Effects of ICT on the Environment and Indicators for Their Measurement

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Abstract: - The relationship between ICTs and the environment is complex and multifaceted, as ICTs can play positive and negative roles. The article's main idea is how the ICT sector can help tackle climate change, from measurement, monitoring, and automation of processes to self-organizing the sector to refurbish and ecologically scrape ICT hardware. The life cycle of services must be managed to minimize their impact on the environment – management of production, use, and end of life. Based on the analysis, the current article identified some groups of indicators used in the proposed model to estimate the ICT footprint. This information contributes to a more accurate measurement of any company the effect on the environment.

Key-Words: - ICT, Climate, Environment, Indicators, Ecology

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1 Introduction

Where we are? We can mark five technological waves in IT based on the logical stance of computer users. The arrival of mainframe computers in the 1960s generated the first wave (one computer for many people). Followed in the late 1970s by personal computers in the second wave (one computer for one person). In 1988, Mark Weiser pointedly noted that computers embedded in everyday objects all around us formed the third wave – what he called the ubiquitous computer (many computers for one person). A decade later Kavin Ashton revealed the ideas of the fourth wave – the Internet of Things. A network of physical objects – devices, vehicles, buildings, and other elements with embedded electronics, software, sensors, and network connectivity and addressing that enable those objects to collect and exchange data. Now we are in the time of the Internet of everything, unifying people, data, processes, and things.

Given the rapid development of ICT and the challenges of climate change, this work aims to analyze the impact of these technologies on the environment and how the ICT sector can help address climate change.

1.1 ICT and the Environment

The relationship between ICTs and the environment is complex and multifaceted, as ICTs can play both positive and negative roles. A recent review of the impact of ICT on the economy and the environment showed conflicting results, [1]. It is found that ICT adoption within urban areas can improve environmental quality in developing and developed countries, [2]. The empirical estimations unfold that ICT and globalization contribute to reducing CO2 emissions, [3]. Positive impacts can come from dematerialization and online delivery, transport, and travel substitution, a host of monitoring and management applications, greater energy efficiency in production and use, and product stewardship and recycling.

Negative impacts can come from energy consumption and the materials used in the production and distribution of ICT equipment, energy consumption in use directly and for cooling, short product life cycles and e-waste, and exploitative applications (e.g. remote sensing for unsustainable over-fishing. The impacts of ICT on the environment can be direct (i.e. the impacts of ICTs themselves, such as energy consumption and e-waste), indirect (i.e. the impacts of ICT applications, such as intelligent transport systems, buildings, and smart grids), or third-order and rebound (i.e. the impacts enabled by the direct or indirect use of ICTs, such as greater use of more energy-efficient transport).

1.2 From Traditional to Future ICT

The invention of mainframe computers in the 60s and personal computers in the 70s focused on improving the efficiency and productivity of different industries by using computers and networks. Since the late 80s the movement towards a digitized economy through the adoption of cloud computing, artificial intelligence (AI), and network of physical objects (with embedded sensors, software, and other technological solutions for data processing and exchange over the Internet), advanced digital technologies (5G mobile networks), big data analysis, [4], [5], [6]. Digital technologies have grown exponentially and in 2023 the global information technology market reached $8852.41 billion in 2027 is expected to grow at an annual growth rate of 7.9% and reach $11995.97 billion, [7].

The development of modern computer, network, and mobile communication technologies has both positive and negative effects on the environment, so how they are used is essential. The example of the positive and negative impacts of ICT are given in Table 1.

ICT tools such as weather forecasting and precision farming can be used for the optimization of crop yields, reducing water consumption, and preventing soil erosion.

The impacts of ICT on the environment can be direct (energy consumption of electronic devices and e-waste), indirect (intelligent transport systems, smart cities, and smart grids), or third-order and rebound (direct or indirect use of ICTs, i.e. extensive use of more energy-efficient transport), [8].

The life cycle of ICT products and services must be managed to minimize their impact on the environment – management of production, use, and end-of-life.

Six Sigma, Lean, and Lean Six Sigma are popular process improvement methodologies that can help to minimize waste, reduce defects, and improve the processes to improve a business's or organization's performance, [9]. Lean focuses on identifying and reducing waste and increasing efficiency in a process. It emphasizes minimizing the steps and resources involved in a process to improve productivity and reduce costs. The main principles of lean include identifying and eliminating waste, continuous improvement, and respect for people. Six Sigma is a data-driven methodology used to identify and eliminate defects in a process. It emphasizes reducing variation in a process to improve quality and reduce costs. The main principles of Six Sigma include defining, measuring, analyzing, improving, and controlling a process.

Table 1. Impact of ICT on the Environment

Industries	Positive	Negative
Energy consumption	✓ Energy consumption can be reduced by using energy-efficient technologies and devices, energy-saving technologies such as virtualization and cloud computing, energy-efficient buildings, etc. ✓ ICT can be used to develop smart grids that can reduce energy consumption by improving the efficiency of the power grid.	✓ ICTs require a significant amount of energy for device operation (computers, data centers, communication networks).
Transport	✓ Virtual meetings and conferences, e-commerce, Intelligent transport systems, and other digital services can significantly reduce the need for physical business travel and resource consumption and can contribute to greenhouse gas emissions.	✓ The energy consumption associated with data centers and communication networks.
Waste	✓ ICTs have enabled organizations to optimize their operations and reduce waste production and paper consumption. ✓ Smart waste management systems for proper disposal, collection, and recycling of electronic waste.	✓ Use of non-renewable and environmentally damaging resources. ✓ The large number of ICT devices and equipment leads to the accumulation of electronic hazardous waste, that can pollute the environment.
Climate Change	✓ ICT is used to monitor climate change (Earth observation satellites for monitoring, gathering, and analyzing environmental data).	✓ ICT generates carbon emissions and contributes to greenhouse gas emissions.

Lean Six Sigma combines the principles of both methodologies to create a comprehensive process improvement methodology. It emphasizes reducing waste and variation in a process to improve quality, productivity, and customer satisfaction. The main principles of Lean Six Sigma include understanding the customer's needs, identifying and eliminating waste and variation, continuous improvement, and respect for people.

Regardless of which of the methodologies will be used to determine the current state and the change, it is necessary to follow the following sequence of actions:

1) Determination of system requirements and objectives;

2) Measuring the current process and collecting the relevant data;

3) Analyzing the data;

4) Controlling the current processes based on the data analysis, and

5) Controlling future state processes to ensure that any deviations are corrected.

The usage of such methodologies relies on properly defined indicators. Therefore, the current article is focused on the determination of specific indicators for the measurement of ICT impact on the environment.

The rest of the article is structured as follows: Section 2 concerns green computing and ICT green sustainability strategies; Section 3 is focused on indicators for measuring ICT effectiveness; Section 4 describes the direct impact of hardware lifecycle on the environment, and the conclusions are drawn in Section 5.

2 Green ICT

Green ICT refers to the use of environmentally sustainable technologies and practices in the design, manufacture, use, and disposal of ICT equipment and services. It aims to reduce the consumption of energy, water, and mineral resources as well as CO2 emissions and their carbon footprint, toxic materials, etc., and other negative impacts of information and communication systems on the environment and society.

Green ICT stands for a set of initiatives organizations undertake to reduce carbon emissions and the carbon footprint produced by their information and communication systems. Technology for energy saving in information, communication, and technology. Green ICT is the study and practice of using computing resources efficiently and effectively with minimal or no impact on the environment.

Green computing involves designing and developing software and applications that are energy-efficient while also promoting sustainable development and economic growth. Green ICT practices include the design of energy-efficient equipment; replacement of energy consumption in data centres; web-based business services; improvement of cooling technology; adoption of carbon offset programs; energy management; etc.,

[10]. Some guidelines for the green design of computer products can be found in [11]. Some authors find that the level of digitalization development effectively promotes green economic growth, [12].

2.1 ICT Green Sustainability Strategies

ICT Green sustainability strategies can be a complex task that requires careful planning and consideration of various factors. This is due to the complex interrelationship of components, which are needed to leverage ICT for sustainable economic development as shown in Figure 1, [13].

Fig. 1: GeSI's 'SMARTer 2030' report

The steps, that could be followed to formulate such green strategies, include:

- Sustainability assessment of ICT business organization or a process (measuring the organization's carbon footprint, identifying areas of waste and inefficiency, existing opportunities to improve the process efficiency;
- Set sustainability goals, which are specific, achievable, relevant, measurable, and time-bound and also to be aligned with the vision and mission of the business company;
- Identification of ICT green solutions that can help the organization achieve its sustainability goals – implementing energy-efficient technologies, using renewable energy sources, optimizing data centers, and reducing paper usage, among other things.
- Development of implementation plan – timelines, milestones, and metrics for measuring progress toward achieving the sustainability goals.
- Engagement of stakeholders (employees, partners, customers, suppliers) in sustainability efforts by providing training, as well as encouraging participation in sustainability initiatives.
- Monitoring and reporting the process toward achieving the green goal.

2.2 The Global e-Sustainability Initiative

The Global e-Sustainability Initiative (GeSI) is a leading international organization, which supports the efforts of ICT companies and non-governmental organizations to promote the use of sustainable innovative technologies and digital solutions to address global sustainability challenges. GeSI was founded in 2001 by a group of leading ICT companies, and it has since grown to include over 40 members from the technology industry, as well as governments, NGOs, and other stakeholders, [14]. It is the source of important information, best practices, and resources for the goal of creating a sustainable world through responsible, transformative digital solutions. To achieve its mission, GeSI focuses on:

- Advocacy (including promoting the use of renewable energy in the technology industry, advocating for policies that encourage the circular economy, and supporting the development of international standards and best practices);
- Collaboration (including working with other organizations to develop joint projects and initiatives, sharing best practices and knowledge, and promoting cross-sectoral collaboration) and
- Thought leadership (includes conducting research and analysis on key sustainability topics, publishing reports and other thought leadership content, and promoting public awareness and understanding of sustainability issues), [15].

2.3 The European Green Deal

The European Green Deal is a comprehensive set of policy initiatives and proposals introduced by the European Commission in December 2019, aimed at transforming the European Union into a sustainable and climate-neutral economy by 2050. The ultimate goal of the European Green Deal is to achieve zero net greenhouse gas emissions by 2050, which would require significant reductions in emissions across all sectors of the economy, as well as the development of new technologies and practices to support sustainable growth, [16].

The design and manufacture of ICT products should be focused on making them more durable, easy to maintain, reusable, upgradable, reliable, recyclable, renewable, energy, and resource-efficient.

3 Indicators for Measuring Impacts on the Environment

Society needs ICT hardware to produce, process, and store highly valuable information. High-quality and transparent data is crucial to achieving the 2030 Agenda. It is difficult to measure the impact on the environment in any area, but there are additional challenges and complications for ICT because of their diversity and rapidly changing nature, as well as difficult determination of causation. The authors found 77 different indicators measuring the impact of ICT hardware, [15].

The different ICTs (mobile phones and mobile telecommunications, general purpose technologies, services, etc.) have different impacts in different countries and contexts. The measurement of impact could be done by analytical techniques, case studies, statistical surveys, panel studies, direct observation, and document examination. Different ICT has different impacts on the environment depending on a range of factors. Depending on the specific objectives and context of measurement of ICT impact on the environment, various indicators can be used for this purpose. Some of these commonly used indicators include:

- Number of individuals, organizations, and communities, which access the ICTs (smartphones, tablets, laptops, internet, households with broadband access, cloud, collaborative platform, Smart robotics, IoT, etc.) can indicate the level of impact on the environment;
- Digital literacy of the users can indicate the number of people who have the skills and knowledge to use these technologies effectively;
- Economic benefits of ICT (innovations, increasing productivity, services developed through the use of technology, smart energy systems or e-government services, gross domestic product (GDP) or employment rates, etc.);
- The amount of e-waste generated by ICT equipment and devices and the percentage of e-waste properly recycled or disposed of;
- Measurement of greenhouse gas emissions associated with the production, use, and disposal of ICT equipment and devices (in terms of carbon dioxide equivalents);
- The amount of energy consumed by ICT devices and infrastructure (including access to distance education and other public services).

Other indicators might include data privacy and security, research, and the role of ICT in promoting sustainable development.

3.1 Model for Assessing the Impact of ICT on the Environment

All of these groups of indicators need to be determined for a particular organization or company and obtained results to be involved in the following mathematical model:

$$min(\text{Footprint}^{ICT}) = \sum_{i=1}^{N} \alpha^i \sum_{j=1}^{M} w_j^i \, k_j^i \quad (1)$$

s.t.

$$\sum_{i=1}^{N} \alpha^i = 1 \quad (2)$$

$$\sum_{j=1}^{M} w_j^i = 1 \quad (3)$$

Here in relation (1), index $i = 1, \ldots, N$ expresses the set of weighted coefficients for the importance of the groups of indicator and has to comply with the relation (2). The parameter k_j^i expresses the normalized value (in the range between 0 and 1) of a particular indicator from *i-th* group determined for a particular organization or company, while w_j^i expresses the weighted coefficient for the importance of the *j-th* indicator from the *i-th* group. Likewise, the relation (3) must be satisfied to have comparable measures.

Some indicator groups have better performance if their value is bigger (for example – the digital literacy of the users) and for some indicator groups, we are looking for minimal value for their performance (for example – the amount of e-waste generated by ICT equipment and devices and the percentage of e-waste properly recycled or dispose of).

Unlike, [17], where only four indicators (primary energy consumption, gross domestic product, CO2 emissions, and N2O emissions) are used, the proposed model can take into account many different groups of indicators to estimate the ICT footprint.

In addition, it is worth mentioning also the environmental impact of cloud computing. To measure the environmental impact of cloud provisioning, a set of critical indicators related to energy use at different levels in the cloud architecture must be defined, [18].

Once these indicators are identified, they can be used in the formulated model (1) – (3) to assess the impact of ICT on the environment.

4 Direct Impact of Hardware Lifecycle on the Environment

The ICT hardware is a diverse gathering of workstations (desktop and laptop), servers, network, and telecommunication devices, and mobile intelligent devices (phones, tablets, etc.). They have a lifecycle in which they are consuming energy and give off heat. Their hardware elements – boards, processors, chips, integral schemes, capacitors, etc. contain toxic elements that pollute the environment if not properly handled. Their waste management done according to standards has its lifecycle, which includes storage, recycling, reintegration, and monitoring. That is why the empirical results unfold that positive shocks in ICT negatively affect CO2 emissions, [19]. In this regard, some authors propose designing sustainable computer systems with an architectural carbon modeling tool, [20].

A product's carbon footprint (PCF) could be used to help us understand its impact on the environment. providing valuable insight to design more sustainably. That is why many companies run what's called a life cycle assessment, which includes a PCF report. The PCF reports typically cover a whole life cycle from the initial extraction of the raw materials, through the manufacturing and assembly process, through distribution, use, and end of life when it is recycled or otherwise disposed of. Knowing the PCF allows us to make informed decisions.

The PCF for typical ICT equipment is as follows [21]:

- Desktop & screen: 621kg CO2e,
- Laptop & screen: 691kg CO2e,
- Desktop & 2 screens: 903kg CO2e,
- Laptop & screen at office & screen at home: 928kg CO2e,
- Desktop & screen & laptop: 1,030kg CO2e.

Reducing the carbon footprint of production leads to a reduction in waste, which in turn requires recycling old technologies, using sustainable packaging, and optimizing delivery logistics. Therefore, reducing IT waste is a step in the right direction to reduce our carbon footprint. In, [22], a global review of consumer behavior towards sustainability environmental and implications for the circular economy can be found. The following simple steps can be used for personal contribution to the footprint: avoid purchasing additional screens; choose of desktop or laptop, but not both; return unused equipment; turn off the computer at the end of the day.

5 Conclusion

Green ICT deals with people, processes, and technologies relating to the environment. Understanding green ICT allows the use of computing resources efficiently and the use of technologies and techniques to lower (or reduce the rate of increase of) the power consumption or carbon footprint of the ICT function. In a broader sense, green ICT also addresses the use of ICT as an enabling technology to help reduce power consumption leading to low greenhouse gas emissions, and using ICTs as an enabler to reduce greenhouse gases in other industries.

Environmentally sensitive information and communication technologies are designed to save energy, compared to their conventional counterparts, an important component is addressing the direct impact of ICT hardware on the environment. The identified indicators facilitate the measurement of environmental impact in different areas, but there are additional challenges and complications for ICTs due to their diversity and rapidly changing nature, as well as the difficulty of determining causality. By usage of the proposed mathematical model, it is possible to estimate the ICT footprint of any organization or company. The team is collecting data to test the applicability of the proposed model, which will be processed and published in the next stage of the present study.

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References:

[1] Zhang, X., Wei, Ch., The economic and environmental impacts of information and communication technology: A state-of-the-art review and prospects, *Resources, Conservation and Recycling*, Vol. 185, 106477, 2022, https://doi.org/10.1016/j.resconrec.2022.106477

[2] Chatti, W., Majeed, M.T., Information communication technology (ICT), smart urbanization, and environmental quality: Evidence from a panel of developing and developed economies, *Journal of Cleaner Production*, Vol. 366, 132925, 2022, https://doi.org/10.1016/j.jclepro.2022.132925.

[3] Ahmed, Z., Nathaniel, S. P., Shahbaz, M., The criticality of information and communication technology and human capital in environmental sustainability: Evidence from Latin American and Caribbean countries, *Journal of Cleaner Production*, Vol. 286, 125529, 2021, https://doi.org/10.1016/j.jclepro.2020.125529.

[4] *Digital technologies for a new future*. United Nations, ECLAC, 2021.

[5] Tsochev, G., Sharabov, M., Artificial intelligence methods used in industry 4.0 in particular industrial control systems, *AIP Conference Proceedings*, Vol. 2333, 070017, 2021, https://doi.org/10.1063/5.0041610.

[6] Garvanov, I., Garvanova, M., Borissova, D., Garvanova, G., A model of a multi-sensor system for detection and tracking of vehicles and drones. In: *Business Modeling and Software Design. Lecture Notes in Business Information Processing*, Vol. 483, 2023, pp. 299-307, https://doi.org/10.1007/978-3-031-36757-1_21.

[7] *Information Technology Global Market Report 2023*, The Business Research Company, 2023.

[8] Shaaban-Nejad, S., Shirazi, F., ICT and Environmental Sustainability: A Comparative Study. *Sustainability*, Vol. 14, No. 14, 8651, 2022, https://doi.org/10.3390/su14148651.

[9] Pathak, S., Pathak, K., Lean, Six Sigma and Lean Six Sigma Overview, *International Journal of Business Quantitative Economics and Applied Management Research*, Vol. 1, No. 6, 2014, pp. 99-127.

[10] Bijwaard, D., Gyupchanova, T., Dunne, A., Survey on the contribution of ICT to the environmental sustainability actions of EU enterprises, *European Union*, Brussels, 2021.

[11] Zong, J., Zhang, X., Yang, Y., Li, H., Yuan, H., Guideline for green design of computer products, *International Conference on Social Development and Media Communication* (SDMC 2022), Vol. 155, 2023, https://doi.org/10.1051/shsconf/202315503025.

[12] Hao, X., Li, Y., Ren, S., Wu, H., Hao, Y., The role of digitalization on green economic growth: Does industrial structure optimization and green innovation matter? *Journal of Environmental Management*, Vol. 325, Part A, 2023, 116504, https://doi.org/10.1016/j.jenvman.2022.116504.

[13] *Policy and Sustainable Economic Development*, United Nations Sustainable Development Goals (SDGs), 2023.

[14] *Global e-Sustainability Initiative* (GeSI), 2022. [Online], Available: https://gesi.org/.

[15] Krumay, B., Brandtweine, R., Measuring the environmental impact of ICT hardware, *International Journal of Sustainable Development Planning*, Vol. 11, No. 6, 2016, pp. 1064-1076.

[16] *A European Green Deal Striving to be the first climate-neutral continent*, European Commission, 2023.

[17] Alkurt, R.D., Dursun, M., Goker, N., Net zero policy performance measurement of European countries, *WSEAS Transactions on International Journal of Environmental Engineering and Development*, Vol. 1, 2023, pp. 107-112.

[18] Achar, S., Cloud computing: Toward sustainable processes and better environmental impact, *Journal of Computer Hardware Engineering*, Vol. 1, No. 1, 2022, pp. 1-9, https://doi.org/10.17605/OSF.IO/NKYHR.

[19] Shehzad, K., Zaman, U., Ahmad, M., Liu, X., Asymmetric impact of information and communication technologies on environmental quality: analyzing the role of financial development and energy consumption, *Environment, Development and Sustainability*, Vol. 24, 2022, pp. 1761-1780, https://doi.org/10.1007/s10668-021-01506-w

[20] Gupta, U., Elgamal, M., Hills, G., Wei, G.-Y., Lee, H.-H.S., Brooks, D., Wu, C.-J., ACT: designing sustainable computer systems with an architectural carbon modeling tool, In *Proc. of 49th Annual International Symposium on Computer Architecture*, 2022,

pp. 784-799, https://doi.org/10.1145/3470496.3527408.

[21] Environmental impact of IT: desktops, laptops and screens, [Online], Available: https://www.it.ox.ac.uk/article/environment-and-it.

[22] Basha, A., Noçka, E., Kapaj, A., A global review of consumer behavior towards sustainability environmental and implications for the circular economy, *WSEAS Transactions on Computer Research*, Vol. 11, 2023, pp. 206-214.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.