IT for Future? Resource Consumption of Information Technology and Measures of Green IT

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***Abstract*—The Information and Communication Technology (ICT) sector is a significant global industry, and addressing climate change is of critical importance. This paper aims to assess the resources utilized by the ICT sector, the associated negative environmental impacts, and potential mitigation measures. In order to understand these aspects, this study attempts to categorize the resources used by ICT, analyze the amount consumed and the resulting negative impacts, and determine what measures exist to mitigate them. An economic and empirical evaluation shows a negative trend in ICT's resource consumption, mainly due to increased energy consumption and rising carbon emissions from devices such as smartphones and data centers. The investigated countermeasures focus on Green IT strategies that encompass energy efficiency, carbon awareness, and hardware efficiency principles as outlined by the Green Software Foundation. Special attention is given to reducing the environmental footprint of data center operations and smartphones. This paper concludes that Green IT strategies, although promising in theory, are often not implemented at an industry level.**

***Index Terms*—ICT Resource Consumption, Sustainable IT, Sustainable ICT Practices, Green Software, Green IT Strategies**

I. Introduction

In recent years, addressing the increasing challenge of climate change has become a global priority. This is shown by global initiatives like the United Nations Framework Convention on Climate Change and the resulting Paris Agreement, where 196 countries agreed to limit global warming to below 2 °C above pre-industrial levels, with a targeted goal of keeping the rise to 1.5 °C. The primary focus has been the reduction of Greenhouse Gas (GHG) emissions, which are responsible for global warming. To meet this critical target, global CO2 emissions caused by human activities must decrease by approximately 45% from 2010 levels by 2030 and achieve 'net-zero' emissions by 2050 [1]. The ICT sector is among the world's most significant industries and is expected to grow even further, surpassing a market size of five trillion dollars by 2024 [2]. Besides being a significant industry on its own, ICT also drives broader economic growth [3]. Concerning the increasing growth and influence on overall economic progress, an essential question arises: What is the effect of ICT on GHG emissions and, consequently, global warming?

The ICT sector offers opportunities to mitigate environmental impacts and decrease energy consumption through various mechanisms. These include dematerialization, illustrated by the transition to digital media; decarbonization, evident in enhanced industrial processes; and the promotion of demobilization with the rise of remote work and e-commerce [4]. Moreover, ICT fosters the integration of intelligent and AI-driven processes, such as efficient electricity management in buildings [5]. Conversely, the ICT sector itself accounts for substantial energy consumption. Evaluating this energy consumption requires a multifaceted approach. Beyond the immediate energy required to operate ICT devices, the energy involved in their manufacturing needs to be considered as well. Given the limited lifespan of certain ICT devices, coupled with their recycling or disposal, a significant amount of energy and resources are expended in the sector's production processes [6]. Furthermore, as ICT enables general economic growth, it is important to note that such growth often correlates with general increased energy consumption [7].

In an era where the digital footprint of society is expanding rapidly, the need to understand and mitigate the environmental impact of Information Technology (IT) is more pressing than ever. Considering both the positive and negative ecological aspects of the IT sector, it becomes crucial to understand how Green IT practices can be employed to reduce its environmental footprint in the future. As articulated by Verdecchia et al., "Green IT and green coding describe a paradigm switch in which software engineers, developers, testers, and IT administrators can make their solutions and services more energy efficient" [8].

With this background, this survey paper is divided into five chapters, each contributing to better understanding and response to the challenges and opportunities presented by IT in the context of environmental sustainability. Chapter II introduces a framework for categorizing IT resource consumption and the fundamentals of Green IT, setting the stage for a nuanced understanding of IT's ecological footprint. Chapter III offers a comprehensive analysis of current IT resource consumption, highlighting its environmental impacts and underscoring the urgency for change. Chapter IV transitions from analysis to action, exploring Green IT strategies aimed

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at minimizing the environmental footprint of IT operations. Chapter V the concluding chapter summarizes the key points and takeaways of this paper and presents ideas for future research. This paper aims to bridge the gap between current IT resource consumption trends and the potential of Green IT strategies, offering insights for more sustainable practices in the IT sector.

II. Taxonomy of IT Resource Consumption and Green IT

To effectively explore and evaluate Green IT measures, it is imperative to first establish a clear definition of Green IT. In the existing literature, a range of terms related to future-oriented IT have emerged, including Green IT, Green Information Systems (IS), and environmentally sustainable ICT. While there is no unified definition of Green IT, various interpretations have been proposed over time. This paper will primarily focus on Green IT, as defined by the prevailing literature, and will later distinguish it from related concepts like Green IS and environmentally sustainable ICT. Murugesan conceptualize Green IT as environmentally sound technologies and practices, highlighting its role in enhancing environmental sustainability through three key IT-enabled approaches [9]. This definition underscores the holistic integration of sustainability into IT systems and applications. In a similar vein, Bose et al. emphasize the efficient and cost-effective utilization of IT resources, pointing to the importance of energy conservation and economic viability in Green IT initiatives [10]. Molla et al. take a slightly different angle, focusing on the IT sector's internal activities and their impact on environmental efficiency, thus underlining the industry's responsibility in mitigating its ecological footprint [11]. Further evolving this concept, Cordero et al. articulate that Green IT contributes significantly to reducing the environmental impacts associated with conventional IT practices [12]. This perspective is echoed by Verdecchia et al., where the paradigm of Green IT and green coding is seen as a transformative approach to make software more energy-efficient [8].

Synthesizing these perspectives, Green IT represents an approach within the information technology sector, that encompasses efforts to enhance energy efficiency, reduce the ecological footprint of IT activities, and promote cost-effective and environmentally responsible solutions. It reflects a paradigm shift towards integrating sustainable practices across all aspects of IT, including hardware, software, and systems operations, guided by a commitment to reduce the environmental impacts of technology.

To effectively navigate the various terms related to future IT, it's essential to distinguish Green IT, Green IS, and environmentally sustainable ICT. Green IS, as Watson et al. note, uses information systems to achieve environmental objectives, extending beyond the IT sector and applying IT solutions for broader environmental sustainability [13]. Environmentally sustainable ICT as defined by Elliot is an integrative approach. It encompasses not only the non-harmful "design, production, operation, and disposal of ICT and ICT-enabled products" [14, p. 107] but also seeks their positive environmental impact throughout their life cycle [14]. In summary, while Green IT focuses on the internal sustainability of IT practices, Green IS applies IT for external environmental objectives, and environmentally sustainable ICT represents a comprehensive approach that encompasses both these aspects throughout the ICT life cycle.

In the field of ICT, resource consumption is a complex and multifaceted issue. To gain a better understanding of this landscape and for a later conducted assessment, this work classifies resources into two distinct categories based on their functional role: Operational and Manufacturing Resources. This categorization simplifies the understanding of resources by highlighting traits like:

- Operational Resources: Operational Resources, are essential and continuously consumed during the active use of ICT devices.
- Manufacturing Resources: Manufacturing Resources, are needed for initial ICT device production and characterized by one-time consumption.

Operational Resources are critical to the direct functioning of ICT systems, with energy being the most prominent. This energy is essential for the operation of various ICT devices, including servers in data centers, network equipment, and end-user devices [15]. Similarly, water is another operational resource that plays a significant role in sustaining the operational efficiency of ICT systems. A notable example is the utilization of water in data centers for cooling purposes, which is vital to prevent the overheating of equipment [16]. Within the scope of Manufacturing Resources for ICT systems, attention is primarily directed toward the materials vital for fabricating various components. This domain encompasses metals, rare earth elements, chemicals, solvents, and various types of plastics, crucial for manufacturing semiconductors, batteries, and display panels [17].

Given the critical importance of energy, which is always necessary for both operating and producing ICT devices, energy sources are categorized based on their GHG emissions and renewability. This categorization aids in understanding their impact on ecological sustainability. The three primary categories are:

- High Carbon Energy (Non-Renewable): This group includes energy generated from fossil fuels such as coal, oil, and natural gas, which produce significant amounts of carbon emissions. These sources are finite and do not regenerate in the foreseeable future, thus classifying them as non-renewable [18].
- Low Carbon Energy (Non-Renewable): Nuclear power is a technology that generates energy without emitting GHGs, but the production of nuclear fuel does result in some GHG emissions. It is important to note that it is non-renewable due to the non-renewable nuclear fuels used [18].
- Renewable Energy: This category includes energy sources such as solar, wind, and hydropower, which do not require

fossil fuels for energy production and thus emit no GHGs during the generation process. The only exception is biomass, which is also a renewable energy source but emits GHGs during energy production. However, it is considered to achieve a net-zero emission impact through its carbon-neutral cycle. [19].

It is important to note that this paper solely focuses on GHG emissions and water-related risks as negative impacts of energy generation. Embodied carbon, radiation, and other ecological impacts are not analyzed.

III. Resource Consumption in Information Technology

Prior to evaluating and presenting Green IT strategies to mitigate negative environmental impacts, it is necessary to analyze the quantity of resources IT consumes, how this consumption negatively impacts the environment, and if it is possible for IT to mitigate its negative effects sufficiently. The European Commission's Environmental Impact Assessment is an approach used to evaluate and mitigate the potential negative environmental impacts of a proposed project or development [20]. Chapter III and Chapter IV present a modified approach to environmental impact assessment, focusing on analyzing impacts and proposing countermeasures broadly within an industry, rather than concentrating on a single project. This approach offers a general overview instead of a detailed project-specific analysis or report [20].

Therefore, an analysis will be conducted from different perspectives: An economic perspective, which focuses on the overall impact of ICT on the economy and thus on the environment, and an empirical-ecological perspective, which concentrates on specific amounts of emissions produced, resources consumed, and possible negative effects on the environment.

A. Economic Perspective

Lange et al. explored in their paper the connection between digitalization and environmental sustainability [7]. The article focuses on the effects of digitalization on energy consumption and, as a result, environmental sustainability, with a particular focus on the decoupling of economic growth and energy consumption. The research examines four critical effects:

- (I) Energy consumption of the ICT sector: The first effect reveals an increasing economic role of ICT in global GDP, stock markets, and investments, contributing to economic growth. This growth is driving a general upward trend in economic indicators of the ICT sector, including energy consumption, production, and physical capital. The effect additionally highlights significant improvements in energy efficiency at several levels, such as processors, energy consumption per data transmission, and data centers in ICT, but these improvements are not strong enough to achieve an absolute reduction in energy consumption.
- (II) Energy efficiency and rebound effects: ICT leads to improved energy efficiency in other sectors, for example by allowing simulation of production processes or enabling intelligent distribution of products. In theory, this approach saves energy, but in practice, it creates a rebound effect, which leads to behavior that mitigates the positive effects.
- (III) Digital growth cycle or digital stagnation?: This effect suggests that digitalization has a positive effect on economic growth and energy consumption.
- (IV) Sectoral change: The last effect cannot clarify whether the ICT sector leads to a tertiarization across other sectors or not, but it suggests that the current development within the sector itself encourages a tertiarization in the ICT sector while preserving the first two sectors in terms of ICT at the same size. Additionally, it highlights the problem that digital services are more energy-intensive than services from the other industrial sectors.

The four effects combined are highlighting an important finding: Digitalization in general does not reduce energy consumption; instead, it leads to increased energy consumption. It is important to note that the effects do not solely focus on ICT. Digitalization covers the entire economy, which falls beyond the scope of Green IT's definition. Therefore, some negative effects are only mitigatable by Green IT and Green IS together. Since this paper focuses purely on Green IT measures, only ICT sector-related effects are mitigatable. Effects I and IV indicate that, despite the ICT sector energy efficiency improvements, consumption is at best stable or increasing, and digital services are more energy intensive than other services. Effects II and III focus on economic growth, which digitalization causes. General economic growth leads to growth in the ICT sector as well [7].

These findings lead to a conclusion regarding Green IT measures and energy consumption. There is a need for enhancements in energy efficiency. From this conclusion arises the question of where to direct the energy-efficiency improvements. This question can be answered through the examination of empirical findings and forecasts about resource usage in the ICT sector. As a result, specific sectors or components within the ICT landscape that contribute significantly to energy consumption and offer potential for optimization can be identified. Before evaluating where to direct energy efficiency improvements and possibly other resource efficiency improving techniques, it needs to be evaluated what effect the types of resource consumption have on the environment. As suggested in Chapter II, there are two types of resources. For the simplicity of this paper, the focus lies on Operational Resources, because the processing chain and the possible environmental impact would be too complex to evaluate in the scope of this work.

B. Empirical Perspective

1) Water: The Operational Resource water, as highlighted by Mytton, is used in data centers both directly in cooling systems such as chillers and towers, and indirectly through the water-intensive power generation required for electricity. Power generation methods consuming significant amounts of water include hydropower, which involves water evaporation from reservoirs, and thermoelectric power plants, often fueled by fossil fuels and including nuclear power, that use water for cooling and steam production. The use of potable water, which constitutes up to 57% of the water used in some data centers, is particularly concerning in regions with water scarcity, as it can strain local drinking water supplies and impact both ecosystems and human communities [16]. Similar issues arise in the manufacturing of ICT components, where the excessive use of potable water can lead to environmental stress in areas where water is a scarce resource [21] [22]. This underscores the importance of responsible water management in data center operations and the ICT manufacturing sector.

2) Fossil Fuels: According to Statista, over 60% of the energy produced worldwide is generated using fossil fuels [23]. Energy generation with fossil fuels causes negative impacts on the environment, such as air pollution, and supports the greenhouse effect [24]. This further applies to fossil fuels used during manufacturing processes. Gases included in GHG emissions are Carbon Dioxide (CO2), Methane (CH4), Nitrous Oxide (N2O), and fluorinated gases. When entering the earth's atmosphere, these gases contribute to the greenhouse effect. The greenhouse effect, which is a natural process that heats the earth's surface, is disturbed by the release of too many GHG emissions and deforestation, causing the earth's average temperature to rise. This change in the earth's temperature can lead to various environmental impacts, such as extreme weather events, rising sea levels, and changes in wildlife habitats [25].

So in addition to looking at the raw energy consumption alone, it is useful to look at the carbon emissions caused by ICT. The benefit of this perspective is that while looking at the energy consumption of ICT, it is not clear whether the energy has high-carbon intensity, low-carbon intensity energy, or is renewable. Therefore, making a reliable statement about energy usage requires additional research about the generation method. Further, by investigating carbon emissions, it is possible to not only include emissions that arise during operation but also embodied emissions, which are emissions that arise during the manufacturing of components.

3) The Carbon Footprint of the ICT Industry: In their paper, Belkhir et al. assessed the global carbon footprint of the ICT industry [6]. The study investigates three ICT device categories: electronic devices (PCs, displays, and handheld devices), data center infrastructure (servers, communications equipment, storage, and cooling systems), communications networks (customer premises equipment, office networks, and telecommunications operating networks). To evaluate the carbon footprint, the authors used the concept of the Life Cycle Annual Footprint (LAF), which aims to evaluate the overall impact of a product throughout its entire lifespan. It is based on Life Cycle Analysis (LCA), which covers raw material extraction, manufacturing, transportation, usage, and disposal or recycling. LAF is calculated by adding the Use Phase Energy (UPE) to the quotient of Production Energy (PE) and Useful Life (UL). UPE refers to the energy consumed during operation and maintenance, while PE encompasses the energy used for manufacturing and raw material processing, and UL is the period during which a product effectively performs its intended function.

To accurately assess the total carbon emissions of the products, the authors estimated the annual life cycle footprint of each electronic device. They then assessed the number of units in use and repeated the process for data center and communication network components. The data utilized for this assessment consists of both actual data and projections spanning from 2007 to 2020. The authors obtained three main results from this assessment.

The ICT global footprint was projected relative to the total global footprint in the range of 2007 to 2020 to rise from 1% - 1.6% to 3% - 3.6%. Following this short projection, which indicates a continuous rise in ICT's GHG share, the authors projected the ICT footprint to the year 2040 with two fits. They used a linear model and an exponential model, but stated that the exponential model is a more realistic fit. The estimate is a share of 14% of the worldwide footprint at the 2016 level. These results indicate that in order for ICT to help reach the climate goals, the current trend needs to be inverted or at least stopped. The last results show the contributions by category for 2010 and 2020, providing indicators for Green IT measures to focus on. In 2010 and 2020, data centers and communication networks were the major contributors to the ICT sector's GHGE footprint. During this period, emissions from desktop computers sharply declined, while communication networks experienced a slight decrease. In contrast, emissions from data centers and smartphones increased, accounting for 45% and 11% of the carbon footprint, respectively, while emissions from other devices remained relatively stable [6].

Based on these findings, it can be concluded that for this paper, Green IT measures should primarily target data centers due to their centralized nature and control by a single group of developers. This focus is beneficial because data centers concentrate devices in one location, unlike communications networks and other electronic devices such as smartphones, which are widely distributed.

4) Characteristics of Data Center Workload: To effectively implement Green IT measures in data centers, it is beneficial to identify the characteristics of these workloads. These traits with regard to data center infrastructure utilization are particularly interesting for Green IT measures. This allows for a better understanding of which types of workloads will be most affected by the Green IT measures presented in the next chapter, or conversely, which ones may not see a significant impact. Wiesner et al. identified the following data center workloads traits [26]:

- Duration:
  - Short-Running Workloads: These workloads typically last only a few minutes [26].
  - Long-Running Workloads: Long-running workloads in computing refer to tasks that have extended run times, often spanning several days. These types of

  tasks, include machine learning training, scientific simulations, and big data analysis jobs [26].
  - Continuously running workloads in data center environments are designed to operate indefinitely and cannot be interrupted. These include user-facing APIs, real-time analytics, and long-running scientific simulations [26].
- Execution Time:
  - Ad Hoc Workloads: Ad hoc workloads in computing environments encompass tasks that are initiated on an unpredictable basis. Although it may be possible to anticipate patterns in these workloads through time series forecasting, the exact timing of specific jobs, such as CI/CD runs and machine learning training, remains uncertain until triggered by external events or user requests [26].
  - Scheduled Workloads: Scheduled workloads are pre-planned tasks set to run at specific future times, often on a recurring basis, like nightly tests and periodic backups [26].
- Instance Sizing: Data center workloads require different levels of computing resources. Cloud providers offer a diverse range of instance sizes to meet the varying needs of data center workloads. These sizes range from smaller instances that deliver limited computational resources to larger instances designed to provide substantial computational capacity [27].

In this chapter, the effects of ICT on energy consumption were clarified. Following an examination of the negative impact of ICT, resource consumption was narrowed down to carbon emissions produced by ICT devices, with data centers and communication networks identified as the primary sources of carbon emissions.

IV. Green IT Strategies to Mitigate Negative Environmental Impacts

In light of the preceding chapter, it is evident that the ICT industry needs to reduce its negative environmental impact. This goal can be achieved by minimizing resource consumption that exerts a harmful environmental influence. Substituting environmentally harmful resources with neutral alternatives, such as replacing potable water with seawater or high-carbon energy sources with low-carbon alternatives, can significantly contribute to this effort. Additionally, promoting behaviors that lead to lower resource usage can be beneficial. Chapter III provides an analysis of the negative impacts of the ICT industry on the environment. Based on this foundation, the following chapter presents an organization that promotes sustainable software, before introducing several strategies aimed at reducing the negative impacts. In addition to presenting each strategy, limitations, or conditions that may affect its applicability are noted. To provide a clear overview of the strategies presented in the following sections, the specific impacts they address, the scope of each strategy, and their respective sources are listed in Table I.

A. Green Software Foundation

One effective way to promote something widely is through an organization. The Green Software Foundation is an institution with the mission to "[build] a trusted ecosystem of people, standards, tooling, and best practices for creating and building green software" [28]. The foundation aims to promote environmentally sustainable software through the promotion of the term 'Green Software', which is defined as software designed to minimize carbon emissions as much as possible. The foundation states three activities that can reduce carbon emissions from software: energy efficiency, carbon awareness, and hardware efficiency [28].

Energy Efficiency: This principle aims to reduce electricity consumption and, as a result, carbon emissions in software development. It encourages the creation of energy-efficient software throughout its life cycle, from design to end-user interaction. It further emphasizes that energy usage is just one aspect of the solution. Additional considerations should also be given to the energy efficiency of the infrastructure and the concept of energy proportionality, which argues that hardware is more efficient per operation the more it is utilized [29].

Carbon Awareness: This principle emphasizes the importance of understanding and adapting to the varying carbon intensity of electricity. Carbon intensity refers to the amount of carbon emissions produced per unit of electricity generated. It varies depending on how the energy is generated. This further depends on time and location, especially for renewable sources like solar and wind, which are dependent on the weather and the day and night cycles. The principle proposes to shift or shape the demand depending on the energy carbon intensity to regions or to periods with low carbon intensity [30].

Hardware Efficiency: This principle focuses on using as little embodied carbon as possible and emphasizes the consideration of the total carbon footprint associated with the hardware used in software development and operation. This encompasses, in addition, hardware operation, its creation, and its disposal. It further highlights the life span of hardware and, as already mentioned in the energy efficiency principle, the utilization of hardware [31].

B. Strategies for implementing the three principles of green software development

The following section is divided into three parts. One for each activity presented by the Green Software foundation aimed at reducing carbon emissions.

1) Energy Efficiency: Minimizing Electricity Usage: The Energy Efficiency principle primarily advocates for awareness by highlighting concepts such as power usage efficiency in cloud environments or energy proportionality. While this is helpful in developing green software, it is not sufficient to cover the entire software development life cycle [29].

Mahmoud et al. proposed a green software model that supports the development of green software. The model consists of two levels. The first level is a green software engineering process that can be used to develop sustainable software products, and the second level discusses software tools that assist in the energy-efficient use of software applications. The authors start their model presentation by identifying the requirements and testing stages of the software life cycle as missing in previous models, despite their significant impact on the environment. A nine-stage model is proposed, with suggested metrics for each stage. The stages include requirements, design, unit testing, implementation, system testing, green analysis, usage, maintenance, and disposal [32]. An iterative approach, influenced by sequential models and agile principles, is used to connect the stages and build a process. The aim is to reduce the risk of project failure and eliminate negative environmental traits, such as incremental delivery, which can hinder later changes in the project's requirements. By incorporating agile principles, changes are allowed even late in the development process, which may support the environmental sustainability of the developed software [32]. The agile elements of the process allow for restarting at the requirements stage and adding further improvements to the software product during unit testing, system testing, green analysis, and maintenance stages. Additionally, the involvement of stakeholders in the process helps prevent undesirable developments in the software. The authors further described every stage in detail, highlighting the environmental benefits [32].

The second level of the model introduces software tools that aid in the energy-efficient use of software applications. This level aligns with the ideas presented in the energy efficiency principle, emphasizing the importance of minimizing quantifiable values. The paper proposes the five categories "operating systems frameworks, fine-grained green computing, performance monitoring counters and metrics, codes written for energy allocation purposes, and virtualization" [32, p. 67]. The first three categories in the listing focus on monitoring, evaluating systems, and reducing hardware component activations. Category four suggests redirecting traffic to areas with lower energy costs. This is discussed in a modified form in the Carbon Awareness subsection. Category five recommends the use of virtualization to deploy multiple applications on a single system [32].

These categories are well-formulated, but they may need to be reevaluated due to changes in the software development and deployment landscape. Especially the first three categories should be reevaluated in light of new virtualization concepts, cloud computing, and microservices. The virtualization category is already in use and has been further developed into containers, which are currently an industry standard.

The authors present metrics for monitoring the application life cycle, Key Performance Indicators (KPI), which define efforts needed to redesign and develop software and to configure the infrastructure. The Green Performance Indicators (GPIs) for Energy Impact are used to measure the environmental footprint of data centers. Organizational GPIs also assess aspects such as the Return of Green Investment, which determines how long it takes for a Green IT solution to become financially beneficial [32].

The paper presented lays a solid foundation for minimizing the power consumption not only of the software itself but of the entire software development lifecycle, some aspects of which will be discussed later in this paper. The model combines aspects of different software development approaches and explains each stage in detail. This makes the first level of the model suitable for use in the IT industry. This is supported by presenting metrics to monitor the software development life cycle from different perspectives [32].

Level two of the model may need to be reevaluated due to changes in the IT development landscape. Additionally, it would be beneficial to not only present the model theoretically but also to evaluate it quantitatively against a non Green IT focused model and in a real-world environment.

In addition to pursuing energy efficiency in general software development, another important focus should be on specialized applications, such as those in data science and Artificial Intelligence (AI), which intersect and overlap in their functionalities and goals. Machine learning models, such as those used for image recognition, natural language processing, and predictive analytics, often require large amounts of computing power. Operating these models involves processing large amounts of data, which is very energy-intensive [33].

An approach to reduce energy consumption, is Energy-Aware Training proposed by Lazzaro et al. in their paper "Minimizing Energy Consumption of Deep Learning Models by Energy-Aware Training". The proposed training algorithm relies on the zero-skipping strategy used by sparsity-based Application-Specific Integrated Circuit (ASIC) accelerators. These hardware components are designed to skip multiplications when the activation input of a neuron is zero. This results in increased throughput and reduced energy consumption. The algorithm aims to reduce the amount of neuron activation while maintaining model accuracy. To verify the proposed algorithm, the authors conducted an experiment and compared it against standard empirical-risk minimization training on three different data sets. The results showed an up to 27% decreased number of operations during inference. The authors conclude their paper by stating its direct applicability to real-world scenarios [34].

2) Carbon Awareness: Adapting to Clean and Dirty Energy Sources: The Carbon Awareness principle identified demand shifting and demand shaping as possible solutions [30]. To enable this solution, workloads should be scalable, flexible, and available on-demand, anywhere in the world. This requires certain characteristics for the deployment environment.

The use of virtualization and container technologies has been crucial in achieving these traits. Virtualization enables the operation of multiple Virtual Machines (VMs) on a single physical machine, improving resource utilization. Containers, which share the host system's kernel and include only the application and its minimal requirements, offer faster startup times and improved scalability [35]. This technology is used by cloud providers to offer a range of services, including computing power, storage, and networking capabilities, all accessible over the internet. These resources offer the mentioned traits scalability, flexibility, and on-demand availability to the users [36].

An example in software development is the microservice architecture, which inherently supports scalability and flexibility. Unlike traditional monolithic application structures, microservices involve decomposing an application into smaller, independent services. This approach is well-suited for demand shifting and demand shaping [37]. Container orchestration systems, such as Kubernetes, have become essential for managing these microservices by automating the deployment, scaling, and operation of workloads across infrastructure clusters. These advancements highlight the essential nature of scalability, flexibility, and on-demand availability in today's dynamic computing landscape [38].

Several approaches were made to design and implement a scheduler that shifts the workload spatially or temporally based on carbon intensity in energy production. James et al. proposed the design and implementation of a low-carbon Kubernetes scheduler that focuses on demand-side management with a focus on spatial workload shifting. The proposed solution is able to identify the best region for workload scheduling based on Diffuse Horizontal Irradiance (DHI) data, which refers to the amount of solar radiation received per unit area by a surface that does not directly face the sun, and reschedule existing workloads to the identified region. The functionality was further extended to operate based on a wind model instead of DHI. The authors identified a limitation of their scheduler: It is only reliable for workloads that do not involve substantial data transport during migration [39].

Although the authors already mentioned some drawbacks of the proposed solution, it is important to note that the implementation is currently only a prototype and may require further refinement before being applied in a real-world scenario.

Another solution is the temporal shifting of workloads. A naive approach to this is to completely turn off the temporal shiftable workload during carbon-intensive times [26]. Hanafy et al. identified two drawbacks to this solution [40]. Firstly, due to the slowly changing carbon intensity, the pause time may be indefinite. Secondly, some workloads cannot be flexibly suspended for an arbitrary amount of time. The authors proposed a self-developed prototype of software based on autoscaling. Autoscaling is a key feature in cloud environments, allowing the automatic adjustment of resources to meet demand, improving efficiency, and ensuring application performance. There are two types of autoscaling: horizontal and vertical. Horizontal autoscaling adjusts the number of instances, such as containers or VMs, in response to demand, while vertical autoscaling adjusts the resources, such as CPU and memory, of existing instances. The carbon-aware scheduler proposed in the paper scales the workload according to both the current carbon intensity and workload scalability behavior, rather than simply suspending it. The developed prototype was able to achieve a 51% reduction in carbon savings compared to scheduling that ignores carbon intensity and a 37% reduction compared to suspend-resume execution [40].

An already existing production-ready solution is the Carbon Aware Kubernetes Event-Driven Autoscaling (KEDA) Operator. It works on top of KEDA and extends Kubernetes' capabilities to event-driven autoscaling. This allows applications to scale based on events from various sources, such as queues and databases. The Carbon Aware KEDA Operator enables temporal shifting within a Kubernetes cluster. Its goal is to optimize resource usage for performance, cost, and carbon footprint reduction. To achieve this, the operator uses the Kubernetes Carbon Intensity Exporter, which uses the Green Software Carbon Aware Software Development Kit (SDK) to retrieve a score-based forecast of carbon intensity for the next 24 hours. The KEDA operator scales workloads up or down, reducing power consumption during carbon-intensive periods and, therefore, carbon emissions [41].

Gebrewald assessed the Carbon Aware KEDA operator, with a specific focus on response times, for microservice-based web application workloads. The main goal was to identify how much to scale these based on carbon intensity. The author conducted a comparison between the Carbon Aware Operator and a Horizontal Pod Autoscaler (HPA), which is a Kubernetes feature that automatically adjusts the number of pods in a deployment based on selected metrics. The thesis found that the Carbon Aware Operator is highly cost-efficient, making it suitable for large clusters. Additionally, the Carbon Aware Autoscaler outperforms the HPA in terms of environmental sustainability. This finding also applies to microservices with heavy workloads, leading to a recommendation to use the KEDA autoscaler for workloads that do not demand real-time handling, like batch processing or the training of AI models [42].

The Carbon Aware KEDA Operator implements temporal shifting as an enterprise-grade solution. To use this technology in a real-world scenario, technical and operational expertise in cloud computing is required, as is a Kubernetes deployment environment that utilizes the KEDA software.

Continuous Integration and Continuous Delivery (CI/CD) pipelines are another location where jobs are scheduled during the software development life cycle. CI/CD is a methodology that focuses on frequent, automated integration of code changes and consistent, automated delivery of software. These practices are typically located in the middle stages of the software development life cycle, between coding and delivery to production. CI/CD involves several tasks, including testing, building, and delivery, resulting in a more efficient and error-free software delivery process.

In their recent paper, Claßen et al. identified CI/CD as a field for introducing Carbon-Awareness. Their approach is similar to the previously discussed methods. The core idea is to identify suitable CI/CD workflows for carbon-aware scheduling and shift them spatially or temporally. The authors determined three promising workflows. Periodic jobs, such as nightly builds, can be scheduled flexibly. Interdependent jobs with varying durations, where historical data can help to schedule the workload flexible. Unnecessary jobs can be eliminated, thus reducing emissions entirely. The paper describes an architecture consisting of two processes: a preprocessor and a carbon-aware scheduler. The preprocessor eliminates jobs that are not schedulable or do not benefit from carbon-aware scheduling. If a job is classified as carbon-aware schedulable, it is rescheduled to another time or location based on carbon intensity data from an API. To verify the architecture, the authors evaluated their prototype against scraped historic workflow executions from GitHub Actions. They compared a round-robin approach as a baseline and location shifting with a time shift of one, three, and six hours. The results showed up to 31.2% relative improvement in relative carbon emissions. Although the results appear promising, the authors also note that certain assumptions were made during the experimentation process to simplify the evaluation, which might conflict with real-world environments. Thus, they acknowledge that the results may deviate in real-world scenarios and plan to conduct future tests in larger companies [43].

3) Hardware Efficiency: Reducing Embodied Carbon: The Hardware Efficiency principle aims to minimize embodied carbon. The Green Software Foundation proposes two solutions to achieve this. For cloud computing, it suggests increasing hardware utilization, while for end-user devices, it recommends extending hardware lifespan. One way to increase hardware utilization is to migrate from private infrastructure to the cloud. Private infrastructure must account for peak workloads, resulting in idle running hardware during non-peak times [31].

Zheng et al. evaluated the energy savings achievable by migrating workloads to the cloud [44]. They proposed a three-step migration process from Traditional Data Centers (TDCs) to Cloud Service Providers (CSPs). The first step is a Lift-and-Shift migration, which involves moving applications and workloads from an on-premises environment to the cloud without redesigning the application or infrastructure. The second step involves optimizing instance sizing, followed by an application rewrite. To demonstrate potential energy savings, the authors evaluated a dataset of 40,000 machines across approximately 300 data centers. The evaluation identified four sources of energy savings. The Lift-and-Shift migration takes advantage of the more efficient data centers of the CPSs. CSPs typically update their hardware more frequently than traditional data centers. This updated hardware, which includes computational components like CPUs as well as support systems such as cooling and lighting devices, is generally more energy-efficient than older hardware. The support hardware contributes only a small amount of energy savings. The majority of energy savings come from using more efficient CPUs and optimizing instance sizing [44].

Finally, the authors evaluated the potential energy savings of auto-scaling, but concluded that their model has limitations and cannot provide an exact factor of energy savings. However, they found that rewriting applications is likely to result in significant energy savings. The whole evaluation resulted in an estimated energy saving factor ranging from 4.5 to 7.8. The authors state that the initial two stages of their migration process can be completed almost automatically. The paper demonstrates that a cloud migration can lead to energy savings even without rewriting the application and infrastructure. This contradicts the common misconception that a cloud migration only saves energy if the application and infrastructure are rewritten [44].

To execute this strategy, technical and operational expertise in regard to cloud computing is necessary. It is also important to note that the proposed migration process becomes more complex with each step.

The proposed solution to reduce the embodied carbon emissions of end-user devices is to extend their lifetime. The end-user devices identified in Chapter III as being on the rise and responsible for the most carbon emissions are smartphones.

One strategy to extend their lifetime is refurbishment. Refurbishment is the process of cleaning, repairing, and updating used products, such as electronics, to restore them to good working condition. This is done to extend their lifespan and minimize waste. This process is already widely used for smartphones and is offered by both smartphone manufacturers and third-party companies. Refurbishing smartphones can significantly extend their lifespan and reduce the environmental impact of the disposal process. This is achieved by delaying their entry into landfills, where they can release harmful chemicals, and by reducing pollution arising from improper recycling techniques. Additionally, the attractive prices of refurbished smartphones can appeal to cost-conscious consumers, potentially reducing the demand for new devices and associated GHG emissions from their production [45].

One major drawback of this strategy is the quality of the refurbished smartphones, which is highly dependent on the refurbishment company. A case study on this topic revealed a lack of transparency in the refurbishment process, particularly when third-party companies are involved. The authors of the case study recommend creating new standards that address best practices for refurbishment. They highlight the need to collect and evaluate operating condition data throughout the lifespan. This data, combined with test data, can be used to predict the reliability of refurbished smartphones. These improvements to the refurbishment process could increase the refurbishment rate and reduce the negative environmental impact [45].

The previous approach extends the lifespan of an end-user device by passing it on to another end-user. In contrast, Switzer et al. investigated the feasibility of using discarded smartphones as computing resources for a smartphone cluster for microservices, which has the potential to replace small cloud computing clusters. Modern smartphones are comparable to or exceed the computational power provided by a microservice instance, making them a viable alternative in terms of computational power. The authors quantified the carbon emissions per unit of computation work and introduced a new metric, Computational Carbon Intensity (CCI), to benchmark this. The results show that when comparing reused smartphones to laptops and servers, smartphones have the lowest carbon emissions per unit of work and outperform a new server [46].

The authors further outlined possible problems in regard to cooling and networking of smartphones and how to work with them and highlighted the potential for carbon-aware charging due to the built-in batteries in smartphones, which

Strategy	Impact Counteracted	Scope	Source
Green Software Development Model	Operational Resource Consumption GHG emissions ↘	Area: Data center Application Level: Workload in general Traits: All traits	[32]
Energy Efficient AI Model Training	Operational Resource Consumption GHG emissions ↘	Area: Data center Application Level: Workload (AI Models during inference time) Traits: Short-running, ad-hoc	[34]
Migration to cloud	Operational Resource Consumption GHG emissions ↘	Area: Data center Application Level: Workload in general Traits: All traits	[44]
Smartphone Refurbishment	Manufacturing Resource Consumption	Consumer	[45]
Junkyard Computer	Operational Resource Consumption Manufacturing Resource Consumption GHG emissions ↘	Area: Data center Application Level: Workload outsourceable to small clusters Traits: Short-Running, long-Running, ad-Hoc, small instances	[46]
Carbon Aware Scaling (Spatial, Temporal)	Operational Resource Consumption GHG emissions ↘	Area: Data center Application Level: Workload that can be shifted Traits: Short-Running, long-Running, scheduled, regardless of instance sizing	[39] [40] [41] [42]
Carbon Aware Scaling CI/CD	Operational Resource Consumption GHG emissions ↘	Area: Data center Application Level: Workload (CI/CD Jobs) Traits: Short-Running, long-Running, scheduled, regardless of instance sizing	[43]

TABLE I
OVERVIEW OF GREEN IT STRATEGIES TO MITIGATE NEGATIVE ENVIRONMENTAL IMPACTS

allow charging during periods of lower carbon intensity. To further evaluate the possibility of building a smartphone cluster from smartphones, the authors build a small cluster and run a benchmark application on it and compare it to a cloud instance. The results of the benchmark indicate that a smartphone cluster is more carbon efficient than the cloud instance [46].

Although this approach shows potential environmental benefits, further refinement is necessary before large-scale adoption can be considered. One reason for this is the small scale of the experiment conducted by the authors, which does not ensure scalability. Another drawback is the lack of evaluation of enterprise-grade standards such as regulatory compliance, data security, and service level agreements.

V. CONCLUSION

The main objective of this paper is to assess the resource consumption of IT and the resulting environmental impact, as well as possible Green IT measures to prevent a negative environmental impact. Green IT focuses on integrating sustainability within the IT sector to improve energy efficiency, reduce environmental impact. It is distinct from Green IS, which concentrates on using IT to improve environmental sustainability in other sectors. An economic and empirical evaluation indicates a negative trend in ICT resource consumption. The economic evaluation shows some positive aspects, but they tend to fall outside the scope of Green IT, and the main effect is an absolute increase in energy consumption. This negative trend is further supported by the empirical analysis, which shows an increasing trend in carbon emissions from ICT devices. Data centers and smartphones have shown a negative trend, providing insight into where to focus Green IT measures. In response to these trends, Green IT measures were evaluated based on the Green Software Foundation principles, which were divided into three directions. The evaluation indicates that strategies exist for every principle. The measures found focus on energy-efficient development, hardware re-use, and various deployment measures, leading to a broad spectrum of strategies for mitigating negative environmental impacts. Green IT is a broad field that covers resource extraction, hardware production, and usage, as well as theoretical aspects such as IT's impact on economic growth and energy consumption. However, comprehensively analyzing and evaluating every influence from one aspect to another within a single study is challenging due to the complexity of the subject. This complexity is a significant limitation, as it makes it difficult to fully understand the interconnections and impacts across the entire IT lifecycle. Although strategies to reduce the negative environmental impact of IT have been proposed and theoretically established, observed trends indicate an increase in its impact. This contradiction may be due to the fact that most of these strategies remain in theoretical stages or are only implemented as prototypes, lacking the development and refinement needed for industry-grade solutions. Future research should aim to address this gap by investigating what is needed for the industry to adopt Green IT measures effectively. A holistic research approach that combines insights from IT, environmental science, and socioeconomics may be necessary. Conducting a survey paper in this direction could be a strategic starting point, offering an overview of current practices, challenges, and needs from various industry stakeholders. The research findings can bridge the gap between academia and industry by translating theoretical measures into practical ones. This research could contribute to making the adoption of Green IT measures more attractive and feasible, leading to a more sustainable and environmentally conscious IT industry in the future.

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