Towards a Sustainable Internet of Sounds

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ABSTRACT

The Internet of Sounds (IoS) is an emerging research area at the intersection of engineering fields and humanities including computing, communication technology, audio signal processing, acoustic monitoring, music and arts. Although this research field is expected to have beneficial impacts on society through entertainment, creativity, well-being, monitoring and security, it is paramount to be aware of the adverse impact of current technology on the environment in terms of greenhouse gases emissions, pollution and soil consumption. In this study we provide a survey of the environmental issues produced by current information and communication technology (ICT) and relate these to the use cases that the IoS envisions. On the basis of this survey, we identify some key aspects to reduce the footprint of IoS services and products and then we provide suggestions to make advancements in IoS environment-aware.

CCS CONCEPTS

• **Applied computing** → *Sound and music computing*; • **Social and professional topics** → **Sustainability**; • **Computer systems organization** → Sensor networks.

KEYWORDS

sustainability, internet of sounds, lifecycle assessment

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1 INTRODUCTION

The Internet of Sounds (IoS) is an emerging research area in academy and industry which stems from different engineering and humanities fields. It relates to the network of devices capable of sensing, acquiring, processing, actuating, and exchanging data serving the purpose of communicating sound-related information. It encompasses the paradigms of the Internet of Musical Things (IoMusT) [63] and Internet of Audio Things (IoAuT) [61], which are respectively extensions of the Internet of Things (IoT) paradigm to the musical and non-musical sonic domains.

As an interdisciplinary field, the IoS is open to questions that fall outside the borders of well established research topics. Being driven by technological research, the field encompasses many technology-related challenges, such as latency, reliability and synchronization, interoperability and standardization [61, 63]. For those applications that deal with musicianship, such as in the IoMusT, artistic challenges are of paramount importance and must deal with all the technical issues involved with remote interactions and networking. Pedagogical challenges may be also an issue [63], together with technical and ethical issues related to privacy and security of the data. These issues parallel those of the IoAuT. Wireless Acoustic Sensor Networks (WASN) may record, process, transmit and store data from human activities that are private and may be potentially exploited against people's will. Therefore, ethical issues arise from the use of novel technologies, as it is the case with many other innovations.

There is one more challenge for the IoS that has received scarce attention thus far, that is the environmental sustainability. In established fields of research, such as computer science, electronics and the IoT, issues related to energy consumption and eco-compatibility of manufacturing materials have been addressed. For the IoS field we believe it is important to address this issue too as well as stimulate a holistic research that takes environmental goals in consideration. The task is complex but we can draw upon prior art in the fields that intersect in the definition of the IoS. Human science-related fields are also growing interest for sustainable arts and media. This is attested by papers recently published in the NIME [42] and ARTECH [21] communities.

In this paper we aim to organize previous knowledge and try to address some key areas for sustainability in the IoS. We will also provide a few pointers that we believe may be necessary to make research and product development in the field sustainable.

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2 STATE OF THE ART

The attempt to evaluate the footprint of the Internet and the related technologies is not new. In the years, a large number of papers have tackled various aspects of the resource consumption implied in the access to the Internet, its infrastructures, devices and services. One issue with this corpus of papers is that they tend to age quickly. Given the swift evolution of physical technologies, access models and consumer habits, the impact of these technologies can change quickly. Unfortunately, while physical devices get lighter in energy consumption, on the other hand their usage gets more pervasive, therefore, to say whether globally their impact reduces or not, a thorough evaluation must be performed case by case by experts in the field. Footprint assessment should be conducted periodically and updated to the latest technological standards and usage models. For this reason, in this work we will concentrate mainly on studies published in the last 15 years and provide a brief survey to introduce some basic concepts to assess sustainability.

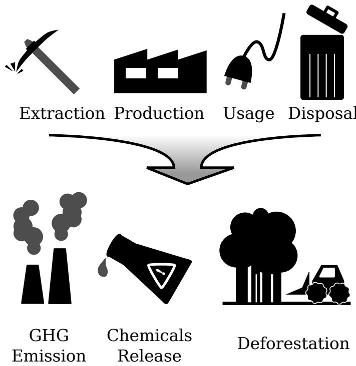

Figure 1: The lifecycle of an electronic product and its impact on the environment.

2.1 Impacts and Assessment Methods

The Internet, at a physical level, is made of the interconnection of electronic devices. These devices impact the environment during all four stages of their life [5]:

- extraction of materials and resources,
- manufacturing,
- usage,
- product disposal at end-of-life.

As shown in Figure 1, all four items have an impact on the environment in terms of [67]:

- carbon dioxide (CO_2) when fossil fuels are used to generate the energy required to operate these devices (*operational energy*) or produce them (*embodied energy*),
- emission of chemicals associated to their manufacturing and released in air, soil or water,
- soil consumption and deforestation related to new mining sites, new industrial sites, bio-fuels, etc.

Among these three issues, the one that is considered the most by decision-making entities and the public opinion, is the emission of greenhouse gases (GHG), which impact and endanger the whole planet. The release of toxic chemicals and the consumption of soil are equally hard to revert and have global consequences. However, their impact is stronger on those populations living beside factories and plants with inadequate pollution control or those living in endangered forests that are cut to free space for industrial activities. Unfortunately, this often happens where populations are in an economical and political subordinate position [37]. Efforts have been done in the academic community to help indigenous populations discover illegal forest cutting [25, 47] [1] and oil extraction activities [43, 50] [2].

2.1.1 Lifecycle Assessment. Many indicators and tools for footprint assessment exist [37], but arguably, the most common one is the Life cycle assessment (LCA) [26]. This methodology can be applied to a large number of products and processes, and considers resource usage, impact on human health, and consequences on the environment. It is based on an analysis from cradle-to-grave, e.g. in the case of a physical product: from the extraction and transportation of the raw materials, to the use of energy and other substances for their manufacturing, to the transportation of the product and its packaging, the energy used during its lifetime and the impact of its disposal and recycling. Several studies exist for semiconductor devices and electronic devices such as personal computers, smartphones and photovoltaic solar cells [5, 6, 29, 46]. The assessment of impact through LCA is a difficult process that needs expertise of the processes behind a given product or service, and which is based on judgments that can be possibly biased by human factors and experience. Generally, different studies conclude with similar results, but some outliers can be found [9]. To overcome these issues, since 1997, the International Organization for Standardization (ISO) has contributed to the standardization of the methods for LCA, leading to the current ISO 14040 standard, dated 2006 (with an amendment done in 2020) [26]. The LCA is useful for assessing anything from consumer devices to streaming services. Hereinafter we make an example that helps understand how it works, clarifying how the environmental impact issue is approached.

Suppose we want to assess whether it is better to use a paper notebook or a digital device for note taking (see e.g., [58]). An LCA assessment allows one to estimate the environmental impact of both and it starts from sketching the processes involved with their production. The paper notebook requires producing fibers and obtaining paper sheets from them. The notebook is assembled and clipped with metal clips and packaged. At the end of its life the notebook and its packaging are disposed (hopefully for recycling). Similar considerations are adopted to produce a pencil. All phases require transporting materials, goods, workforce, etc.

Differently, the digital device - suppose it is a touchscreen tablet - requires many more materials for manufacturing its components: plastic and metal parts, the screen, the electronics, the battery, a touch pencil. All the materials, and the semifinished products are processed with chemicals, water, heat, etc. They are also transported from various parts of the world (i.e., mining sites to industrial plants) and finally assembled and packaged. After the device is transported to the end user it requires electrical energy to operate. Additionally, software repositories and cloud data storage require energy to operate and communicate with the device. At the end of the device life, it must be disposed following Waste of Electrical and Electronic Equipment (WEEE) directives and recycled, requiring additional heat and chemicals.

All these considerations allow to weigh each of the two solutions. Naturally, the digital device can spare tons of paper to be printed, and serves many more purposes. In the analysis we should consider that electronic equipment require rare materials found in remote areas of the world and that materials used for production may be toxic (e.g., whitening the paper, etching the chip silicon, etc.). According to the authors of [46]: *"The ecological consequences of semiconductor chip manufacturing are the most predominant within the electronics industry. This is due to current reliance upon large amounts of solvents, acids and gases that have numerous toxicological impacts."*. Other aspects to take in consideration are the ethical and geopolitical consequences of looking for materials and cheap workforce in countries with little protection for the workers or the environment. These factors cannot be measured.

[1] See also the Rainforest Connection project: https://rfcx.org/
[2] See also https://hivos.org/program/all-eyes-on-the-amazon/

2.2 Internet Footprint

The Internet, despite presenting its own impact on the environment, is surely perceived as an important tool in mitigating the impact of other human activities, such as the transportation of people and the delivery of physical information media, such as books and newspapers.

In a paper from 2009 [15] the authors investigated the role of the Internet for conferencing, if compared to airplane, car and train traveling to various end-user connection technologies. All the technologies provided a positive CO_2 reduction if, e.g., more than 5% of car travels were replaced by teleconferencing. A more recent study [18] confirms that teleconferencing reduces GHG emissions, provided that the equipment used for allowing conference calls is frequently used. Teleconferencing is also proposed in [3] as a tool to reduce carbon footprint by up to 44% for academic research activities. The ICT, as a whole, can provide energy savings in more subtle (but significant) ways, such as optimizing logistics and transportation, optimizing energy consumption in industrial use and in buildings, and the IoT paradigm comes at help here, together with optimization algorithms [28]. The thesis here is that the energy consumption of the whole ICT field is much smaller than that of other fields (e.g., transportation and industry) [3] and advancing ICT, although expensive in terms of energy, can induce larger potential savings in the more energy-intensive fields. In line with this, a study from 2020 [8] considers *"plausible that ICT infrastructure can help save electric power in society as a whole"*, as other authors expect [49]. Unfortunately, in 2030 the study predicts a growth of electricity consumption despite any optimistic assumptions about improved energy efficiency of the ICT devices.

Estimating and predicting global power usage of such complex systems requires some simple measurable variables to be correlated to power consumption. A very established proxy for energy consumption is network traffic [10]. [4] However, network traffic may not be anymore a good index to estimate computer electricity [7], since nowadays data centers consume a lot of power for data processing. Estimating the number of operations in ICT devices and the energy cost in terms of J/operation is proposed as an alternative [8]. This is mainly due to the steep rise of Deep Learning algorithms into every aspect of life. Neural Networks training is responsible for enormous amounts of electricity [57] [5] and this is partly due to the inefficient procedure of training from scratch that is done every time a hyperparameter optimization is conducted or every time a network must be scaled down for an embedded device. Although solutions exist [20], these are not yet widely adopted. Finally, another reason for the growth of computing energy demand is the mining of cryptocurrencies [13]. The most popular one, the Bitcoin, consumed in 2018 as much energy as the state of Israel [23]. Notably, some authors have proposed the use of blockchain for the IoS [64].

[3]The paper cites data from 2012 [65] stating that the ICT consumed 4.7% of the electricity worldwide, which in turn is only 15% of the worldwide energy production. A more recent study estimates the ICT energy footprint, including devices, to be approximately 10% of global electricity demand [36].
[4]In 2015, it was estimated that 0.06 kWh were required per GB, and since 2000 it decreased approximately every 2 years.
[5]see also https://mlco2.github.io/impact/

2.3 Devices and the Internet of Things

The Internet has already increased the number of digital devices we use in our daily life, especially smartphones, tablets and personal computers, which are nowadays essential to get access to basic citizenship services as well as social and leisure services. With the IoT taking shape, we can expect an even larger number of devices to be produced and deployed in all sort of environments.

A 2020 study suggests that the semiconductor industry will increase its energy demand dramatically due to the increase in production of IoT sensors, actuators, processors and connectivity chips, rising from 2 EJ in 2016 to 35 EJ in 2025. On the other hand, the operational energy will decrease due to more efficient devices [22]. Studies also suggest that high-complexity devices such as multicore CPUs have a larger footprint than low-power microcontrollers, and that energy-intensive devices such as the former have a larger operational energy than embodied energy [16, 29].

This means that different strategies must be conceived to reduce our footprint based on the devices we are using: for those that are energy-intensive we must first target their energy requirements; for those that are low-energy but deployed in large quantities we must first address the impact of their manufacturing [17]. Another strategy is extending the lifetime of a product, e.g., it is best to extend the lifetime of personal computers rather than replacing them after a few years with newer, more energy-efficient ones [52].

Another issue that comes with portable devices and sensor nodes, is the batteries: these have a weight on the environment, especially for their ecotoxicity and their disposal. In this regard, the IoT paradigm has been often matched with an energy harvesting approach, i.e., one where the device or sensor node is capable of autonomously gather energy from the environment [54]. Wireless Sensor Networks (WSNs) powered by energy harvesting have been proposed and their energy balance have been analyzed [12, 27, 56]. Supercapacitors have been proposed as an alternative to batteries [39, 44], but their lower energy density still represents an issue.

The reduction of energy consumption in IoT requires dedicated communication standards that aim at optimizing transmission for energy efficiency. This is obtained by dedicated medium access (MAC) and networking protocols (layers 2 and 3 of the ISO/OSI communication stack), long-distance low-power physical access (PHY) technology (layer 1 of ISO/OSI stack). The literature present a plethora of works in that regards [2, 24, 38, 53] and wireless communication standards for low-energy applications are nowadays widely adopted (i.e. IEEE 802.15.4, ZigBee, 6LoWPan, BLE and IEEE 802.11ah).

For more references and data about environmental issues in the IoT two recent surveys can be found in [4, 41].

2.4 Streaming Multimedia Content

ICT and the Internet serves a plethora of roles in modern society and part of it is delivering, creating and editing multimedia contents, i.e., audio, video, images and such. Nowadays, Internet is a vast source of movies and songs, people are able to deliver audio and video contents through social platforms, and video-calls are common not only in the business world but also among friends. The second most active social network is YouTube [1] which is entirely based on video contents. Multimedia contents are heavy in terms of bandwidth and, as discussed above, data traffic is one way to estimate energy consumption of ICT.

Some works in the literature target the energy demand of multimedia services such as video delivery. Two studies from 2012 [32, 60] discuss the issue of delivering video content to mobile devices and their energy impact, however, data is likely changed in the last 10 years. A recent work discusses the use of YouTube as a streaming platform and its sustainability [66]. The work cites research stating that videos took 72% of global consumer traffic in 2017. Furthermore, on-demand video and other entertainment sources contributed to 41.4% of fixed and 32.9% of mobile peak traffic demand in Europe in 2015, and 67.3% and 35.4% in North America in 2016. Since the Internet infrastructure growth is planned based on peak traffic, it is natural to conclude that video traffic has a role in the ICT footprint: not only in the energy that data traffic requires, but also in the overall cradle-to-grave impact of the infrastructure.

With video data being the most bandwidth-intensive activity on the network, several works investigated the impact of watching various aspects of movie streaming [31, 48, 55]. From these it emerges that the main impact is due to networking and end-user device operational energy. The current standard for enjoying movies is digital download, which is better than the old DVD distribution model. However, according to [48] *"in 2017 consumer movie viewing in the USA was almost 8x higher than at the time of peak movie consumption when the physical distribution dominated"*, therefore, the energy demand for movie watching may have increased in absolute terms. This is what in Economics is called *rebound effect* or *Jevons paradox*: i.e., when efficiency gains are overtaken by the increasing affordability and infrastructure availability [30].

Another very recent work [59] estimates the average CO_2 emission per MB in audio streaming services in Japan, which may result useful for further research. Then it discusses video streaming, concluding that *"Online video streaming accounted for 87.7% of the total emissions, which corresponded to approximately 0.23% of domestic CO_2 emissions derived from electric power generation."*.

Data streaming efficiency has been the object of study of many technical papers. Since data transmission accounts for an important part of the energy consumption of the devices, transmission should have the least overhead (e.g., transceiver activation, network driver caching, etc.) and should, thus, be conducted quickly. Video streaming services always have some buffering mechanism, for the goal of providing a glitch-free watching experience. However, a large buffer is desirable from a user experience point of view, but when the user skips parts of the video or jumps to other videos, the energy consumed to download the video that has not been watched is wasted. These topic and strategies to address it are discussed in several works [11, 14, 33, 34, 51].

Technical standards and policy-making has also been considered for energy saving in video streaming. In [40] three scenarios (worst case, best case and median) for regulatory interventions and technical standards have been modeled to predict European energy savings related to video streaming in the years 2020-2030. The models show that these interventions could have a significant impact on electricity consumption and CO_2 emissions.

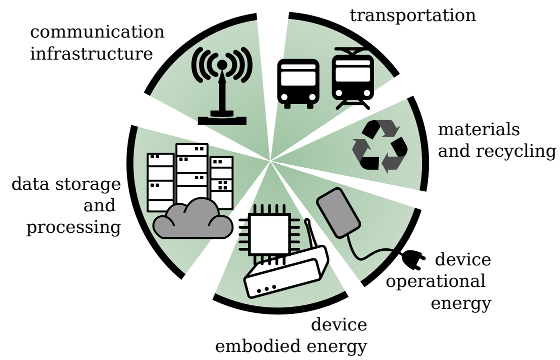

Figure 2: Key areas to monitor to reduce the impact of the Internet of Sounds. The illustration does not attempt at representing accurate proportions.

2.5 Summary

The literature survey provided some useful information that we can try to summarize. First of all, the main areas that we should monitor for a more sustainable development of the IoS are at least the following (see Figure 2): the communication infrastructure, its deployment and construction; the data centers were data is stored and processed; the end-user devices with their embodied and operational energy; the transportation of goods and people; the materials employed for the device and the cost of recycling them.

More detailed considerations follow:

- The environmental cost of current ICT infrastructure is mainly due to network infrastructure and end-user devices operational energy, as well as the embodied energy of manufacturing the devices and deploying the infrastructure;
- For some applications the embodied energy is larger than the operational energy and vice versa, thus, each use case must be analyzed carefully to decide where to intervene;
- In the first case we must improve reuse and extend device lifetime, in the second we must reduce energy consumption;
- Network traffic and data centers have an impact. In particular video streaming is responsible for most of the Internet traffic globally;
- Whenever the network avoid people to travel or commute, the carbon footprint is reduced;
- Heavy data processing applications, such as training Deep Neural Networks, are an emerging issue in terms of energy and CO_2;
- The ever increasing energy efficiency of products and services is often paired with increased affordability, making them more widespread. This fails to take to the expected savings: what in Economics is known as rebound effect or Jevons Paradox.

3 SUGGESTIONS FOR AN ENVIRONMENT-AWARE IOS

The IoS is an umbrella definition that incorporates several artistic, scientific and social activities, all having different environmental impacts. While technology drives new ways of dealing with sounds, music and users, it also offsets negatively our impact on the planet. In a pre-industrial society, music could only be performed by humans, sounds could only be emitted by living bodies or crafted tools. Traveling was not even an option for most people and little space was dedicated to entertainment or the arts for the majority of human beings populating the Earth. Nowadays, devices and services are complex to manufacture and often require energy to be operated. Artists as well as regular citizens travel a lot to produce and enjoy culture.

However, how and where can we look for sustainable practices to adopt in the current context? In this section we aim at providing a few concepts. We will not discuss technical advancements, since these are already actively researched by experts in the field: from energy-efficient algorithms to low energy silicon chips and devices, from better energy storage and distribution infrastructures to efficient data centers, the IoS will lessen its impact by adopting low-footprint technology as soon as this gets out from a research stage.

What we can do, instead, is devising guidelines for research and development that reduces the impact of IoS applications and examine critically what are the odds of some of our choices in research and commercialization of IoS services and products.

3.1 Design Challenges

When conceiving an object or a software, a careful design phase is of uttermost importance, especially if the environment is added as a variable in the process. Design choices that take the environment into consideration can be resumed as follows:

(1) conduct an energy optimization phase of software and hardware;
(2) select computing hardware that is not oversized for the application;
(3) select algorithms that are not oversized for the application, e.g., favoring traditional DSP algorithms over Deep Learning ones when not necessary,
(4) ensure longevity;
(5) make the product or service modular and serviceable.

The first three points are almost self-evident to a skilled developer or researcher, e.g., (1) energy optimization can be done by rewriting portions of a software after a first working proof-of-concept. (2) computing hardware can be selected to match the requirements of the algorithms (this should also have a beneficial impact on the production cost).

As for point (3) there are still many application, if not most, that can benefit from employing traditional DSP algorithms rather than the most cutting edge Deep Learning ones. An example is sound synthesis. Algorithms based on sampling and physical modeling are simpler, well understood and much less expensive in terms of required computational hardware than Deep Learning algorithms (e.g. WaveGAN, WaveNet, etc.). For sound analysis, many handcrafted features such as logMel and STFT are also way less expensive than learned convolutional layers and although they would be considered not novel during a scientific peer review, they may reduce the training cost and make edge computing lighter.

The other two points require a further discussion, which will also be useful to draw some useful examples and derive future strategies.

3.1.1 *Design for Longevity.*

Ensuring longevity is hard [45] and it may counter recent engineering and marketing trends in consumer devices and services, therefore making our effort harder and giving a penalty in competing with similar ones. In current society, novelty is seen as an added value *per se*, i.e. notwithstanding the real benefits it carries. Marketing trends adopt this attitude and tend to make new products more appealing, in order to convince the user to leave the old product for the new one. Often the selling point is a novel technical feature that is not necessarily fundamental to the user[6]. An unnecessary increase in sales of new products (and abandonment of older ones) leads to an increase of our footprint, which inevitably takes us closer to the deadline for reversing global warming.

Engineering trends include the use of highly integrated components (e.g., soldered RAM chips versus removable RAM chips in computers) and the use of consumer-grade components rather than industrial-grade ones[7]. These also accelerate the production and selling of new products in spite of environmental issues.

Similarly, software components like programming languages, operating systems and SDKs must satisfy several criteria to allow a long product lifetime:

- they must be widely adopted, i.e., there is a large community of users and developers that will likely maintain it still for a long time. Components with a wide support are less likely to be abandoned quickly;
- they must be optimized for energy efficiency and use a programming language with native support for the target (e.g., C/C++) or an energy-aware interpreted language (e.g., Java code on the Android Runtime);
- they must develop slowly, have stable long-term releases (as it is done with long-term support releases of operating systems), or strictly maintain backward compatibility: this means that old software can still be operated and current software will still run in the next years.

3.1.2 *Design for Modularity and Serviceability.*

Point (5) above requires that products and services are modular and serviceable. For hardware products, this means that they can be repaired rather than disposed in case of failure of a single component. For software projects, this means that they are not strictly dependent on other software or hardware components, so that their life is not endangered by the end of support of a related library or the specific version of an operating system supporting it. An example in the audio domain would be a virtual instrument plugin that is very dependent on the software host. A VST plugin, e.g., has a long chance of surviving, since the format is developed since the late 1990s and is not likely of being abandoned any soon. On the other hand, a plugin developed for a brand new computer music programming

[6]Sometimes a reduced energy consumption is a selling proposition. However, as we have learned above, the effects of this reduction must counterbalance the embodied energy of the new item.

[7]Industrial-grade components are guaranteed for 10+ years of support and stock availability, thus are more expensive. Consumer-grade components are cheaper and evolve quickly, but after a few years they will not be available, forcing re-design of product and breaking serviceability.

language that is maintained by a single PhD student is not likely to be usable in the years.

3.2 Human factors

While technical advancements are very important for the evolution of a more sustainable technology, we cannot expect radical changes in environmental impact of ICT in the years to come or, at least, we cannot rely only on these. Thus, we must react to environmental issues considering a worst case scenario in which technology itself cannot improve as fast as required by the global warming constraints, and leverage human action. Indeed, as we have seen from the literature survey, technical improvements can reduce the impact of technology by some extent, but on the other side it can make technology more widespread, thus increasing in absolute value our environmental footprint.

Human factors may impact more than we believe. By human factors we indicate a set of policies, behaviors of the individual and the society, that can help mitigate our impact. It is worth addressing those areas that, from the data provided by the literature, have a major impact: electricity, transportation and embodied energy.

3.2.1 Less Consumption. Electricity consumption can be lowered by a more careful usage of the devices and data streaming. Like closing the tap of a sink when we are not using water should be a daily habit, shutting devices and closing streaming should be too. Furthermore, some actions are more expensive than others. An interesting comparison is the listening of music from a video streaming service, such as YouTube and a music streaming service such as Spotify. We collected some statistics from three usage examples: streaming a music video, streaming a music video showing a still image (e.g., the album cover), streaming music from an audio only streaming service. Data has been collected using GNU/Linux tools textttnethogs and `iftop` and is reported in Table 1. As it can be seen, there is almost an order of magnitude between the highest and lowest download rate per minute of content. Furthermore, handling and decoding a music stream is more efficient for the device in terms of energy. Figure 3 depicts two implementations of a typical use case: a music streaming system at home or in a store. On the one side, a laptop is used to stream and playback music on a hi-fi system from a video streaming service; on the other side the laptop is replaced by a smartphone (possibly old and repurposed for the scope, to reduce its footprint) and only streams audio data. The power has been estimated from two laptops employing the GNU/Linux tool `gnome-power-manager`, running on battery while watching music videos at 480p or 1080p, with LCD screen at full brightness or dimmed. The data for the smartphone has been estimated considering a 2 Ah battery capacity operating at 3.3 V, lasting for 6 h of uninterrupted music streaming.

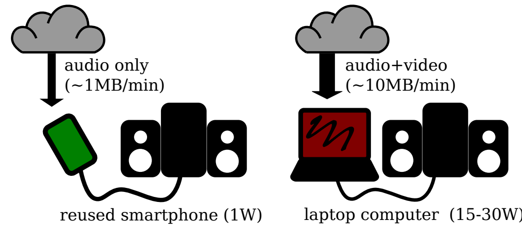

Figure 3: Listening to music in an indoor environment: two examples with different energy requirements.

		RX (MB/min)	TX (MB/min)
A+V	YT 1080 HD	12.5	0.02
	YT 480p	3.4	0.02
Still	YT 480p still	1.6	0.02
Audio only	SP High (160kbps)	3.5	0.06
	SP Normal (96kbps)	1.8	0.06

Table 1: Estimated bandwidth (in MB per minute of content) for streaming on Youtube (YT) and Spotify (SP) using audio and video (A+V), audio and still image (Still), audio only. Please note that by default Spotify selects the data rate according to network conditions.

3.2.2 Less Traveling. Transportation is one of the areas where we need to cut emissions globally. City commuting, medium range travels and air travels are all equally necessary in arts- and music-related activities. Fortunately, the field of Networked Music Performance (NMP) systems and online collaborative music can help reduce emissions in this regards. Music rehearsals and music lessons are a great example. By leveraging low-latency music networking such as JackTrip [19] or Elk.live [62] and online music writing platforms, musicians can greatly reduce their commuting and traveling for teaching, learning and rehearsing. It also makes easier for students from underdeveloped rural areas or dislocated far from cities to learn from experienced teachers, thus developing their potential further and making their chances for a career higher. Technology can help sharing scores and perform together at distance or work on a music sheet collaboratively online. All these scenarios come at very little expense for the environment if they are enabled by general purpose devices, such as personal computer, regular internet connections and home or office gateways. In this case there is no extra hardware associated with the scenario and the relatively low CO_2 impact of transmitting data is compensated by sparing the CO_2 emissions of traveling. If dedicated devices are required, however, a LCA should be conducted. Some applications, e.g., takes advantage of popular DIY platforms such as the Raspberry Pi. This platform is relatively efficient in terms of energy, has a lightweight software layer that allows an extended lifetime and can be reused for many purposes, therefore its environmental cost can be compensated by its extended lifetime.

As a final remark, NMP can also be a platform for novel network-mediated concerts and shows. It is questionable whether an in-presence show with some remote performers has a positive impact on the environment, since the cost of organizing it, heating and lighting the venue, moving the audience to the venue may be higher than the traveling of a few performers, unless they come from a long distance. For the sake of clarity, collective cultural activities should not be abandoned in favour of, e.g. a passive fruition of streamed media at home, just on the basis of reducing traveling impacts. We must not forget the cohesive role of culture and arts, their dialectical values and the support it can give to collective action for sustainability [35].

3.2.3 Reuse. Lastly, reusing equipment, limiting purchases and buying equipment that is foreseen to last longer is a necessary step towards a more sustainable ICT. Currently, many industries push towards a consumeristic model that reduces the lifespan of electronic equipment by design. This strategy is generally enforced through software: many smartphone and computer applications require frequent updates to continue using them. However, updates may break compatibility or make the application heavier to run on older hardware. As an example, among the three most widespread operating systems, GNU/Linux provides lightweight distros that can run on 10-15 year old computers. They also allow to run audio software with low latency, such as Pure Data, which makes them useful for sound installations, electronic music performances and more. On the other hand, the support for audio device drivers is scarce, therefore, they may not connect to all devices. MS Windows has the best availability of device drivers and can still run old 32-bit software. Mac OS, on the other hand, is the most common platform for digital creativity, but it enforces short hardware lifecycles by restricting updates of the operating system to old computers and providing e.g., computers with soldered RAM. All in all, when it comes to audio and sound, for most purposes we do not need recent hardware if the software is designed for lasting long and optimizing computing resources.

The practice of reuse in audio applications has been already considered previously. In [21] reuse is discussed for DMIs, providing strategies and promoting students didactic activities fostering reuse. Another successful project is that from Rainforest Connection, which we have discussed above.

4 CONCLUSIONS

In this paper we have addressed the topic of sustainability in the realm of digital audio and particularly of the Internet of Sounds. Through a literature survey we have gathered some insight about the aspects that may matter the most to researchers in the IoS community: what are the major sources of environmental impact of current ICT?

From the survey we have found that the embodied energy is an important factor to consider together with the energy employed by the devices and the network infrastructure, therefore, in some use cases it is important to extend the lifetime of devices and services as much as possible and we provided examples to apply careful design choices and reuse. Following the literature review we also discovered that digital media can reduce our footprint by replacing physical media and traveling. However, the increased availability and affordability of technologies can increase their usage to a level that counterbalances the environmental benefits (Jevons Paradox). Furthermore, all markets rely on change and innovation to maintain and increase sales, at the expenses of the environment. Although many environmentalists propose *sustainable degrowth*, this has never been embraced on a large scale and we do not know whether humans on a large scale would be able to accept such a paradigm.

Looking at the technical side we must consider new IoS-related trends and services in the future that we expect to come. Among these, the so-called metaverse, and the demand for more Virtual Reality and 3D audio contents will push towards larger network traffic, processing power and the manufacturing of new entertainment devices. Before even considering how to reduce their impact, it would be necessary for the academics to consider whether it is worth investing resources in their development. Are these promoting new and better forms of socialization or just new industrial products for profit? What new emotional, social and political messages are they carrying that previous media and arts where not able to convey? In other words, considering that these new technologies will presumably harm the environment, will they at least empower humanity in some sense? These are questions worth asking ourselves, and if the answer is positive then we can start thinking how to reduce their impact.

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