated viewer-hours to calculate the overall energy use for a given configuration. These are then summed, and combined with configuration-independent subprocesses in the model, to yield the total energy use in a given period of study.

Data Sources and Allocation

Table 1 summarises the various data sources we used, together with the approach we have adopted with regard to allocation of burden for the various parts of the system described above. Details of all data, together with a measure of data quality for each, are provided in the appendix. With the exception of the BBC-specific primary data, this can be applied to any media company. A full description of allocation methods used, allowing replication of our approach, is available in (Schien et al., 2020).

A summary of energy intensities and power values for main processes is available in Table 2.

Subprocesses	Components and Unit Processes	Data types and sources	Allocation	Modelling assumptions
Preparation	Playout datacentre	Primary power data from Data Centre	Service share	
	Playout specialist equipment	BBC R&D estimate of power consumption		
	Localisation using private internal network	Data volume from BBC	Data volume	Energy per Gb modelled as standard internet
	Encoding and Multiplexing	Primary energy data from BBC data centre.		Data includes cooling and 'hot spare' datacentre.
Broadcast Distribution	Distribution Network Equipment	Primary energy data from provider	Service share	
	Satellite Uplink Equipment	Power usage estimate from BBC R&D		Manufacture and Launch of satellite not included
	Distribution Network Equipment	Cable Company Scope 2 Electricity reporting	Share of TV vs Broadband	One cable company considered representative of others.
Internet Distribution	3rd Party Cloud Infrastructure (Preparation)	Time of use of virtual servers, from provider. Industry power data per server.	Service share	We do not consider energy used in user analytics processes.
	Streamed Media Origin Data Centre	Primary power data from BBC		
	Content Delivery Network servers	Primary power data and data volume data from BBC		BBC primary data used as proxy for other CDNs involved.
	Core and Edge network data transfer	Primary data volume data from BBC iPlayer analytics		Energy per Gb from (Schien and Preist 2014), normalised to reference year.
	Mobile network data transfer	Primary data volume data from BBC iPlayer analytics		Energy per Gb from (Andrae and Edler 2015), normalised to reference year. Ratio of 3G/4G usage from Ofcom.
	Fixed broadband access network equipment (eg DSLAM)	Power data from industry reports	Data volume transferred	FTTP technology not considered as <1% UK penetration
	Home network equipment (Router and WiFi)	Power data from industry reports and measurements	Data volume transferred	
Viewing devices	Hours of viewing over different digital device types across UK population	Primary device access data from BBC iPlayer analytics		
	Hours of viewing over different TV distribution platforms (DTeT, Cable, Satellite) across UK	Primary survey data from Broadcasters Audience Research Board		TV screens in public places (eg bars) not included.
	Hours of digital waste - uncovered viewing	Primary survey data from Broadcasters Audience Research Board		
	Hours of digital waste - over-recording	BBC R&D expert estimate		
	TV screen size	From detailed BARB data for different distribution platforms		Distribution used, rather than mean.
	TV power consumption (inc Standby)	Energystar		Linear regression across EnergyStar database used to calculate power for a given screen size.
	Set-top boxes and recorders (inc Standby)	Direct measurements, industry and community reporting.		
	Other viewing devices (laptops, smartphones etc)	EnergyStar, direct measurements, industry and community reporting.		
TV and STB time in active and passive standby	From detailed BARB data for different distribution platforms		Standby energy allocated pro-rata to viewing according to hours of viewing on a given device.	

Table 1: Data Sources and Allocation approaches for system components and unit processes

Device	Mean Intensity	Unit	CAGR	Reference Date for CAGR	Source
Power Games Console	147	W	0	01/01/2016	(Webb et al., 2013)
Power Cable Router	11.4	W	0	01/01/2017	Own Measurements of Virgin WiFi Router
Power Main TV	47	W	0	01/01/2016	Energy Star & (BARB 2016)
Power Secondary TV	30	W	0	01/01/2016	Energy Star & (BARB 2016)
Power Desktop and Screen Cable	77	W	0	01/01/2016	https://www.eu-energystar.org/calculator.htm
Power DSL Router	9.7	W	0	01/01/2017	(ISP Review, 2017)
Power PVR	18	W	0	01/01/2016	Primary data from measurements various STBs at BBC and domestic environments and analysis of Complex STB voluntary agreement data from 2011-2016
Power IP STB	3.5	W	0	01/01/2009	(Ting blog, 2016)
Power Laptop	15	W	0	01/01/2016	https://www.eu-energystar.org/calculator.htm
Power Tablet	5.5	W	0	01/01/2016	https://www.eu-energystar.org/calculator.htm
Energy intensity core network	5.4756E-06	J/bit	-0.22	01/01/2016	(Schien and Preist, 2014), Extrapolated with 22% annual improvement.
Energy intensity cellular 3G 4G mix	1.72E-04	J/bit	-0.22	01/01/2016	Calculated from estimates for intensity of 3G and 4G and proportion of 4G (60% in Ofcom. 2016. "Connected Nations 2016.") and (Andrae and Edler, 2015.). Mean of triangular distribution.

Table 2: Summary of process intensities. The detailed list of a model variables is included in the appendix.

Representing Uncertainty and Variability

As with all models used in LCA, our understanding of the system being modelled is subject to both aleatory variability and epistemic uncertainty. In our model, the most common cases of aleatory variability are with system processes that represent a set of several alternative models of infrastructure, all of which are well understood. An example is our assumption of an average cellular network energy efficiency that in fact varies with cell size and cellular base station utilisation. On the other hand, there are system processes that we know *of*, the details of which, however, we have no information about. These processes are epistemically uncertain. We handle both of these by representing variables in the model as distributions, rather than working with average values alone, and

performing a Monte Carlo simulation of the whole model that draws from these distributions. The final result is a distribution with a mean value identical to the result of a scalar model that also represents confidence intervals wherein the true energy consumption and carbon emissions value will likely lie.

Variability occurs based on choices made by the user population, such as what device to view on or which set-top box model to purchase. Although we aim to model much of the variability endogenously – in particular, through our use of configurations described above – we cannot do so completely. It is possible to reduce the variability of the system processes by representing them in more detail; however, this results in greater model complexity and requires additional data collection, thus forming a trade-off. We can use sensitivity analysis to decide on that trade-off by calculating the relative effect of some input variability on the output variability.

To illustrate, we have an estimate of the number of people using cable set-top boxes or TV sets of a given screen size, but we do not know exactly which models they are using. To handle this, we estimate mean power-use profiles for each type of device and assign a probability distribution based on the knowledge of the values associated with different models. These are necessarily approximate, and we tend to take conservative bounds (rather than underestimating uncertainties).

We chose the distribution function that fits the available data. In cases where only minimum and maximum values (and, possibly, a most likely value) are known, we sample from a triangular distribution. In cases where only an assumption for the average value is available, we commonly use a normal distribution with some context-dependent assumption for the standard deviation.

Epistemic uncertainty occurs when we have imperfect knowledge about the variable within the model. This is often based on expert knowledge, so again we use conservative bounds. For example, we use a wider range for a variable such as Satellite Uplink energy, which is estimated by BBC R&D staff based on their knowledge, rather than playout datacentre energy use, where we have primary data based on energy bills. Similarly, we use a range to represent cellular access via 3G/4G energy use based on different values reported in the literature. Full details of the ranges adopted are provided in the accompanying materials.

Results

Figure 2 presents a boxplot of the overall results based on a Monte Carlo simulation of 10,000 runs (Weidema and Beaufort, 2001). It presents the distribution of total energy consumed to deliver BBC television services over a year, and the results broken down according to delivery platform. The vertical lines at the centre of the boxes represent the median values. The left and right borders of the boxes represent the first and third quartiles, respectively, defining the inter-quartile range. The lower whisker marks the distance to the smallest value that is at least 1.5 times the inter-quartile range below the first quartile. And respectively for the upper whisker above the third quartile. Small circles mark outliers, which are points outside the whisker range.

Our analysis estimates overall energy used for the delivery and watching of BBC television services in the UK in 2016 in an interval with a most likely value of 2,171 GWh (0.6% of total UK electricity use; (UK Department for Business Energy & Industrial Strategy, 2017))

Using the UK Government emission conversion factors for greenhouse gas company reporting for 2016 (UK Department for Business Energy & Industrial Strategy, 2016) we include the Scope 2 factor of 0.412 kgCO_{2e}/kWh and the Scope 3 factors for transmission losses and 'Well to Tank' factors for both generation and transmission that total 0.105 kgCO_{2e}/kWh, giving a total emissions factor of 0.517 kgCO_{2e}/kWh. This then equals 1.12 million tonnes (Mt) CO_{2e}, or 0.24% of the UK's total 2016 emissions (467.9 MtCO_{2e}).

In the results that follow the figures in square brackets are MtCO_{2e} figures based on the emissions factor above.

This results in an average power consumption associated with BBC services of 248 MW. Total energy use associated with satellite viewers was greatest at 931 GWh (43%) [0.48 MtCO_{2e}], terrestrial viewers was 675 GWh (31%) [0.35 MtCO_{2e}], cable viewers was 386 GWh (18%) [0.20 MtCO_{2e}], and iPlayer viewers was 172 GWh (8%) [0.09 MtCO_{2e}]. Shared denotes those processes, such as Payout that are common to all platforms.

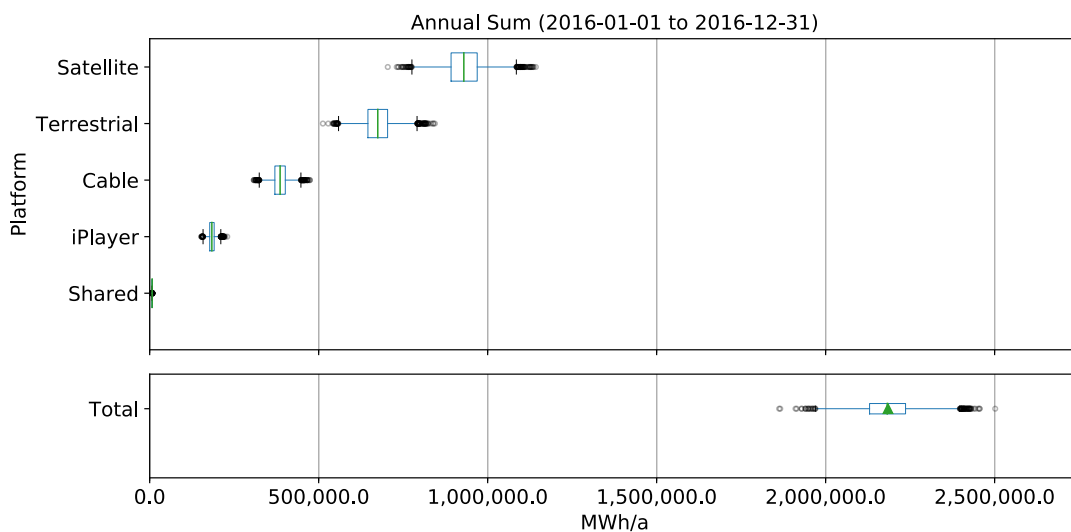


Figure 2: Estimate of total 2016 electricity use per annum by the BBC distribution and consumption, and electricity use by each distribution platform, based on a 10,000 run Monte Carlo simulation

We now consider electricity used per device-hour of viewing. Energy use associated with shared infrastructure used during preparation is allocated between platforms based on their proportion of overall device-hours of BBC viewing. Figure 3 gives an average per device-hour figure for different platforms. iPlayer at 0.184 kWh/device-hour [93 gCO_{2e}/device hour], cable 0.175 kWh/device-hour [93.0 gCO_{2e}/device hour], satellite at 0.166 kWh/device-hour [88 gCO_{2e}/device hour], and terrestrial at 0.07 kWh/device-hour [36 gCO_{2e}/device hour].

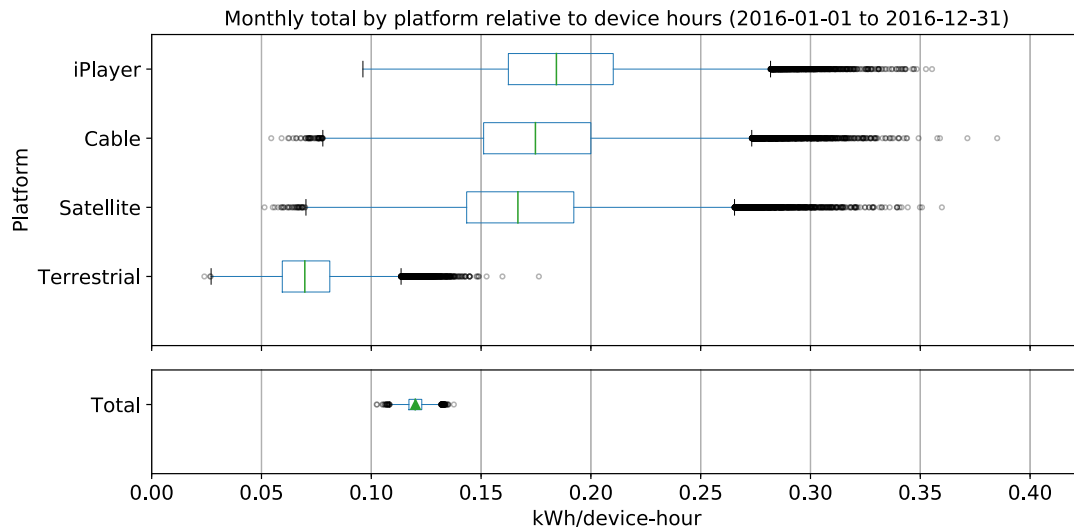


Figure 3: Estimate of energy use of distribution and consumption for one device-hour of BBC content over different distribution platforms (2016-01 to 2016-12).

If we consider the different processes and devices involved in the delivery of the overall service, we see that the bulk of electricity use occurs within the home (including mobile devices). The equipment in the home (including user devices, STBs and customer premise network equipment) is responsible for around 1,982 GWh (0.56% of total national and 1.5% of domestic electricity consumption in the UK) through the year, and distribution is responsible for around 180 GWh [0.09 MtCO_{2e}] (0.05% of total electricity consumption (Department for Business, Energy & Industrial Strategy, 2017)). Figure 4 provides more detail of this, showing a breakdown of total energy consumed according to the different processes and devices involved. It can be seen that set-top boxes and PVRs dominate (980 GWh [0.51 MtCO_{2e}]), although TVs in total consume nearly as much (903 GWh [0.47 MtCO_{2e}]).

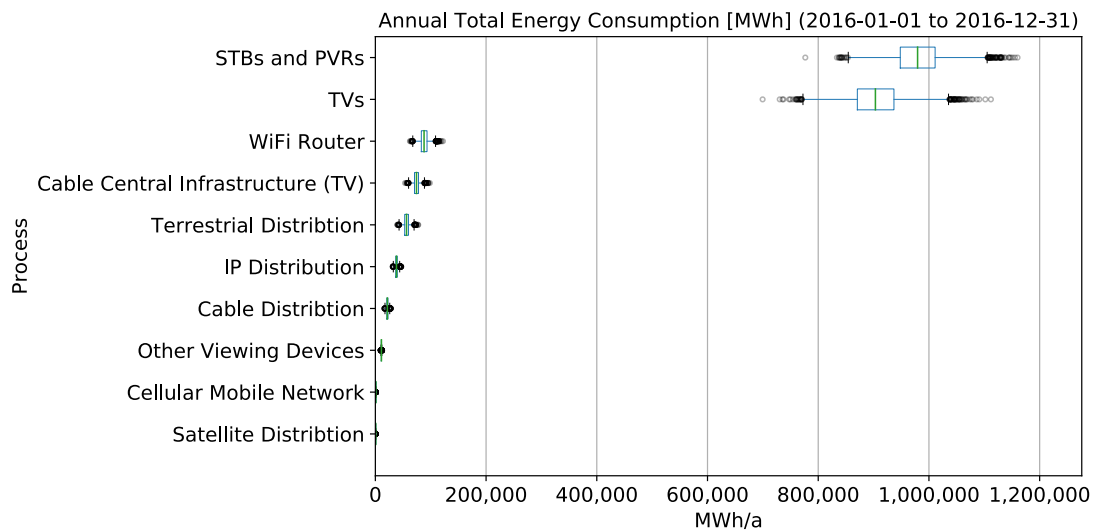


Figure 4: Breakdown of total BBC distribution and consumption energy use in 2016, based on process groupings.

Figures 5 to 8 give more details of the breakdown of electricity use per delivery mode; these do not include shared infrastructure.

Figure 5 shows the breakdown for terrestrial broadcast delivery. Viewing device (almost always a TV set) is dominant here (449 GWh, 67% [0.23 MtCO_{2e}]), larger than the set-top box and PVR contribution combined (158 GWh, 23% [0.08 MtCO_{2e}]), whereas the broadcast preparation and distribution infrastructure (20GWh, 3%) is a small share. The aerial amplifiers (37GWh, 5% [0.02 MtCO_{2e}]), often fitted in the loft of a house, amplify the DTT signal. There is very limited data available on their deployment, hence the very large uncertainty.

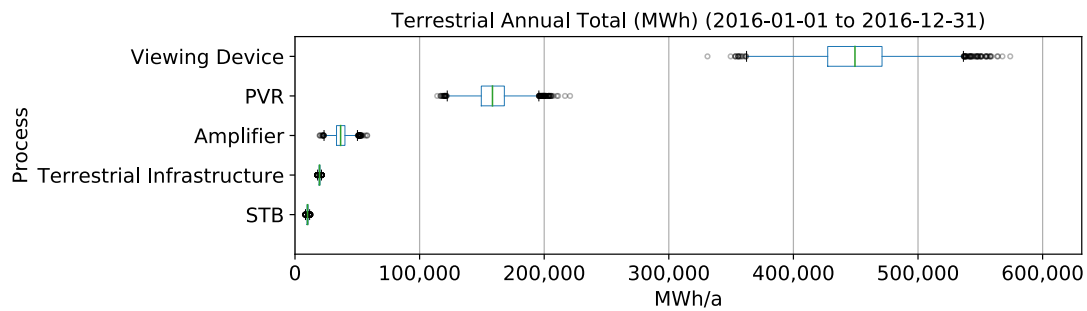


Figure 5: Breakdown of BBC distribution and consumption energy use associated with consumption of terrestrial broadcast in 2016, based on process groupings.

Figure 6 gives the breakdown for cable distribution. This time energy consumption is more evenly spread through the different components. Set-top boxes are highest, responsible for 189 GWh (49%) [0.10 MtCO_{2e}], TV sets and other viewing devices for 122 GWh (32%) [0.06 MtCO_{2e}], and the cable infrastructure for 74 GWh (19%) [0.04 MtCO_{2e}].

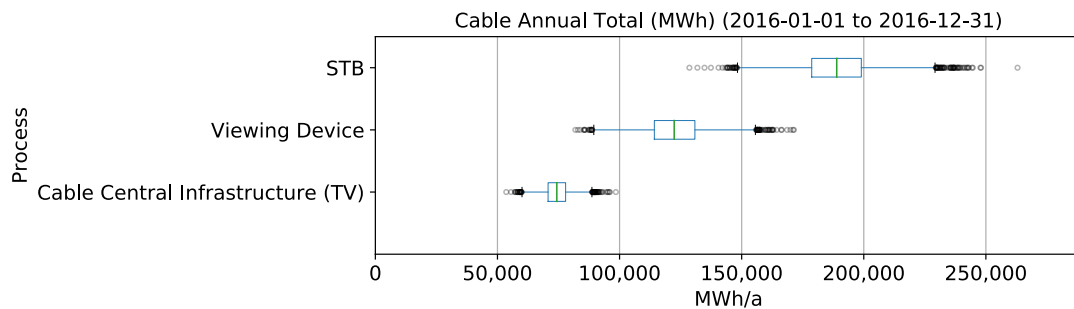


Figure 6: Breakdown of BBC distribution and consumption energy use associated with consumption of cable broadcast in 2016, based on process groupings.

Satellite, shown in Figure 7, similarly has STB consumption (621 GWh, 67% [0.32 MtCO_{2e}]) higher than viewing devices (308 GWh, 33% [0.16 MtCO_{2e}]) but, unlike cable, electricity for the broadcast infrastructure is small (661 MWh, <0.1% [<0.001 MtCO_{2e}]).

Both cable and satellite platforms generally use more complex STBs than those used by digital terrestrial TV; for example, Cable and Satellite set-top boxes generally include PVR functionality. Over 80% of TV sets used to consume DTT services use built-in decoders rather than set-top boxes.

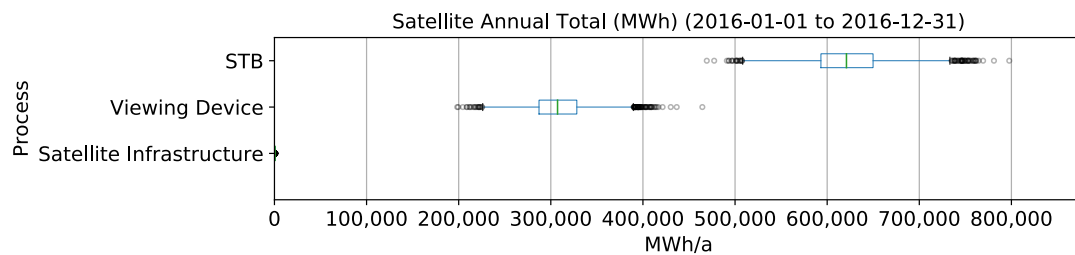


Figure 7: Breakdown of BBC distribution and consumption energy use associated with consumption of satellite broadcast in 2016, based on process groupings.

Figure 8 gives the breakdown for iPlayer viewing on all devices (including Smart TVs, satellite and cable set-top boxes, tablets and smart phones), which has a very different pattern from the others. Viewing device is a relatively small share at 34 GWh (20%) [0.02 MtCO_{2e}], Network Customer Premises Equipment (CPE), such as home Wi-Fi, modems, and routers, is greatest at 88 GWh (51%) [0.05 MtCO_{2e}] and network energy use outside the home (including cable, access, and cell networks) is a significant share at 48 GWh (28%) [0.02 MtCO_{2e}]. Server usage (iPlayer video encoding and CDNs) to prepare, store, and transmit content is almost negligible at 1.6 GWh (0.9%) [0.001 MtCO_{2e}].

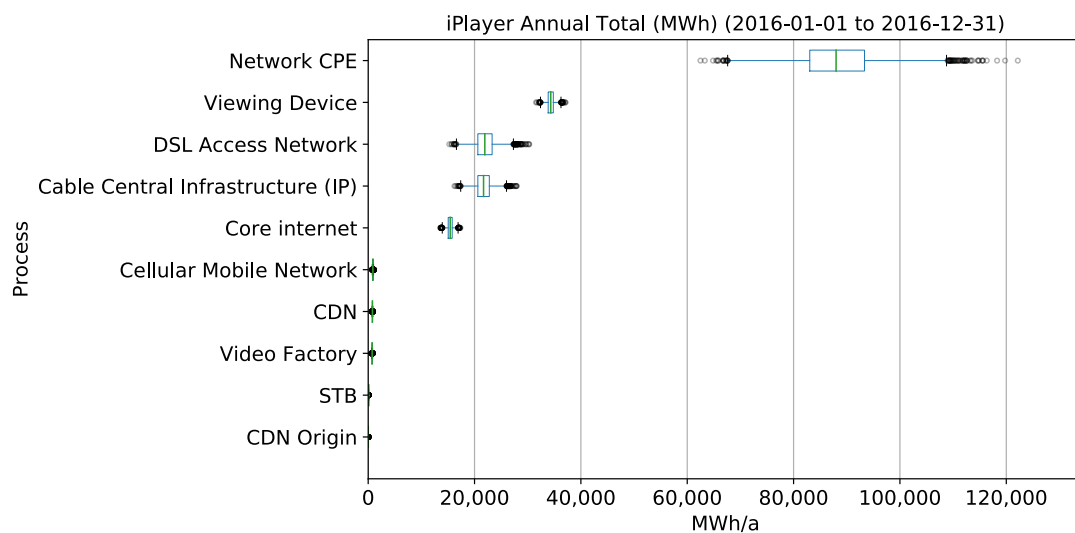


Figure 8: Breakdown of BBC distribution and consumption energy use associated with consumption of iPlayer services in 2016, based on process groupings.

Uncertainty and Sensitivity Analysis

The coefficient of variation (the standard deviation relative to the mean) of the estimate of energy consumption is 12.5%. The interquartile range of the

overall energy consumption has a 25th percentile value at 2,083 GWh and a 75th percentile value at 2,241 GWh.

In order to understand which processes contribute most strongly to the variability of the outcome, we perform sensitivity analysis based on Monte Carlo simulation. An analytic analysis based on error propagation (Finnveden et al., 2009) is too involved given the large number of variables (261). Our model structure is monotonic with non-linear, multiplicative random variables. We perform a One-At-a-Time (OTA) sensitivity analysis (Iooss and Saltelli, 2015). Here, we fix all model variables to their mean values and only allow a single variable to vary according to its original distribution. With this approach, we can explain approximately 48% of the variability of estimated energy consumption. The remaining variability is due to interactions between two or more of the input variables and has not been studied. Among the variables affecting the overall uncertainty of energy consumption estimate, most are the variables related to power draw and time of use of terrestrial, satellite, and cable receivers – each individually, affecting between 5 and 1 percent of output variability. These are the variables that additional research effort should be directed to first in order to most effectively reduce outcome uncertainty.

Discussion

The distribution and consumption of digital services, such as entertainment, provided by single large organisations such as the BBC can alone be responsible for non-trivial quantities of energy. In the case of the BBC, we have used a process-based electricity footprinting method to demonstrate that the distribution and consumption of BBC television services accounted for approximately 0.6% of electricity use in the UK in 2016. Domestic electricity consumption accounts for approximately 30% of total national electricity consumption (UK Government, 2017). The BBC being one of several of television services these results align with previous estimates of electricity use in the UK from the use of Televisions (UK Government, 2019) of the order of 1.8% of national electricity consumption. At this level, choices made by such organisations and their partners regarding which delivery platforms to support and which technologies to adopt will have implications for energy consumption patterns in the regions they operate.

When comparing the carbon footprint per viewer-hour with other assessments, (Chandaria et al., 2011) arrive at a range of 0.078–0.088 kg CO₂e/viewer-hour for distribution and consumption on TV over DTT and IP and 0.02 kgCO₂e/viewer-hour for IP distribution and consumption on Laptops, which is similar to our values of 0.088 to 0.093 kgCO₂/viewer-hour for Satellite, Cable and iPlayer. Our average per-viewer-hour result for DTT is lower due to improved TV energy efficiency, and from use of updated audience data from BARB, that differentiates between types of STBs and different size TV for different platforms. As DTT STBs consume lower power than complex STBs with Cable and Satellite, the relative significance of STBs for DTT is much lower than for Satellite or Cable distribution. Our per-viewer-hour result for iPlayer is representative of the entire audience of iPlayer viewers, which explains the similarity of our result with their scenario of IP distribution and consumption on TV (0.088 compared to 0.093 kgCO₂e/viewer-hour). Studying IP delivery

exclusively, (Carbon Trust, 2021) arrive at a value of 0.048kgCO₂e/ viewer-hour for typical IP-delivered video streaming in the UK. The discrepancy to our results can be explained by their figure representing an average (mix of) user devices, while also applying lower energy intensity numbers to networks, given a more recent reference year. For the European average case, they arrive at an impact from streaming to phones of 0.008kgCO₂e/viewer-hour and 0.016kgCO₂e/viewer-hour, which is lower but relatively similar to our values for iPlayer. The difference can be explained, in part, by us modelling a mix of devices, including some TVs.

Before discussing further, we re-iterate the point that while our focus here has been use phase energy and associated carbon emissions, we strongly advocate the need to include other life cycle impacts of digital services of all kinds. As noted in many studies (e.g. (Krug, Shackleton, and Saffre 2014)), estimating embodied carbon equivalent emissions for digital products and services is highly problematic and uncertain. However, while it has not been in scope of this piece of work, we believe it is important to estimate the order of magnitude of embodied emission associated with the product system. To that end we applied the life cycle ratio method and data from the GHG ICT Sector Guidance (Greenhouse Gas Protocol, 2012) to our analysis along with estimates from literature on networking footprints (e.g. (Krug, Shackleton, and Saffre 2014) and (Shehabi, Walker, and Masanet 2014)). This indicates that, although highly uncertain, it is likely that the embodied footprint of the system is of the same order-of-magnitude as the use phase emissions and should therefore be a significant consideration in policy, planning and decision-making processes.

Similarly, we argue that other environmental lifecycle impact categories such as eutrophication, human toxicity, ecotoxicity, photochemical and resource depletion should also be considered. These can be highly significant, for example, Whitehead et al. (Whitehead, Andrews, and Shah 2015) argue, in their LCA work on UK data centres, that “The release of carcinogens is one of the largest contributors to the whole life cycle impact [on human health] ...”.

With respect to use phase as modelled above, the majority of this electricity consumption occurs within the home. Of this, the majority is from set-top boxes, rather than television sets and other viewing devices. This contrasts with the scoping study conducted by Chandaria, Hunter, and Williams (2011), which found that TV sets dominated. This reversal is a consequence of technology trends within domestic electronics. Television technology has become increasingly efficient in the last few years, particularly as a consequence of efficiency improvements in flat-screen technology. Despite increases in average screen size, models draw lower power when operating, and use almost no energy when in standby mode.

In the case of set-top boxes, the trend has been the opposite. Complex set-top boxes, used for cable and satellite services, are becoming more widespread in the home and have more sophisticated functionality than the simple set-top boxes they are replacing, resulting in higher energy usage both when on and when in standby mode. Voluntary agreements in both the European Union and the United States have resulted in reductions of energy use by complex set-top

boxes (D+R International, 2017) but, among BBC viewers in the UK, this has been offset by increased numbers of people using such devices. This is likely to also hold in other regions where terrestrial broadcast, rather than cable, has traditionally been dominant. However, in the USA, the penetration of cable TV was already far higher and so the same technology improvements are likely to result in absolute reductions in overall STB energy usage. Our analysis suggests it is important to continue this focus as this is the main hotspot within the current delivery footprint. This can be reduced further either through technology improvements within the set-top boxes, or by moving to a “thin client” model where the processing occurs elsewhere and is shared with a number of households. However, we note anecdotal evidence that users may disable power management settings on both TVs and STBs. The impact of this on overall energy consumption is an important area for further investigation.

Newer delivery platforms offer more convenience and choice but at the price of increased use of electricity compared with terrestrial broadcast. The electricity use per device-hour of delivery over the Internet is one of the largest of the four delivery platforms used by the BBC, but, due to the small proportion of content currently delivered in this way in 2016, the overall electricity footprint of the service is correspondingly small. This pattern is likely to hold for other traditional broadcast companies which also offer their content online. It is interesting to note that the pattern of energy consumption is different from those of other delivery modes. For iPlayer, electricity use during service delivery is dominated by the networking equipment, inside and outside the home, while the viewing device is responsible for a relatively small share. This is partly because the iPlayer service is viewed on smaller and lower powered personal devices instead of TV sets approximately 60% of the time. Consumption of on-demand television services such as BBC iPlayer has increased annually, and this trend is expected to continue. This will increase both the overall electricity footprint of TV distribution, and also alter the location of energy hotspots within the footprint. This will continue and magnify the trend identified in global energy use of Entertainment, Media and IT sectors (Malmodin et al., 2018, 2010). Other trends likely to impact the overall footprint of the TV involve the likely increase in screen size and numbers of TVs in a household, the potential introduction of new technologies such as higher resolution video (such as 4K or 8K) and high dynamic range (HDR) in the home.

To anticipate and prepare for the impact of such changes, it is valuable to conduct scenario analyses based on possible future trends. We note that, because the analysis presented above is a attributional in style, determining the impact of increased use of on-demand services and reduced use of other services is more complex than simply taking the “per device-hour” figures we have calculated and multiplying it by the new usage figures. A realistic evaluation of future trends must requires running the entire model under a new set of assumptions. We identify analysis of such future scenarios and trends as future work, but note that the more granular structure of the model provides flexibility towards this. Such work can contribute quantitative examples of the impacts of such changes, alongside qualitative scenario modelling to explore the impacts of digital technology in the future (Fauré et al., 2017; Pargman et al., 2017; Picha Edwardsson, 2014).

Such scenarios of future trends are different from the modelling of the immediate changes to energy consumption as a result of behaviour change, which are subject to further constraints due to the attributional nature of our model; and all LCA-style models reviewed in the literature. The use of average energy intensities from aggregates (i.e. all energy consumption divided by all use per system part) for the modelling of, mainly, networks and multiplexes is constraining, as these have low energy elasticity. This is a measure of the degree to which the power draw of a device varies with utilisation. In inelastic system parts a change of utilisation does not result in a proportional change of power draw. As (Chan et al., 2016) note, internet network devices are highly inelastic. This also applies to the antennas network of terrestrial broadcast. An analysis of changes to electricity footprints from the change of service use thus should take a mid-term perspective in form of scenarios.

In addition to exploring such scenarios, there is the opportunity for future work to understand the implications on electricity consumption of design decisions of the digital services. Two classes of decision can have a significant impact on energy usage. The first is that of the software architecture, particularly regarding the delivery architectures used. For example, the structure and location of the CDN caches used by a TV distribution system, or the adoption of multicasting over IP for the efficient distribution of linear channels to many receivers simultaneously. Approaches from Green Software Design of cloud systems (Baliga et al., 2011; Hintemann and Clausen, 2016; Procaccianti et al., 2014) can be of benefit here. The second class of decision is with regard to the user interaction and what practices and behaviours it encourages (or not). Here, approaches from Sustainable Interaction Design applied to large-scale systems (Blevins, 2007; Preist et al., 2016; Preist and Shabajee, 2010) can be used. It is also beneficial to understand how such practices interact with the wider set of entertainment and IT practices in the home and their resulting energy impacts (Bates et al., 2014; Lord et al., 2015; Widdicks et al., 2017). Such work, together with scenario analysis, could provide valuable insights resulting in long-term reductions in both cost and environmental impact. This can form part of a more general effort to design digital services while taking sustainability factors into account (Kern et al., 2018; Lundström and Pargman, 2017; Remy et al., 2018).

The work presented in this article, like many other analyses of digital systems, has electricity consumption during the use phase as its scope, and so is not a complete LCA. This is a deliberate choice, as the results are intended for use when considering the impact of TV services on electricity consumption. As we omit the energy and environmental impacts of the manufacture and deployment of the infrastructure required to deliver the services, results presented in this article should not be taken as a definitive statement of which delivery modes are “environmentally best.” For example, electricity use associated with satellite broadcast is very low in our model, using simply what is necessary to create a narrow beam transmission of content to the satellite. Broadcast is then dealt with using solar power harnessed by the satellite. A full environmental analysis would include a share of the impacts of manufacture and launch of the satellite, and the rocket carrying it to orbit. An extension of system boundaries to provide a more complete analysis is an option for future work. It would be possible to do this very coarsely for home equipment using the approach of Teehan, Kandlikar,

and Dowlatabadi (2010), but data on the specification and lifetime of distribution equipment is much harder to obtain. The work of Chan et al. (2016) provides a promising approach to incorporating network equipment. Such an analysis is likely to be significantly more uncertain than the work presented here. We also omit (in line with GHG protocol guidance) the impact of software development, but note that the approach of (Kern et al., 2015) to provide this.

Our analysis identifies the total annual electricity consumption to provide BBC television services. For energy policy planning, it is also helpful to have data about the likely peak demand of energy from TV services both currently and under potential future technology scenarios. This is outside the scope of traditional LCAs, which consider quantity rather than rate of resource consumption, but there is potential for future work to extend the model to allow the peak rate of electricity use (i.e. peak power consumption) to be determined. Current practices mean that “peak entertainment demand” (and therefore the timing of its peak electricity use) is later in the evening than the overall peak electricity use. This has potential to change, however, and such changes can be influenced by design choices in the provision of entertainment services (Morley et al., 2018).

Conclusions

In this article, we have presented a methodology for the assessment of energy use by TV distribution and viewing. It combines the use of detailed behavioural data obtained through user monitoring and analytics with a Life Cycle Assessment approach. We have presented a detailed process model of TV television distribution and viewing, and applied the method to assess energy use associated with a representative national TV company – the BBC. In doing so, we have demonstrated that TV distribution and viewing can account for a non-trivial share of national electricity use – with BBC services responsible for consumption of the order of 2,171 GWh [1.12 MtCO₂e] in 2016, or 0.6% of total UK electricity use in that year and approximately 0.24% of the UK GHG emissions. We have shown that viewing on digital terrestrial broadcast is the least electricity-intensive distribution platform and that Cable, Satellite and streaming is are of a similar order. As it is likely that on-demand streaming media consumption is likely to increase, we have identified the need for future scenarios exploring the implications on electricity consumption of this and other technology trends.

Acknowledgements

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