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Supplement

ITU-T L Suppl. 53 (10/2022)

SERIES L: Environment and ICTs, climate change, e-waste, energy efficiency; construction, installation and protection of cables and other elements of outside plant

Guidelines on the implementation of environmental efficiency criteria for artificial intelligence and other emerging technologies

ITU-T L-SERIES RECOMMENDATIONS

ENVIRONMENT AND ICTS, CLIMATE CHANGE, E-WASTE, ENERGY EFFICIENCY; CONSTRUCTION, INSTALLATION AND PROTECTION OF CABLES AND OTHER ELEMENTS OF OUTSIDE PLANT

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Supplement 53 to ITU-T L-series Recommendations

Guidelines on the implementation of environmental efficiency criteria for artificial intelligence and other emerging technologies

Summary

Supplement 53 to ITU-T L-series Recommendations provides guidelines to policy-makers, technologists, innovators, environmentalists and other stakeholders from the technology industry, environmental sciences and policy arena on the topic of environmental efficiency criteria to assess the environmental impacts of artificial intelligence and other emerging technologies. These guidelines aim to serve as common factors for the above-mentioned stakeholders to consider while developing, deploying and promoting any piece of technology into the market and society, rather providing than a comprehensive list of criteria.

While "emerging technologies" is a broad term, this Supplement identifies a few sample technologies through their accordant applications and areas of work in 16 applicable industry domains, which stakeholders can use as references to improve the environmental efficiency of their own technological products and/or services. When discussing environmental efficiency, this Supplement approaches environmental efficiency criteria from an adjusted model of life-cycle assessment of a product, within which three stages of environmental impacts – materials, use and end of life – are examined. The Supplement provides both long-term and short-term strategies, which include not only specific examples for certain technologies addressing the three stages of environmental efficiency, but also an instrument to be used to localize such guidelines as well as to allow global benchmarking.

History

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FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications, information and communication technologies (ICTs). The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

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Supplement 53 to ITU-T L-Series Recommendations

Guidelines on the implementation of environmental efficiency criteria for artificial intelligence and other emerging technologies

1 Scope

The Supplement is intended to be used for policy-making and business decision-making by governments and enterprises at different scales in various industries. This Supplement achieves three goals.

The first goal is to identify artificial intelligence (AI), AI-enabled, various forms of other emerging technologies and enablers from other emerging technologies taking consideration of regional differences, priorities and industries. By assessing mainstream as well as upcoming technologies in each particular region (with all ITU categorized regions included) most, if not all, of our stakeholders will be relevant to the conversation on technological impacts.

The second goal is to explore the environmental impacts of possible examples of technologies identified through both qualitative and quantitative factors of environmental indicators. The model to help achieve this goal is an adjusted life cycle assessment of a product, which consists of three stages of implementing a technology. The three stages examined in order to connect environmental impacts to identified technology include a) materials; b) use; and c) end-of-life. Although only a few examples of technologies are given in this Supplement, similar analysis and guidelines for implementing the environmental efficiency criteria of other technologies beyond this report can be conducted using the same framework as discussed in clauses 7 and 8 and the appendices.

The third goal is to propose guidelines on implementing environmental efficiency criteria for AI and other emerging technologies at both the macro and micro levels, including 1) data collection strategy prior to implementing guidelines in order to meet localized needs and ensure evidence-based approach for decision making; 2) proposed actions to be implemented at all three environmental stages identified for AI and other emerging technologies in the Supplement; 3) possible actions for other emerging technologies from a technological and environmental perspective; and 4) general guidelines for different stakeholders working in industries related to AI and other emerging technologies.

2 References

[ITU-T L.1410] Recommendation ITU-T L.1410 (2014), *Methodology for environmental life cycle assessments of information and communication technology goods, networks and services*.

3 Definitions

3.1 Terms defined elsewhere

This Supplement uses the following terms defined elsewhere:

3.1.1 artificial intelligence [b-ITU-T F.749]: An interdisciplinary field, usually regarded as a branch of computer science, dealing with models and systems for the performance of functions generally associated with human intelligence, such as reasoning and learning.

3.1.2 augmented reality [b-ITU-T J.301]: A type of mixed reality where graphical elements are integrated into the real world in order to enhance user experience and enrich information.

3.1.3 big data [b-ISO/TR 24291]: Extensive datasets – primarily in the data characteristics of volume, variety, velocity, and/or variability – that require a scalable technology for efficient storage, manipulation, management, and analysis. Big data is commonly used in many different ways, for example as the name of scalable technology used to handle big data extensive datasets.

3.1.4 blockchain [b-ITU-T F.751]: A type of distributed ledger that is composed of digitally recorded data arranged as a successively growing chain of blocks with each block cryptographically linked and hardened against tampering and revision.

3.1.5 digital twin [b-ISO/TR 24464]: Compound model composed of a physical asset, an avatar and an interface.

3.1.6 drone [b-ISO/IEC 21384-4]: Unmanned system which is remotely or autonomously operated.

3.1.7 internet of things [b-ITU-T Y.2060]: A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies.

3.1.8 mixed reality [b-ISO/IEC 18038]: Merging of real and virtual worlds to generate new environments where physical and synthetic objects co-exist and interact.

3.1.9 quantum computing [b-ISO/TS 80004]: Use of quantum phenomena for computational purposes.

3.1.10 virtual reality [b-ISO 9241-394]: Set of artificial conditions created by computer and dedicated electronic devices that simulate visual images and possibly other sensory information of a user's surrounding with which the user is allowed to interact.

3.1.11 3D printing [b-ISO/ASTM 52900]: Fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology.

3.2 Terms defined in this Supplement

This Supplement defines the following terms:

3.2.1 extended reality: Combines all forms of real–virtual environments and human–machine interactions, including but not limited to augmented reality, mixed reality and virtual reality.

3.2.2 Industry 4.0: An industrial approach where one or more digital technologies are used throughout industrial processes in order to the quantity and quality of production.

4 Abbreviations and acronyms

This Supplement uses the following abbreviations and acronyms:

ABS Acrylonitrile Butadiene Styrene

ADP Abiotic Depletion

AI Artificial Intelligence

AP Acidification Potential

CFRP Carbon-Fibre-Reinforced Polymers

CNC Computer Numerical Control

CPU Central Processing Unit

DL Deep Learning

DVFS Dynamic Voltage/Frequency Scaling

EP Eutrophication Potential

FAEP Freshwater Aquatic Ecotoxicity Potential

FPGA	Field Programmable Gate Array
GHG	Greenhouse Gas
GPU	Graphics Processing Unit
GWP	Global Warming Potential
HDD	Hard Disk Drive
HTP	Human Toxicity Potential
ICT	Information and Communications Technology
LCA	Life Cycle Assessment
LIB	Lithium-Ion Battery
LiPo	Lithium Polymer
LMD	Last-Mile Distributor
MAEP	Marine Aquatic Ecotoxicity Potential
NiCad	nickel cadmium
NiMH	Nickel-Metal Hybrid
PET	Polyethylene Terephthalate
PLA	Polylactic Acid
POCP	Photochemical Ozone Creation Potential
SDG	Sustainable Developmental Goal
SSD	Solid-State Drive
TETP	Terrestrial Ecotoxicity Potential
UAV	Unmanned Aerial Vehicle

5 Conventions

None.

6 Introduction

6.1 Introduction of this Supplement

While "emerging technologies" is a broad term, this Supplement presents a few sample technologies – such as artificial intelligence, drone, 3D printing and Industry 4.0 and Industry 4.0 applications – that are discussed in detail, and covers others – such as blockchain, digital twins, Internet of things, extended reality, quantum computing and big data – with generic environmental guidelines. This Supplement identifies 16 applicable domains that can be used as a reference to improve the environmental efficiency of technological products and/or services. Some of the 16 application domains overlap with United Nations Sustainable Development Goals (SDGs), such as education, health, infrastructure, energy; others include key State concerns, such as defence; the rest involve other practices of a society such as entertainment.

When discussing environmental efficiency, this Supplement approaches ecofriendly criteria from an adjusted model of the life cycle assessment of a product. It examines three stages of environmental impact:

1) Materials: This stage includes raw material extraction and the transport and manufacturing of a technology;

2) Use: This stage includes the relevant operation, consumption, maintenance, repair, replacement and refurbishment of a technology; and

3) End of life: This stage includes the deconstruction or demolition, waste processing, disposal and recycling (reuse, recovery, recycling, remanufacturing) of a technology.

This Supplement provides both long-term and short-term strategies. Such strategies include not only specific examples for certain technologies addressing the three stages of environmental efficiency, but also an instrument – a set of three surveys to facilitate evidence-based policy-making and/or technology launching – to be used to localize such guidelines as well as to allow global benchmarking. Generic survey templates for the main stakeholders are provided in the appendices of this Supplement.

6.2 Introduction of technologies and applications

Before moving into the analysis of the environmental efficiency of AI and other emerging technologies, Table 1 gives a list of AI and other emerging technologies categorized by their technological application and applicable area of work for different domains.

Table 1 – Identification and examples of applications of AI and other emerging technologies through applicable domains

S.no.	Domain	Emerging technologies	Technological applications and applicable areas of work
1	Education	• Artificial intelligence • Internet of Things • Digital twins • Extended reality • Blockchain • 3D printing	• e-Education platform • Digital libraries • Maintaining authenticity of certificates • Skill development • The working of complex machines
2	Health	• Artificial intelligence • Internet of Things • Digital twins • Extended reality • Blockchain • 3D printing • Drones	• Digital health • Ingestible sensors • m-Health • Diabetic retinopathy diagnostics • Physical disabilities • Health Data protection • Robots • Prosthetics • Dentistry • Robotic surgeries • Precision biopsies • Disease management • Parkinson's disease • Phobia management • Post-traumatic stress management • Rehabilitation • Drone-based • Defibrillators • Pathology sample collection • Organ transport

Table 1 – Identification and examples of applications of AI and other emerging technologies through applicable domains

S.no.	Domain	Emerging technologies	Technological applications and applicable areas of work
3	Manufacturing	• Artificial intelligence • Internet of Things • Digital twins • Extended reality • 3D printing	• Industry 4.0 • Predictive maintenance • Robots • Condition monitoring • 3D manufacturing • Prototype development • Drones • Health care products
4	Infrastructure	• Artificial intelligence • Internet of Things • Digital twins • 3D printing	• Condition monitoring • Asset management • Drilling platforms • Construction • Robots
5	Governance	• Artificial intelligence • Internet of Things • Blockchain • Big data and analytics • Digital twins	• Control of corruption • Revenue collection • Assets management • Digitization of records
6	Agriculture	• Artificial intelligence • Internet of Things • Blockchain • Big data and analytics • Digital twins	• Smart farming • Marketing information • Protection of crops from diseases and locust attacks • Weather forecasting • Robots
7	Financial inclusion	• Artificial intelligence • Internet of Things • Digital twins • Big data and analytics	• Direct transfer benefits • Mobile banks
8.	Disaster management	• Artificial intelligence • Internet of Things • Digital twins • Extended reality • Big data and analytics	• Disaster preparedness • Disaster management • Emergency response
9	Security	• Artificial intelligence • Internet of Things • Digital twins • Extended reality • Big data and analytics	• Crime and criminal tracking system • Banking sector
10	Smart Energy	• Artificial intelligence • Internet of Things • Digital twins • Big data and analytics	• Smart grids • Smart meters • Renewable energy • Net metering

Table 1 – Identification and examples of applications of AI and other emerging technologies through applicable domains

S.no.	Domain	Emerging technologies	Technological applications and applicable areas of work
11	Environment	• Artificial intelligence • Internet of Things • Digital twins • Extended reality • Blockchain • Drones • Quantum computing	• Air quality monitoring • Water management • Waste management • Green patches management • Forest cover management • Marine resources management • Repair of damage underwater
12	Habitat	• Artificial intelligence • Internet of Things • 3D printing • Digital twins	• Urban planning • Water management • Waste management • Affordable housing • Asset management
13	Entertainment	• Artificial intelligence • Internet of Things • Extended reality	• Digital content • Gaming
14	Mobility	• Artificial intelligence • Internet of Things • Digital twins • Drones	• Road traffic management • Real time information display • Autonomous vehicles
15	Transportation	• Artificial intelligence • Internet of Things • 3D printing • Big data and analytics • Digital twins	• Vessels management • Trucks management • Air traffic management • Autonomous vehicles
16	Defence	• Artificial intelligence • Internet of Things • Digital twins • Extended reality • Big data and analytics • Blockchain • Quantum computing • Drones	• Reconnaissance • Resource management

7 Environmental impacts of AI and sampled emerging technologies

7.1 Definition of stages for the analyses of the environmental impact

For any technology that is transformed into a product, there is a product life cycle. An example of the product life cycle of AI and emerging technologies is illustrated in Figure 1.

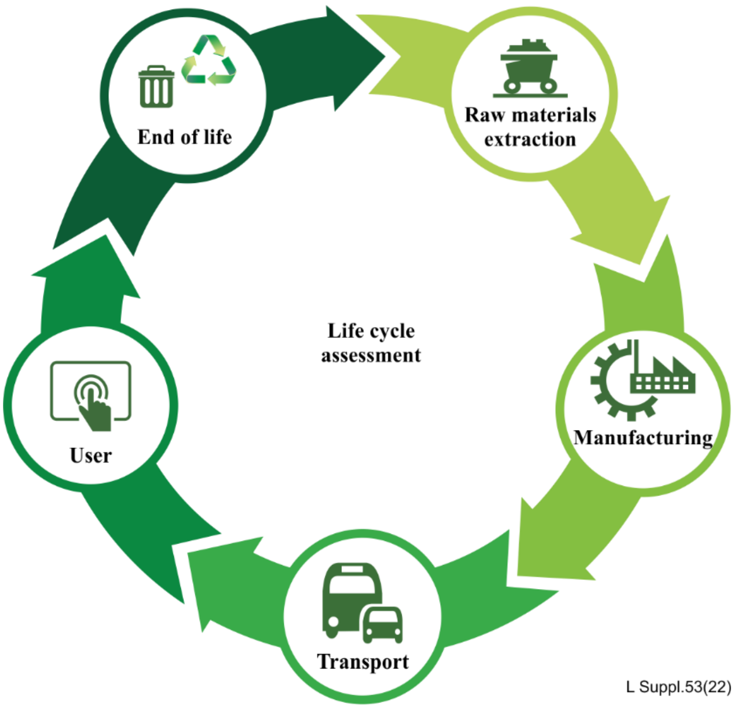

Figure 1 – Life cycle assessment

Life cycle assessment (LCA) is a method to assess all the potential environmental impacts of a product, process or activity over its whole life cycle (refer to [ITU-T L.1410] for detailed methodologies for LCA applicable to AI technologies). It is a theoretical approach that employs a conceptual structure to assess and record the differing dimensions of environmental impact, e.g., pollution to air, land and water when predicting the overall impact of a development or process [b-An].

As an environmental assessment tool, it quantifies all the environmental impacts of a product or service over its entire life, hence one of its alternative names being 'cradle to grave analysis'. Engineering professionals are routinely tasked with determining design options that offer the minimum environmental impact during building, operation and the end-of-life phases of a project. LCA is uniquely valuable in assessing and documenting the evidence used in this decision process. Full details about the LCA process are available from a number of sources [b-Laurent]; [b-Mälkki]; [b-Rousseaux], but all LCAs must be carried out in accordance with the international standard on LCA [ITU-T L.1410], [b-ISO14044], [b-ISO14040].

The environmental categories considered in environmental assessment are global warming potential (GWP), abiotic depletion (ADP elements), abiotic depletion (ADP fossil), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAEP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAEP), ozone layer depletion potential (OLDP), photochemical ozone creation potential (POCP) and terrestrial ecotoxicity potential (TETP).

Based on the standard LCA, this study analyses each technology based on the adjusted model of product life cycle, divided into the three stages below:

1) Materials: This stage includes raw material extraction, transport and manufacturing.

2) Use: This stage includes operation, consumption, maintenance, repair, replacement and refurbishment.

3) End of life: This stage includes deconstruction/demolition, transport, waste processing, disposal and recycling (reuse, recovery, recycling, remanufacturing).

To assess the impact of these technologies in other sectors please refer to [ITU-T L.1480].

7.2 Sampled technologies and their environmental efficiency

7.2.1 Artificial intelligence

7.2.1.1 Materials

AI requires computing power. The computing power is, in general, provided by computers or servers equipped, nowadays, with central processing units (CPUs), graphical processing units (GPUs) or field programmable gate arrays. They are built with an assembly of digital circuits that are, eventually, based on transistors. Moreover, for data storage, hard disk drives (HDD) or solid-state drives (SSD) are utilized. All the components of a computer are then interconnected by circuit boards.

CPUs are primarily made out of silicon, copper, phosphorous and boron. GPUs are made of tantalum and palladium transistors and capacitors, gold and silicon. Circuit boards are primarily made of aluminium, copper, tin, zinc, gold or silver for connections and switches, and ABS or fibreglass. SSDs are based on memories exploiting transistors made of wafers of silicon. HDDs are made of aluminium or glass and coated with a magnetic material. Magnetic underlayers were previously made of nickel, cobalt and iron, but are today replaced by more expensive metals such as platinum and ruthenium for their superior properties.

The main environmental impact is in the mining of the earth's crust. The impact is firstly from depletion of natural resources, secondly from the energy used in mining, transporting and manufacturing, and thirdly from the chemical processes used in the manufacturing. The latter produces hazardous waste. While silicon comes from widely available sand, ruthenium is ranked 76^{th} out of the 90 rare earth metals. Some metals such as tantalum, used for transistors, are found abundantly; however, places where such metals can be found may not always be in a condition for efficient mining activities due to factors such as social instability, which add a greater burden to the environmental process; for example, additional transportation may need to be arranged, which results in more CO2 emissions.

7.2.1.2 Use

While studies show that AI can address some of earth's environmental challenges, it is also reported that the use of power intensive GPUs to run machine learning training contributes to increased CO2 emissions.

Between 2012 and 2018, computing power has increased 300 000 fold, impacting energy consumption. A study released in 2018 in the MIT Technology review [b-Hao] found that a "regular" AI using a single high-performance graphics card has the same carbon footprint as a flight across the United States. For example, an algorithm is designed to be trained to recognize a cat and it needs to process millions of cat images. A sophisticated process using 213 million parameters resulted in 300 000 kgs of CO2 emissions, which equates to the emissions of five cars during their entire lifetime including emissions from their manufacturing.

The energy use of AI depends on several factors:

a) Hardware type;

b) Hardware architecture;

c) Application type;

d) Source of energy (depending on the location).

Hardware type

Figure 2 shows a continuum between hardware type denoting flexibility and power efficiency.

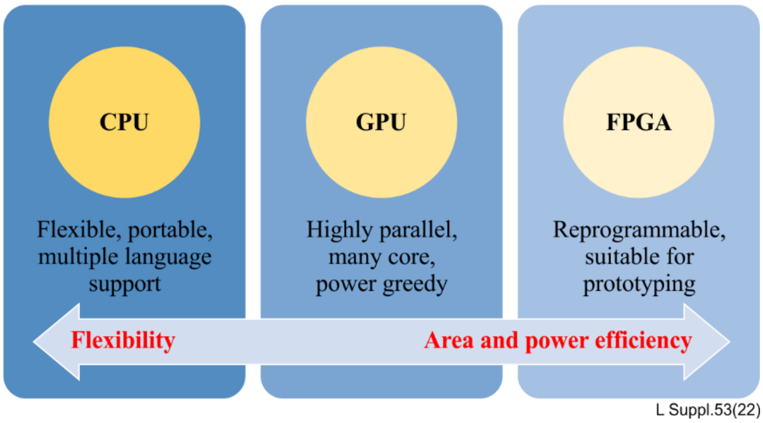

Figure 2 – Hardware platform comparison

Power consumption is divided into leakage power and dynamic power, arising from being on with no runtime activities and from switching of transistors during runtime activities respectively.

It is important to also consider the environmental impacts associated with the capture, storage, analysis and transfer of AI applications using networks and data centres.

7.2.1.3 End of life

The end of life of AI hardware presents many commonalities with consumer electronics in general. End of life electronic and electrical equipment, or e-waste, generates waste management issues that can have negative environmental and health consequences if such waste is not properly disposed of.

Hardware is generally recycled, and metals are removed for reuse. Failure to close the loop on e-waste leads not only to significant adverse environmental impacts, but also to the systematic depletion of the resource base of secondary equipment. Recycling involves either dismantling and separation or direct reuse, repair or refurbishment.

7.2.2 Drones

7.2.2.1 Materials

The design and production of a drone depend on many factors such as application, environment, size and weight [b-Koiwanit], [b-Chung]. These factors also have an influence on the choice of materials used in manufacturing its components.

The increasing demand for payload capacity and drone performance has led the industry to switch to carbon-fibre-reinforced polymers (CFRPs), which are now the primary material used in the construction of unmanned aerial vehicles (UAV) airframes. Kevlar/epoxy composites have been used in propeller construction, as they are lighter than CFRPs.

A study by Koiwanit in 2018 illustrates the environmental impacts of a drone delivery system in Chiang Mai, Thailand [b-Koiwanit]. The components considered were frame, electronic speed control, battery, servo motor, propeller and a box.

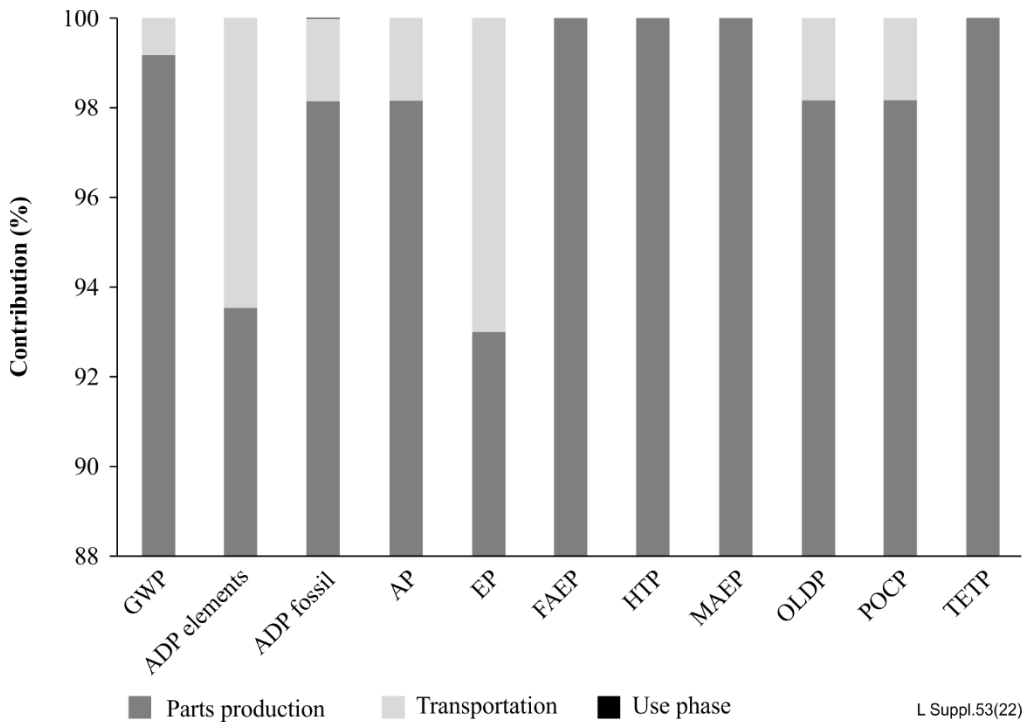

Figure 3 – Contributions of each process toward all impact categories [b-Koiwanit]

Based on Figure 3, it is evident that the production of drone components negatively affects the environment more than the transport and use phases.

7.2.2.2 Use

One of the main applications of UAVs is as delivery drones. Following the first commercial drone delivery approved by the Federal Aviation Administration in 2015, drone delivery was considered likely to become widespread by 2033, particularly for what is known as the "last-mile" logistics of small light items. Drones could augment, or in some situations even replace truck fleets and could have important implications for energy consumption, public safety, personal privacy, air pollution, city noise, air traffic management, road congestion, urban planning, and goods and service consumption patterns in urban areas.

A study by Stolaroff et al. in 2018 assessed the life cycle greenhouse gas emissions of drones for commercial package delivery in different regions of the United States of America [b-Stolaroff]. The study compared three delivery modes: drones, delivery truck and retail pick. For last-mile delivery, drones were found to have the least environmental impact.

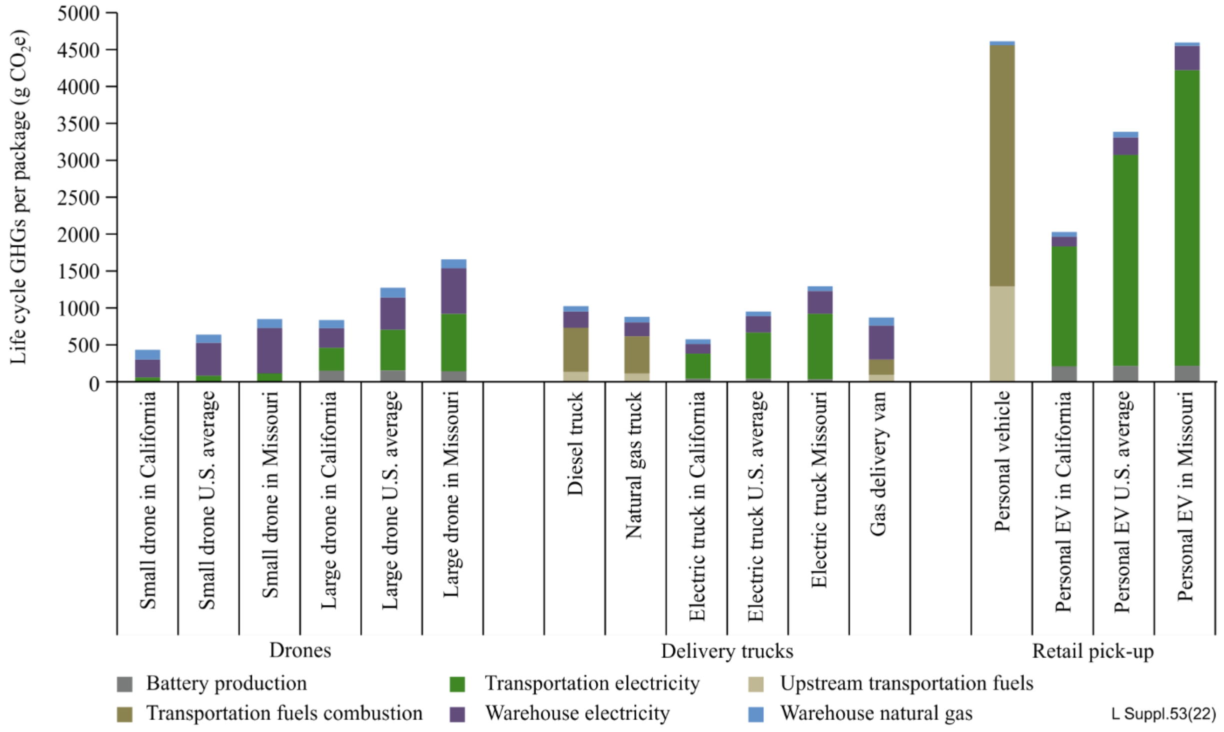

Figure 4 – Comparison of life cycle greenhouse gas emissions per package delivered for drone and ground vehicle pathways under base case assumptions [b-Stolaroff]

Drones could reduce CO2 emissions as well as other air pollutants for that sector. Several comparative studies [b-Park], [b-Stolaroff] show that delivery drones are more CO2-efficient than conventional means of transport, with the amount of CO2 emissions being greatly reduced.

These studies do not consider broader systemic effects along the entire logistics chain. For instance, even if the environmental impacts from direct emissions were reduced, emissions relating to the extra warehousing required by a drone-based logistics system may reduce or eliminate the benefits [b-Stolaroff].

In addition, as for many other technologies, the life cycle of batteries needs to be factored in. At present, the absence of comprehensive assessments of the environmental impact of delivery drones prevents robust conclusions about greenhouse gas and air pollutant emissions.

Among significant negative environmental effects, the threat to wildlife, especially birds, is a key concern. Operating at low altitude, usually below 500 metres, drones are likely to come into contact with wild animals. Beyond the obvious risk of collision, birds could be affected by the noise and stress caused by the frequent presence of drones in their habitat. Drones can also have a detrimental impact on an animal’s reproduction and survival. Bird species, animals in larger groups (more than 30 individuals) and animals in the non-breeding stage of their reproductive cycles were found to be more sensitive to disturbances relating to the presence of drones.

Other potential environmental implications include noise pollution, which can lead to discomfort and health impacts on humans living close to delivery air corridors, and negative visual impacts on urban environments.

Potential environmental risks include debris resulting from collisions and dropped cargo and the related responsibility for their disposal. Generally made from plastics, metals and other non-biodegradable materials, UAVs or drones could pollute environments if they were to crash in an inaccessible or protected area.

7.2.2.3 End of life

CFRPs are used in manufacturing drones [b-ElFaham]; however, they are incredibly difficult to recycle [b-Kim].

Glass-based products are extremely difficult to recycle, as is cellulose-based material, while aluminium and thermoplastics are highly recyclable.

Use of plastics for manufacturing drones leads to a decrease in plastic waste since it will have a long-term usability instead of a use and disposal logic.

The latest UAVs are powered by lithium-ion batteries (LIBs) while ancient drone models use nickel cadmium (NiCad) and nickel-metal hybrid (NiMH). Owing to their high energy-density, light weight and low self-discharge rate, lithium-polymer (LiPo) batteries remain the commonly used ones. It has been demonstrated that LIBs can result in harmful environmental conditions such water and soil contamination when sent to landfill. The high cost of the processing to recover resources from the battery, which could be more than that of manufacturing new ones, prevents recycling from being viable. Batteries also contain heavy metals and other hazardous materials.

7.2.3 3D printing

7.2.3.1 Materials

Materials for 3D printing include various materials such as glass, starch, ceramics, organic materials, elastomers, resins, concrete and metals. However, 3D printing is not yet versatile enough to work with most materials. For example, not every metal or plastic can be temperature controlled enough for printing.

Depending on the material component used, materials can have the biggest environmental impact of all the impacts throughout the life cycle.

A study of an industrial 3D printing application by Agustí-Juan et al. in 2017 evaluated the environmental impacts of a robotically fabricated concrete wall [b-Agustí-Juan]. The results of the impact analysis are presented in Figure 5, where "robot+tool production" refers to the in-situ fabricator construction robot and an attached tool for welding, bending and cutting. Based on Figure 5, it can be concluded that the production of robots and tools has the least impacts on the environment compared with the material consumed in the process such as concrete and reinforced steel.

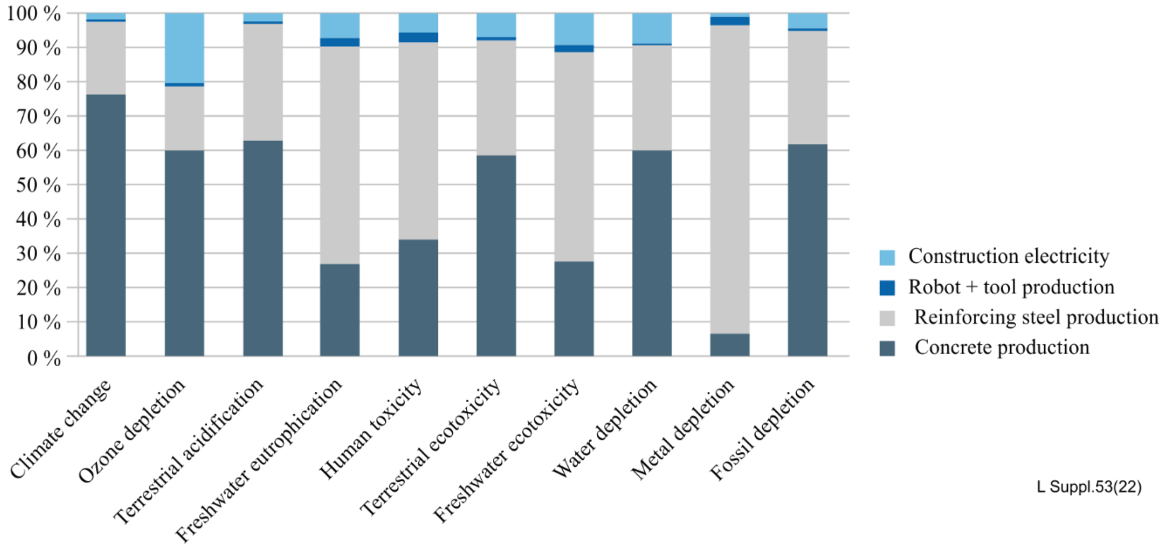

Figure 5 – Environmental impact of a robotically constructed concrete wall [b-Agustí-Juan]

While Agustí-Juan et al. assessed the environmental impacts of robots and tools in the 3D printing of a concrete wall, it is important to note that other components of the 3D printer were not considered. For example, the computer hosting the digital model and 3D printer's batteries were not discussed. On further examination of the literature, it emerged that there is paucity of research on the complete information related to the different parts of a 3D printer. Hence, most studies often focus on the material used in the 3D printing process. Mikula et al. in 2021 examined the recyclable content of polymers for 3D printing of commercial filaments [b-Mikula]. In the same year, Han et al. assessed the environmental impact of 3D printed buildings with recycled concrete [b-Han] (See Figure 6).

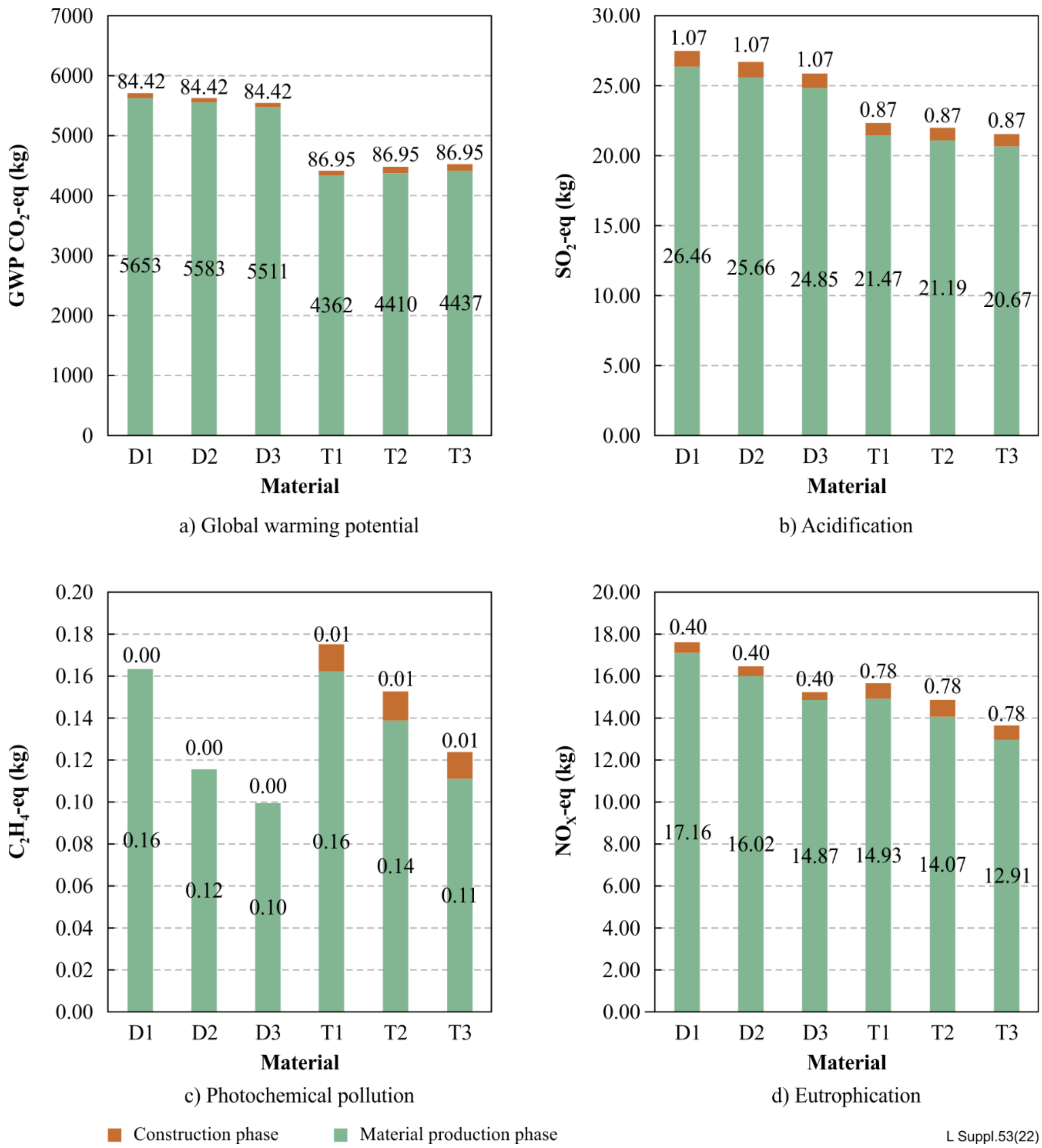

Figure 6 – Environmental impact of 3D printed buildings with recycled concrete [b-Han]

D1, D2, D3 for 3D Printing and T1, T2, T3 for conventional construction techniques are the mixed proportions of 1 m^3 concrete presented in Han et al. As shown in Figure 6, the impact of the production of concrete is higher for all the categories of indicator.

Different materials have different environmental impacts. A study by Telenko and Seepersad in 2012 found selective laser sintering of Nylon 12 to cause three times the embodied energy of acrylonitrile-butadiene-styrene granulate (ABS) or polyethylene terephthalate (PET) and 48 times that of salt without epoxy [b-Telenko].

While the literature on 3D printers often states that waste levels are near zero due to parts being constructed using only the necessary amount of material, 3D printers do not necessarily compare favourably with traditional production techniques in terms of waste. Although not a dominant life cycle impact, waste is generated where support structures are required, while inkjet-style 3D printers waste around 40% of their material, not counting support material. While they may generate less waste than computer numerical control (CNC) machining (which could result in levels of waste as high as 95%), there may still be waste material generated in the form of the print bed and supports necessary for complex geometries, resulting in waste levels higher than injection moulding. It should be added that prototyping also generates waste.

The materials used for the equipment must also be factored in for a holistic view of the environmental impact.

7.2.3.2 Use

It was argued in a more recent publication that the specific energy of current additive manufacturing systems is one to two orders of magnitude higher compared with that of the conventional manufacturing process [b-Kellens].

A life cycle study found that in contrast with a high production scenario, printing just one part a week and leaving the machine on the rest of the time had roughly 10 times the impact per part compared with using the same machine at maximum utilization. In an industrial environment, the use of the minimum number of printers to process the maximum quantity of jobs can substantially reduce the environmental impacts of 3D printing by amortizing the impacts of printer manufacture and reducing wasted energy use while idle.

The impact of utilization levels on energy consumption will depend on the specific printing technology. Some printers require extensive idle energy in the form of atmosphere generation, warm up and cool down between jobs, while others are able to print almost without interruption.

Energy impacts depend on the machine design. The following factors can have an influence on 3D printing energy impacts in an industrial environment:

- Build volume: This will determine the number of parts that can be printed simultaneously on a specific printer. There will be energy efficiency gains for machines that are able to print more parts at once.
- Layer thickness: Low layer thicknesses will provide improved surface finish and higher geometric tolerances but are likely to result in lower process speed and higher energy consumption, due to the greater total number of layers required to build the part.
- Material type: Variation in specific heat capacities and material densities will have an influence on energy required in the printing process. Printers using materials that can be worked with at lower temperatures are likely to have lower impacts.
- Process speed: Process speed can vary considerably between printers due to build volumes, layer thickness and so on. The longer the process speed, the higher the energy impacts are likely to be per part.

There is also another aspect of in-use energy to consider – the usage of the 3D printed part itself. Models are capable of producing stronger and lighter 3D printed objects than those produced with other production methods [b-Zhang]. For example, due to their closed infill structure metal FFF-printed parts are lighter than conventionally manufactured metals [b-Adams]. They also result in carbon savings in the aeronautical parts-use stage equalling “three to four orders of magnitude more” than the amount of CO_2 emitted to make them.

Studies have found that small pieces of plastic and some volatile organic compounds are released into the air when printing. Air pollution should be considered.

7.2.3.3 End of life

Most material for 3D printers is made of thermoplastics. In theory, most types of thermoplastics can be melted down and recycled, with differing amounts of efficiency and material loss between each type. However, the types of plastics that are processed by recycling plants can vary significantly.

Polylactic acid (PLA) is a biodegradable plastic, which means it can be broken down over time by bacteria and fungi. However, PLA’s long degradation time, as well as its potential to produce trace heavy metal residues after it degrades, makes it incompatible with commercial composting facilities.

8 Guidelines

8.1 Strategy for localizing decision-making and/or creating global benchmarking guidelines

To assess the understanding, attitudes, behaviours and practices of key stakeholders in this digital policy territory that links technologies and environments, we suggest adopting the survey method as an instrument to gain crucial insights for (re)shaping a comprehensive policy framework as well as business decisions based on local contexts. The survey instrument contains three parts, each targeting a major stakeholder – namely policy-makers, industry executives and private citizens – who are involved in either part or all of the material, use and end-of-life stages of a technology product or service. Combined, these three surveys can produce crucial insights for international organizations, national governments and the private sector to identify key areas of concern and actions prior to setting the international, national and industrial agenda of technology and environment for both public and private interests.

If the surveys are conducted at a national scale, they can ideally include all regions and provinces of the country, including under-represented areas for comprehensive localization. If the surveys are conducted at an international scale, besides the national approach of inclusion, such surveys can also aim to have a fair distribution of Global North and Global South countries for a balanced global benchmark.

8.1.1 Survey for policy-makers

It is proposed that this survey include 10 questions and target senior national policy-makers in ministries responsible for digital policy and for the environment. The aim is to include about 100-500 policy makers nationwide from all sectors of related ministries for the national survey and all continents for the international survey. The survey can contain the following themes:

1) existing policy and its situation on implementation;
2) effectiveness of current policy; and
3) foreseeing policy areas that can be helpful to address current concerns.

This survey template can be found in Appendix I and consists of 10 questions.

8.2.1 Survey for private industry executives

This survey can assess the awareness of private companies operating at different levels and include executives of technological industries in order to gain knowledge about their approach to addressing environmental concerns (e.g., minimize carbon emissions) and their willingness to:

1) adopt proactive sustainability measures;
2) invest in new climate friendly technologies;
3) enable sustainable energy efficiency solutions in their implementation; and

4) minimize e-waste.

The survey can include 100–500 executives of national or international technological corporations.

This survey template can be found in a Appendix II and consists of 11 questions.

8.1.3 Survey for private citizens

This survey is a representative survey among citizens in all regions and provinces of a country and is aimed to include 500–1000 citizens. The survey seeks to access:

1) citizens' awareness and perception of this issue;
2) known practices developed to enable climate neutral technology use;
3) different levels of knowledge among citizens regarding environmental pollution and health related issues exacerbated by technology use.

This survey template can be found in Appendix III and consists of seven questions.

8.1.4 Case study-related surveys: examples of contextualizing survey templates

While the questions included in the generic survey templates in the appendices have the potential to accommodate the needs for insights from almost all relevant stakeholders, it is equally important to localize certain generic questions and/or add questions to the survey based on the local context of technology and environmental efficiency. In order to facilitate the adoption of contextualized surveys, the following case studies are provided as examples; however, the questions proposed in this case study section are to be considered when adjusting the generic questions and are intended for users to brainstorm their contextualization strategies rather than to be used directly as survey questions.

(1) Case study for policy-makers

A new product, a portable drone available for personal and commercial use, is about to be released into the market by the fictional company DroneX. It is expected to be a massive success and to be used in several sectors, from drone enthusiasts to delivery companies.

Upon approving the product for rollout, it is discovered that the drones are rich in CFRPs, which are extremely difficult to recycle. Not only so, but the production reports released by DroneX have shown that manufacturing the products causes much more carbon emissions than the established average for companies that make UAVs of similar sizes.

Questions from the generic survey template can be contextualized with the following considerations:

1 Are there existing policies in your territory to ensure manufacturers keep carbon emissions of technology products under a particular ceiling? What about recyclable materials?

2 If there are no such policies or if they need to be created or updated, what data would the appointed ministry need before conducting the process?

3 Regarding releases with massive commercial potential such as that of DroneX, how does the government balance economic benefits with environmental responsibility?

4 Are there policy levers currently in place within the government to ensure environmental preservation? These could include applied research facilitators, tech R&D branches and capacity to regulate innovative sectors.

5 If policy-makers decide to tackle the issue with DroneX, requesting the company to reduce their carbon emissions and use more recyclable materials, what would you say are the biggest challenges to accomplish changes in the product rollout?

(2) Case study for private industry executives

Your company is ready to release a new technological product that has tremendous commercial potential. Upon receiving government approval for the rollout, you are notified that governmental programmes supporting green initiatives in the territory have requested the use of more recyclable materials (which are more expensive) and lower carbon emissions during manufacturing in order to approve the product for market launch.

Questions from the generic survey template can be contextualized with the following considerations:

1 How much are you willing to pay extra for recyclable materials to bring a product into the market with an eco-friendly approval? Do you have a specific return on invested capital metric for such situations?

2 If lower carbon emissions are the only means to ensure this product release, what manufacturing benefits would you usually require from the government in exchange for compromising your profits?

3 In contrast, what are the measures considered too drastic that would steer your company away from fulfilling a territory's request? Is there a specific formula you utilize to verify if a product rollout is still worthwhile under a sizing sample of the target population?

4 Would you consider sacrificing the performance of a product in order to fit the environmental guidelines?

5 How would the changes towards an environmentally friendly label affect the selling price of the product? Would you consider a higher gross-profit margin if the product can be advertised as low carbon-emissive and as made of recyclable materials?

(3) Case study for citizens/general technological users

You are well past the point to get a new phone; you have had yours for a few years and it is working quite poorly to the point of compromising your work routine and social reach. Upon research, you find that major tech companies A and B have released their new respective phones; A1 and B1, which are extremely similar in all performance and design factors.

Company A's phone is made with highly recyclable materials and manufactured under low carbon emissions, while B's is not. However, A1 is about 30% more expensive than B1, and B1 fits quite well within your price range.

Questions from the generic survey template can be contextualized with the following considerations:

1 Would you be willing to purchase A1 instead of B1 if it were an extremely similar product but simply pricier?

2 What if eco-friendly A1 was the same price as B1, but with poorer performance? E.g., worse battery, camera, screen resolution or design.

3 If A1 and B1 were similar in every way and you found yourself completely split between choosing one or the other, would discovering A1's environmentally friendly features make you choose it over B1?

4 How willing are you to trade obsolete tech products in for recycling at a low return rate than selling them on platforms such as eBay for a higher return? If you are not, is there any factor that would change your mind?

5 On a scale of 0–10, how much do you keep up with information regarding carbon emissions, technology consumption and environmentally friendly initiatives relating the companies of whom you are a regular customer? Please justify the rating.

8.2 Possible actions to improve environmental efficiency on AI and sampled emerging technologies

8.2.1 Artificial intelligence

8.2.1.1 Material

A general approach from the material viewpoint is the replacement of electronic components with optical components. As mentioned in [b-Hamerly-1] "Computing with light could slash the energy needs of neural networks". Indeed, the utilization of computers based on the optical elaboration of the signals could potentially not only benefit energy consumption but also contribute to the saving of rare earth materials.

From the energy efficiency viewpoint, in general, an optical elaboration of the signal requires less energy than an electronic one. For example, in deep learning the relevant operations to be conducted are mainly multiply-and-accumulate operations. Such operations could be easily performed by letting two optical beams, representing the two factors, impinge on a beam splitter and then adding the received photocurrent [b-Hamerly-2]. Other approaches based on other optical devices are possible, such as Mach-Zehnder interferometers.

However, fully replacing electronics with optics requires further study because, for example, optical memories are only prototypes and not yet ready for mass production. However, a new technology has become available, namely integrated photonics.

8.2.1.2 Use

There are several techniques for improving energy efficiency of processors, namely:

– Dynamic voltage/frequency scaling (DVFS) based techniques
– CPU-GPU workload division-based techniques. A scaling experiment revealed that CPU and GPU dynamic scaling can save significant amount of energy while providing reasonable performance.
– Architectural techniques for saving energy in specific GPU components, such as caches.
– Application-specific and programming-level techniques for power analysis and management.
– Hardware cooling solutions.

Best practices are recommended as training models repeatedly to achieve accuracy by a very small measure may incur very high costs. Datasets should be equally optimized.

More research can be promoted on Tiny AI as this solution is made to dramatically reduce the size of the algorithms which can be built on small hardware or on devices with low-power consumption thus ultimately reducing the environmental impact.

On energy sources, the promotion of usage of alternative and renewable resources should be sought.

Architecture

Different hardware accelerators are being investigated to overcome the increasing complexity demand and provide a better energy efficiency for different deep learning applications [b-Capra]. Today's trend is driven by Internet-of-Things (IoT) applications where the computation capability should be near the sensors, which requires strict power constraints since they are battery powered or rely on energy harvesting systems [b-Shaque]. With IoT applications, the power consumption may exceed the required power when integrating GPUs. In this scenario, deep learning (DL) algorithms should be accelerated with alternative technologies such as low-power FPGAs, which are reprogrammable and flexible. The flexibility of FPGA establishes a possible hardware optimization required for the energy-efficient acceleration of DL models.

Location

Tracking the emerging consumption and emission from AI software is equally important as AI deployed hardware. The purpose of such calculation is to measure the amount of CO2 produced by the cloud or the computing resources that are used when executing the algorithm codes. Developers can reduce emissions by targeting their cloud infrastructure in regions that use lower carbon energy sources.

8.2.1.3 End of life

The hardware can be diverted from landfill or incinerators through recycling and reuse.

Governments can initiate collective recycling plan programmes, through which different models of a type of technology can be recycled. Authorities can also negotiate with private sector companies for reuse.

Extended producer responsibility such as a take-back obligation for manufacturers and importers can be a solution, as the e-waste can be appropriately channelled to recycling plants, or to repair and refurbishment centres.

8.2.2 Drones

8.2.2.1 Materials

Materials can be substituted with materials from renewable sources, recycled materials or recyclable materials. Plant-based bioplastic is both recyclable and biodegradable. It can be used for 3D printing of drones. 3D printed drones would also allow quick repairs in remote locations.

Highly energy-efficient batteries should be used in running drones. Batteries that can be recyclable should be used. Solar energy can also be used to power some quadcopter drones [b-Lin].

8.2.2.2 Use

Reductions in emissions will depend on finding ways to diminish the size of drones [b-Stolaroff] and continuously increase the use of renewable energy sources, such as solar and wind power, for drone operation [b-Park].

For delivery applications, energy from renewable sources should be considered to power warehouses.

As for any technology, the optimization of processes, such as aerial mapping or travel route identification, is important.

8.2.2.3 End of life

The recycling of hardware can be achieved through flexible take-back plans involving collaboration within the private sector. For example, the recycling of drones may not necessarily be via the original vendors but instead flexible options of recycling through other consumer electronic companies may be made available.

The reuse of waste from electronic and electrical equipment and deeper manual dismantling prior to mechanical treatment can be promoted.

Research can be promoted in the field of recycling and reuse of waste products from batteries.

8.2.3 3D printing

8.2.3.1 Materials

Environmentally efficienct material should be used as printing material and for the manufacturing of the different components of 3D-printers.

For consumer and small-scale industrial printers, some more environmentally sound feedstock options exist in the form of corn-starch polymer, wood-based composite and recycled plastic feedstock in contrast with the previously prevalent ABS feedstock.

The following factors need to be considered for optimization: shrinkage, emissions from the material, finishing needs, heat capacity and melting point for thermal 3D printing.

8.2.3.2 Use

In order to reduce the impacts of in-use energy, the following could be considered:

– Reduce active print time per part.
– Hollow parts and supports rather than solid could be used.
– Optimized layer thickness: Larger layer thicknesses mean faster processing speed and lower energy consumption, due to the reduced number of layers required to build the part. The largest layer thickness should be chosen to achieve an acceptable level of surface finish and geometric tolerance.
– Optimized orientation: To eliminate supports by carefully orientating the part, reducing waste impacts.
– Increase the build volume: For metal sintering, printing multiple parts can result in reductions in per-part energy of from 3% to 98%.

An industry standard of reporting plant information should be defined to allow the easy computation of embodied energy, material quantities and CO_2 emissions associated with manufacturing.
Energy from renewable sources should be used to operate the 3D printers.
Ink for 3D printer should be as environmental efficient as possible.

8.2.3.3 End of life

Some printed plastics are not contaminated but are often discarded after being used once. Instead of the clean plastics being discarded, they can be directly recycled and reused. Furthermore, non-contaminated plastics can be used in 3D printing.

The packaging of 3D printers and their components should be recycled at the end of their life.

Most studies have focused on the environmental impacts of materials used in printing. Further studies about the impacts of the 3D printers need to be conducted.

8.3 Possible actions to improve environmental efficiency for all application of other emerging technologies

While emerging technologies have different meanings in different contexts, the following Recommendations given in Table 2 provide examples and options for possible actions to be taken in order to improve environmental efficiency while implementing technologies.

Table 2 – Examples for possible actions connecting technology implementation and environmental efficiency

No.	Environmental impact areas	Possible environmental efficiency action items
1	Energy consumption in data centres or platforms	• IT infrastructure including the data centre needs to be localized as far as possible from areas with inhabitants to prevent cross-continental usage, which has environmental implications. • Maximum possible use of renewable energy sources • Heat generated in the data centre can be used for heating or cooling the buildings to save on further consumption of energy

Table 2 – Examples for possible actions connecting technology implementation and environmental efficiency

No.	Environmental impact areas	Possible environmental efficiency action items
2	Energy consumption in quantum computing	• The quantum computing infrastructure needs to be localized as far as possible to prevent cross-continental usage, which has environmental implications • Maximum possible use of renewable energy sources • Heat generated in the quantum computing centres to be used for heating and cooling the buildings, housing them to save on further consumption of energy
3	Materials used for the IoT sensors	• The materials used need to be environmentally friendly, i.e., easily degradable after the completion of their life cycle, since recovering millions or billions of such devices may not be physically or commercially viable
4	Battery recycling	• The suppliers of electronic hardware, including batteries, for a large number of IoT devices should also be made responsible for collecting the product at the end of the life cycle to prevent these batteries and electronics from creating hard to manage e-waste
5	Materials used for aids for physically challenged people	• Materials used for prosthetics should be environmentally efficient • Ingestible sensors in medical devices should dissolve in the body without causing harm
6	Handling e-Waste	• There is a need to incentivize entrepreneurs to establish e-waste management plants

It is also important to consider not only the environment efficiency of the technologies but also the effects of using technologies in applications.

For example, Industry 4.0 includes the ongoing digitalization of manufacturing and industrial practices to improve their productivity, flexibility and cost-effectiveness. It is an industrial approach where one or more digital technologies are used throughout industrial processes in order to produce more and better.

Digital technologies such as robots and AI applied to manufacturing can effectively make manufacturing more environmentally efficient. Examples of the direct impact of adopting Industry 4.0 technologies are given in Table 3.

Table 3 – Examples of the direct impact of Industry 4.0 on environmental efficiencies

Manufacturing processes	Examples of adopting Industry 4.0 technologies	Direct impacts on environmental efficiency
Development	– Using simulations to understand the mechanisms of machines – Using big data analytics to characterize the dynamics of supply chains	Fewer experiments (waste↓)
Design	– Using cyberphysical systems to design machines	Fewer design cycles (waste↓)
Prototype	– Using 3D printing for rapid prototyping	Less material consumption in making prototypes (waste↓)
Production	– Using big data analytics to optimize the allocation of production workstations – Using smart sensors and controllers to monitor and reduce CO2 emissions by machines	Optimized production processes (waste↓ and CO2 emissions ↓)
Test	– Autonomous inspections based on robots and computer vision	N/A
Quality assurance	– Using big data analytics to understand patterns in product defects – Autonomous condition monitoring of equipment based on the Internet of Things	Reduced number of defective products (waste↓ and CO2 emissions ↓)
Support	– Remote technical support and training based on augmented reality	Less travel (CO2 emissions ↓)
Logistics	– Cloud planning for supply chain management and delivery	Less travel (CO2 emissions ↓)

Industry 4.0 technologies generally improve the environmental efficiency of manufacturing processes by allowing less waste to be generated in the production of a unit product.

Industry 4.0 can also help build a more circular economy. A circular economy is an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them while in use, then recover and regenerate products and materials at the end of each service life. Figure 7 is an illustration of the circular economy.

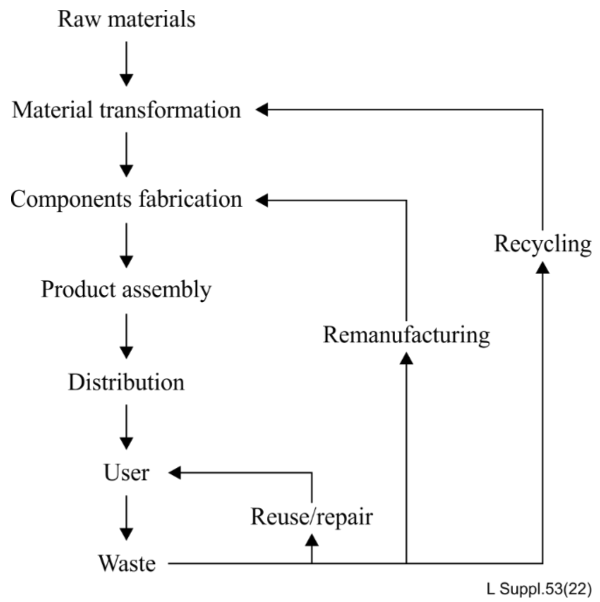

Figure 7 – The life cycle of a product in Industry 4.0

Industry 4.0 technologies can help build the circular economy in a number of ways including but not limited to:

- Use of robots to accelerate disassembly.
- Use of 3D printing for high-value product repair.
- Augmented reality and virtual reality to support product repair and remanufacturing.
- Use analytics to support product design.
- Adoption of ICT to support the development of new business models focused on repair, reuse, remanufacturing and recycling.
- Adoption of digital twins to enable real-time asset monitoring and remanufacturing planning.

8.4 Guidelines for different stakeholders

Throughout the implementation of any emerging technology, stakeholders from both the public and private sectors (who are likely involved in one or more of the following processes, 1) development, 2) deployment, 3) market and business, and 4) regulations, policies and standards) need to be aware of environmental consequences. Clauses 8.4.1–4 give a list of generic guidelines to facilitate the understanding of links between technology and environmental factors.

8.4.1 Development

– **Track breakthrough innovations** worldwide without dismissing country of origin since a potential global benefit might hide under assumptions and or prejudices.

– **Challenge and educate technological entrepreneurs** to think laterally, aiming for greater impact and good.

– Consider **the full life cycle** of a new product.

8.4.2 Deployment

– **Reinforce the resilience** of critical technological infrastructure nodes.

– When deploying frontier technologies to developing countries through foreign development investment, be intentional from the onset about **supporting ongoing repair and maintenance by local stakeholders** in the host country.

– Create long-term strategic partnerships with last-mile distributors (LMDs) to ensure steady benefits of these technologies to low-income consumers in developing countries, including:
  - **Manufacturers** of emerging technology-enabled products should **engage in ongoing consultation with LMDs and their customers** through the different design, test, and iteration phases of products;
  - service providers (software and training companies) should focus on low cost tailored platforms and **services they need**;
  - governments should acknowledge the key role of LMDs in **supporting SDGs** and ensure they are included in dialogues and collaboration with the private and public sectors.

– **Include active participation of the end users of new technologies** throughout the different phases of their implementation, in order to make sure **maintenance** is assured as well as financial, material and human return of investment.

8.4.3 Business and market

– **Raising funds through green bonds and gasoline taxes** to a local-first financing approach to address green economy from the root.

– Enable **ultra-long-term financing and investment strategies**, with a triple target of investing in people, in sustainable and resilient infrastructure as well as in innovation.

8.4.4 Regulations, policies and standards

– **Multistakeholder engagement** to call for consensus-making.

– **Licensing agreements** between the public and private sectors to better inform regulations.

– **Enforcement of mandatory quality standards** to support sustainable markets.

– Research to create **evidence-based** regulations, policies and standards.

– Provision of **clarification about end-of-life responsibilities** to different stakeholders, including users.

Appendix I

Generic survey for national policy-makers

(1) When you think about your policy strategies for the next few years,

How do you see the link between technological development and environmental issues?

(Only tick <u>one</u> response)

- □ We see environmental issues as a key priority in our technological policy strategies.
- □ We will address the environmental implications sometime in the coming years.
- □ Our focus is entirely on technological development, and we cannot do much regarding environmental implications.
- □ We will wait for international best practice models before we approach environmental issues.
- □ Don't know.
- □ Other (please fill in): ....

(2) Are you following international policy discussions regarding the implications of technology on the environment?

- □ All the time (please continue with Q 3).
- □ Most of the time (please continue with Q 3).
- □ Sometimes (please continue with Q 3).
- □ No (please continue with Q 4).

(3) When do you tend to follow international policy discussions regarding implications of technology on the environment?

- □ When they address a specific technology sector.
- □ When they address a specific environmental sector.
- □ When they address a specific technology life cycle.
- □ When they address a specific Sustainable Development Goal.
- □ When they address our larger region.
- □ When they address our country.
- □ Don't know.
- □ Other (please fill in): ....

(4) What are the policy targets when addressing technology related environmental implications in your country?

(Tick all that apply)

- □ Reduce energy consumption.
- □ Preserve natural habitat.
- □ Minimize waste.
- □ Enable recycling.
- □ Enhance the circular economy.
- □ Minimize pollution and environmental hazards.
- □ Reduce emission.
- □ Don't know.

- □ Other (please fill in): ....

(5) How do you approach environmental policy targets while enabling technological transformation?

(Tick all that apply)

- □ Use established policy tools.
- □ Refine existing policy tools.
- □ Develop new policy tools.
- □ Don't know.
- □ Other (please fill in): ....

(6) What are your aims in terms of policy targets?

(Tick all that apply)

- □ Enable a holistic approach across most or all technology sectors.
- □ Develop technology-sector-specific policy approaches.
- □ Develop policy approaches along government sectors.
- □ Environmental issues are a key focus of our government.
- □ Don't know.
- □ Other (please fill in): ....

(7) Are you developing strategies to enable public awareness for environmental issues relating to technologies?

- □ Yes (please continue with Q 8).
- □ No (please continue with Q 9).

(8) How do you enable public awareness?

(Tick all that apply)

- □ Press briefings.
- □ Media campaigns.
- □ Social media campaigns.
- □ Social media news feeds by government officials.
- □ Advertising.
- □ Working together with technology sectors to enable public awareness.
- □ Don't know.
- □ Other (please fill in): ....

(9) How do you promote environmental sustainability in the technological sector in your country?

(Tick all that apply)

- □ Enable tax reduction for environmental efficiency.
- □ Encourage private/public partnerships to target sector specific environmental issues.
- □ Launch awareness campaigns for local technology industries.
- □ Produce best practice models based on international strategies.
- □ Don't know.
- □ Other (please fill in): ....

(10) Which monitoring measures do you have in place?

- □ Regular government assessments.
- □ Benchmarking processes.
- □ Specific government committees following up with technology industries.
- □ Regular meetings with specific industries.
- □ We do not actively monitor progress.
- □ Don't know.
- □ Other (please fill in): ....

Appendix II

Generic survey for technology industry

(1) What is the geographical focus of your company?

- □ National.
- □ Broader region.
- □ International.
- □ Truly global (all continents).

(2) Do you orient your company along national or international plans of environmental efficiency?

- □ National.
- □ International.
- □ Both.
- □ Don't know.
- □ Other (please fill in): ....

(3) How important are <u>concrete</u> investments in <u>environmental efficiency</u> for your company?

- □ Top priority.
- □ Very important.
- □ Somewhat important.
- □ Not important as we have other issues to address.

(4) Specifically, <u>carbon free energy</u> has become a topic in public debates internationally:

how is carbon free energy relevant to your company?

Below are a few statements, please tick all that apply:

- □ It helps to minimize costs.
- □ It will enable us to position ourselves as a leader in our sector.
- □ It is a selling point for our products.
- □ It is key to our customers, so we must incorporate it.
- □ The environment is a high priority for our company.
- □ It is just a current trend which will pass.
- □ It is not relevant to us as we have other priorities at the moment.
- □ Don't know
- □ Other (please fill in): ....

(5) What <u>energy-efficient</u> measures do you already have in place?

(Tick all that apply)

- □ We source material from energy-efficient companies.
- □ Energy efficiency is relevant to us in all in-house production processes.
- □ We only collaborate with energy-efficient industry partners.
- □ We use energy-efficient data storage.
- □ Our delivery/logistics uses energy-efficient transportation.

- □ We adopt models to enable energy efficiency during the lifetime of our products.
- □ We are in the process of developing energy-efficient approaches.
- □ We have not yet developed energy-efficient approaches.
- □ Don't know.
- □ Other (please fill in): ....

(6) When you consider the different components of your business, which are the segments you consider most relevant when addressing broader <u>environmental issues</u>?

The response options below apply to technology-centred and data-centred businesses.

(Tick all that apply)

- □ Product development.
- □ Manufacturing processes.
- □ Data servers.
- □ Cloud computing.
- □ Data centres.
- □ Blockchain procedures.
- □ Logistics/transport to reach the customer.
- □ Recycling of our products.
- □ Don't know.
- □ Other (please fill in): ....

(7) Are some of the segments of your business listed in Question 6 processed overseas?

- □ Yes (please continue with Q 8).
- □ No (please continue with Q 9).

(8) Do you assess your <u>overseas</u> business partners regarding their <u>environmental efficiency</u>?

- □ Yes, we would not enter an international business partnership unless this is guaranteed.
- □ Yes, from time to time.
- □ Yes, we have adopted concrete measures to assess their environmental efficiency.
- □ That is not necessary as we focus on our own environmental efficiency.
- □ Don't know.
- □ Other (please fill in): ....

(9) Do you assess your <u>national</u> business partners regarding their <u>environmental efficiency</u>?

- □ Yes, we would not enter a national business partnership unless this is guaranteed.
- □ Yes, from time to time.
- □ Yes, we have adopted concrete measures to assess their environmental efficiency.
- □ That is not necessary as we focus on our own environmental efficiency.
- □ Don't know.
- □ Other (please fill in): ....

(10) How do you promote environmental efficiency among your staff to develop a 'green' corporate culture?

- □ In newsletters.
- □ Through corporate guidelines.
- □ We have a special committee for informing staff.
- □ We hold regular meetings to maximize environmental efficiency.
- □ We promote best practice models.
- □ Don't know.
- □ Other (please fill in): ....

(11) Where do you see the main future challenges for achieving environmental sustainability?

(Please fill in): ....

Appendix III

Generic survey for private citizens

(1) When it comes to the implications of technologies on the environment, how aware are you of the implications?

- □ Very aware.
- □ Aware.
- □ Somewhat aware.
- □ Not really aware.
- □ Don't know.

(2) When you think about these implications, what are you most concerned about?

(Tick all that apply)

- □ My health and the health of my family and friends.
- □ The broader environment.
- □ Safety of my home.
- □ Safety of resources, clean water, clean food, etc.
- □ Energy efficiency.
- □ Implications for future generations.
- □ Don't know.
- □ Other (please fill in): ....

(3) How would you rate your knowledge about the implications of technologies on the environment?

- □ Significant knowledge.
- □ Good knowledge.
- □ Some knowledge.
- □ Very basic knowledge.
- □ None.

(4) Would you be willing to pay a higher price if a technology had high 'green' standards?

- □ Yes.
- □ No.

(5) What are your sources for getting information about environmental protection and technologies? (Tick all that apply)

- □ Educational institutions such as schools or universities.
- □ Media, such as radio and television.
- □ Digital search platforms.
- □ My social media community.
- □ Digital newsfeeds.
- □ Blogs.
- □ Friends and family.
- □ Government.

- ◻ Events.
- ◻ Don't know.
- ◻ Other (please fill in): ....

(6) When you consider your technology recycling practices, which components do you normally recycle at a dedicated recycling station?

- Batteries.
- Old mobile phones.
- Computers.
- Cables.
- Household technology.

(7) How do you think you could contribute to increasing public awareness for environmentally efficient technologies?

(Please fill in): ....

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