Sustainability and the Internet of Sounds: Case Studies

Leonardo Gabrielli, Emanuele Principi, and Luca Turchet, *Senior Member, IEEE*

***Abstract*—The Internet of Sounds (IoS) is an emerging field promoted by a large network of research institutions and companies, which fosters research and new industrial and civil applications in domains such as audio processing, music performance, entertainment and environmental monitoring. Being based on novel technologies and computing paradigms, its environmental costs are yet to be assessed. In previous works, the foundations for an environmental impact assessment in the field were laid down. In this paper, a methodology is built based on an extensive literature survey to identify the foremost emission drivers in the IoS, and apply the collected knowledge to the qualitative analysis of five relevant case studies in the IoS that the authors identify. These are identified from the IoS literature in order to cover two orthogonal axes: artistic-functional and emerging-mature. Their discussion allows a qualitative prediction of their impact, which is positive in two over five cases, negative in the other two and very low in the last one. Considerations, design tips, social suggestions, and future challenges are also outlined.**

***Index Terms*—Internet of sounds, 5G, environmental impact.**

I. Introduction

In RECENT years, a novel research area at the intersection of several technical and artistic fields has been growing, known as the Internet of Sounds (IoS) [1]. This broad topic has interested academia and the industries and relates to networks 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) [2], the Internet of Multisensory, Multimedia and Musical Things (Io3MT) [3], the Internet of Audio Things [4] and the Web of Audio Things [5]. These are subfields of the general Internet of Things (IoT) paradigm. In essence, the IoS refers to the part of the IoT that deals with sound-related information, both in musical and non-musical contexts. Differently from many typical IoT applications, which require low bandwidth, raw audio signals convey much information calling for a high capacity network or a high computational power to compress before transmitting. IoS applications will, thus, have a larger per-device energy cost, which poses questions of sustainability.

Received 3 May 2024; revised 9 July 2024, 23 October 2024, and 4 December 2024; accepted 5 December 2024. Date of publication 24 December 2024; date of current version 22 May 2025. *(Corresponding author: Leonardo Gabrielli.)*

Leonardo Gabrielli and Emanuele Principi are with the Dipartimento di Ingegneria dell'Informazione, Università Politecnica delle Marche, 60131 Ancona, Italy (e-mail: l.gabrielli@univpm.it).

Luca Turchet is with the Dipartimento di Ingegneria e Scienza dell'Informazione, Universita degli Studi di Trento, 38123 Povo, Italy.

Digital Object Identifier 10.1109/TTS.2024.3513777

The interdisciplinary character of the IoS opens questions that go beyond technical challenges. The IoS community, gathered around the recent Internet of Sounds Research Network (IoS-RN) https://internetofsounds.net/, is committed to addressing technological and non-technological questions, including networking, privacy, security, and artistic challenges, as well as pedagogical, ethical and sustainability issues. In this work, the authors are interested in the latter, which is a topic that has been largely overlooked thus far. This work, thus, aims at providing a first knowledge-base and guideline for the IoS-RN, for future works to build upon.

Established fields of research, such as computer science, electronics and IoT, addressed issues related to energy consumption and eco-compatibility of manufacturing materials, as will be pointed out in the literature review of Section IV. These studies can serve as a starting point to build a knowledge base related to sustainability and apply it to the emerging vertical field of the IoS. However, this work broadens the perspective by accounting for factors such as durability, rebound effects, and a clearly stated formulation of the overall CO_2 balance. It also describes key case studies in the IoS and evaluates their impact in a qualitative way.

Other scholars recently approached the concept of sustainability. The NIME (New Interfaces for Musical Expression) community has been particularly prolific (see, e.g.: [6], [7], [8], [9]). Other related conference published papers related to this topic, e.g., ARTECH [10] and Audio Mostly [11]. Some of these are position papers, while others tackle very specific aspects, therefore a unitary research framework that provides operating principles and design considerations is still absent from the literature.

The paper is organized as follows. Section II summarizes the aims of the work. The method adopted to reply to the research aims is described in III. Section IV provides a basic understanding of the environmental issue defining the concepts of CO_2 balance, operational and embodied energy. It also briefly describes how the environmental impact is assessed. Section V examines previous knowledge on the environmental impact of the IoT and ICT in general, by focusing on three different aspects: devices, networking and computing. This provides an informative framework for the reader that will help to understand the remainder of the paper. Section VI starts examining issues specific to the IoS by considering five typical use cases and providing, for each one, an account of possible environmental issues and variables that can have a great effect in mitigating or worsening them. Section VII provide a discussion on the findings of the research work and

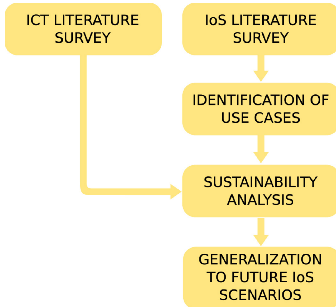

Fig. 1. Graphical representation of the research methodology.

suggests recommendations that may be of help to mitigate the environmental footprint of the IoS. Section VIII concludes the paper.

II. Objectives

This paper extends a previous paper, which introduced key concepts for designing sustainable applications within the IoS [12]. In that paper, an initial overview of the environmental issues was provided, with a focus on multimedia streaming and the Internet infrastructure. The work aimed to open a debate on the subject by setting some pillars and stimulate reflection on the environmental footprint of researchers' and developers' activities in the IoS.

This paper has four research objectives (RO):

- RO1: Provide an updated literature review of the environmental impact of ICT;
- RO2: Identify the foremost emission drivers for the IoS, after defining its typical architecture;
- RO3: Identify typical use cases in the IoS and formulate an analysis on their potential impact;
- RO4: Infer recommendations that are general to the entire IoS field.

Essentially, the paper is meant to design a method for the engineering and conception of IoS applications that complements the existing literature on the Design for Sustainability [13] with domain-specific knowledge.

III. Methodology

The employed literature review approach is that of a scoping review, aimed at mapping the breadth of current research in the field of sustainability, identifying key concepts and potential gaps in knowledge. The methodology adopted for the writing of this paper is depicted in Figure 1 and is composed of several phases. A broad literature survey has been conducted from Scopus, Web of Science, IEEE Xplore, ACM Digital Library to collect works in the ICT field dealing with the environmental impact of technology. Specifically, the following text strings were searched for in the title, abstract and text of the papers to collect useful results: "life cycle assessment", "sustainability", "environmental impact", "CO2 emissions", "green", "LCA", "carbon dioxide emissions". Only journal or conference papers were selected, published from 2009 onward. The results were filtered by keeping only those papers that included at least one of the following terms: "electronics", "ICT", "Internet", "IoT", "streaming", "wireless", "multimedia" and that were cited more than twice. Duplicates coming from the different databases were automatically removed by string matching the title. The final number of papers was 404.

TABLE I
The Four Identified Use Cases

	EMERGING	MATURE
ARTISTIC	Smart Instruments	Networked Music Performance
FUNCTIONAL	Smart Rehabilitation	Wireless Acoustic Sensor Networks

From these papers the authors started a manual bibliographic study. Titles were carefully read to evaluate the relevance and scope of the paper (e.g., works dealing with life cycle assessment in electronic products such as wind turbines are out of scope). Only papers for which full text was available were utilized in the study. The papers were studied and organized in conceptual maps on a digital document and divided by topic thematically or related to other papers. This process was at the base of a first draft for Section IV, which was then refined several times by iteratively reading the papers to extract salient knowledge, delete unnecessary information or connect this to other papers. The final outcome is the survey in Section IV that provides facts and trends on a large number of case studies in the various subfields of ICT.

In parallel with this work a comprehensive study of the IoS field was conducted. In this case a literature search was conducted by just using the filter term "Internet of Sounds" from the aforementioned sources and also considering all the papers from the International Symposium on the Internet of Sounds, which has been organized by one of the authors since its beginnings. Then all the subtopics were collected from the four main research areas addressed by the IoS-RG and clearly indicated on their website (the topics can be found at https://internetofsounds.net/about/). These are: Sound Things, Networking, Applications and services, Datasets and storage. These were intersected with the papers provided by the IoS literature search to find significant use cases to equally represent emerging vs. mature research scenarios and artistic vs. functional applications. The identified use cases are shown in Table I.

By taking into consideration the use cases, a qualitative sustainability analysis for each one of the use cases was laid down. Finally the extrapolated knowledge is used to generalize to future use cases in the IoS in the form of recommendations. The paper is qualitative in its nature and constitutes a foundation for quantitative studies, each one dealing with each of the identified use cases (or a subpart of it), that are expected to be conducted in the future.

IV. The Environmental Footprint of ICT

The Internet and its impact in terms of CO_2 has been a subject of study since the early 2000s. Advantage can be taken of the scientific literature to learn how experts have studied its footprint and apply the same reasoning and tools to the IoS. Since technology is evolving fast, some of the papers become

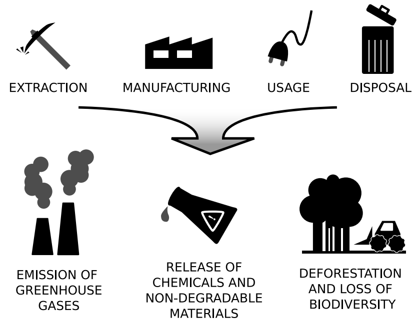

Fig. 2. The lifecycle of a product (on top) and its impact on the environment. The carbon footprint introduced by GHG emissions is only one of the many concurring factors.

obsolete in the span of a few years. Therefore, in this overview, only results that are less than 15 years old are considered. The older papers will be considered only when they provide a methodology for assessing environmental impact.

The IoT, and by extension the IoS, which is a subfield, comprises interconnected electronic devices. These devices impact the environment during all three stages of their lifecycle [14]:

- manufacturing;
- usage;
- product disposal at the end of the physical lifetime.

All three items have an impact on the environment in terms of [15]:

- carbon dioxide (CO_2) when fossil fuels are used to generate the energy required to sustain these devices or produce them;
- 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 public opinion is the emission of greenhouse gases (GHG), which impacts and endangers the whole planet. The release of toxic chemicals and the consumption of soil are equally hard to revert and have global consequences, but 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 economic and political subordinate position. Efforts have been made in the academic community to help indigenous populations discover illegal forest cutting [16] and oil extraction activities [17], [18] (see also https://hivos.org/program/all-eyes-on-the-amazon/), however, considering the social and political complexity of these topics, the focus of the paper will be on CO_2 emissions and energy consumption as a proxy for sustainability.

In the following, the *embodied energy* of a product can be defined as the energy required for the extraction of its constituent materials, the manufacturing of its parts and components, the transportation, and the final disassembly, disposal, and recycling. Moreover, the *operational energy* can be defined as the energy directly required by the device to operate during its lifetime. When referring to ICT, all devices are powered by electric energy, which at the time of writing is still largely produced using fossil fuels (estimates from [19] says that 63.3% of the current worldwide electric energy mix is composed of fossil fuels).

In this paper, the carbon footprint balance B of some scenarios is defined as the difference

$$B = CO_{2S} - CO_{2E}, \quad (1)$$

where CO_{2E} is the emitted carbon dioxide imputable to the system, while CO_{2S} is the one spared thanks to its operation. It is necessary to understand that to revert global warming and reduce overall human-related GHG emissions, a technological system must have a positive balance B, i.e., the GHG emissions related to its operational and embodied energy must be less than those that would be emitted if the system was not available. Unfortunately, the term "green" is often associated with technologies or systems that do not fulfill this requirement but rather provide improved efficiency with respect to a previous technological achievement. Since the term has a positive environmental meaning, it should be carefully used. As an example, many papers related to the IoT associate the term "green" with reduced energy consumption [20] or to applications where the IoT can monitor and improve the efficiency of carbon-generating human activities [21]. However, their balance is positive only if the improvement does not come at the expense of other hidden costs, e.g., a higher embodied energy related to the use of a more complex manufacturing process or the deployment of the system itself, or rebound effects that increase the use of the new technology with respect to its previous iterations (see Section V-A) for further details. In the remainder of the paper, the term "green" is avoided and the paper will only refer to the carbon dioxide balance, for clarity.

As a last note, some of the activities related to the IoS have a recreational goal, or serve as mere entertainment: in this case, they will employ resources (both matter and energy), that would otherwise be available to current or future human generations to satisfy their primary needs. To be fair (considering that a large part of the world still has no access to modern technologies, and that future generations may have reduced access to natural resources), it is needed that novel IoS applications are carefully designed to attenuate their impact.

A. Footprint Assessment

As suggested in the introduction, assessing the impact of a process or product is somewhat complex. For this reason, indices and measures can be considered rough approximations, useful for grasping this complexity in a way that is understandable to humans and allows us to take action and address the problem.

Among the many tools for footprint assessment [22], the most common methodology is the Life Cycle Assessment (LCA) [23]. This can be applied to a large number of products and processes and considers resource use, impact on human health, and consequences on the environment. It is based on an analysis from cradle-to-grave of the product, i.e., considering all the environmental aspects related to the 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.

The assessment of impact through LCA is a difficult process that needs expertise on the processes behind a given product or service and is based on judgments that can possibly be biased by human factors and experience. Generally, different studies on a given product or service conclude with similar results, but some outliers can be found [24]. For this reason, 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) [23]. The standard defines the objective and scope of LCA, and describes the life cycle inventory (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase. It also provides a critical review of LCA, including known limitations and conditions for using value choices.

V. Three Emission Drivers for the IoS

Based on the current knowledge map provided by the IoS-RN and detailed in [1], the IoS comprises *sound things* such as smart musical instruments, embedded audio devices, distributed systems, sensors, and actuators. Additionally, the dependence on ubiquitous networking infrastructure entails the use of networking appliances, servers, and storage devices, which consume energy continuously to deliver their services. Lastly, pervasive computing is present both at the network's endpoints and in the cloud.

In this context, three primary drivers to the IoS's carbon footprint are identified, which are examined in detail in the following sections:

- electronic devices (and their embodied energy),
- networking infrastructure (and its constant consumption),
- computing workforce (and its power demand).

A. The Electronic Devices

There are many sources in the literature that help understand how manufacturing electronic devices impacts the environment [14], [25], [26], [27]. In the electronic products domain, the semiconductor industry has the predominant impact due to the current reliance upon large amounts of solvents, acids, and gases that have numerous toxicological impacts [26].

The industrial trend in IoT is to reduce the operational energy footprint but increase the number of active devices and make their use more pervasive. This can adversely affect the environment and overcome the operational energy savings. Despite the production of increasingly efficient devices, a 2020 study suggests that the semiconductor industry will increase its energy demand dramatically due to the growth in the production of IoT sensors, actuators, processors, and connectivity chips. The overall demand will rise from $2 \cdot 10^{1}8$ Joule in 2016 to $35 \cdot 10^{1}8$ Joule in 2025 [28]. This is what in disciplines such as economy is called *Jevons Paradox* or rebound effect, i.e., when the effect of technological progress or other human-actuated policies increases the efficiency of a process/system, but the increasing affordability increases the demand/usage, undermining the efficiency gains.

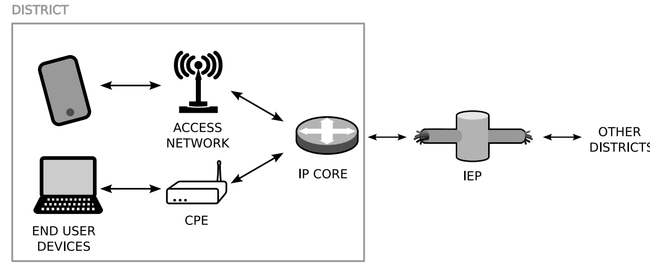

Fig. 3. The network infrastructure divided into its components.

B. The Networking Infrastructure

The Internet presents an impact on the environment, although users are generally unaware of it [29], as most of its devices act remotely from the user. The networking infrastructure that sustains the Internet is composed of a large variety of devices, to which an embodied and an operational energy must be associated. Fig. 3 shows a simplified view of the various components involved in current networking infrastructures. The end-user equipment, such as smartphones and personal computers, is connected to the IP core through the mobile access network or the customer premise equipment (CPE). The IP core routes the traffic to other networks through the Internet Exchange Point (IEP). The embodied energy with networking devices is generally a fraction of their operational energy [30], and their expected lifetime is usually long, lasting years after their deployment until they are obsolesced or break. The footprint associated with the networking infrastructure has grown in the years, however, at a slower rate than other ICT components. A study from 2018 [31] projects the carbon footprints for several ICT components (desktop and notebook computers, data centers, network, smartphones), showing that from 2010 to 2020 the network footprint decreased relatively to all other components, from 28% to 24%, while, e.g., the data centers increased from 33% to 45% and the footprint related to the smartphones only, increased from 4% to 11%. Despite the increase in global bandwidth consumption and, thus, in the networking infrastructure size, service providers have made steps to make it more efficient. The network itself is composed of an IP core network, transport nodes, and access nodes. The latter accounts for 70% of the energy requirements according to [30]. A more recent work dealing with the 4G Long Term Evolution (LTE) network [32] analyzes the carbon footprint of several districts, dividing it in several components and confirming that the network access requires the most operational energy, together with the end-user devices. Indeed, the base stations in mobile communication are the most power-demanding devices [33]. However, within the advancements of 5G networking, a large effort has been put into making base stations more efficient (see, e.g., the survey in [34]).

The Internet is often considered a resource in reducing human environmental impact as the energy required to transmit a given amount of information is much less than that compared to other media, such as printed paper. Therefore, the network can undoubtedly be employed as a tool for mitigating the impact of some human activities. The role of the Internet in reducing conferencing footprint has been investigated for many years and compared to other transportation means [35], [36], [37]. For instance, studies confirm that teleconferencing reduces GHG emissions, provided that the equipment used for allowing conference calls is frequently used, i.e., their embodied energy becomes negligible with respect to the avoided traveling.

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 buildings. The IoT paradigm comes at help here, together with optimization algorithms [38]. 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), and enhancing its use can induce larger savings in energy-intensive fields. Just to provide some data, recent estimates say that the ICT energy footprint, including devices, is approximately 10% of the global electricity demand [39], which in turn is a small portion of the total energy produced by humans [40]. The study reported in [38] also concludes that "although ICT usage is bound to grow at a quick pace during the next ten years, the associated electricity consumption should grow much more moderately". In line with this, a study from 2020 [41] considers "plausible that ICT infrastructure can help save electric power in society as a whole" as some expect [42], [43].

Estimating and predicting global power usage of complex systems in the Internet, the IoT, and the IoS is not an easy task. Frequently, the footprint of the Internet as a whole is measured relying on measurable variables that are then correlated with power consumption. A very established proxy for energy consumption is network traffic [44]. Estimates indicate that the power demand for 1 GB of network traffic was around 0.06 kWh in 2015, with a decreasing trend. In the following section, the contents that mostly populate the Internet will be investigated.

Multimedia contents such as audio and video are of particular interest in the IoS. A very recent study discussed the rebound effect and its role in making digital music streaming less sustainable than older physical supports for the distribution of musical records [45]. However, the current largest source of Internet traffic is the sharing of videos. According to a recent statistic, the second most active social network is YouTube [46] which is entirely based on video content. A recent work discussing the use of YouTube as a streaming platform and its sustainability [47] 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 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. Another study from 2019 [48] forecasts the bandwidth required by IoT, video streaming, 4K technology, and Virtual Reality/Augmented Reality (VR/AR), showing that video entertainment with 4K and VR/AR will drive future bandwidth growth.

C. The Computing Workforce

The IoS relies not only on the transmission of audio signals but also on their processing. Compression and coding are only the tip of the iceberg, with applications that also require machine listening, information retrieval, and real-time processing. Since raw audio signals have a rather high bitrate (with respect to, e.g., IoT applications based on sparse sensor readings), the IoS may require an intensive computation workforce that can be found either on the leaf node (edge computing), in the cloud, or can be distributed among the two. Silicon chips require most of their energy for transistor commuting, therefore, computing bears a high impact on the energy demand of IoS applications.

Although the network infrastructure was traditionally designed for information transmission and thus, as explained previously, the network traffic can be a good proxy for estimating the energy footprint, things are changing, as more and more services implying some data processing or application runtime can be accessed through the Internet. The Internet is now able to run online applications, generate content on the fly, and perform complex data processing techniques on demand. For this reason, network traffic may not be a good index to estimate computer electricity [49], 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 Joule per operation is proposed as an alternative [41]. This is mainly due to the steep rise of Machine Learning into many services and applications provided by the Internet. Specifically, neural networks training is responsible for an enormous amount of electricity [50], partly due to the need for hyperparameter search and training from scratch. With the quick rise of generative AI a dramatic increase in the energy footprint of servers can be foreseen. It should be noted that another important reason for the growth of computing energy demand is the mining of cryptocurrencies, but this falls out of the IoS scope.

D. Summary

According to RO1, the previous sections, described the most prominent factors that an LCA analysis must address to understand the impact of the Internet of Sounds, drawing from the literature that addresses the Internet and the IoT. From there, it was possible to answer RO2, by creating a visual mapping from the two main impact factors (operational and embodied energy) to the three functional areas of the Internet, i.e., the end-user devices, the networking infrastructure, and the cloud infrastructure.

Fig. 4 depicts the IoT as a connection of end-user devices, cloud services, and communication infrastructure mediators. The end-user devices are quite diverse: from personal computing hardware to sensors, actuators, data loggers, etc. These can

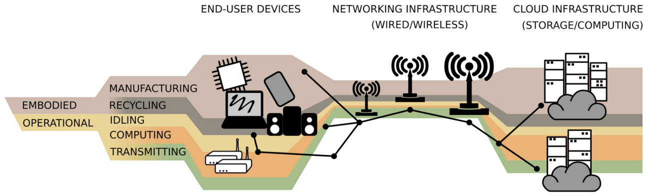

Fig. 4. An overview of embodied and operational energy split into different components and the mapping between these and three Internet segments. Each one of the segments has a different amount of energy, shown by strip thickness. The illustration does not attempt at representing accurate proportions.

transmit data, compute, and conduct other "idle" operations (e.g., showing data on a screen, sleeping, etc.). The communication infrastructure has the role of relaying and transmitting information, although some computing (e.g., modulation, encryption, spoofing, etc.) and storage (e.g., caching, data packets logging) are also done. Finally, the cloud is able to store, retrieve, and process any sort of data. In the figure, each of the three functional areas has an impact in terms of embodied and operation energy, and more specifically in terms of manufacturing and recycling, or computing, transmitting, and idling. Since the IoS is structurally analog to the IoT, what is depicted in Fig. 4 holds true for the scope of this work. To make the discussion more focused and precise, it is worth describing some specific use cases of the IoS and putting what was learned so far into practice.

VI. The Internet of Sounds: Case Studies

To clarify the discussion and answer to RO3, a few well-documented use cases in the IoS literature that emerged from Section III are described (see Table I). They will be presented in brief, and for each one, the principles outlined in the previous chapter are applied to discuss environmental risks and benefits.

A. Networked Music Performances

A Networked Music Performance (NMP) [51] is a form of artistic performance mediated by the network. Although the concept can be generalized to any sort of artistic performance (theatre, dance, and more experimental intersections of media), it is quite established for remote jamming [52] and multi-site concerts [53]. NMP may differ in the requirements: some performances require very low latency (e.g., for remote jamming using a realistic jam approach [51]), while other approaches have looser latency requirements. For some performances, a bidirectional mono audio stream suffices, while others are based on high-quality video streams with multi-channel audio. These factors influence the number and complexity of links and devices involved, as well as the choice of collaborative software, which must be specifically designed for NMP.

Let us consider a simple use case: a home-to-home rehearsal setup (see Fig. 5). This was a forced option to practice an instrument with other people during the COVID-19 pandemic [54], [55]. Research works describe the experiences and the technological tools that were employed, and they suggest that difficulties could be overcome with the use of off-the-shelf

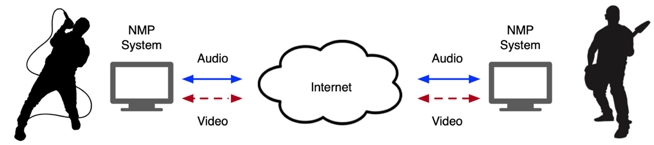

Fig. 5. A diagram of the dataflow exchanged during a NMP between two geographically displaced musicians.

components, such as laptops or small form factor computers (e.g., Raspberry Pi [56]), audio interfaces, and webcams.

From an impact assessment perspective, this is one of the few practices in the field of IoS that can easily have a positive CO_2 footprint: the devices (laptops, audio interfaces, etc.) and the infrastructure (the Internet) are already available, therefore, the remote jamming is one of the many services that can be built on top of those. In addition to this, the operational energy of the devices and the communication infrastructure is largely counterbalanced by the huge savings due to avoiding traveling. Remote rehearsal, thus, is one of these outcomes of the IoS that have a positive impact on the environment.

Other types of NMP, however, may not be as light as remote jamming. Many NMPs are done with specific components that are very complex and are hardly reused for other purposes. Such systems are based on, e.g., LOLA [57] or Ultragrid [58], and allow to involve musicians as well as dancers, thanks to the video streaming [59]. To meet strict time-critical audio and video transmission, the hardware must be able to send uncompressed/lightly compressed audio and video frames in small chunks (a few samples for audio signals, a single frame for video signals). Therefore, specific hardware devices for which a driver has been written and that have a fairly high performance (e.g., industrial-grade imaging sensors, PCI audio cards, etc.) are required. The communication infrastructure cannot be the common best-effort delivery network provided by Internet Service Providers to regular users, but a custom network that can be tuned to optimize hop number, delivery quality, and other networking parameters. Fortunately, however, the infrastructures are those employed by academic institutions, therefore, although these kinds of NMP are not very democratic, they do not require a specific infrastructure to be built on purpose.

In recent years, however, NMPs can make use of the 5G low-latency protocols [60], [61], enlarging the range of venues where low-latency NMP is possible thanks to the growing presence of 5G base stations in urban areas. To conclude this evaluation, the NMP may have a positive effect on the environment when savings due to reduced traveling overcomes the environmental cost of building the performance. Among these costs, the manufacturing of specific hardware can fit, as well as the transportation of technicians, performers, audience before and during the performance, the operational energy of the devices, the impact of running an infrastructure and multiple venues. Social and cultural benefits must be also considered in weighing the impact of a NMP. The risk of rebound effect is small, since the economic and management overhead of organizing cultural events is not remarkably reduced by the availability of networking technologies. Concerts are also limited by the available spare time of the audience.

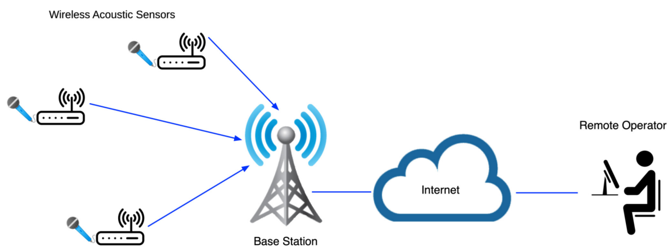

Fig. 6. A schematic representation of a WASN.

B. Wireless Acoustic Sensor Networks

Wireless Acoustic Sensor Networks (WASNs) are an established subject of research [62], [63]. As shown in Fig. 6, WASNs are based on acoustic sensors (e.g., microphones, accelerometers, etc.) that form meshes of autonomous devices capable of connecting remotely to transmit the actual raw information (e.g., acoustic signal), an intermediate representation (e.g., sound intensity, spectrograms, etc.) or very high-level information (e.g., alarm for a detected intrusion). They evolved quickly with the evolution of enabling technologies such as low-power processors and transceivers, domain-specific communication protocols and radio technologies, and high-density energy storage devices.

A WASN node generally consists of a processing unit, a radio transceiver, acoustic sensors, and an energy storage device, such as a battery. The network, however, also requires base stations, relaying devices, and servers that receive the information. The transmitted data can be stored and processed in the cloud, where AI algorithms can potentially be used. Their footprint depends on their computational cost and the energy required during training. All the involved devices, as well as their operational energy, matter to the scope of this work. Two different cases will be investigated: indoor and outdoor applications.

1) Outdoor Environment Monitoring: This case study relates to WASN deployed in outdoor environments for wildlife monitoring [64], illegal forest cutting [16], [65], urban noise pollution monitoring [66], urban soundscapes [67], [68] or environment surveillance [69]. These kinds of systems typically encompass a set of microphones distributed in various parts of the outdoor environment; a distributed set of computing units that analyze the audio stream collected by the microphones via machine listening techniques [70]; a network link that allows to send the data to a central unit for the collection and further process the data.

Raw audio data can be expensive to process and transmit. For this reason, it is not trivial to decide whether processing should be conducted on the node, reducing the transmission burden (edge computing), or conversely, whether the node should just conduct minimal computing and leave the heavy computing in the cloud by transmitting all the data (cloud computing). The design depends on the applications at hand, and trade-offs can be found, e.g., by conducting some pre-processing and compression in the node, leaving the server to do the rest. In this choice, design constraints come from the hardware capabilities and costs, the available energy, the number of nodes, the interdependence between their data, etc.

As with any IoT application, WASNs pose an environmental problem in terms of embodied energy (how many sensors are manufactured and deployed?) and ecotoxicity (are there going to be leaks, e.g., from battery chemicals?). To reduce the embodied energy, some use cases allow multi-purposing the same device. As an example, a sensor node in a city could both manage traffic lights, gather audio information from the street, and air quality information. This, however, requires careful planning or the possibility of retrofitting new sensors and functionalities to an older system (a modular design is required).

The energy storage poses two issues: one has to do with its embodied energy (batteries tend to have a high footprint [71]), and the other is with leaks. While devices in an urban area may be easily powered with electricity from the grid, in rural or natural areas, the only choice is energy harvesting, which must be coupled with batteries. Several years ago, other solutions were proposed to store energy instead of regular batteries, such as supercapacitors [72]. These devices store energy in electric rather than chemical form, as in capacitors, but have a much higher energy density (however, still much lower than that of chemical batteries). A recent work addressed the use of supercapacitors in WASNs to reduce the environmental impact of batteries [11]. The problem with supercapacitors is their lower energy density, which reduces the autonomy of the device, and which, in conjunction with unpredictable solar power shortage, requires algorithms to be robust to power outages [11].

Some applications may be directly related to an environmental cause. For example, acoustic monitoring may be applied to the preservation of forests [16]: in this case, the carbon footprint of the system can be lower than the CO_2 saved from trees. In some special cases, WASNs are useful to gather global warming-related information from acoustic data [73], or to monitor wildlife [74]. This information can be useful for research and dissemination and thus can potentially harness savings that are larger than the WASN footprint. In all other cases, the carbon footprint balance of a WASN is negative.

2) Indoor Monitoring for Industry 4.0: Industry 4.0 scenarios make use of WASNs for sound-based remote predictive maintenance or sound-based anomaly detection (e.g., malfunctioning machines and hazard situations). Different authors proposed examples of this category [75], [76], [77]. These kinds of systems typically encompass a set of microphones distributed in various parts of a factory hall or an indoor environment where the machines to be monitored are present; a central or a distributed set of computing units that analyze the audio stream collected by the microphones via machine listening techniques; a network link that allows signaling the detected anomalies to remote operators for their intervention.

Industrial WASNs, with respect to outdoor WASNs, are potentially less harmful to the environment. First of all, they do not strictly require batteries to operate, greatly reducing the embodied energy of the device itself. The lifetime of the system is expected to be long because industries require a return on investments (ROI) that, in turn, requires the upfront costs to be amortized in the span of several years. Finally, when data transmission is limited in distance to the plant size, only a few hops are required, hence a few devices (switches, relays, etc.) are required. On the other hand, the continuous acoustic monitoring of a production plant requires steady processing of the audio streams and a very prompt response from the server in case of alarms and failures, therefore the data transmission and processing infrastructure must always be on.

C. Queries-by-Playing to a Music Repository via a Smart Guitar

Electronic musical instruments generally have a very low impact on the environment since they are built to last decades. Musicians and collectors are still able to run old analog gear, modular synthesizers are easily serviceable, and each module can be replaced. Circuit bending [9] and no-input mixing [78] are established practices that allow old gear to be repurposed for aesthetic use. However, recent digital instruments are not easy to repair since they are built using surface mount components, service manuals are rarely available, and the microcode that is embedded in their processor is not available to the user or easily programmable as it was with Electrically Erasable Programmable Read-Only Memory chips (EEPROMs). Smart musical instruments for the IoS carry an additional element, that is, connectivity. How is this going to impact the sustainability of these instruments?

Here, the case of a query-by-playing smart guitar [79] is reported. It consists of an IoMusT system devised to support recreational music-making, improvisation, composition, and music learning via queries by playing to an online music repository via a smart guitar. Specifically, the system involves a guitar enhanced with embedded processing and wireless capabilities, which is able to interact with the Jamendo repository of Creative Commons music content. The smart guitar analyzes a short audio excerpt recorded by the guitar player to perform the query and extracts content-based features such as tempo, chords, keys, and melody. Such features are then used as keywords to retrieve from the Jamendo repository music having those characteristics.

Originally, this system was based on the cloud-computing paradigm. Nevertheless, the new possibilities offered by 5G (and beyond) allow the exploration of different networking architectures in the edge-cloud continuum. Fig. 7 shows an IoMusT architecture that encompasses a Multi-access edge computing (MEC) server positioned near the base station (and thus near to the user) to reduce the latency in the retrieved content. The MEC server hosts a reduced copy of the large Jamendo repository. The user can perform the query by playing, and if the content is available on the MEC, it is retrieved with minimal latency. However, if the reduced storage abilities of the MEC do not allow to retrieve the content desired from the user, then the MEC server forwards the request to the centralized cloud-based server hosting the whole Jamendo repository.

It is worth analyzing the environmental impact of the various components of this IoMusT system. The system consists of a conventional guitar, which is smartified by the addition of a 5G wireless module, a microphone, a loudspeaker, and an embedded processing unit. The guitar could be repurposed, therefore its environmental cost is only that of the electronics.

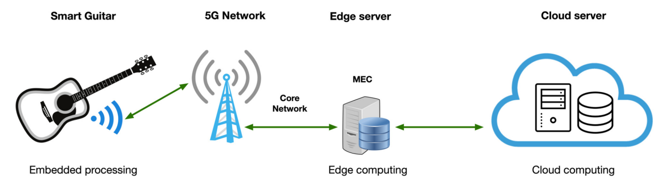

Fig. 7. A diagram of the IoMusT architecture supporting the use case of a smart guitar performing queries by playing to a server on the edge-cloud continuum.

The system involves the wireless network, which encompasses a 5G base station and a MEC server. Their environmental footprint is mitigated by the fact that they are deployed worldwide for many other services, therefore it could be considered negligible. The MEC server is connected to the cloud-based server. This last element hosts the whole Jamendo repository and will require energy, storage, and processing power, which must be accounted for when considering an assessment of the environmental footprint. However, Jamendo serves multiple purposes, from providing royalty-free music for commercial use to helping promote independent artists and is a popular music platform. Therefore its costs are shared among a large number of users, and it is expected to run for a long time. It can be concluded that as long as the platform is active and its APIs are callable from the smart instrument, the instrument will be usable as expected. Of course, any change in connectivity (e.g., a switch to 6G that will make the use of a MEC server obsolete) or software APIs that the manufacturer cannot address or is unwilling to address will make the instrument unusable for that purpose. At the same time, the instrument will still be usable as a regular instrument, therefore, repurposing is guaranteed. From the above discussion it can be claimed that, most probably, the impact of the system is going to be sufficiently low, since the application will interest a niche of potential users, and it reuses existing infrastructures and instruments.

D. Smart Sonic Shoes for Gait Rehabilitation

The use of sound to improve one's own interoception and body attitude, have been investigated for quite some time [80] and is particularly useful for specific groups of people, such as the elderly and those affected by neurological conditions. The connection between sound and gait analysis has been explored in the past [81], but it is only until recently that the IoS paradigm has been tackled in this field. As an example, the use case from [82] can be taken, which is a system for clinical scenarios that concerns new kinds of sound-based therapies for gait rehabilitation, where real-time sound stimuli are utilized to help guide and improve the walking actions of patients with motor impairments. The system is illustrated in Fig. 8. A patient wears a pair of instrumented shoes, each encompassing a set of sensors tracking the movement of the feet (pressure sensors and inertial measurement units), an embedded processing unit providing a real-time interactive sonification of the feet movements via ground surface simulators [83],

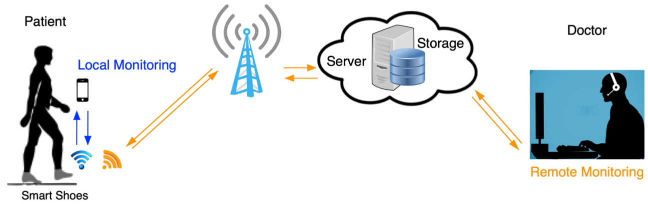

Fig. 8. A schematic representation of the local and remote interactions enabled by the shoe-based system as well as its main components and users.

a loudspeaker, and a wireless module that transmits over a wide-area network the sensor values to a remote doctor. The doctor monitors the motor progress of the patient and can send control messages to the shoes in order to adjust, even in real-time, the sound to be provided to the user during the motor exercises. In addition, the user can also monitor their progress via an app connected to the shoes, and this app also allows the configuration of the sound of the shoes. In this way, the control of the sound generation may be shared by both patients and doctors remotely connected. Moreover, the data collected about the motor exercises are stored in a cloud-based database.

From an environmental perspective, this use case requires dedicated shoes with embedded devices and special materials, and a dedicated server. However, a big gain in terms of footprint is achieved since the everyday exercise can be conducted from home, thus significantly reducing traveling to the clinic. This also makes it easier for the patient to practice rehabilitation without suffering possible legs or feet pain involved with traveling from home to the clinic. Finally, reusability can be an option when they are provided by the hospital for a short time frame, and users do not wear them too much.

E. Summary

Several IoS use cases have been discussed to illustrate the application of the proposed framework. The use cases outlined here represent a wide range of implementations, making it challenging to perform a highly specific analysis. A comprehensive LCA has yet to be attempted, as it requires specialized expertise. However, based on existing experience in the IoS field, directions for future LCA studies are provided.

Table II summarizes the use cases discussed in Section VI and includes predictions of their expected environmental impacts, derived from the principles outlined in Section IV. These predictions are intended for validation and refinement by LCA experts. Each use case requires significant effort, as the analysis depends on assumptions about specific implementations, sensitivity analyses of key variables, and technological advancements at the time of evaluation. The outcomes are heavily influenced by these assumptions, which are detailed in the text and summarized in Table II to aid future LCA validation. The table highlights the factors and variables most likely to affect the environmental outcomes and suggests areas for sensitivity analysis, which may significantly alter results.

The table also serves as a guide for IoS researchers when implementing use cases. Environmental impacts often hinge on small but significant details, such as repurposing existing equipment rather than purchasing new items. Research equipment, though often unused after project completion, may still hold value for the same group, other colleagues, or the broader community.

The principles outlined here are intended to support the evaluation of future IoS use cases. After analyzing the technical details of a given technology, the three main emission drivers should be identified and assessed. Additional considerations include the use of toxic or rare materials and the transportation requirements for people and goods. Once environmental impacts are assessed, social and economic implications should be examined to inform ethical evaluations (see, e.g., [84]). Special attention should be paid to factors such as geography, socioeconomic conditions, ethnicity, and culture, as these can influence sensitivity analyses and ethical considerations related to novel technologies.

VII. Socio-Technical Discussion

This section is dedicated to presenting the findings from the research study and providing useful recommendations, in accordance to RO4. It also cites additional literature to support the claims and to provide further ideas to the reader.

A. Technical Advancements

Engineers, designers, practitioners, and researchers should always monitor technical advancements but also evaluate them critically, asking questions such as: (1) What are the benefits of a new technology? Do they justify the impact of replacing an existing technology? (2) Will the new technology last/be supported for years? (3) Will new systems built on this technology be able to be maintained and repaired? (4) What is the environmental impact of this new technology?

The development of a new project, system, or product should follow principles that take sustainability into consideration. In the IoS, this is a principle that is easily overlooked, because *(a)* the IoS is generally not considered harmful to the environment; *(b)* research or business projects in the IoS are easily started and discarded due to their low prototyping cost. However, there are factors to consider before starting a new project or adopt more sustainable design practices.

The following sections outline technical considerations suggested in the literature for future developments.

1) Efficient Computing: To reduce the operational energy of a device several ways are known, e.g., employing low-power devices (especially transceivers, MCUs, and CPUs) and exploiting their sleep/low-power modes; optimizing code execution times; adapting lighting (e.g., LEDs, LCD backlighting, etc.) to the environment; etc. The computing hardware should not be oversized for the application at hand, and some processors or chips ensure higher efficiency for specific data processing tasks than other more general-purpose ones. Processing algorithms should not be oversized for the application: in this regard, deep learning has been recently favored to traditional DSP methods for a plethora of tasks, but there are still applications where DSP provides similar performance at a fraction of the computational power.

TABLE II
COMPARISON OF THE IOS USE CASES ANALYSED IN THE PAPER

NETWORKED MUSIC PERFORMANCE		
Pros	*Cons*	*Sensitivity analysis*
Can reduce travelling	Sometimes involves special hardware and infrastructure	number of travelling people involved (audience, performers, tech staff)
Generally involves commodity hardware (highly reusable)		Involvement of specialized hardware
Overall balance		
Probably positive in most cases (reduces traveling, general purpose hardware and network). Low risk of rebound effect.		

ENVIRONMENT MONITORING WASN		
Pros	*Cons*	*Sensitivity analysis*
Useful when monitoring wildlife or protecting natural resources	Leaks and ecotoxicity issues	Battery vs grid powered
Energy harvesting possible		Expected lifetime of the project
Processing and transmission can be sparse		Density and complexity of nodes hardware
Overall balance		
Probably negative, unless directly related to ecological applications. It can be mitigated by batteryless operation and reuse		

INDUSTRY 4.0 WASN		
Pros	*Cons*	*Sensitivity analysis*
Long-term usage reduces the impact of embodied energy	Always on	Density and complexity of nodes
Most probably grid-operated	Low latency and continuous data processing	
Overall balance		
Probably negative, but the longevity of the system and the lack of batteries can make its impact low		

SMART GUITAR WITH QUERY BY PLAYING		
Pros	*Cons*	*Sensitivity analysis*
Retrofitting of specialized gear (e.g. musical instruments) possible	Low latency network and processing power requirements	Lifetime depends on long-term compatibility with server APIs
Network resources are shared with other general purpose infrastructure		
Overall balance		
Generally low impact (niche application using partly existing infrastructures)		

GAIT REHABILITATION SHOES		
Pros	*Cons*	*Sensitivity analysis*
Allows everyday rehabilitation practice without traveling	Dedicated materials, devices and servers	Avoided traveling distance vs. embodied energy of the system
Reusability can be an option		
Overall balance		
Probably positive in most cases due to the avoided traveling		

A strategy to reduce the footprint of computational hardware is to harvest energy from the environment [85], [86], [87]. This technique can be quite effective for some wearable devices (one of the earliest examples is the automatic watch that recharges with the movements of the wearer) or for outdoor devices that are exposed to elements carrying a large amount of energy, such as wind and sun.

As for the software, modern operating systems are energy-aware and can reduce the backlight of screens or shut some unused peripherals. They also provide software layers that monitor the energy consumption of applications to put them to sleep or interrupt them. Unfortunately, this collides with many applications dealing with digital audio, where the processing needs to have very low latency, be continuous and interruption-free, and needs to be computationally intensive. Compressed sensing and variable sampling rates may be a solution for some audio applications [88], and the adoption of power shortage-tolerant algorithms would be ideal in WASNs, when possible [11].

One advantage of the connectivity available in the IoS is that the audio processing can be implemented where it is most efficient. In this regard, two opposed approaches, namely edge computing and cloud computing, may be employed alternatively, complemented, or bridged, depending on the application, in order to optimize energy consumption. IoS applications include large-scale audio/video security systems with sound event detection (SED). These topics are getting covered by the scientific literature. A recent paper [89] shows that the performance of SED algorithms is not directly proportional to their size or energy footprint. In [90], speech recognition algorithms are implemented on a Raspberry Pi, evaluating their accuracy vs. energy. Many other papers deal with latency and energy constraints in the frame of edge computing offloading for IoT and VR (see, e.g., [91], [92]).

2) Efficient Streaming: One way to address the energy usage of multimedia applications is by tackling data streaming efficiency. One approach is to cache data that is frequently accessed. This is why many music streaming apps reserve a large memory portion for caching. This has been the object of several studies since data transmission accounts for an important part of the energy consumption of the devices. Some relevant studies are presented in the following paragraph.

Transmission overhead can be reduced (e.g., transceiver activation, network driver caching, etc.), and transmission should be better done in short bursts [93]. 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. In [94], a pre-fetching mechanism guided by video statistics is proposed, while in [95], predictive resource allocation is proposed for efficient video streaming in wireless networks. In [96], strategies are addressed for energy saving, using an adaptive Quality of Experience (QoE) based on neural networks.

Some IoS applications, however, require tight interaction, thus, buffering is limited. These applications also enforce robust and redundant communication networks. To reduce their cost, best effort delivery networks can be aided by data reconstruction through inpainting with low-dimensionality representations when data packets are lost or arrive too late [97].

3) Optimal Replacement: Technological advancements in terms of greener manufacturing processes of electronic components, antennae, plastic, and metal casing are continuously evolving. Sometimes, they produce higher performance, sometimes a reduced environmental impact. Future IoS applications will benefit from these as a domino effect from other industrial fields where improvements will be introduced.

However, to improve energy efficiency, manufacturing and disposal impacts must be also considered. For this reason, to obtain optimal efficiency, one simple strategy is to extend a product lifetime [98]. The gained benefit is deterministic since it does not require the (unpredictable) advent of new technologies. Suppose that a user decides to prolong the lifetime of a smartphone from 3 to 6 years, then the product footprint is halved, under the hypothesis that in these years, no disruptive innovation comes that largely reduces the operational energy of a smartphone. A similar 50% footprint reduction is hard to be matched by a technological innovation in the span of a few years. If, however, a technological improvement comes that has the potential of greatly reducing the impact of an old device, an LCA analysis should be conducted anyway. Indeed, [98] shows that replacing older computing devices with newer (more efficient) ones does not have a positive yield if the replacement happens too soon because the operational energy improvement is low compared to the heavy manufacturing cost of producing a new device. The study suggests that for several scenarios, a good amortization period for replacing old laptops with new ones would be in the range of 5-12 years if the operational energy improvement of the new devices is 70%, rising up to 33-87 years if the improvement is of a mere 10%.

The IoS, is a nascent field with very specific hardware and software requirements, therefore it is hard to follow similar indications. However, industrial applications (e.g., WASN) are less prone to this issue, since industrial deployments are design to maximize the returns of an investment. It is advised that the deployment of future applications takes durability into account, therefore the replacement of components (e.g., in a WASN) does not happen too soon only to chase slight energy efficiency improvements of new devices. As a final note, in some cases, devices are not only replaced to achieve higher objective performance (be it in computing or in efficiency), but also to please the eye or achieve new perceived benefits given by a novel design. This process is called *design-driven obsolescence*, and it is a known environmental issue [99].

4) Design for Longevity: To increase longevity, a system or product should be serviceable and modular. This tip is also valid for software projects and their infrastructure. Hardware and software platforms should be widely supported: this enhances the probability that they will be maintained, fixed, and adopted for many years. In the hardware design, durable components and materials should be preferred. The most vulnerable components should be easy to replace. Prefer suppliers and materials that come from companies with certified records of sticking to sustainability initiatives or recur to procurement companies that provide refurbished telecom appliances.

Designing a product for longevity, however, requires the adoption of a design approach that leans towards higher costs and reduced immediate income (selling fewer devices). Suppliers that certify their efforts in reducing their impact are usually more expensive because they invest more human and economical resources on these efforts, with respect to other suppliers. Therefore, sustainability has a cost that is charged to the consumer. On the other hand, the lack of sustainability has indirect costs that are charged to the collectivity in terms of health, social and environmental issues. These costs are known as externalities [100], [101] and are generally hard to quantify.

Designing long-lasting products, however, does not only have to do with their intrinsic durability but also with the appeal to prospective users. IoS researchers propose a number of possible products and services without guarantee about their reception by society. Once sold commercially, their adoption affects the will of the designer to maintain and sustain production/servicing. This issue has been tackled at the NIME conferences, where novel expressive musical interfaces are proposed every year, but many of them fail to reach the final production or marketing phase [102]. In some cases, this is expected since they are prototypes from the academia. Their footprint is usually low since it involves the work of a few researchers and testers, few materials, and a relatively low effort (a few man-months typically). When the product is designed to hit the market, however, all the efforts and carbon footprint are wasted if it fails to do so. Even worse is a product that hits a large success (thus, it bears a large carbon footprint) but fails to last long (maintenance and repair have a lower carbon footprint than production and distribution).

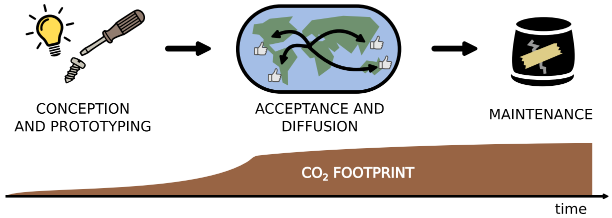

Fig. 9. Carbon footprint from the idea to the end of product. When a product is massively produced it better last long to make the introduced carbon footprint worth. Product durability and the ability to maintain and repair it are fundamental in this.

This is exemplified in Fig. 9. [102] suggests several issues that the designer should consider before proposing something new. It turns out that "Both developers of mobile apps and designers of tangible DMIs [Digital Musical Instruments] suggested choosing commonly available platforms" and "a general consensus endorsed the use of open-source software and hardware platforms". These considerations apply to the IoS too: a growing field with a large inventory of experimental applications that may be extremely innovative but are likely to fail if these design considerations are not evaluated.

B. Societal Advancements

Technical advancements depend on the developer's good will to adhere to environmental policies or a company's interest in delivering greener products (beyond a mere *green-washing* façade). On the other hand, policy-makers and citizens can have their say on the impact of a product, making a collective effort rather than an individual one.

1) Policy Making: A very recent work addressing the impact of regulatory standards is described in [103], where technical standards and policy-making are analyzed in energy saving for video streaming. 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, showing that these interventions could have a significant impact on electricity consumption and CO_2 emissions. If regulatory interventions are significant for the environment, the authors advocate for the definition of policies related to the world of multimedia, the IoT, and the IoS.

2) Consume Less and Reuse: Some actions are extremely effective in reducing energy consumption, such as video-conferencing instead of traveling or audio-streaming instead of video-streaming for casual music listening and podcasts (as discussed in the authors' previous work [12]). Some devices can be used only when necessary, or can be programmed to yield power saving, when possible. Materials also carry a lot of energy, thus they should be reused as much as possible. Refurbishing or repurposing objects has a high value in reducing the environmental impact. From a musical perspective, some papers suggest practices of repurposing, such as circuit bending [9]. One example that fits inside the IoS is found in [65], where smartphones are reused for acoustic monitoring of illegal forest cutting. However, at the moment, there is still much to do in order to build scalable practices and disseminate them in the field of IoS.

Until there are no shared practices oriented towards the IoS, recommendations can be drawn from more generic examples. As an example, consider the purchase of a desktop computer for data processing in a research project, as mentioned in the ending question of Section VI-E. The footprint of a desktop computer varies greatly, depending on its manufacturing process, components, and power demand. Many manufacturer brands provide details of their products' estimated carbon footprint using the PAIA method from MIT (msl.mit.edu/projects/paia/main.html). Taking, e.g., figures from Dell's report on their Precision series desktop computers (https://www.dell.com/en-us/dt/corporate/social-impact/advancing-sustainability/climate-action/product-carbon-footprints.htm), numbers between 279 $kgCO_2e$ +/− 65 kgCO and 2496 $kgCO_2e$ +/− 350 $kgCO_2e$ are found (but other companies show similar values). This is equivalent, e.g., to the amount of CO_2 spent on traveling from 1426 km (best case) to 18973 km (worst case) on flights, assuming a long-haul flight takes 150g of CO_2 per passenger per kilometer [104]. Therefore, the money and CO_2 involved with this purchase, if not necessary could be, e.g., converted to other academic activities such as traveling and conferencing, or be spared.

C. Learn and Teach

There are many actions that every citizen can take to reduce their impact on the environment or that an engineer or a researcher can do in their own job. Learning from others and teaching to others can have benefits. Dissemination can be one-to-many, as in the case of a tutorial video or a paper, but it is also many-to-many, as in local communities. The former is more scalable (through the Internet, one video or webpage can reach a tremendous number of people), but the latter is more engaging and builds communities that can grow. One such example is Repair Café (www.repaircafe.org), a network of laboratories where practices of maintenance and reuse are locally taught and learned. Dissemination in the IoS is a common practice that can reach communities outside the academia, from music enthusiasts to school students, therefore, it is expected to be a fruitful practice.

The scientific literature has discussed the role of music in sustainability education. In [105], a good literature review can be found, while some perspectives on music and sustainability are found in [106], [107]. However, to the best of the authors' knowledge, there is much to explore in the literature for experiencing and teaching sustainable practices in the emerging music interaction scenarios fostered by the IoS. In conclusion to this chapter the recommendations are resumed in a dedicated table, for simplicity, see Table III.

VIII. Conclusion

This paper contributes to understanding the environmental impact of an emerging research area such as the Internet of Sound and its many applications. It first presents a survey that identifies the manufacturing and transportation of electronic

TABLE III
A SUMMARY OF THE RECOMMENDATIONS DRAWN IN CHAPTER VII

RECOMMENDATIONS
Technology
– Evaluate benefits/impact of new technologies
– Increase computing efficiency (address all HW and SW layers, find optimal distribution of workload between edge and cloud)
– Replace technology and equipment only if predicted balance B is positive
– Design for longevity (durable materials, maintainable software and hardware, widely adopted platforms and protocols)
Society
– International policy making for energy saving is useful
– Consume less data whenever possible
– Share devices with peers and colleagues, reuse devices (better than recycling)
– Buy responsibly (e.g. one server is CO_2-equivalent to several flights)
– Learn, share, teach sustainability tips and design methods (both 1-to-many through the Internet and many-to-many through local workshops)

devices as an important contributor to CO_2 emissions (the so-called embodied energy) as well as the streaming of large multimedia contents and the computing power required for large data processing. It also outlines the risks of rebound effects that are common when introducing newer and more affordable technologies.

From the gained perspective, the environmental footprint of typical use cases in the IoS could be discussed, i.e., networked music performance, environment and industry wireless sensor networks, smart guitar with query by playing and gait rehabilitation shoes. Although the discussion is qualitative, ground has been provided for a future LCA to validate the analysis, highlighting key variables for sensitivity analysis and offering a preliminary judgment on the potential environmental outcomes, which are positive for two use cases. The last part of the paper contributes with recommendations in different areas of concern, including technical and human-related ones. Among these, it is worth to highlight the importance of: designing power-efficient computing and networking algorithms; replacing products only when needed; designing for longevity (which asks for the need of a sufficiently large user base); policy-making; foster reuse; disseminate sustainable practices.

A. Future Outlook

While some applications of the IoS are currently well established, some other may ramp up in the following years. Future trends in the IoS that may drive vast CO_2 emissions are the surge of generative AI and VR/AR applications and the potential deployment of beyond-5G/6G networking technologies. Let us examine them briefly.

There is awareness about the energy requirements of AI both inside and outside the scientific community. Efforts to devise lighter deep learning models are being made, but the potential of building new services and business models will likely increase the need for high-performance computing data centers, together with an increase in the overall environmental impact of AI, which is especially high for multimedia data.

AR and VR require extensive bandwidth for multichannel audio and high-quality video transfers, as well as intensive 3D rendering and a whole new set of hi-tech devices and visors that are going to be carbon-intensive in their production. These technologies may have a positive balance, e.g., by reducing emissions related to traveling (think, e.g., of VR conferencing systems), but the adoption of such technology is slow and a LCA analysis is premature until common usage models do not spread. From an ethical standpoint, AR and VR may impact society, thus the effect of new virtual forms of social interactions (or lack thereof) should be evaluated. As supported by some of the referenced work, global guidelines could help prevent a flood of multimedia data and information that may increase human impact on the planet.

Finally, since the roll-out of 5G Radio Access Networks (RAN) is still ongoing in most countries, the industry is concerned by the cost of a potential hardware deployment required by future 6G RAN standards, as stated by the Next Generation Mobile Network Alliance (NGMN) [108]. The NGMN proposes software upgrades to the 5G infrastructure to enable new 6G features, therefore implicitly fostering reuse of the current infrastructure. They also suggest backward compatibility with 5G network and absolute energy reduction. The latter statement seems to implicitly consider the risks involved with the Jevons Paradox if energy consumption is reduced only on a relative scale. It is believed that, if all these suggestions were followed, the deployment of a 6G networking infrastructure would not pose significant environmental threats and on top of that infrastructure, vehicular communication could bring remarkable energy savings [109]. It is still unclear whether the IoS can benefit from 6G technologies [110].

Although the scope of this paper was deliberately broad and the results wholly qualitative due to the exploratory nature of the research, it is intended to help disseminate ideas in the field, provide useful pointers to specific topics and papers, and stimulate reflection on research objectives that better align with societal needs and findings that can reduce consumers' carbon footprints.

REFERENCES

[1] L. Turchet et al., "The Internet of Sounds: Convergent trends, insights, and future directions," *IEEE Internet Things J.*, vol. 10, no. 13, pp. 11264–11292, Jul. 2023.

[2] L. Turchet, C. Fischione, G. Essl, D. Keller, and M. Barthet, "Internet of Musical Things: Vision and challenges," *IEEE Access*, vol. 6, pp. 61994–62017, 2018.

[3] R. Vieira, D. C. Muchaluat-Saade, and P. César, "Towards an Internet of Multisensory, Multimedia and Musical Things (Io3MT) environment," in *Proc. 4th Int. Symp. Internet Sounds*, 2023, pp. 1–10.

[4] L. Turchet, G. Fazekas, M. Lagrange, H. S. Ghadikolaei, and C. Fischione, "The Internet of Audio Things: State of the art, vision, and challenges," *IEEE Internet Things J.*, vol. 7, no. 10, pp. 10233–10249, Oct. 2020.

[5] B. Matuszewski and F. Bevilacqua, "Toward a Web of audio things," in *Proc. Sound Music Comput. Conf.*, 2018, pp. 1–8.

[6] R. Masu, A. P. Melbye, J. Sullivan, and A. R. Jensenius, "NIME and the environment: Toward a more sustainable NIME practice," in *Proc. Int. Conf. New Interfaces Musical Exp. (NIME)*, Apr. 2021, p. 24. [Online]. Available: https://nime.pubpub.org/pub/4bbl5lod

[7] Z. Argabrite, J. Murphy, S. J. Norman, and D. Carnegie, "Technology is land: Strategies towards decolonisation of technology in artmaking," in *Proc. Int. Conf. New Interfaces Musical Exp. (NIME)*, Jun. 2022, pp. 1–12. [Online]. Available: https://nime.pubpub.org/pub/uv5rj19j

[8] S. Fasciani and J. Goode, "20 NIMEs: Twenty years of new interfaces for musical expression," in *Proc. Int. Conf. New Interfaces Musical Exp. (NIME)*, Apr. 2021, pp. 1–42. [Online]. Available: https://nime.pubpub.org/pub/20nimes

[9] E. Dorigatti and R. Masu, "Circuit bending and environmental sustainability: Current situation and steps forward," in *Proc. Int. Conf. New Interfaces Musical Exp. (NIME)*, Jun. 2022, pp. 1–27. [Online]. Available: https://nime.pubpub.org/pub/025d4cv1

[10] L. Costalonga, D. Hora, M. Pimenta, and M. Wanderley, "The ragpicking DMI design: The case for green computer music," in *Proc. 10th Int. Conf. Digit. Interactive Arts*, New York, NY, USA, 2021, pp. 1–10.

[11] V. Lostanlen, A. Bernabeu, J.-L. Béchennec, M. Briday, S. Faucou, and M. Lagrange, "Energy efficiency is not enough: Towards a batteryless Internet of Sounds," in *Proc. 16th Int. Audio Mostly Conf.*, New York, NY, USA, 2021, pp. 147–155. [Online]. Available: https://doi.org/10.1145/3478384.3478408

[12] L. Gabrielli and L. Turchet, "Towards a sustainable Internet of sounds," in *Proc. 17th Int. Audio Mostly Conf.*, New York, NY, USA, 2022, pp. 231–238. [Online]. Available: https://doi.org/10.1145/3561212.3561246

[13] T. Bhamra and V. Lofthouse, *Design for Sustainability: A Practical Approach*. London, U.K.: Routledge, 2016.

[14] O. Andersen, J. Hille, G. Gilpin, and A. S. Andrae, "Life cycle assessment of electronics," in *Proc. IEEE Conf. Technol. Sustainabil. (SusTech)*, 2014, pp. 22–29.

[15] E. Williams, "Environmental effects of information and communications technologies," *Nature*, vol. 479, no. 7373, pp. 354–358, 2011.

[16] G. A. Mutiara, N. S. Herman, and O. Mohd, "Using long-range wireless sensor network to track the illegal cutting log," *Appl. Sci.*, vol. 10, no. 19, p. 6992, 2020. [Online]. Available: https://www.mdpi.com/2076-3417/10/19/6992

[17] M. Orta-Martínez, L. Pellegrini, and M. Arsel, "'The squeaky wheel gets the grease'? The conflict imperative and the slow fight against environmental injustice in northern peruvian Amazon," *Ecol. Soc.*, vol. 23, no. 3, pp. 1–13, 2018.

[18] C. F. Mena et al., "Community-based monitoring of oil extraction: Lessons learned in the Ecuadorian Amazon," *Soc. Natural Resour.*, vol. 33, no. 3, pp. 406–417, 2020. [Online]. Available: https://doi.org/10.1080/08941920.2019.1688441

[19] H. Ritchie, M. Roser, and P. Rosado (Our World Data, Oxford). *Energy*. 2022. [Online]. Available: https://ourworldindata.org/energy

[20] J. Huang, Y. Meng, X. Gong, Y. Liu, and Q. Duan, "A novel deployment scheme for green Internet of Things," *IEEE Internet Things J.*, vol. 1, no. 2, pp. 196–205, Apr. 2014.

[21] M. A. M. Albreem et al., "Green Internet of Things (IoT): An overview," in *Proc. IEEE 4th Int. Conf. Smart Instrum., Meas. Appl. (ICSIMA)*, 2017, pp. 1–6.

[22] B. Krumay and R. Brandtweiner, "Measuring the environmental impact of ICT hardware," in *Environmental and Economic Impact on Sustainable Development*. Southampton, U.K.: WIT Press, 2016, p. 238.

[23] *Environmental Management—Life Cycle Assessment—Principles and Framework*, ISO Standard 14040, 2006.

[24] A. S. Andrae and O. Andersen, "Life cycle assessments of consumer electronics—Are they consistent?" *Int. J. Life Cycle Assess.*, vol. 15, no. 8, pp. 827–836, 2010.

[25] T. Higgs, M. Cullen, M. Yao, and S. Stewart, "Developing an overall CO2 footprint for semiconductor products," in *Proc. IEEE Int. Symp. Sustain. Syst. Technol.*, 2009, pp. 1–6.

[26] E. Mullen and M. A. Morris, "Green nanofabrication opportunities in the semiconductor industry: A life cycle perspective," *Nanomaterials*, vol. 11, no. 5, p. 1085, 2021.

[27] A. S. Andrae, "Life-cycle assessment of consumer electronics: A review of methodological approaches," *IEEE Consum. Electron. Mag.*, vol. 5, no. 1, pp. 51–60, Jan. 2016.

[28] S. Das and E. Mao, "The global energy footprint of information and communication technology electronics in connected Internet-of-Things devices," *Sustain. Energy, Grids Netw.*, vol. 24, Dec. 2020, Art. no. 100408. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352467720303398

[29] R. Obringer, B. Rachunok, D. Maia-Silva, M. Arbabzadeh, R. Nateghi, and K. Madani, "The overlooked environmental footprint of increasing Internet use," *Resour., Conserv. Recycling*, vol. 167, Jan. 2021, Art. no. 105389. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0921344920307072

[30] R. Bolla, R. Bruschi, F. Davoli, and F. Cucchietti, "Energy efficiency in the future Internet: A survey of existing approaches and trends in energy-aware fixed network infrastructures," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 2, pp. 223–244, 2nd Quart., 2011.

[31] L. Belkhir and A. Elmeligi, "Assessing ICT global emissions footprint: Trends to 2040 & recommendations," *J. Clean. Prod.*, vol. 177, pp. 448–463, Mar. 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S095965261733233X

[32] D. Ruiz et al., "Life cycle inventory and carbon footprint assessment of wireless ICT networks for six demographic areas," *Resour., Conserv. Recycling*, vol. 176, Jan. 2022, Art. no. 105951. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0921344921005607

[33] P. Gandotra, R. K. Jha, and S. Jain, "Green communication in next generation cellular networks: A survey," *IEEE Access*, vol. 5, pp. 11727–11758, 2017.

[34] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.

[35] J. Baliga, K. Hinton, R. Ayre, and R. S. Tucker, "Carbon footprint of the Internet," *Telecommun. J. Aust.*, vol. 59, no. 1, pp. 5.1–5.14, 2009.

[36] C. Borggren, Å. Moberg, M. Räsänen, and G. Finnveden, "Business meetings at a distance–decreasing greenhouse gas emissions and cumulative energy demand?" *J. Clean. Prod.*, vol. 41, pp. 126–139, Feb. 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652612004672

[37] W. M. Achten, J. Almeida, and B. Muys, "Carbon footprint of science: More than flying," *Ecol. Indicat.*, vol. 34, pp. 352–355, Nov. 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1470160X13002306

[38] E. Gelenbe and Y. Caseau, "The impact of information technology on energy consumption and carbon emissions," *Ubiquity*, vol. 2015, pp. 1–15, Jun. 2015.

[39] N. Jones, "How to stop data centres from gobbling up the world's electricity," *Nature*, vol. 561, no. 7722, pp. 163–167, 2018.

[40] W. Van Heddeghem, S. Lambert, B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, "Trends in worldwide ICT electricity consumption from 2007 to 2012," *Comput. Commun.*, vol. 50, pp. 64–76, Sep. 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0140366414000619

[41] A. S. C. Andrae, "New perspectives on Internet electricity use in 2030," *Eng. Appl. Sci. Lett.*, vol. 3, no. 2, pp. 19–31, 2020.

[42] T. Ono, K. Iida, and S. Yamazaki, "Achieving Sustainable Development Goals (SDGs) through ICT services," *Fujitsu Sci. Tech. J.*, vol. 53, no. 6, pp. 17–22, 2017.

[43] S. Ren, Z. Liu, R. Hanbayev, and M. Du, "Does Internet development put pressure on energy-saving potential for environmental sustainability? Evidence from China," *J. Econ. Anal.*, vol. 1, no. 1, pp. 49–65, Sep. 2022.

[44] J. Aslan, K. Mayers, J. G. Koomey, and C. France, "Electricity intensity of Internet data transmission: Untangling the estimates," *J. Ind. Ecol.*, vol. 22, no. 4, pp. 785–798, 2018.

[45] V. Lostanlen and L. Bouchet, "Rebound effects make digital audio unsustainable," in *Proc. IEEE Int. Symp. Internet Sounds (IS)*, Erlangen, Germany, Sep. 2024, pp. 1–8. [Online]. Available: https://hal.science/hal-04701414

[46] 2024, "Most popular social networks worldwide as of April 2024, ranked by number of monthly active users," Statista. [Online]. Available: https://www.statista.com/statistics/272014/global-social-networks-ranked-by-number-of-users/

[47] K. Widdicks, M. Hazas, O. Bates, and A. Friday, "Streaming, multi-screens and YouTube: The new (unsustainable) ways of watching in the home," in *Proc. CHI Conf. Human Factors Comput. Syst.*, 2019, pp. 1–13.

[48] Y. Al Mtawa, A. Haque, and B. Bitar, "The mammoth Internet: Are we ready?" *IEEE Access*, vol. 7, pp. 132894–132908, 2019.

[49] A. S. Andrae, "Comparison of several simplistic high-level approaches for estimating the global energy and electricity use of ICT networks and data centers," *Int. J. Green Technol.*, vol. 5, no. 51, pp. 50–63, 2019.

[50] E. Strubell, A. Ganesh, and A. McCallum, "Energy and policy considerations for modern deep learning research," in *Proc. AAAI Conf. Artif. Intell.*, Apr. 2020, pp. 13693–13696. [Online]. Available: https://ojs.aaai.org/index.php/AAAI/article/view/7123

[51] A. Carôt, P. Rebelo, and A. Renaud, "Networked music performance: State of the art," in *Proc. 30th Int. Audio Eng. Soc. Conf.*, 2007, pp. 16–22.

[52] F. Meier, M. Fink, and U. Zölzer, "The JamBerry-a stand-alone device for networked music performance based on the raspberry pi," in *Proc. Linux Audio Conf.*, Karlsruhe, Germany, 2014, pp. 1–9.

[53] J.-P. Cáceres, R. Hamilton, D. Iyer, C. Chafe, and G. Wang, "To the edge with China: Explorations in network performance," in *Proc. 4th Int. Conf. Digit. Arts, ARTECH*, Porto, Portugal, 2008, pp. 61–66.

[54] M. Bosi, A. Servetti, C. Chafe, and C. Rottondi, "Experiencing remote classical music performance over long distance: A jacktrip concert between two continents during the pandemic," *J. Audio Eng. Soc.*, vol. 69, no. 12, pp. 934–945, Dec. 2021.

[55] T. Zlabinger, "Managing telematic pain: Migrating a student ensemble online during COVID," in *Proc. Int. Conf. 150th Audio Eng. Soc. Conv.*, 2021, p. 644.

[56] S. Ubik and J. Melnikov, "High-quality audio network transmissions with raspberry pi," in *Proc. 29th Int. Conf. Syst., Signals Image Process. (IWSSIP)*, 2022, pp. 1–3.

[57] C. Drioli, C. Allocchio, and N. Buso, "Networked performances and natural interaction via LOLA: Low latency high quality A/V streaming system," in *Proc. Int. Conf. Inf. Technol. Perform. Arts, Media Access, Entertain., 2nd Int. Conf. (ECLAP)*, Porto, Portugal, 2013, pp. 240–250.

[58] P. Holub, J. Matela, M. Pulec, and M. Šrom, "UltraGrid: Low-latency high-quality video transmissions on commodity hardware," in *Proc. 20th ACM Int. Conf. Multimedia*, 2012, pp. 1457–1460.

[59] S. Ubik et al., "Cyber performances, technical and artistic collaboration across continents," *Future Gener. Comput. Syst.*, vol. 54, pp. 306–312, Jan. 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0167739X15002198

[60] J. Dürre et al., "In-depth latency and reliability analysis of a networked music performance over public 5G infrastructure," in *Proc. 153rd Audio Eng. Soc. Conv.*, 2022, pp. 1–10.

[61] A. Carôt, F. Sardis, M. Dohler, S. Saunders, N. Uniyal, and R. Cornock, "Creation of a hyper-realistic remote music session with professional musicians and public audiences using 5G commodity hardware," in *Proc. IEEE Int. Conf. Multimedia Expo Workshops (ICMEW)*, 2020, pp. 1–6.

[62] M. Cobos, F. Antonacci, A. Alexandridis, A. Mouchtaris, and B. Lee, "A survey of sound source localization methods in wireless acoustic sensor networks," *Wireless Commun. Mobile Comput.*, vol. 2017, no. 1, 2017, Art. no. 3956282.

[63] F. Alías and R. M. Alsina-Pagès, "Review of wireless acoustic sensor networks for environmental noise monitoring in smart cities," *J. Sensors*, vol. 2019, no. 1, 2019, Art. no. 7634860.

[64] S. S. Sethi, R. M. Ewers, N. S. Jones, C. D. L. Orme, and L. Picinali, "Robust, real-time and autonomous monitoring of ecosystems with an open, low-cost, networked device," *Methods Ecol. Evolut.*, vol. 9, no. 12, pp. 2383–2387, 2018.

[65] C. Ferguson, "Discarded cellphones could protect the Indonesian rainforest," *New Sci.*, vol. 218, no. 2920, p. 20, 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0262407913614190

[66] J. Segura-Garcia, S. Felici-Castell, J. J. Perez-Solano, M. Cobos, and J. M. Navarro, "Low-cost alternatives for urban noise nuisance monitoring using wireless sensor networks," *IEEE Sensors J.*, vol. 15, no. 2, pp. 836–844, Feb. 2015.

[67] J. Ardouin et al., "An innovative low cost sensor for urban sound monitoring," in *Proc. INTER-NOISE NOISE-CON Congr. Conf. Proc.*, 2018, pp. 2226–2237.

[68] J. P. Bello et al., "SONYC: A system for monitoring, analyzing, and mitigating urban noise pollution," *Commun. ACM*, vol. 62, no. 2, pp. 68–77, 2019. [Online]. Available: http://doi.acm.org/10.1145/3224204

[69] G. Kokkonis, K. E. Psannis, M. Roumeliotis, and D. Schonfeld, "Real-time wireless multisensory smart surveillance with 3D-HEVC streams for Internet-of-Things (IoT)," *J. Supercomput.*, vol. 73, no. 3, pp. 1044–1062, 2017.

[70] D. Stowell, D. Giannoulis, E. Benetos, M. Lagrange, and M. Plumbley, "Detection and classification of acoustic scenes and events," *IEEE Trans. Multimedia*, vol. 17, no. 10, pp. 1733–1746, Oct. 2015.

[71] J. F. Peters, M. Baumann, B. Zimmermann, J. Braun, and M. Weil, "The environmental impact of li-ion batteries and the role of key parameters–a review," *Renew. Sustain. Energy Rev.*, vol. 67, pp. 491–506, Jan. 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032116304713

[72] M. Mencarelli, M. Pizzichini, L. Gabrielli, S. Spinsante, and S. Squartini, "Self-powered sensor networks for water grids: Challenges and preliminary evaluations," *J. Select. Areas Telecommun.*, 2012, to be published.

[73] A. Luque, J. Romero-Lemos, A. Carrasco, and J. Barbancho, "Non-sequential automatic classification of anuran sounds for the estimation of climate-change indicators," *Expert Syst. Appl.*, vol. 95, pp. 248–260, Apr. 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957417417307662

[74] M. W. McKown, M. Lukac, A. Borker, B. Tershy, and D. Croll, "A wireless acoustic sensor network for monitoring wildlife in remote locations," *J. Acoust. Soc. Am.*, vol. 132, no. 3, pp. 2036–2036, 2012.

[75] M. Antonini, M. Vecchio, F. Antonelli, P. Ducange, and C. Perera, "Smart audio sensors in the Internet of Things edge for anomaly detection," *IEEE Access*, vol. 6, pp. 67594–67610, 2018.

[76] T. Michailidis, G. Meadow, C. Barlow, and E. Rajabally, "Implementing remote audio as a diagnostics tool for maritime autonomous surface ships," in *Proc. 27th Conf. Open Innovat. Assoc. (FRUCT)*, 2020, pp. 157–163.

[77] H. Wu, Y. Shen, X. Xiao, A. Hecker, and F. H. Fitzek, "In-network processing acoustic data for anomaly detection in smart factory," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, 2021, pp. 1–6.

[78] A. Chamberlain, "Surfing with sound: An ethnography of the art of no-input mixing," in *Proc. Audio Mostly Sound Immersion Emot.*, 2018, pp. 1–5. [Online]. Available: https://doi.org/10.1145/3243274.3243289

[79] L. Turchet, J. Pauwels, C. Fischione, and G. Fazekas, "Cloud-smart musical instrument interactions: Querying a large music collection with a smart guitar," *ACM Trans. Internet Things*, vol. 1, no. 3, pp. 1–29, 2020.

[80] A. Tajadura-Jiménez, M. T. Fairhurst, and O. Deroy, "Sensing the body through sound," in *The Routledge Handbook of Bodily Awareness*. London, U.K.: Routledge, 2022, pp. 230–246.

[81] A. Tajadura-Jiménez, M. Basia, O. Deroy, M. Fairhurst, N. Marquardt, and N. Bianchi-Berthouze, "As light as your footsteps: Altering walking sounds to change perceived body weight, emotional state and gait," in *Proc. 33rd Annu. ACM Conf. Human Factors Comput. Syst.*, New York, NY, USA, 2015, pp. 2943–2952. [Online]. Available: https://doi.org/10.1145/2702123.2702374

[82] L. Turchet, "Interactive sonification and the IoT: The case of smart sonic shoes for clinical applications," in *Proc. Audio Mostly Conf.*, 2019, pp. 252–255.

[83] L. Turchet, "Footstep sounds synthesis: Design, implementation, and evaluation of foot–floor interactions, surface materials, shoe types, and walkers' features," *Appl. Acoust.*, vol. 107, pp. 46–68, Jun. 2016.

[84] J. Brusseau and L. Turchet, "An ethics framework for the Internet of Musical Things," *IEEE Trans. Technol. Soc.*, early access, May 23, 2024, doi: 10.1109/TTS.2024.3398423.

[85] F. K. Shaikh and S. Zeadally, "Energy harvesting in wireless sensor networks: A comprehensive review," *Renew. Sustain. Energy Rev.*, vol. 55, pp. 1041–1054, Mar. 2016.

[86] J. A. Azevedo and F. Santos, "Energy harvesting from wind and water for autonomous wireless sensor nodes," *Inst. Eng. Technol. Circuits, Devices Syst.*, vol. 6, no. 6, pp. 413–420, 2012.

[87] L. Gabrielli, M. Pizzichini, S. Spinsante, S. Squartini, and R. Gavazzi, "Smart water grids for smart cities: A sustainable prototype demonstrator," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, 2014, pp. 1–5.

[88] A. Griffin and P. Tsakalides, "Compressed sensing of audio signals using multiple sensors," in *Proc. 16th Eur. Signal Process. Conf.*, 2008, pp. 1–5.

[89] F. Ronchini and R. Serizel, "Performance and energy balance: A comprehensive study of state-of-the-art sound event detection systems," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, 2024, pp. 1096–1100.

[90] F. Brodbeck, P. Seidler, and D. D. Hromada, *Power Consumption of Diverse Speech Command Classification Methods on the Raspberry Pi Zero*, Universität der Künste Berlin, Berlin, Germany, 2021.

[91] M. Guo, L. Li, and Q. Guan, "Energy-efficient and delay-guaranteed workload allocation in IoT-edge-cloud computing systems," *IEEE Access*, vol. 7, pp. 78685–78697, 2019.

[92] A. Alshahrani, I. A. Elgendy, A. Muthanna, A. M. Alghamdi, and A. Alshamrani, "Efficient multi-player computation offloading for VR edge-cloud computing systems," *Appl. Sci.*, vol. 10, no. 16, p. 5515, 2020. [Online]. Available: https://www.mdpi.com/2076-3417/10/16/5515
[93] W. Hu and G. Cao, "Energy-aware video streaming on smartphones," in *Proc. IEEE Conf. Comput. Commun. (INFOCOM)*, 2015, pp. 1185–1193.
[94] M. A. Hoque, M. Siekkinen, and J. K. Nurminen, "Using crowd-sourced viewing statistics to save energy in wireless video streaming," in *Proc. 19th Annu. Int. Conf. Mobile Comput. Netw.*, 2013, pp. 377–388.
[95] R. Atawia, H. Abou-Zeid, H. S. Hassanein, and A. Noureldin, "Joint chance-constrained predictive resource allocation for energy-efficient video streaming," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 5, pp. 1389–1404, May 2016.
[96] W. Pan and G. Cheng, "QoE assessment of encrypted YouTube adaptive streaming for energy saving in smart cities," *IEEE Access*, vol. 6, pp. 25142–25156, 2018.
[97] C. Aironi, S. Cornell, L. Gabrielli, and S. Squartini, "A score-aware generative approach for music signals inpainting," in *Proc. 4th Int. Symp. Internet Sounds*, 2023, pp. 1–7.
[98] S. Prakash, R. Liu, K. Schischke, and P. L. Stobbe, "Early replacement of notebooks considering environmental impacts," in *Proc. Electron. Goes Green*, 2012, pp. 1–8.
[99] M. Mancini, "Design-driven obsolescence," *Design J.*, vol. 22, no. 1, pp. 2243–2246, 2019.
[100] A. C. Pigou, *The Economics of Welfare*, 4th ed. New York, NY, USA: Macmillan, 1932.
[101] E. S. Goodstein and S. Polansky, *Economics and the Environment*, 9th ed. Hoboken, NJ, USA: Wiley, 2020.
[102] F. Morreale and A. McPherson, "Design for longevity: Ongoing use of instruments from NIME 2010-14," in *Proc. Int. Conf. New Interfaces Musical Exp. (NIME)*, 2017, pp. 1–6.
[103] R. Madlener, S. Sheykhha, and W. Briglauer, "The electricity-and CO_2-saving potentials offered by regulation of European video-streaming services," *Energy Policy*, vol. 161, Feb. 2022, Art. no. 112716.
[104] (EIS U.K. Dept. Bus. London, U.K.). *Government Greenhouse Gas Conversion Factors for Company Reporting: Methodology Paper*. 2019. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/904215/2019-ghg-conversion-factors-methodology-v01-02.pdf
[105] E. Østergaard, "Music and sustainability education—A contradiction?" *Acta Didactica Norge*, vol. 13, no. 2, pp. 2–20, 2019.
[106] Ø. Varkøy and H. Rinholm, "Focusing on slowness and resistance: A contribution to sustainable development in music education," *Philos. Music Educ. Rev.*, vol. 28, no. 2, pp. 168–185, 2020.
[107] D. O. A. Ogunrinade, "Music education as a pillar to sustainable development in Nigeria," *J. Econ. Sustain. Develop.*, vol. 6, no. 3, pp. 83–87, 2015.
[108] (NGMN Alliance, Düsseldorf, Germany). *6G Position Statement–An Operator View, Version 1.0*. 2023. [Online]. Available: https://www.ngmn.org/wp-content/uploads/NGMN_6G_Position_Statement.pdf
[109] S. Roger, C. Botella-Mascarell, D. Martín-Sacristán, D. García-Roger, J. F. Monserrat, and T. Svensson, "Sustainable mobility in B5G/6G: V2X technology trends and use cases," *IEEE Open J. Veh. Technol.*, vol. 5, pp. 459–472, 2024.
[110] L. Turchet and P. Casari, "The Internet of Musical Things meets satellites: Evaluating starlink support for networked music performances in rural areas," in *Proc. IEEE 5th Int. Symp. Internet Sounds (IS2)*, 2024, pp. 1–8.

Leonardo Gabrielli received the M.Sc. and Ph.D. degrees in electronics engineering from the Università Politecnica Marche in 2011 and 2015, respectively, where he is an Assistant Professor with the Department of Information Engineering. He has been a Co-Founder of the Startup DowSee Srl, he holds several industrial patents and developed several industrial products. He is the author of two books, and a coauthor of numerous scientific papers. His main research topics are related to audio signal processing and machine learning with application to sound synthesis, computational sound design, networked music performance, and several audio classification tasks. He have served as a Guest Editor for scientific journals. He is an Audio Engineering Society Member and is part of the board of the Ass. Informatica Musicale Italiana.

Emanuele Principi was born in Senigallia, Italy, in 1978. He received the Italian Laurea degree (with Hons.) in electronic engineering and the Ph.D. degree from the Università Politecnica delle Marche, Italy, in 2004 and 2009, respectively, where he is currently an Associate Professor of Electrical Engineering with the Department of Information Engineering. He has authored and co-authored numerous international scientific peer-reviewed articles. His primary research interests lie in the field of digital signal processing and computational intelligence, with a particular emphasis on smart grids and electrical machines applications. Furthermore, he has been serving as an Associate Editor for *Neural Computing and Applications* (Springer) and *Artificial Intelligence Review* (Springer) since 2017. He actively participates in the organization and technical committees of various international conferences. He also served as a member and a secretary of the Adriatic section of the Italian Association of Electrotechnics, Electronics, Automation, Computer Science, and Telecommunications. From January 2020 to December 2022, he served as the Chair of the IEEE CIS Task Force on Computational Audio Processing.

Luca Turchet (Senior Member, IEEE) received the master's degree (summa cum laude) in computer science from the University of Verona in 2006, the degrees in classical guitar and in composition from the Music Conservatory of Verona in 2007 and 2009, respectively, the Ph.D. degree in media technology from Aalborg University Copenhagen in 2013, and the degree in electronic music from the Royal College of Music of Stockholm in 2015. He is an Associate Professor with the Department of Information Engineering and Computer Science, University of Trento, Italy. He is a Co-Founder of the Music-Tech Company Elk. His scientific, artistic, and entrepreneurial research has been supported by numerous grants from different funding agencies, including the European Commission, the European Institute of Innovation and Technology, the European Space Agency, the Italian Ministry of Foreign Affairs, and the Danish Research Council. He serves as an Associate Editor for IEEE TRANSACTIONS ON HUMAN-MACHINE SYSTEMS, IEEE ACCESS and the *Journal of the Audio Engineering Society*, and has been a Guest Editor for the *IEEE Communications Magazine*, the *Personal and Ubiquitous Computing Journal*, the *Journal of the Audio Engineering Society*, *Frontiers in VR*, and *Digital Creativity*. He is the Chair of the IEEE Emerging Technology Initiative on the Internet of Sounds and the Founding President of the Internet of Sounds Research Network.

Open Access funding provided by 'Universitá Politecnica delle Marche' within the CRUI CARE Agreement