POLITECNICO DI TORINO

Master's Degree in Electronic Engineering

Master's Degree Thesis

Life Cycle Assessment Of Electronic Devices

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To My Mother
& To My Father

Summary

Life Cycle Assessment (LCA) and green electronic design presents a development strategy in the manufacturing of sustainable electronics. As resources get depleted, pollutants continue to be discharged, energy usage increases and global warming becomes a major menace, and LCA gives a methodical structure to study total environmental implications within the life cycle of the product from its extraction to end-of-life management. This thesis provides a comprehensive Lifecycle Assessment (LCA) of electronic devices to assess their environmental consequences and pinpoint potential for sustainable enhancement. The research complies with ISO 14040 and ISO 14044 standards, highlighting the essential stages of Life Cycle Assessment. The research commences with a comprehensive examination of the historical development of LCA, its techniques, and its significance within the electronics industry. A comprehensive literature study identifies the key problems in implementing Life Cycle Assessment (LCA) for electronics, such as intricate product compositions, restricted data accessibility, and the energy-demanding processes involved in semiconductor manufacturing. The study emphasises low-power design strategies as a primary tool for mitigating environmental effect. Both static and dynamic power reduction techniques are analysed, along with cross-layer optimisation strategies and the associated trade-offs in power management. Additionally, the thesis presents the Design for 3R (Reduce, Repair, Refurbish) paradigm and examines eco-design practices. To enhance the environmental performance of device fabrication, this work also explores the substitution of conventional dielectric materials (e.g., SiO_2) with low-temperature, high-κ alternatives such as Ta_2O_5. The chapter on data interpretation and analysis examines power dissipation and corresponding CO_2 emissions across several CMOS technology nodes, incorporating region-specific emission variables to evaluate operational and manufacturing effects. The findings indicate that technological scaling improves device efficiency but increases leakage currents and energy consumption in advanced nodes. Thus, power-conscious design and sustainable manufacturing are essential. This study promotes green electronics by supporting a lifecycle-oriented approach to sustainable design and policy by supporting a lifecycle-oriented approach to sustainable design and policy.

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"It always seems impossible until it is done."
[Nelson Mandela]

Chapter 1

Introduction

1.1 Overview

Accelerated advancement of technology innovation has seen the proliferation of electronic devices at the center of modern life. However, this upsurge in electronic consumption has raised concerns over the impact it makes on the environment, especially in terms of resource depletion, energy consumption, and waste generation. Conventional product design methodologies often neglect the comprehensive environmental expenses linked to the life cycle of a good, from initial resource exploitation to the final stages of waste [1]. "Life Cycle Assessment (LCA)" is a useful tool that may guide the development of an eco-friendly electronic device in assessing ecofriendly impacts at every stage of the LC of a product [2]. Having integrated LCA into the design stage allows manufacturers to have knowledge of areas of improvement and decrease the rate of waste, optimize the consumption of energy, minimize ecological damage, and hence allow the development of more sustainable electronics [3]. Through such integration, sustainability becomes more of a holistic process to the development of electronic products than an afterthought of manufacturing electronics.

LCA is a methodical approach for evaluating the ecological effect of a product or process across its entire lifecycle, including all phases from raw material exploitation to manufacture, distribution, utilization, and destruction [4]. With an examination of these phases, LCA identifies critical points where improvement can be made like the carbon footprint of a production process or using recyclable materials [5]. For electronic devices, LCA can help reduce manufacturers in terms of using rare or toxic material, energy efficiency in producing the product as well as at usage and easy disassembling and recyclability. For instance, a life cycle analysis might indicate that the environmental impact of a device is mainly due to energy-intensive manufacturing processes or non-recyclable components, and thus there would be design changes to decrease energy consumption or increase recyclability [6]. Therefore, LCA offers manufacturers a powerful tool to make decisions that can reduce the environmental burden of electronic devices.

Integration of LCA in the design phase not only advantages for the planet but also helps business. As consumer awareness increases regarding environmental concerns, so does the demand for environmentally friendly products, and electronic products are on that list. Adopting environmental design practices guided by LCA increases a firm's reputation, allows a firm to stay ahead of regulation requirements, and differentiate a product in an increasingly competitive marketplace [7]. This would also help reduce costs since LCA identifies the inefficiencies of the production process and cuts down on waste. For instance, the choice of material that requires less energy for production or the designing of a product that requires less resource utilization may reduce manufacturing costs [8]. Besides, LCA can encourage innovation because of new materials, technologies, and manufacturing processes being developed. Ultimately, the integration of LCA into the design of electronic devices provides a pathway for achieving both environmental sustainability and business success, ensuring that the future of electronics is both technologically advanced and environmentally responsible.

1.2 History of LCA

Life Cycle Assessment (LCA) is a methodical approach to verifying environmental concerns regarding items, measures and services that has existed for quite a while. It was not originally considered a contemporary topic, but its origins date back to the 1960s when resource depletion was a cause for concern and therefore environmental degradation ensued. LCA has evolved from being at the level of an informal analytical tool to become a norm methodology addressing among others energy consumption, material, emissions, and overall sustainability performance. This has been backed by enhanced knowledge regarding the environment and the need for fact-based decision-making of industrial and policy segments where the evolution of this methodology has been the key discrimination against environmental concerns.
It is possible to divide the evolution of LCA into four stages in which the most important paradigm breaks were the developments in methodology, scope, and regulatory systems. The first LCA was concerned with the efficiency in use of resources and energy which was subsequently approved as a product standard of the 1990s [9]. Then, during the final 2000s, the project was structured to develop more, becoming other operational carbon footprint, biodiversity effects, and the economic factors were incorporated as well. On the digitalization, artificial intelligence, and standard policies, since the most significant conditions that are at the speeding end of the LCA, sustainability is one of those needs to be evaluated. The improvement of LCA with data science and automation will be a key driver for dissemination across sectors.

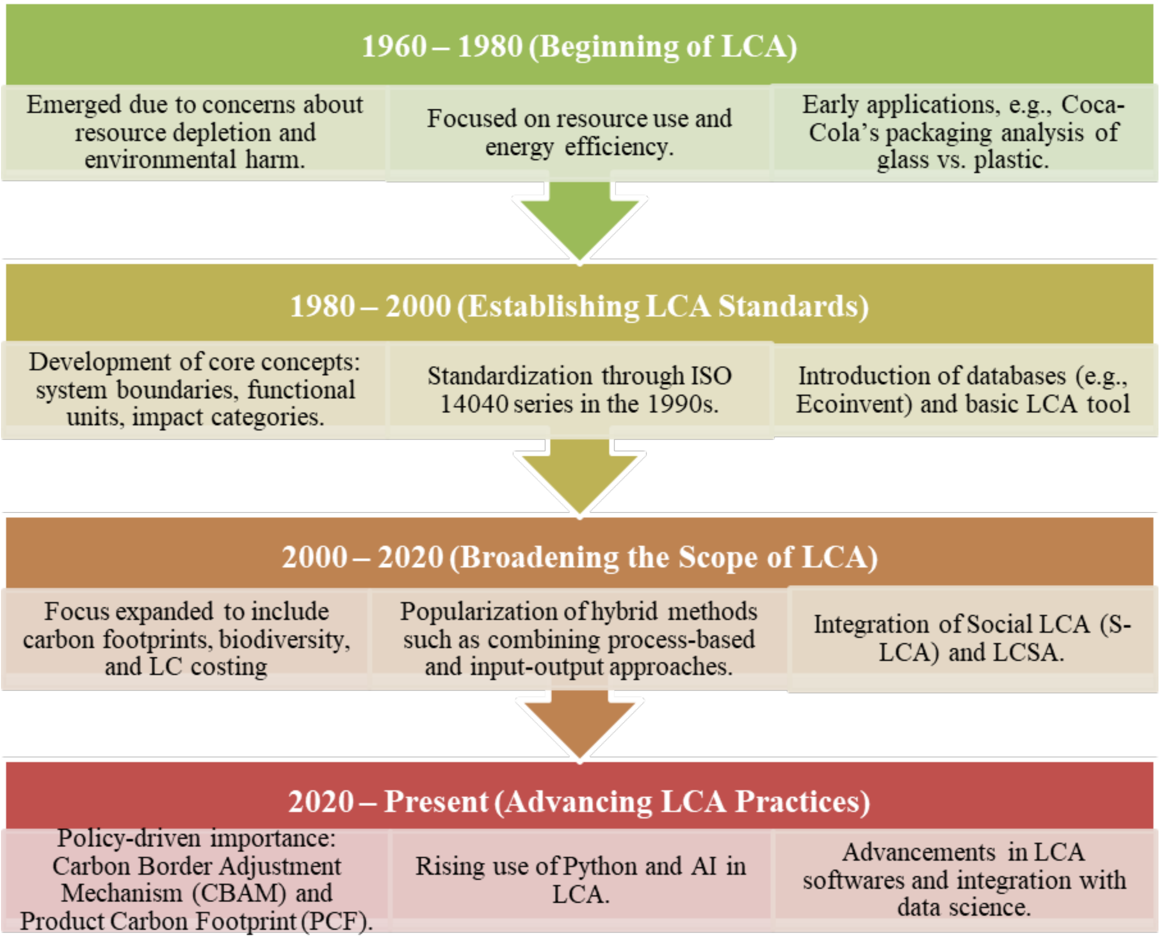

Figure 1.1. History of LCA

1.2.1 1960 – 1980 (Beginning of LCA)

Depletion and contamination of resources were the principal motivation for life cycle assessment (LCA) between 1960-1980. In the initial period, energy and materials employed during manufacturing were in the limelight. One such extremely interesting instance was the comparative analysis by Coca-Cola of glass and plastic packaging with respect to their environmental footprints, pointing toward the importance of balancing environmental burdens of production processes [10]. Nevertheless, formal evaluation requirements and standardized practices served as a constraint limiting consistency and comparability of such analysis.

1.2.2 1980 – 2000 (Establishing LCA Standards)

In the time span of 1980 to 2000, the circularity of the life cycle assessment transitioned from being just a concept towards a formalized methodology with unifying norms. The initial structural components to be worked on were the establishment of system boundaries, selection of functional units, and determination of various impacts criteria, which facilitated construction of more comprehensive documentation of environmental evaluation. A milestone during the 90s was the release of the ISO 14040 series that provided international standards for conducting LCA [11]. The development of databases (Ecoinvent) and the coming of simple LCA software tools facilitated improved and data-based analysis.

1.2.3 2000 – 2020 (Broadening the Scope of LCA)

Between 2000 and 2020, LCA actually expanded by introducing not just environmental concerns but also the latest at that time's wider sustainability into the equation. Growth extended to the extent that the necessity of quantifying carbon footprints, biodiversity, and Life Cycle Costing (LCC) emerged, leaning towards the application of a more comprehensive approach for sustainability analysis [12, 13]. Hybrid approaches, consisting of a blend of the process-based and input-output approaches, also gained prevalence, thereby making an impact assessment more accurate. It was also during the time when Social LCA and Life Cycle Sustainability Assessment (LCSS) were merged, understanding the reality that social and economic aspects, in the context of the sustainability field, are as important as environmental aspects. The introduction of extensive global databases and advanced analytical software also contributed to LCA's robustness in application across diverse industries [14].

1.2.4 2020 – Present (Advancing LCA Practices)

From 2020, better digitalization, artificial intelligence, and regulatory frameworks have been established providing LCA methodologies [15]. Policies like the Carbon Border Adjustment Mechanism (CBAM) [16, 17] and Product Carbon Footprint (PCF) [18] have again brought into focus the applicability of LCA in the policy and business world approaches. The coupling of AI and Python-based computational models has resulted in enhancing the efficiency and accuracy of LCA research, making it possible for real-time analysis and automation [19]. Gibb, the computer program, also encountered new software functionality and data integration leading to easy and useful application of LCA by businesspeople and policy makers.

1.2.5 Future of LCA

Life Cycle Assessment, or LCA, is the direction in which this environmentally reliant world image of the energy industry has already proceeded and thereby achieved the realization of the presence of various New Ways of thinking. Particularly the universalization and automation are observed in nearly all levels that concern the environment, ranging from the most elementary one, such as green production to the level of government. Along with it, the same factors become more and more vital to the organizations that have a concern for the environment. Thus, LCA will inevitably become an integral element of assuring the multinational companies' sustainability accounting. Enhanced accessibility of both data and the universal language to apply across sectors will provide a real boost in the accuracy and uniformity of the environmental effects assessment. The adoption of harmonized approaches in every industry will enable governments and companies to make proper decisions with high confidence in the existence of the required and all-encompassing indicators of sustainability [20].
Digital technologies, artificial intelligence, and machine learning will certainly render LCA procedures completely different and, as such, they will be capable of giving instant analysis, forecasting, and data automatic processing. [21] Algorithms driven by AI will be incorporated into LCA, thereby helping to perfect the analyses both in terms of quality and the time required for carrying out the analysis to be made public. Further, LCA software tools shall also become more sophisticated, and use of blockchain for managing data will be essential for lifecycle information to be employed in even more precise manners [22]. As far as green technology and something going green and all, popularity demonstrated by the said one confirms the procedure of the environment and the fact that it is really upgrading cannot be halted or evaded. The LCA is estimated to be a very significant sustainable instrument in corporatizing the company strategy, finding new products, and meeting legal requirements. As a result, it will be an eco-friendly option that also translates into using the resources more effectively and taking care of the future as well.

1.3 Phases of LCA

An LCA is a methodical approach assessing the environmental impacts of a product, which are emitted to the environment by the product alone during the lifecycle. For greening electronic devices, LCA is a method to determine the steps a sustainability improvement can be achieved, which in turn ensures that environmental issues from the selection of material to the disposal. The four essential LCA stages—Goal and Scope Definition, Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation—are elaborated below::

1.3.1 Goal and Scope:

This is the stage where the goal and the type of the LCA study are established. Here in this chapter, the aim is to assess the entire ecological footprint of the life cycle from extraction of raw material to manufacture, use, and end-of-life disposal. The functional unit can be placed collocated in the form of the length of the life of the individual unit. System boundaries are the those that follow besides others the process of manufacturing straight to the end-user disposal [23]. The phase entails defining the key impact categories like energy usage, carbon footprints, usage of resources and generation of e-waste are also established here.

1.3.2 Life Cycle Inventory (LCI) – Data Collection:

This stage involves a thorough analysis of every phase in the lifecycle of the electronic device to gather specific information regarding inputs of resources, energy consumption, emissions, and

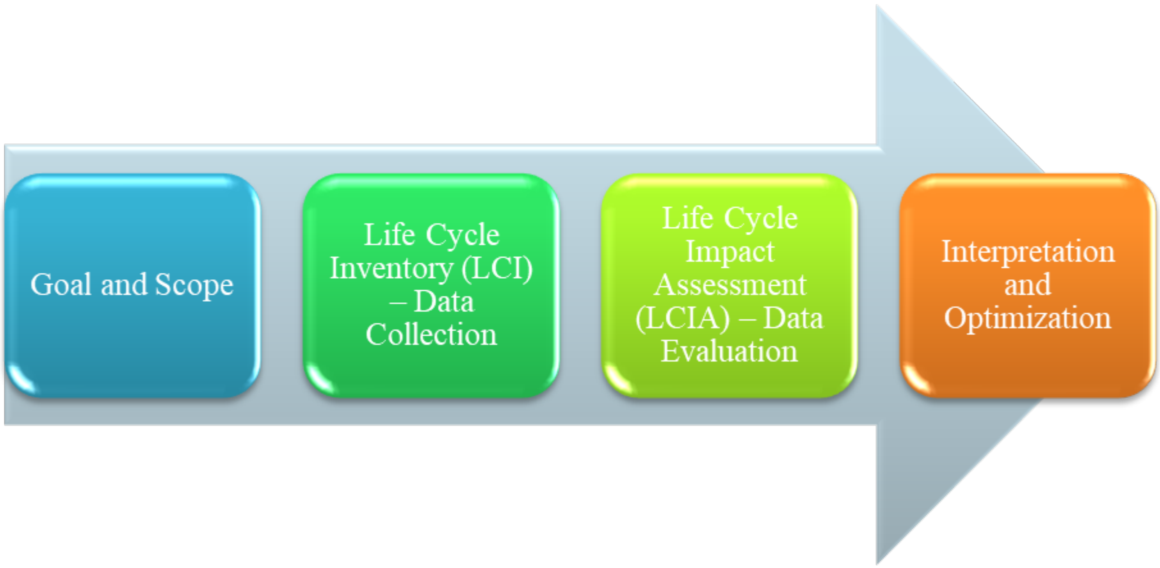

Figure 1.2. Phases of LCA

waste output. For green electronic devices, the information gathered is on the extraction of resources, for instance, the application of recycled metal or bio-based polymers as well as the use of energy in production, logistics, patterns of usage, and the modes of disposal [24]. Secondly, the supply chain data is highly significant, and they encompass transport and production process emissions. The foremost is to determine the processes and materials having the highest environmental impact which will, in turn, allow focused requests to be made for sustainability measures. At this stage, gather data to measure inputs like raw materials and energy, as well as outputs such as emissions and waste throughout the product or system's life cycle. This collected data is referred to as the Life Cycle Inventory (LCI), encompassing all relevant information for the processes involved in the study. LCI data can be broadly categorized into two main types according to its usage and sources:

Foreground Data

Data about the processes you are directly studying.
– Usually comes from specific factories, products, or measurements.
– Example:
The amount of electricity consumed in a factory.
Ingredients or materials used directly in the manufacturing of a product (e.g., steel for car manufacturing or wheat for bread production).

Background Data

Data about things you don't control directly but still affect your system.
– Often comes from databases like Ecoinvent or other national datasets.
– Example:
The environmental impact of electricity generation from the national power grid
The production of raw materials supplied by external vendors

1.3.3 Life Cycle Impact Assessment (LCIA) – Data Evaluation

The inventory data are initially gathered in the interim based on which the environmental impacts are measured through standardized impact assessment methodologies. This identification thus becomes the foundation for the process of the determination of critical life cycle environmental impact categories like CO_2 emissions, toxicity, water use, and energy depletion. During this phase, green electronic devices can lead to the escalation of the environmental impact by a variety of mechanisms involving hazardous e-waste production, energy-demanding semiconductor fabrication, and the use of rare earth metals [25]. Life Cycle Impact Assessment (LCIA) is among the approaches which are used, and it plays a vital role in the identification of the points of contention or the "hot spots" that have to be addressed by an eco-friendly alternative such as energy-efficient circuits, recyclable cases, and non-toxic substances.

1.3.4 Interpretation and Optimization:

On this final step, the outcomes of the LCIA are interpreted in order to conclude the results and recommendations for action. The analysis process ensures the findings are aligned with sustainability goals and therefore the executives (manufacturers and product designers) are able to make more informed decisions. For green electronic products, optimization strategies are susceptible to some redesigning of components with less energy use, so biodegradable or recyclable materials are an option, the process of manufacturing could be optimized, and product durability could be improved by the use of repairable and mod price rising options, respectively. Additionally, effective end-of-life management strategies like take-back programs and increased recyclability can be incorporated in order to reduce environmental impact.[26]

Green electronics producers and designers employing LCA for ecological assessment can minimize ecological footprints, encourage circular economy principles, and be part of the shift towards sustainable electronics. Through this approach, the electronic products will not only fulfill performance and cost requirements but also maintain environmental responsibility throughout their lifecycle.

1.4 Summary of ISO - 14040 and ISO 14044 guidelines in LCA

The founding of global standards for LCA “(ISO 14040:1997, ISO 14041:1999, ISO 14042:2000, ISO 14043:2000)” [27, 28] represented an important advancement in the consolidation of LCA techniques and methodologies. Their part in the widespread adoption of LCA across all parties involved and the worldwide society was important.

Achievement, for example, may be quantified by the volume of papers sold. Despite the absence of comparative standards, the purchase of 1200 replicas of ISO 14040 in Sweden and 909 copies in the Czech Republic indicates that the item has been both beneficial and effective [29]. All the technical specifications were effectively included in the new ISO 14044, establishing it as the primary source of information for LCA specialists. The revised ISO 14040 seeks to delineate the concepts and architecture of LCA in a manner that is comprehensible and accessible to both LCA professionals and a wider audience [30]. The updated 14040 will include a single, explicit mandate for adherence to the new ISO 14044 guideline.

LCA is an integrated approach established for evaluating the ecological impacts associated with harvests, processes, and facilities from cradle to grave. These norms are ISO 14040 and ISO 14044 that present the framework and the methodology of the LCA [31]. These standards are necessary in order to guarantee that LCA studies are made with accuracy, efficiently, and with adequate quality for being used in decision making and sustainability evaluation.

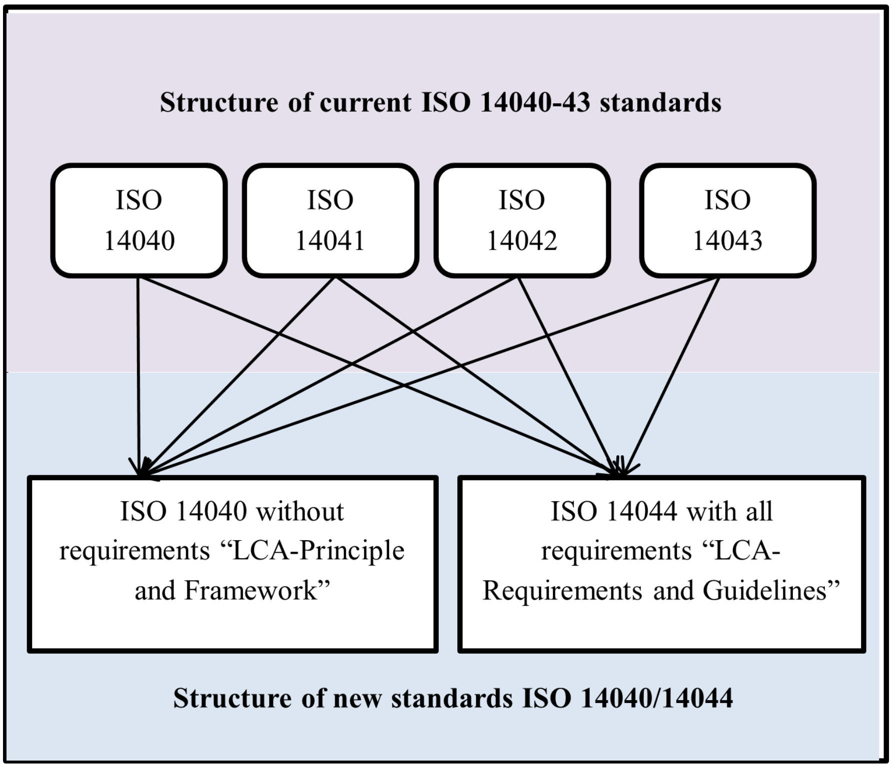

Figure 1.3. General outline of the new standards

1.4.1 ISO 14044: Requirements and Guidelines for LCA Implementation

ISO 14044:2006 is much more specific and comprehensive in providing guidance on how to apply the principles of ISO 14040. While ISO 14040 provides a broad framework, ISO 14044 provides detailed technical procedures and requirements for every stage of the LCA study [32]. It presents in greater detail the methodologies that would be applicable for each of the different phases under the study.

Key elements of ISO 14044 include:

- **Detailed Guidelines for Goal and Scope Definition:**

This section underscores the significance of how functional unit and system boundaries and assumptions are captured. It also appreciates the aspect of specifying the use that is going to be made of the study results, to ensure that the scope addresses the context of decision making.

- **LCI Analysis:**

This is well illustrated in the ISO 14044 standard where there is provision specifically dealing with data collection and data quality. These are the guidelines on selection of data, the sources of data and steps in terms of data quality [33]. It also captures aspects of data completeness, consistency, and relevance since these influences the validity of the LCA outcomes.

- **LCIA:**

ISO 14044 also provides more detail on the actions taken within an impact assessment. It provides an overview on how impact categories are defined and selected, how characterization factors are used to express the impact, how normalization is used to put them into perspective, and how weighting is used to prioritize impacts [34]. It also outlines how to determine suitable methodologies in the conduct of the impact assessments.

- **Interpretation and Critical Review:**

ISO 14044 also points to the need in assuming the critical review to provide the objective and quality of the LCA study. This involves pre–review by peers, analysis of assumptions for sensitivity, and full disclosure of methods and bias [35]. Interpretation also entails arriving at conclusions which achieve the purpose of informing the decision makers of the best course of actions to take in order to minimize the effects of the environment.

- **Documentation and Reporting:**

The core theme of ISO 14044 is the transparency of the results of LCA. This standard gives precise guidelines on how to report the results, especially data presentation, methodologies, assumptions, limitations, and conclusions. It states that LCA reports should be transparent, understandable, and accessible to a non-technical audience as well as to the technical audience.

1.4.2 Importance of ISO 14040 and ISO 14044 in LCA Practice

ISO 14040 & 14044 are initialized to be a framework, which includes steps for carrying out LCA. It coordinates LCA practitioners by providing a consistent language and approach for their work making the results scientific, consistent, and reliable. Of the utmost importance is that these standards are crucial for business, research, and policy as they help to inform and address the implications of product and service footprints.

- **Consistency and Comparability:** LCA, through obedience with ISO 14040 and ISO 14044, can be said to be standardized since organizations have to follow certain milestones in their studies. These make it easier for decision makings since results for different studies, industries, and regions can easily be compared and also make environmental performance benchmarking possible [36].

- **Credibility and Transparency:** Through compliance with ISO 14040 and ISO 14044, LCA studies are well conducted with high standards of professionalism hence bringing high credibility to the results produced [37]. In combination with transparency, accurate definition of methodologies, assumptions and limitations, the results are credible and can help stakeholders make correct decisions.

- **Support for Sustainable Decision-Making:** As the ISO standards recommend, LCA studies offer useful information to organizations wanting to lessen their environmental impacts. It means companies are able to define the PLC stages which are characterized by the greatest effects on the environment and then introduce measures for eco-design, material substitution, energy, and waste minimization etc.

These standards are fundamental standards for LCA as they offer a systematic approach, an organized framework, and built-in scientific principles to quantify impacts on the environment. Such guidelines assist organizations in conducting effective and comprehensive LCAs, to provide requisite information on sustainability, product development and improvement as well as boosting on Corporate Environmental Management. In that way, practitioners guarantee that their LCA research contributes to the systematic decision-making process leading to CPA.

1.4.3 Other ISO Standards

ISO 14067: Carbon Footprint of Products (2018)
– Focuses on carbon footprint (climate change) of a product
– Considered as the international reference standard for conducting PCF (Product Carbon Footprint).
– Has additional requirements to include carbon emissions or absorption from land conversion, plant growth, organic decomposition, and changes in soil carbon stocks.

ISO 14020, ISO 14021, ISO 14024, ISO 14025, ISO 14026:
– Related to environmental labels and declarations.
– Provide principles and specify general requirements applicable to all types of productrelated environmental statements and programs.
Following ISO standards enhances the transparency and consistency of LCA which ensures LCA as a more reliable and comparable study across various applications. While knowing every standard isn't necessary, ISO 14044 is essential. This outlines the four main stages of LCA and serves as a commonly referenced standard for both industry professionals and academics.

1.5 Key Stages of the Life Cycle in Electronic Devices

Each product within the electronic category falls under a process of developmental stages before reaching disposal. These stages are essential for understanding their environmental, economic, and societal impacts:

Design and Development

During this stage, the idea of the device is developed, the purpose of the device is established, and the parameters of the device are set out. It also involves the choice of materials and components, relying on energy consumption on the one hand, longevity, and recyclability on the other [38]. Green design ideas are used to cap environmental effects and optimize the durability of the equipment.

Material Extraction

The manufacturing of these devices depends on raw material inputs including metals and alloys, rare earth elements and polymers [39]. This stage entails extraction and processing of such materials which are known to cause pollution, greenhouse emissions as well as depletion of natural resources.

Manufacturing and Assembly

Then the raw materials are utilized to fabricate parts and integrate the electronic gadgets. This phase mostly consumes a lot of energy in addition to generating industrial wastes. They are central to the objective of enhancing sustainability within the manufacturing processes.

Distribution and Marketing

Finally, outcome circuits are circulated through different channels to the users of devices. This entails delivery, packaging, and promotional activities in that it harnesses resources and ads to the impacts of climate change. These effects can however be reduced through efficient supply chain management [40].

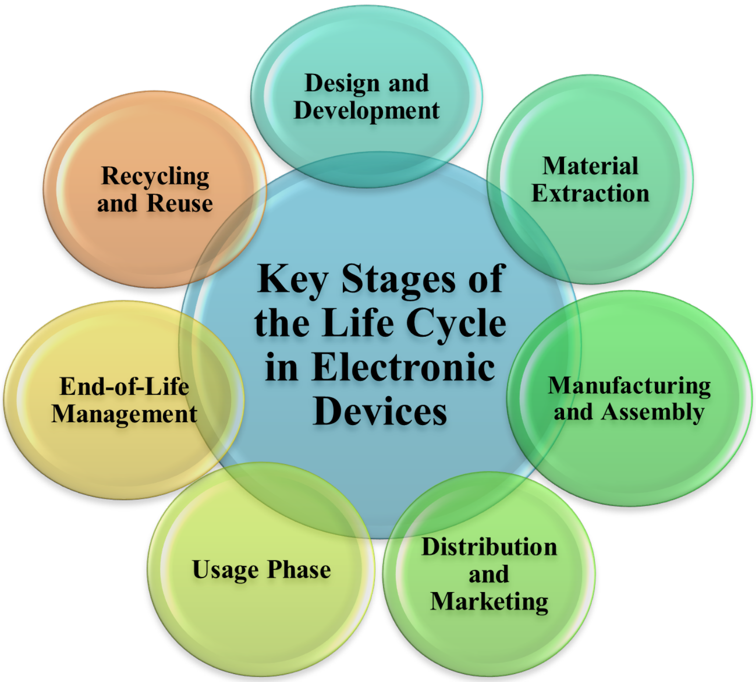

Figure 1.4. Essential Phases of the Life Cycle of Electronic Devices

Usage Phase

The usage stage is distinguishable from the other two by the fact that devices are being operated by consumers. At this phase, it gets a bit more complicated because the environmental impact comprises aspects such as energy consumption, degree of maintenance needed, and utilization. Energy-efficient usage only is enough to cut down the total lifecycle emissions to a great extent.

Management of End-of-Life

This stage of product life cycle focuses on disassembling, recycling, or reusing the electronics equipment having exhausted their usefulness. Appropriate e-waste management is important to collect reusable products, reduce landfill index and decrease hazardous emissions [41]. Highlights include refurbishment, and material recovery as well as proper disposal of material is encouraged.

Recycling and Reuse

The last stage reiterates resource loops by melting down used up components and materials from the devices. Proper evolved recycling minimizes demand for virgin material and lowers the life cycle effects impact in its total level. This impacts the reduction of environmental. Incorporating sustainability at all phase of the LC contributes to reducing environmental harm, improving resource efficiency, and advocating for a circular economy in the electronics industry.

1.6 LCA of repurposed waste electronic devices

Electronic and electrical scrap is one of the most rapidly expanding waste sources inside the European Union. The effective elimination and management of WEEE are primary goals of European environmental policy [42]. Computer garbage is a significant category of WEEE, owing to its volume and elevated creation rate [43, 44]. Current European laws and legislation for WEEE management emphasize direct reuse and preparation for reuse in accordance with the waste pyramid [45]. To implement this hierarchy effectively, certain targets have been set for

recycling and reuse of WEEE. The European Commission [46] defines recycling as any process in which items or components, not classified as trash, are used subsequently for their original intended purpose.
Processing for recycling is defined as the examination, sanitation, or restoration of recovered materials activities, wherein items or components that have become trash are made ready for reuse without further pre-processing. The repurpose and preparation for reuse of WEEE may mitigate environmental consequences by conserving resources and reducing pollutants linked to recycling or landfill disposal of trash. Moreover, from a social or economic perspective, they provide benefits by enhancing access to equipment and fostering the growth of a segment that creates jobs and income [47].

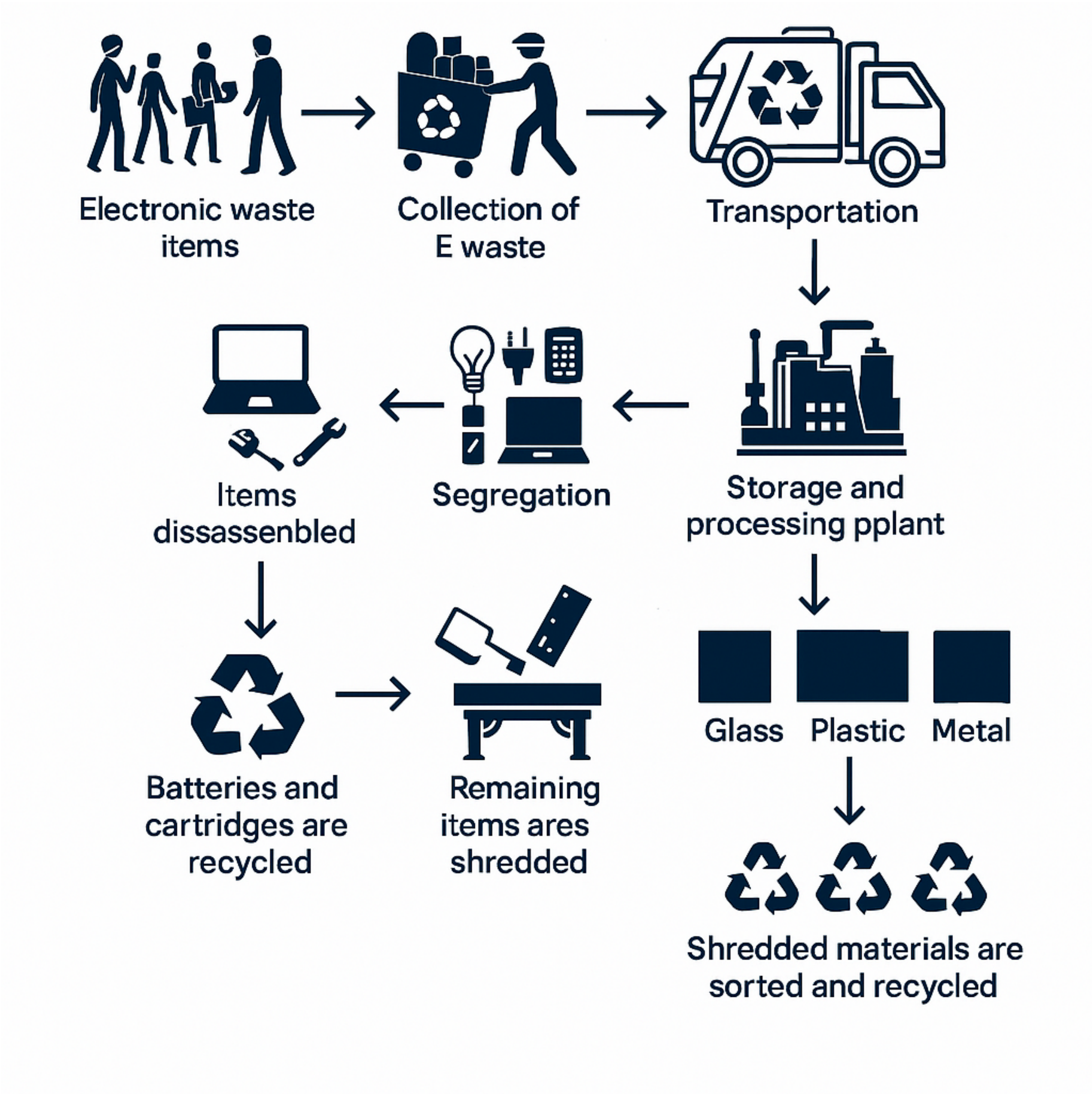

Figure 1.5. Electronic waste recycling procedure

However, the execution of recycling and preparation for reusing is occasionally the most advantageous option from a sustainability perspective [48, 49]. On the one hand, adaptation, transport, evaluation, or repair requires assets, power, and components, leading to negative environmental impacts. Conversely, the resultant items may have a more detrimental effect throughout their use phase compared to identical products accessible on the market.

1.7 Challenges in Applying LCA to Electronics Manufacturing

LCA is an efficient tool for evaluating the ecological effects of goods and processes across all phases of their LC. Consequently, industry-specific challenges associated with this framework are thoroughly elucidated due to the complex structural structure of the electronics manufacturing sector. Presented below is a comprehensive account of these problems:

1.7.1 Complexity of Product Design and Composition

All electronic devices are very complex, consisting of many, many parts, which may be made from a myriad of metals, plastics and especially from rare earth elements. This material complexity becomes problematic especially when using Life Cycle Assessment (LCA) because every material produces different environmental burdens, and these impacts are not always easy to track or quantify exactly [50]. Furthermore, placing different functional components within small-form-factor dense high-performance solutions, including microchips and multi-layered printed circuit boards, makes it even more difficult to conduct environmental evaluations of specific components [51]. The designs and the embodied materials for electronics are updated frequently and this directly affects the rate at which LCA data and information have to be updated; nonetheless, it is challenging to follow the rate of change of the electronics industry.

1.7.2 Data Availability and Transparency

One major impediment in using LCA in the context of manufacturing electronics products is probably the absence of sufficient and consistent information, which is central to the evaluation of the impacts for environment. Products that are manufactured in the electronics industry are usually supplied in a layered structure, so it is challenging to gather data that includes all the necessary details about materials' procurement and used processes from all the levels of supply chain at different geographical areas [52]. In addition, most of the manufacturers keep the important details on the production process, raw materials, and product formulation rather secret owing to restrictions on proprietary rights thereby limiting the coverage of LCA research. Further, since manufacturing technologies change with constant advancement in technology, some data collected earlier may become obsolete and may need to be updated regularly in order to get the real picture of the conservational impacts and control them in proportion to the evolution of the manufacturing processes.

1.7.3 Energy-Intensive Manufacturing Processes

Process industries such as manufacturing of electronic components, Semiconductor and Integrated Circuits are very energy-intensive and GHG emitters. Some core processes include the manufacture of wafers, photolithography and etching to name but a few uses a considerable amount of energy, a significant proportion of which is probably drawn from exotic resources [53]. One limitation of LCA methodology that is highly relevant to the electronics manufacturing context is that data on energy and emissions are often unavailable at a level of detail sufficient to differentiate between the multiple subprocesses that are involved in manufacturing electronics products [54].

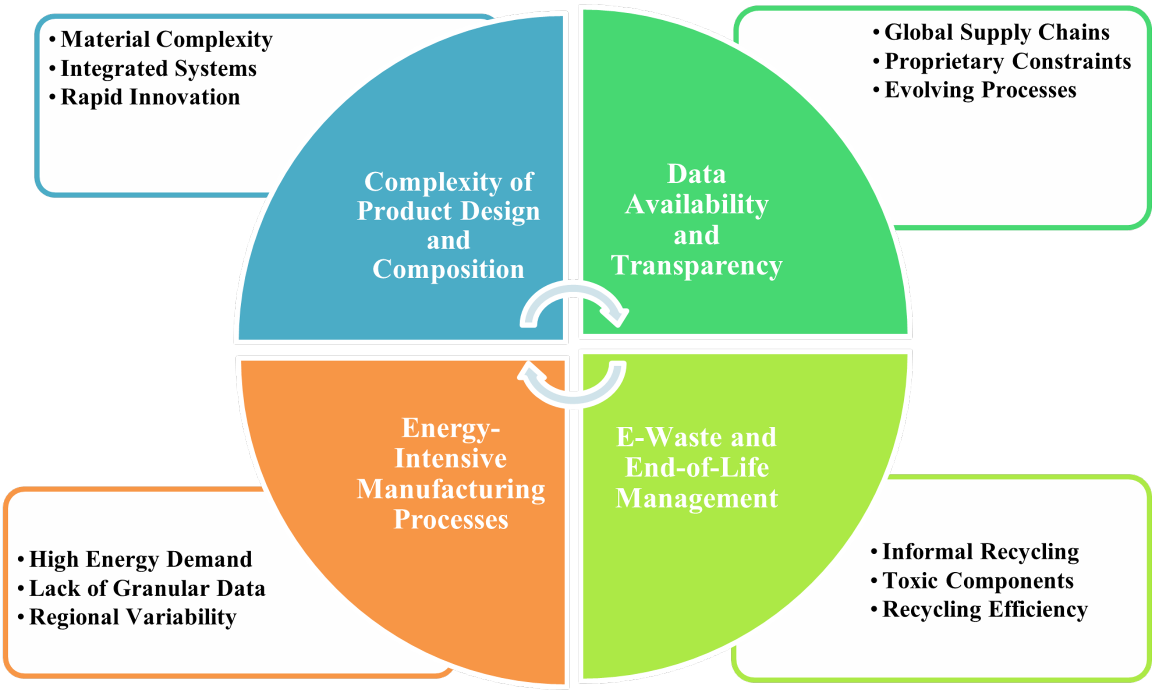

Figure 1.6. Obstacles in Implementing LCA in Electronics Production

This problem aggravates in the case of production at more than one facility or across different regions as supply mix and intensity of energy use can differ significantly from one region to another, and, thus, global measurements of environmental effects are far from being accurate. This variability hinders the establishment of optimized LCA models that can be universally used in all electric/electronics manufacturing operation.

1.7.4 E-Waste Management

A challenge with the application of LCA addresses the evaluation of environmental consequences of discarded electronics or what is referred to as e-waste. E-waste is usually processed through informal sources of recycling in many countries across the world with little regard to health impacts and emissions on the environment. Further, it's stated that many electronics have dangerous components, including lead, mercury, and cadmium, which make the process of their disposal and recycling more challenging [55]. The effectiveness of end-of-life recycling operations for extracting secondary resources such as rare earths is highly inconsistent by region and specific recycling plant. The information on the efficiency of these recycling processes is frequently fragmented or inaccurate, and this hinders the precise determination of the environmental saving potential of recycling and recovery in LCA work correctly.

1.8 Eco-Friendly Electronic Devices

Green electronics are circuits or devices that require minimal negative influence on the environment at every stage in production and disposal. These devices ensure that the metals and plastics in them are recycled metals and biodegradable plastics respectively to ensure that the natural resources are not depleted and cut on waste production [56]. Lead, mercury and brominated flame retardants by their design are not used in its production in order to provide a safer way of manufacturing them as well as their disposal to the environment. This approach not only avoids pollution but also complies with high standards of environmental policies set to encourage environmentally-friendly production methods [?]. Possibly one of the most telling aspects of

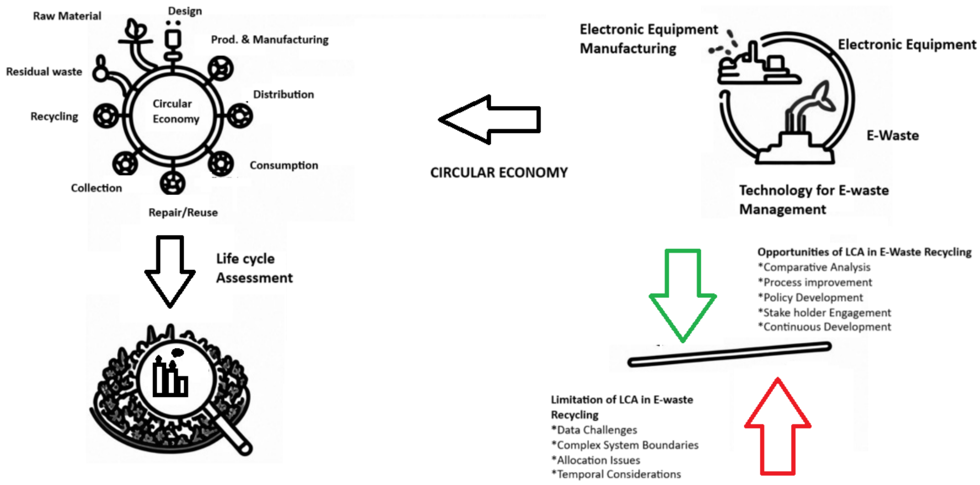

Figure 1.7. LCS of electronic devices

green electronics is energy conservation, the result of creativity and technology. Most devices come with low power chips and implements such as power-saving and therefore they do not consume much energy when in use. Comparing guidelines like requisites of ENERGY STAR [57] and similar ratings and approvals is proof of the company's willingness to decrease greenhouse gas emissions and expenses. Moreover, these devices are designed to be tough and easy to repair, retooled to be easily repaired and upgraded using modular design philosophies. It makes the device last longer than to become spoilt hence fewer replacements are made and its Environmental Conservation & Protection thus reducing its wastage [58].
Many environmentally sustainable devices also apply the circular economy model specifying that parts of the item need to be recycled, revealed, or reused once they reach their useful life [59]. Many manufacturers create take-back programs and work with designated e-waste recyclers to recycle what they can and dispose of the products properly. Such an approach helps to minimize the generation of e-waste and decrease dependence on virgin materials which in turn save resources and minimize energy trapped in mining processes [60]. Consumers have become more educated as to the negative impacts of their actions to the environment and sustainable electronics is now instrumental in meeting environmental issues and innovation in that sphere.

1.9 Research Motivation

The proliferation of electronic devices has lately added to the problems of environmental challenges including resource depletion, energy consumption, and hazardous e-waste [61]. Traditional designs and manufacture of electronics have a long time focused on performance and cost rather than considering the impacts on the environment [62]. Environmental sustainability in electronic device design became important due to rising global concern about climate change, pollution, and unsustainable use of resources. LCA provides a comprehensive methodology that accounts for all environmental consequences throughout a product's entire life cycle, from raw material extraction and production to final disposal. Use of LCA in eco-friendly design for electronics can

lead towards the identification and mitigation of key environmental hotspots hence enabling a step toward more sustainable industrial practices [63]. This study attempts to bridge the gap between LCA methodologies and practical applications in eco-friendly electronic design. This is in light of the urgent need for sustainable solutions in the electronics industry, considering the raising consciousness about the effects on the environment of electronics but remaining significant challenges in embedding sustainability into their life cycle.
The complexity of electronics, in the diversity of materials, intricate manufacturing, and global supply chains, throws up barriers to the assessment of the ecological footprint and its mitigation. Rapid technological cycles and short product lifetimes amplify the e-waste issue and pose a threat not only to environmental health but also to resource availability. This research is led by the promise of LCAs as a decision tool in the design phase because it allows manufacturers to think about energy efficiency, the sustainability of materials, and recyclability at the end of life [64]. This study therefore attempts to contribute to improvements in eco-friendly electronics using innovative design strategies that embrace global sustainability goals, ranging from the low-power design strategies up to carbon neutrality. This would then go on to inspire innovations toward better ways in the production of sustainable electronics and provide actionable insights into various policymaking, industry engagement, and research collaborations aiming toward common environmental challenges through this electronics sector.

1.10 Problem Statement

The electronics industry is marked by significant challenges in reducing its footprint since the manufacturing, usage, and disposal of devices become rather complex and resource-intensive. Even though knowledge regarding the environmental impacts of electronic waste and energy consumption by the devices is increasing by the day, most electronic products remain designed with little life cycle consideration. The failure to take such opportunities in minimizing environmental harm relates to the integration that ought to exist between LCA and the product design process. There is, therefore, a pressing need to develop a holistic framework integrating LCA into early stages of the design process so that manufacturers are able to identify potential environmental hotspots, optimize resource use, and improve recyclability of material. This paper addresses the gap by looking into how LCA can be systematically integrated into the design of eco-friendly electronic devices as a step toward more sustainable and responsible electronics production.

1.11 Research Methodology

1.11.1 Overview

Research methodology is a systematic and comprehensive investigation of the approaches used in performing research. The process comprises every step of the approach, beginning with formulating goals for the inquiry and continuing with the collection, examination, and interpretation of data. The methodology section offers a thorough description of the design, methods, and techniques used for data collecting and assessment. A research methodology outlines the methods used by researchers to carry out their investigations and provide reliable, genuine data that achieves their objectives (Snyder, 2019).
The research methodology for this thesis focuses on quantifying the CO_2 emissions associated with various electronic devices and converting these emissions into an equivalent distance traveled. This approach provides a tangible perspective on the environmental impact of digital technologies.

1.11.2 Objectives of the Study

- To evaluate the environmental impact of electronic devices .
- To assess the sustainability of fabrication processes and identify eco-friendly alternatives.
- To promote circular economic practices, including recycling, reuse, and modular designs.

1.11.3 Research Methods

This study adopts a multi-step analytical methodology aimed at quantifying the carbon footprint of electronic devices and evaluating how circuit-level power optimization techniques can reduce operational CO_2 emissions across different countries. The approach integrates both life-cycle emissions and regional energy data to offer a comprehensive environmental assessment.

Data Collection and Power Analysis

- Identification of commonly used electronic systems such as laptops, mobile phones, and data center processors.
- Documentation of typical power usage patterns (in watts) for these devices.
- Collection of country-specific carbon intensity data (in gCO_2/kWh) based on national electricity generation mixes (renewables, nuclear, fossil fuels).

CO_2 Emissions Calculation

- Estimation of operational emissions using the formula:

$$\text{Emissions (gCO}_2\text{)} = \frac{\text{Power (W)} \times \text{Carbon Intensity (gCO}_2\text{/kWh)}}{1000}$$

- Conversion to kilograms for standardized comparison:

$$\text{Emissions (kgCO}_2\text{)} = \frac{\text{Emissions (gCO}_2\text{)}}{1000}$$

Distance Conversion (Relatability Metric)

- Calculation of the equivalent travel distance using:

$$\text{Distance (km)} = \frac{\text{Emissions (kgCO}_2\text{)}}{0.192}$$

- Based on average CO_2 emissions of a standard passenger vehicle, this serves as a relatable benchmark for interpreting emissions data.

Lifecycle CO_2 Impact Estimation

- Manufacturing CO_2 is estimated via:

  $$\text{Manufacturing CO}_2\text{ (kg)} = \text{Manufacturing Energy (kWh)} \times \text{Carbon Intensity (kgCO}_2\text{/kWh)}$$

- Operational energy use over a 2-year lifecycle:

$$\text{Operational Energy (kWh)} = \frac{\text{Power (W)} \times 24 \times 365 \times 2}{1000}$$

- Location-specific emissions factor applied for Italy:

$$\text{Operational CO}_2\text{ (kg)} = \text{Operational Energy} \times 0.3307$$

- Combined lifecycle impact:

$$\text{Total 2-Year CO}_2\text{ Impact (Italy, in kg)} = \text{Manufacturing CO}_2 + \text{Operational CO}_2$$

CO_2 Savings from Power Optimization Techniques

To assess how low-power circuit design can mitigate emissions, a standardized scenario was modeled assuming a 100 kWh operational energy reduction. The following formula was used:

$$CO_2 \text{ Saved (kg)} = \frac{\text{Carbon Intensity (gCO}_2\text{/kWh)} \times \text{Energy Saved (kWh)}}{1000}$$

Each technique's power saving percentage was based on literature or industry reports:

Technique	Estimated Power Saving (%)
Clock Gating	25
Power Gating	50
DVFS	40
MTCMOS	40
Body Biasing	30
Subthreshold Operation	90
Capacitance Reduction	15

Table 1.1. Estimated Power Savings by Technique

- Seven common techniques were analyzed, including Clock Gating, Power Gating, DVFS, MTCMOS, Body Biasing, Subthreshold Operation, and Capacitance Reduction.
- Power saving percentages (e.g., Clock Gating = 25%) were applied to calculate the CO_2 savings per country, reflecting how much carbon can be mitigated based on grid intensity.

Data Presentation and Visualization

- All calculated values were organized into structured tables and comparative charts.
- CO_2 savings were plotted by country and technique to visualize which nations benefit most from IC-level power optimizations.

Analysis and Interpretation

- Cross-country and cross-technique comparisons were conducted to identify patterns in emissions and mitigation potential.
- The environmental benefits of deploying efficient circuits in high carbon intensity countries were emphasized.

• Broader implications for sustainable electronics, green data centers, and climate-aware hardware deployment were discussed.

The writer's Comments on the use of artificial intelligence.

This dissertation utilizes artificial intelligence tools to enhance the information process of composition, analysis, and transmission. We utilized the OpenAI-developed ChatGPT model to facilitate the following tasks:

- Enhancing the organizational layout of the literature and providing tips for systematic material organization.
- Explain complex concepts and enhance the coherence and cohesiveness of academic writings.

- Synthesizing scholarly literature and reformulating research results while maintaining their critical significance.
- Developing equations,drawing useful interpretations from data tables, developing coding snippets in Chapter 4.
- Assessing the structure of the text, correctness in grammar, and spelling ability.

The information used by the artificial intelligence tools came from the original research of the author, analytical conclusions, and scholarly sources. The final decision was solely made by the author, who also conducted the necessary assessments and carried out the editorial decisions. Artificial intelligence was only used in support functions and did not replace the scholarly work, subject expertise, or intellectual property involved in the ideas expressed.

This methodology combines device-level energy profiling with regional carbon emission factors and power-saving techniques to present a holistic view of sustainability in integrated circuit design. By connecting design-level optimizations to real-world environmental impacts, this research supports actionable pathways for low-carbon computing.

1.11.4 Research Tools

The study used the following research instruments:

MS Excel

The Microsoft Excel software is a widely used statistical tool that helps manage work-related tasks, such as understanding statistical ideas and executing calculations to verify complex manual computations. This software allows you to assess and save numerical information. Excel, a software application for creating and manipulating spreadsheets, is included in Microsoft's Office suite. Microsoft Excel is a software tool designed for organizing, structuring, and performing calculations on data in spreadsheets. Accessing, reading, and altering the data are simple.

1.12 Outline of the Study

The thesis is divided into multiple sections considering the "Life Cycle Assessment of Electronic Devices: A Pathway to Sustainable Electronics."

Chapter 1:

Introduction defines the concept of life cycle assessment of electronic devices, its stages and challenges associated with it and about the green electronics .

Chapter 2:

Literature Review describes the particulars of the previous studies of the authors which are carried out in the framework.

Chapter 3:

Various strategies (Low power design) for sustainable and green electronics has been discussed.

Chapter 4:

Result and Implementation, in this phase, the result and analysis are shown in which there is a discussion about the experimental results.

Chapter 5:

Findings and Conclusion, this chapter accomplishes the thesis and presents a perspective about future work regarding the topic.

Chapter 2

Review of Literature

2.1 Overview

This section gives a brief summary of the request for conducting LCA in the designing Green electronic devices with a view to minimizing the impacts of electronics on the environment. Using LCA, a complete and all-encompassing method designed for assessing the ecological footprints of products throughout the life-cycle, product designers are able to focus on e-waste problems as well as determine how the environmental quality of an end product can be optimised. The chapter focuses on the benefits of applying LCA before the design phase and such advantages include right materials selection, energy conservation, and minimizing the emission of waste. It looks at a number of methods that have been employed in LCA research, including evaluating life carbon footprint, life resource consumption, and life environmental impact of certain materials used in electronics production.
In addition, this chapter also presents the work of important academics who have contributed to the conceptualization of sustainable electronics design and an understanding of how LCA can be used to make decisions by manufacturers and policymakers. It discusses and summaries varieties of research and their results in order to provide comprehensive comprehension of how LCA may be used to mitigate environmental impact effects of electronics from manufacture to end of life. This chapter concludes by pulling together and synthesizing the knowledge regarding eco-friendly manufacturing processes, sustainable material use, and energy-efficiency enhancements for the electronics industry to build further study of how LCA can be integrated in the development of environmentally friendly electronic devices.

2.2 Literature Review

The quest for sustainable development in the field of electronics design and manufacturing has attracted significant attention from researchers, especially in the areas of life cycle assessment (LCA), biodegradable materials, energy efficiency, and circular economy-related concepts. This review seeks to consolidate the existing literature on five major topics:

- Sustainable Materials and Biodegradable Electronics.
- AI and Digital Tools for Sustainable Design.
- LCA Integration in Product Development.
- Circular Economy and Reuse Strategies.
- Modeling and Simulation Approaches to Enhance Sustainability.

2.2.1 Sustainable Materials and Biodegradable Electronics:

A growing body of work focuses on reducing environmental impact through biodegradable materials and eco-conscious fabrication techniques. **Dulal et al., (2024)** [65] presented a sustainable model for the production of entirely inkjet-printed "Smart, Wearable, and Eco-friendly Electronic Textiles (SWEET)", accompanied by the first thorough evaluations of biodegradability and LCA. SWEET monitored the body of humans in real-time to overcome its current restrictions: it used inkjet-printed diamond and PEDOT to achieve surface temperatures and a heart rate of around 74 beats per minute in a manner that was compatible with, and very efficient compared to, industry standards. Electronic garments were made from polystyrene. Experiments conducted on five human subjects using a wearable device proved the capability of the system to detect electrocardiogram signals and skin temperature. These ecological and biodegradable e-textiles experienced around 48.3% weight reduction and a loss of about 98% strength over a period of four months. According to LCA, the minimal impact of climate change due to graphene-based electrodes is noted as 0.037 kg CO_2 equivalent with a comparison value being about 41 times less compared with the used comparison electrodes. Similarly, **Cantarella et al., (2023)** [66] published an environmentally friendly and completely sustainable method for making various devices using paper made from fruit waste. Electronic devices for food tracking, heart and respiratory activity measurement, and capacitors, biosensors, and electrodes were achieved by adjusting the lasing parameters. Cellulose derived from fruit had no known biocompatibility issues when used topically. Two methods for recycling electronics were made possible by using that natural and plastic-free substrate. On the other hand, cellulose-based electronics made a comeback in nature, perhaps as a seed-growing medium or soil amendment. Green, inexpensive, and circular electronics became attainable, thanks to those findings. They found use in smart agriculture and the Internet of Things, as they produced no waste and had no negative or good effects on the environment. **Kokare et al.,(2022)** [67]further evaluated the various stages of the product life cycles of flexible and stiff electronic gadgets. In compliance with the LCA methodology offered by the ISO 14044:2006 standard, the impact assessment had been carried out using the SimaPro 9.1 software. The elastic heart monitor had outperformed its rivals in every one of the eighteen impact areas included in the LCA study. Additionally, compared to rigid electronics, the production of stretchable electronics had less of an effect on the environment, according to this study. The research indicated that stretchable electronics and theirproduction method exhibited superior environmental performance compared to stiff devices and the way they are produced, as per the LCA results of a heart monitoring device.

2.2.2 AI and Digital Tools for Sustainable Design:

While material substitution only tackles a portion of sustainability, computational tools provide proactive means of incorporating sustainability into early design. **Esho et al., (2024)** [68]studied the revolutionary capabilities of AI-based solutions in energy-efficient production and sustainable materials generation for electronics. As world energy consumption and electronic wastes continue to increase, generating new technologies has become essential for mitigating their environmental implications. AI models showed significant possibility in making smart grids smarter with real-time energy consumption forecasts and adjustments in household as well as industrial energy infrastructures. This study highlighted the role of AI and sustainable materials in attaining national sustainability and climate objectives, thus fostering a more energy-efficient and ecologically responsible future. The study concluded by suggesting avenues for further research, showing the long-lasting impacts of these technologies on the electrical engineering domain and their contribution to sustainability. A practical application of digital design was demonstrated by **Lu et al., (2023)** [69] who introduced ecoEDA, an interactive instrument that enabled electronics designers to investigate the recycling of electrical components during the design phase. It accomplished this by (1) generating recommendations to aid users in recognizing and using recycled materials; and (2) curating a repository of pertinent information on reuse (e.g., enabling users to ascertain whether devices used certain components). The study illustrated, through specific use scenarios, how our platform facilitated many avenues for recycling electronic trash. A user study was conducted to assess the tool, during which users designed an electrical schematic using components from disassembled e-waste devices. Participants' designs using ecoEDA had utilized 66% of the components used were recycled on average. Finally, we contemplated the problems and potential associated with developing software that facilitated e-waste repurposing. Complimenting this, **Liao et al., (2022)** [70] analyzed the advantages of sustainable laptop computer innovations that enabled customers to use various features for the co-development of environmentally friendly electronic devices that provided superior performance. The authors utilized conjoint analysis to determine the relative significance of various laptop properties as perceived by consumers. The paramount feature of laptops was pricing, followed by battery, chassis, Central Processing Unit (CPU), display, storage device, and keyboard. From these features, many criteria were established, including energy efficiency, waste recycling, pollution mitigation, and compatibility, to create new functions and modules. By evaluating the benefits of certain qualities, vendors of computers enhanced user value, optimized disposal of waste, decreased energy usage, and progressed their electronic creation of goods initiatives.

2.2.3 LCA Integration in Product Development:

Adding LCA to the product development process makes sure that environmental issues are not just an afterthought , but are part of the design from the start. **Da Luz et al., (2020)** [71] presented an approach for the inclusion of LCA in the goods creation procedure. The proposed method was implemented in three main phases: Pre-inclusion, Inclusion, and Post-inclusion. The primary phases included four stages: selection of the referred product, LCA of the standard item, integration of the LCA into the "Product Development Process (PDP)," and assessment of LCA inclusion within the PDP. Each phase had certain duties to accomplish. During the integration of LCA in the PDP stage, tasks were delineated for the various stages of the PDP, and the evaluation of the resulting outcomes was conducted using a ranking matrix that accounted for effect classes and the product's lifetime phases. The suggested technique had been validated by a case that involved the production of a softening package, utilizing the Umberto LCA program NXT Universal. Building on this **Garvey et al., (2020)** [72] included an actual case study of creating materials requirements to meet environmentally friendly electronics standards as part of a structure that integrated LCA with an analysis of choices approach to improve the implementation of LCA. The suggested DA-LCA architecture monitored data transfer between decision-making analysis and LCA through a five-stage procedure. The investigation considered the amount of bio based or post-consumer materials that were used in laptop covers. A utility-based influencing graph was created to connect changes in materials inclusiveness with sustainability goals using life cycle effect ratings, and a means-ends system was constructed by gathering information from a fake participant panel. In this case, 5% or 10% of materials were the best option out of the range of 0–35%. Compared to Da Luz et al., Garvey et al.'s method provides a more user-centric and decision-guided integration strategy.

2.2.4 Circular Economy and Reuse Strategies:

The feasibility of reuse as a sustainable strategy has been contested in the literature. **Kouloumpiset et al., (2023)** [73] examined, whether the life cycle environmental disadvantages associated with the preparation for reuse of WEEE were counterbalanced by the advantages of circumventing a new product acquisition, which exhibited reduced energy use throughout its operational duration. Data for PCs, laptops, monitors, printers, cellphones, and vacuum cleaners had been gathered from the two comprehensive sorting centers in Greece, and life cycle evaluations had been conducted. Findings demonstrated that the repair and reuse of cellphones decreased their environmental consequences by as much as 25%. Desktops, computers, and monitors contributed to a reduction in environmental consequences ranging from 1.4% to 19.2%. The reductions for printers were minimal, ranging from 0.3% to 3%. The repair and reuse of vacuum cleaners resulted in an escalation in nearly all major environmental consequences, surpassing 70% for ocean and freshwater eutrophication. These results fed policy discussions on particular preparation for reuse objectives and aided in decision-making. **Pérez-Martínez et al., (2021)** [74]utilized LCA in agreement with the ISO 14040 standard to evaluate the ecological effects of two procedures for preparing desktop computers, classified as WEEE, for reuse. The outcomes included reused products with commercial applications: a "Programmable Logic Controller (PLC):" and a 'Perimeter Security System (PSA)." Those circumstances had been juxtaposed with alternative counterparts in which the goods had originated from pristine raw resources. The findings indicated that the environmental performance of repurposed PLC was inferior to that of the original, primarily due to differences in the distribution and use phases. The increased size, diminished lifespan, and mostly the heightened operational power exacerbated the negative effects of the reuse situation. Nevertheless, remanufactured PSA had a decreased adverse impact relative to its original maker across all assessed ecological categories. This mostly resulted from its reduced operating capacity and the absence of rigorous technical standards. This strategy enabled the promotion of new products resulting from these processes, so improving the responsible disposal of WEEE and fostering the development of the economy that is circular.

2.2.5 Modeling and Simulation Approaches to Enhance Sustainability:

Numerical simulation has become an effective method for guiding the design of sustainable materials and devices. **Pathak et al., (2020)** [75] provided a method for designing and evaluating the feasibility of Pb-free PSC to examine the various parameters. Device simulation software was used to evaluate several design concepts, focusing on defect weight, distinctive decay forces, and capturing cross-section region. A Gaussian distribution was used to model the deeper-level imperfections, while an exponentially decaying band tail was utilized for the shallower-level defects in the absorber layer. The improved device parameters facilitated a simulated conversion efficiency of 13.36% under AM1.5G illumination, with an open-circulation voltage (Voc) of 0.882 V and a fill factor (FF) of 65.29%. Study investigated how the density of interface defects and the thickness of the absorber layer affected the solar cell's performance. Scientists used these simulation findings to make better material choices and create high-performance PSCs. Complimenting this, **Ho et al., (2021)** [76] evaluated the effects on the environment of the electrically-enhanced palm oil mill effluent (POME) filtering process parameters and the formulation of conductive membranes using Graphene Oxide (GO) and Multi-walled Carbon Nanotubes (MWCNTs). For conductive membrane fabrication, we used a cradle-to-gate strategy, and for POME filtration, we used a gate-to-gate technique. Process operational variables (such as electric field strength and electricity operating mode) and conductive-membrane formulation parameters were studied. Here, we discover two things. First, as compared to pure MWCNTs, the optimal weight ratio of GO: MWCNTs for producing conductive membranes was determined to be 1:9. This was due to the fact that this ratio produced membranes with better electrical conductivity while simultaneously reducing environmental consequences by 8.51%. It was determined that 5 wt% of carbon nanomaterials were the optimal concentration since it had the fewest negative effects on ecosystems, human health, and resource depletion. Both the ideal circumstances for membrane formation and the parameters for electrically-enhanced filtering were determined in the current investigation. Similarly, **Kim et al., (2019)** [77] aim was to compare the solar-only option to a standard system for small-town use, which included PV panels, batteries made from lead acid, a charging controller, and a converter, and to determine the ecological impact of the former. Both alternatives had been defined and sized, and LCA had been used as a methodical structure for this reason. The findings indicated that PV modules accounted for a substantial 65% of the overall effect in the reuse situation, while PSUs, UPSs, and a microprocessor kit had a negligible influence, amounting to just 0.12%. The combined impacts of lead-acid cells' pounds, decreased effectiveness, and the need for regular replacement meant that reusing them still had substantial implications. The most important metric for assessing the environmental impact of a reusing solution was the efficiency of repurposed "Power Supply Units (PSUs)" and "Uninterruptible Power Supplies (UPSs)." **Bixler et al., (2019)** [78] extended simulation to green infrastructure (GI), modeling nutrient cycles over a 30-year lifespan. It assessed seven distinct GIs using a dynamic system that mimicked the GIs' daily nutrition loads and therapies throughout the course of their 30-year longevity, in conjunction with a conventional LCA. For the seven GIs that were already in place on the URI campus, a foundational model had to be built, checked, and verified. Location, usage, GI layout dimensions, and warming temperatures were among the variables that were included in the main model to evaluate alternative scenarios. The life cycle nitrogen decreases ranged from 100.91 to 513.01 kg N eq., and the life cycle phosphorous decreases ranged from 23.76 to 63.44, indicating that such variables significantly impacted GIs' life cycle outcomes. In addition, some GIs had nutritional content limits that they needed to meet in order to compensate for the chemical outputs that resulted from their development and upkeep processes. Simulation-based optimisation continued to inform decisions about devices and systems that use sustainable energy. **Cusenza et al., (2019)** [79] analyzed the framework that supplied energy to a nearly net-zero domestic structure (25,000) using a BESS constructed from expired Li-ion battery packs, a 20 kW PV plant, and the power grid. To optimize load matching and ecological effects from a life cycle viewpoint, it became necessary to determine the ideal size of the BESS, which was represented as its energy capability. A BESS with a power reserve of 46 kWh did a lot in terms of increasing the load match and being environmentally sustainable. A LCA and a load matching investigation were both used in the study's sustainability evaluation. It drew attention to the ways in which the construction and automobile industries worked together in harmony, guided by the ideas of synergy in industry and the economy of circularity. **Arvesen et al,(2018)** [80] further formulated comprehensive methodology for extracting coefficients from thorough, bottom-up LCA that could be used in integrated assessment (IA) models, enabling IA researchers to investigate the life cycle effects of technological and scenario variations. The method disaggregated LCA values into life cycle stages and energy transport utilization by sectors, thereby enabling the assignation of life cycle impacts to specific years and ensuring a uniform and complete application of IA model-specific situation data while LCA coefficients were utilized in IA circumstances modeling. We illustrated the implementation of the technique for global power supply through 2050 along with our mathematical results (as supplemental material) for future reference by IA experts.

The current literature shows a consistent trend towards the creation of sustainable electronics using biodegradable materials, life cycle assessment frameworks, and circular design-based methodologies. Comparative studies demonstrate that, while the concepts of reuse and biodegradation offer promising prospects, their realization is largely dependent on contextual circumstances. Tools like artificial intelligence and eco-design tools support proactive sustainability, while simulation-based approaches ensure accuracy in material and device optimization. Together, the studies highlight the need for an overarching and interdisciplinary approach to sustainable electronics—where material science, digital innovation, and systems thinking come together to reduce the environmental footprint across the whole product life cycle.

2.3 Research Gap

Large gap in research exists with respect to the methodical incorporation of LCA into the early design stages of electronic products despite increased interest in green electronics and the tool's use for measuring environmental impacts. While many studies concentrate on investigating the environmental impacts of some materials, processes, or product categories, few frameworks combine LCA and eco-design principles in a way that guides the entire development of electronic devices which are all sustainable and recyclable. Again, LCA methodologies give importance to only specific parts or steps in the production process and do not consider the whole cycle life in an integrated approach. This gap prevents the opportunity for making informed decisions in terms of material choice, energy conservation, and disposal, which are some of the important domains for the reduction of the ecological footprint of electronics. Additionally, to keep up with the rapidly developing LCA methodology in line with technologies like AI-driven innovation and biodegradable materials, further robust research is needed to fill this gap and improve the application potential of LCA in the rapidly changing electronics sector.

Chapter 3

Low Power Design Techniques

3.1 Introduction to Low Power Design

The demand for energy-efficient electronic devices has risen due to growing environmental concerns and the need to reduce operational costs. Semiconductor manufacturing and usage account for a significant portion of global electricity consumption. Low power design techniques play a crucial role in mitigating power dissipation while maintaining device performance.

Why is Low Power Design Important?

- Increases battery life in portable devices (e.g., smartphones, laptops, IoT devices).
- Reduces heat generation, leading to better reliability and longevity.
- Lowers operational costs for data centers and computing infrastructure.

There are two major types of power dissipation:

3.1.1 Static Power

Static power, or leakage power, refers to the power that a circuit draws even though it is inactive (i.e., not switching). Unlike switching activity-based dynamic power, static power is a result of the leakage currents within transistors. These currents are the results of subthreshold conduction, gate leakage, and junction leakage of MOSFETs. The overall static power (P_{static}) for CMOS circuits is given by:

$$P_{\text{static}} = V_{DD} \times I_{\text{leak}} \tag{3.1}$$

Where V_{DD} is the supply voltage and I_{leak} is the leakage current, which has a number of components:

$$I_{\text{leak}} = I_{\text{sub}} + I_{\text{gate}} + I_{\text{junction}} \tag{3.2}$$

Where I_{sub} is the sub-threshold, I_{gate} is the gate, I_{junction} is the reverse-biased junction leakage current, respectively.

Where I_{sub} is the sub-threshold, I_{gate} is the gate, and I_{junction} is the reverse-biased junction leakage current, respectively.

Static power dissipation is now a major concern in today's nanometer-scale CMOS circuits, since leakage currents increase exponentially with transistor scaling. Various methods are employed to minimize leakage power in green electronic devices to improve energy efficiency.

3.1.2 Static Power Increase Trend in Advanced CMOS Technologies

In contemporary CMOS technologies, the contribution of static (leakage) power has grown dramatically, as seen in the above figure, particularly as device dimensions decrease below 100 nanometres. Because subthreshold leakage currents are in the nanoampere range, CMOS transistors, which include NMOS and PMOS pairs, were initially intended to have very low static power. Nevertheless, these leakage currents have increased into the microampere and even milliampere range at advanced technology nodes (such as 45 nm and below), leading to significant static power dissipation. In sub-100nm nodes, the percentage of leakage power approaches—and occasionally surpasses—dynamic power consumption, according to data from Intel and UMC. The fact that a historically dominant dynamic power now has a non-negligible static component highlights a significant design and sustainability challenge. Thus, it is now crucial to comprehend the mechanisms and mitigation techniques for leakage current in order to develop semiconductor devices that use less energy.

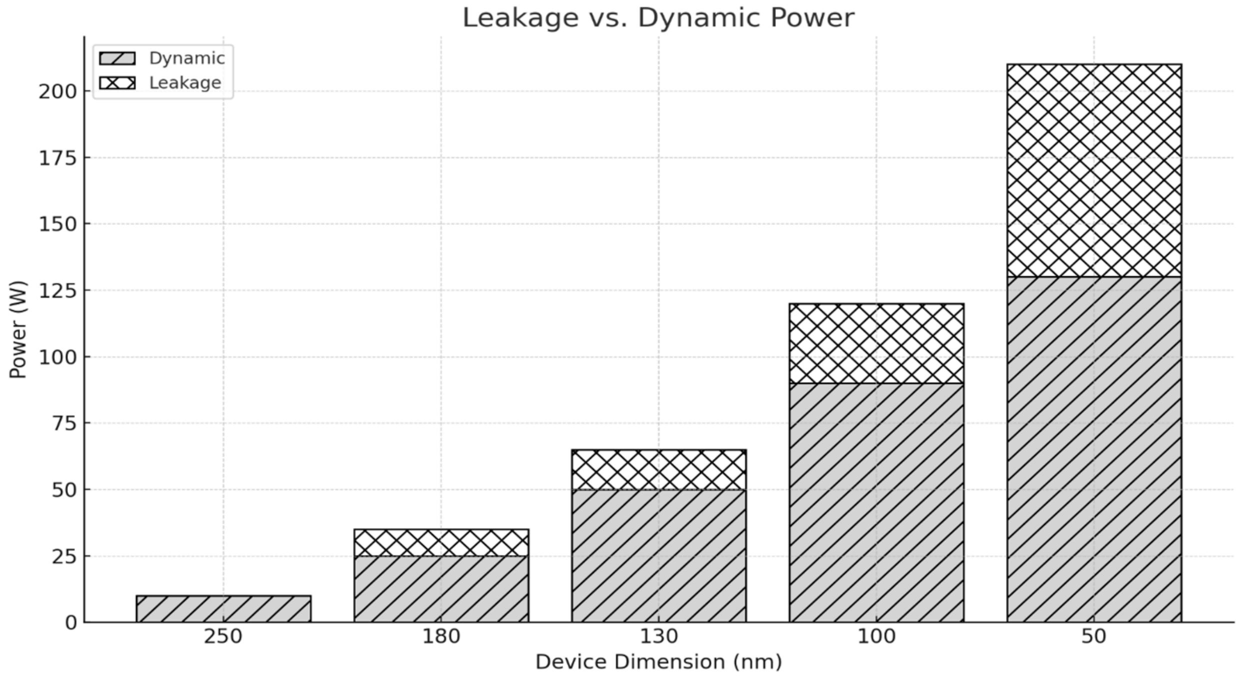

Figure 3.1. Increasing Leakage Power in Scaled Technologies

3.1.3 Leakage Current Sources and Mechanisms in Scaled CMOS Technologies

Several physical leakage mechanisms that become more prevalent as device dimensions decrease are responsible for the observed rise in static power consumption at advanced technology nodes. The main sources of leakage in MOS transistors under aggressive scaling are categorised in the figure below, which is an adaptation of Keshavarzi et al. (ITC 1997). Leakage is almost nonexistent in long-channel devices ($L > 1$ µm). However, a number of leakage currents become noticeable when the channel length and oxide thickness are decreased (for example, $L < 90$ nm, $Tox < 20$ Å):

Band-to-Band Tunnelling (BTBT): This phenomenon, which is particularly noticeable in areas with high doping, happens at reverse-biased junctions as a result of tunnelling from the valence band to the conduction band.

Gate-Induced Drain Leakage (GIDL) and Subthreshold Leakage Weak inversion and barrier lowering permit current to move from drain to source even when a transistor is "off."

Gate Oxide Tunnelling: Under strong electric fields, electrons can tunnel through the gate dielectric in scaled technologies with ultrathin oxide layers, causing gate leakage.

As CMOS technology scales, the emergence and dominance of different leakage currents shift

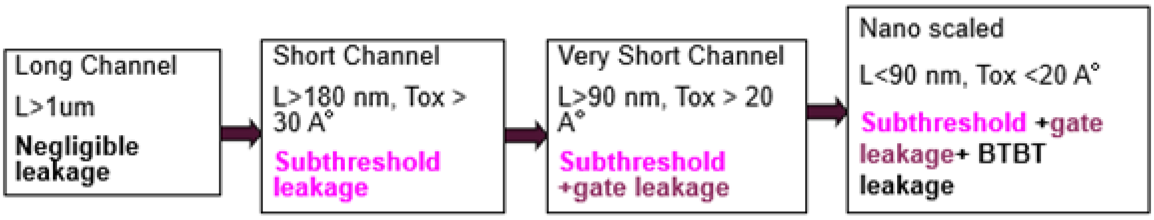

Figure 3.2. Sources of Leakages

depending on channel length (L) and oxide thickness (Tox). The table below summarizes how key leakage components—subthreshold leakage (Isub), gate-induced drain/gate tunneling leakage (IGIDL/ IGT), and band-to-band tunneling (IBTB)—become increasingly prominent as transistors scale from long-channel to nano-scaled geometries.

Table 3.1. Leakage Current Trends with CMOS Scaling

	L(μm)	Tox(μm)	I_{SUB}	I_{GIDL}/I_{GT}	I_{BTB}
Long Channel	>1	>3	x	x	x
Short Channel	>0.18	>3	Y	x	x
Very Short channel	>0.09	>2	Y	Y	x
Nano Scaled	<0.09	<2	Y	Y	Y

In long-channel devices (L > 1 µm), leakage is generally negligible. However, in short-channel and especially nano-scaled technologies (L < 90 nm), subthreshold leakage becomes significant. Gate leakage and band-to-band tunneling appear progressively as oxide layers thin and electric fields intensify, highlighting the need for robust leakage control mechanisms in deep submicron CMOS designs.
The evolution of static power components across CMOS technology nodes is summarised in the above figure. The contribution of various leakage mechanisms changes dramatically as technology becomes smaller. Leakage currents like subthreshold leakage, gate-induced drain leakage (GIDL), and junction reverse bias leakage were more evenly distributed and easier to control in previous generations (e.g., 180nm to 130nm). The other types of leakage have been greatly reduced by a variety of low-power design strategies, but in more sophisticated nodes—especially at 65nm and 45nm—gate leakage from direct tunnelling becomes the predominant component. Notwithstanding these developments, gate leakage is still a major problem in nanotechnology, necessitating additional material science and device architecture innovation to lessen its effects.

3.2 Static Power Reduction Techniques

Several low-power design techniques are used to minimize leakage power in electronic circuits. Below are the key methods, along with relevant formulas and principles.

3.2.1 Clock Gating:

Clock gating is not primarily used for static power reduction but can indirectly contribute to it by disabling clock signals to inactive circuit blocks. By preventing unnecessary toggling, it reduces switching activity, which in turn lowers overall power dissipation, including leakage power in idle states.

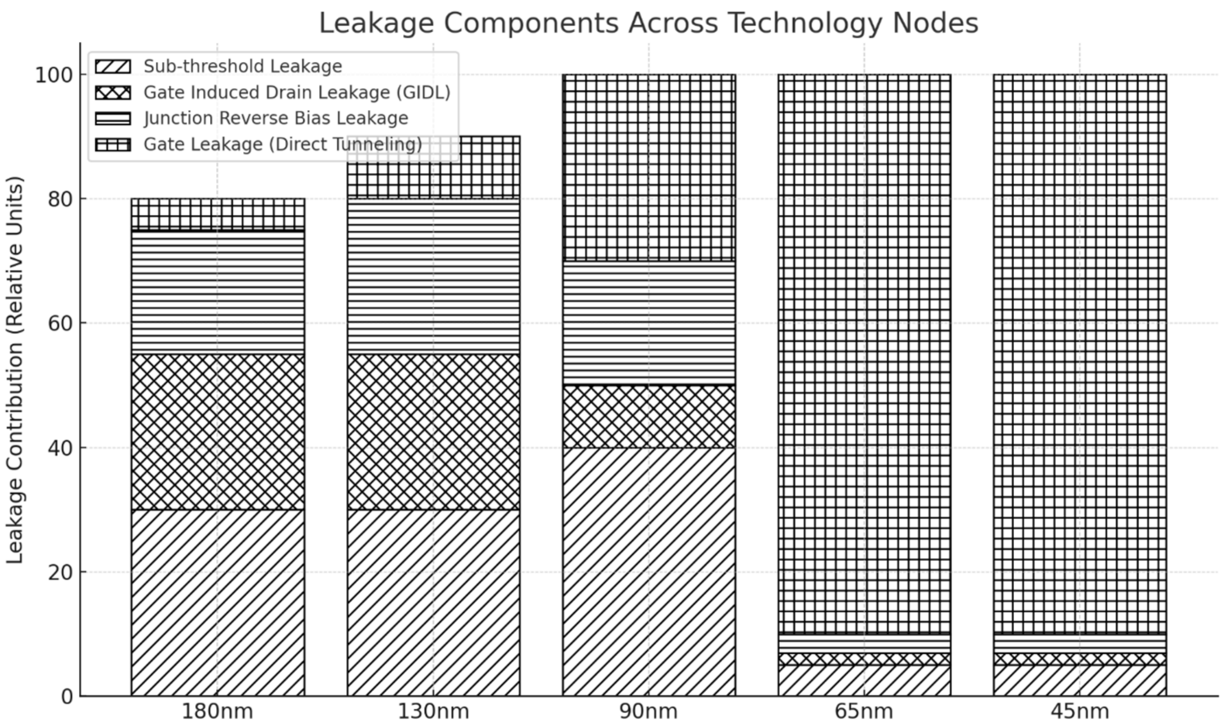

Figure 3.3. Leakage Components Across Technology Nodes

A clock gating circuit inserts an AND or OR gate before the clock signal to selectively disable it when certain conditions are met.

$$P = \alpha C_L V_{DD}^2 f$$

Where α is the switching activity factor, C_L is load capacitance, V_{DD} is supply voltage and f is the clock frequency.
By gating the clock signal when not needed, f effectively reduces, lowering power dissipation.

3.2.2 Multi-Threshold Voltage (Multi-Vth) Design

The Multi-V_{th} technique uses transistors with different threshold voltages (V_{th}) in different parts of the circuit. High-V_{th} transistors reduce leakage in non-critical paths, while low-V_{th} transistors maintain performance in timing-critical paths. The subthreshold leakage current (I_{sub}) is given by:

$$I_{\mathrm{sub}} = I_0 e^{\frac{V_{GS} - V_{\mathrm{th}}}{n V_T}}$$

Where I_0 is a process-dependent constant, and V_{GS}, V_{th}, and V_T are gate-source voltage, threshold voltage, and thermal voltage, respectively.

Using a higher V_{th} in non-critical paths exponentially reduces leakage current, leading to lower static power dissipation.

3.2.3 State Retention Power Gating (SRPG):

SRPG combines power gating with state retention. Unlike traditional power gating, which disconnects power completely, SRPG uses state retention flip-flops (SRFFs) to store logic states before turning off power. This enables fast wake-up with minimal data loss. The power savings come from reducing both leakage and dynamic power by selectively shutting down blocks without losing the system state.

$$P_{\text{leak}} = V_{DD} \times I_{\text{leak}}$$

With SRPG, I_{leak} is minimized during idle periods, leading to a significant reduction in static power.

3.2.4 Reverse Body Biasing (RBB)

RBB dynamically increases the transistor's threshold voltage V_{th} when the circuit is idle, thereby reducing leakage power.

$$I_{\text{sub}} = I_0 e^{\frac{V_{GS}-(V_{\text{th}}+V_{\text{body}})}{nV_T}}$$

where V_{body} is the reverse body bias voltage. By increasing V_{body}, leakage current exponentially decreases. RBB is especially useful in low-power standby modes of embedded and portable devices.

3.2.5 Sub-Threshold Logic

: Sub-threshold logic operates circuits below the transistor threshold voltage V_{th}, leading to ultra-low power consumption. This technique is widely used in sensor networks, biomedical devices, and energy-harvesting applications. Since dynamic power depends on V_{DD}^2, operating at sub-threshold levels dramatically reduces power. However, it comes at the cost of reduced performance.

$$P = C_L V_{DD}^2 f$$

Operating at sub-threshold levels reduces V_{DD}, leading to a quadratic reduction in power. Leakage Current Consideration is represented as in RBB:

Since V_{GS} is very small, leakage current is minimized, significantly lowering static power.

3.3 Dynamic Power

Dynamic power, also known as switching power, is the power consumed when transistors switch between logic states ($0 \rightarrow 1$ or $1 \rightarrow 0$). Unlike static power, which exists even when the circuit is idle, dynamic power dominates during active operation, making it a major concern for high-performance processors, mobile devices, and IoT systems.
The total **dynamic power** (P_{dyn}) in a CMOS circuit is given by:

$$P_{\text{dyn}} = P_{\text{switching}} + P_{\text{short-circuit}}$$

Where $P_{\text{switching}}$ is the power due to charging and discharging of load capacities and $P_{\text{short-circuit}}$ is power due to short circuit current when both NMOS and PMOS transistors conduct momentarily during switching.

Switching Power Formula:

$$P_{\text{switching}} = \alpha C_L V_{DD}^2 f$$

Where α is switching activity factor.
Short Circuit Power:

$$P_{\text{short-circuit}} = I_{SC} V_{DD}$$

Where I_{SC} is the short-circuit current caused by simultaneous conduction of PMOS and NMOS transistors during transitions.

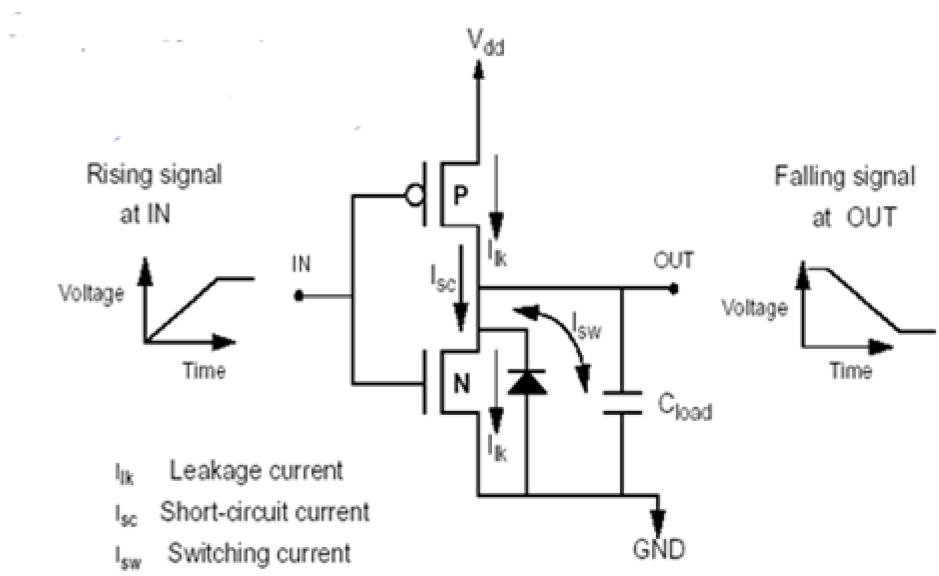

Figure 3.4. Power dissipation

Since dynamic power scales with frequency and voltage, efficient reduction techniques focus on reducing switching activity, voltage levels, capacitance, and short-circuit currents to improve energy efficiency in green electronic devices.

3.3.1 Dynamic Power Reduction Techniques

Several low-power design techniques are used to minimize dynamic power dissipation while maintaining performance. Below are key methods along with relevant formulas and principles.

Power Gating:

Power gating reduces dynamic power by completely disconnecting power from idle circuit blocks using sleep transistors. This prevents unnecessary switching activity in unused portions of the circuit.
o Sleep transistors (high-Vth MOSFETs) are inserted between the circuit and power supply.
o When idle, the sleep transistor is turned off, cutting power to the circuit block.
o When needed, the transistor is turned on, restoring normal operation.
Reduces both **switching power** and **short-circuit power** by preventing unnecessary transitions.

$$P_{\text{saved}} = \alpha C_L V_{DD}^2 f$$

Since f becomes zero in gated blocks, switching power is eliminated in those areas.

Dynamic Voltage and Frequency Scaling (DVFS):

DVFS **dynamically adjusts** the supply voltage (V_{DD}), and operating frequency (f) based on real-time workload demands, reducing power when full performance is unnecessary.

Since switching power depends on V_{DD}^2 and frequency f, reducing both significantly lowers power consumption:

$$P_{\text{dyn}} \propto V_{DD}^2 f$$

When high performance is needed → higher V_{DD} and f.

When workload is low → lower V_{DD} and f to save power.

Used in processors, mobile devices, and IoT applications to balance energy efficiency and performance.

◦ **Adaptive Body Biasing (ABB)**: ABB dynamically adjusts transistor body bias voltage to optimize performance and power trade-offs.

◦ **Forward body bias (FBB)**: Decreases threshold voltage (V_{th}), increasing speed but increasing power.

◦ **Reverse body bias (RBB)**: Increases threshold voltage, reducing leakage and lowering dynamic power.

Low Swing Signaling:

Reduces power by lowering the voltage swing (V_{swing}) of signals in interconnects, leading to lower capacitive charging power.

$$P_{\text{interconnect}} = C_L V_{\text{swing}}^2 f$$

Since V_{swing} is reduced, power consumption is minimized while maintaining data integrity.Used in high-speed communication buses, memory interfaces, and IoT sensors.

Energy-Efficient Encoding (Bus Encoding):

Minimizes bit transitions in buses by using encoding schemes like gray coding, T0 encoding, and bus-inversion encoding.

$$P_{\text{bus}} = \alpha_{\text{bus}} C_{\text{bus}} V_{DD}^2 f$$

Since encoding reduces α_{bus} (switching activity factor), significant power savings are achieved.

3.4 Cross-Layer Approach in Low Power Design

A single technique or design abstraction cannot solve the naturally multi-level difficulty low power design presents. As the table below highlights, good power optimisation calls for a complete plan including contributions from all tiers of the design and implementation stack. Neither architectural decisions, circuit design, nor transistor-level process technology—all of which contribute to optimal power efficiency—is enough on its own.

Practically, effective low power solutions result from a harmonic integration of methods covering:

- Power management at the systems and software levels
- Architectural refinements including parallelism and pipelining
- Clock gating, dynamic voltage scaling, and power gating—along with logic and circuit-level methods
- Innovations at the process and device levels including body biassing, SOI technologies, and FinFETs

This layered approach is crucial since every level targets various sources and kinds of power wastefulness. Designers can satisfy the strict power and performance criteria of modern electronics only by combining techniques across several domains—from the high-level system design down to silicon-level fabrication.

Table 3.2. Overview of Low Power Design Techniques

Dynamic Power	**Leakage Power**	**Design**	**Architectural**	**Circuit and Process Technology**
Clock gating	Multi Vth	Multi Vth	Pipelining/parallel	Multi Vth
Variable frequency	Power gating	Clock gating	Asynchronous	PD SOI
Variable power supply	Back (substrate) bias	Power gating	Low power IPs	FD SOI
Multi Vdd and Voltage islands	Use new devices - FinFet, SOI	Multi Vdd		FinFet
Glitch suppression, low swing signals		DVFS		Body Bias
DVFS		ABB		Multi oxide devices
Power/performance sizing		Glitch suppression		Minimize capacitance by custom design

3.5 POWER MANAGEMENT TECHNIQUES: Tradeoffs and design implications

Table 3.3. Tradeoff Analysis of Power Optimization Techniques

Power-reduction Technique	**Power Benefit**	**Timing Penalty**	**Area Penalty**	**Architecture**	**Design**	**Verification**	**Implementation**
Multi-Vt Optimization	Medium	Little	Little	Low	Low	None	Low
Clock Gating	Medium	Little	Little	Low	Low	None	Low
Multi-supply Voltage	Large	Some	Little	High	Medium	Low	Medium
Power Shut-off	HUGE	Some	Some	High	High	High	High
Dynamic and Adaptive Voltage	Large	Some	Some	High	High	High	High
Substrate Biasing	Large	Some	Some	Medium	None	None	High

Above table summarizes **tradeoffs** associated with different power management techniques.

Power gating and DVFS demand large methodology change whereas multi V_T and clock gating affect least.

Unless large leakage optimization is not necessary it is always beneficial to go with either multi-V_T or clock gating techniques.

Based on the design complexity and requirements combination of any low power techniques can be adopted. Multi-V_T optimization along with the power gating is found to be efficient in some of the complex designs.

Advanced improvements in the implementation (i.e. fabrication) technology has allowed substrate biasing techniques to be used heavily as it does not pose any architectural and design verification challenges **and also** provides high leakage reduction.

3.6 Design for 3R

The **"Reduce"** principle emphasizes the importance of maximizing power and energy efficiency for the system and circuit levels in detail as described in this chapter. In the meantime, the **"Repair"** and **"Refurbish"** principles, while more general, recommend sustainability through extended product longevity, reducing electronic waste, and reducing emissions of initial manufacturing processes. The principles are directed towards emphasizing importance for lifecycle thinking and environmentally friendly design processes, which are essential for low-power and eco-friendly design of electronics, especially for technical circuit design improvements.

3.6.1 Design for Reduce

The **"Design for Reduce"** approach focuses on minimizing power consumption throughout the lifecycle of electronic systems, from data centers to IoT devices, contributing to environmental sustainability. This strategy aligns with **green computing principles**, emphasizing **dynamic power reduction, energy-efficient architectures, and sustainable materials** to lower greenhouse gas (GHG) emissions. The **Reduce** strategy in green electronic design emphasizes minimizing resource consumption by enhancing efficiency in manufacturing and usage. It aims to lower energy demand, reduce material usage, and extend product lifespans to decrease environmental impact. Key aspects include:

- **Energy-efficient design**: Implementing low-power computing strategies such as **Dynamic Voltage and Frequency Scaling (DVFS)** and **multi-threshold voltage techniques** to reduce power consumption without compromising performance.
- **Material optimization**: Using fewer raw materials and adopting eco-friendly alternatives to limit resource depletion.
- **Modular and reconfigurable architecture**: Designing products that allow **component upgrades** instead of full replacements, reducing electronic waste.
- **Eco-conscious manufacturing**: Minimizing greenhouse gas emissions and waste production at every stage of the product lifecycle.
  By focusing on Reduce, electronic designs can significantly decrease environmental impact while maintaining high performance and reliability.

3.6.2 Design for Repair

The **Repair** strategy ensures that faulty electronics can be **fixed and maintained**, preventing premature disposal, and reducing electronic waste. This approach supports the concept of "Right to Repair", advocating for accessible repairs and component replacements. Key considerations include:

- **Disassembly-friendly design**: Allowing easy removal and replacement of defective parts, such as screens, batteries, and circuit boards.
- **Modular hardware and standardized interfaces**: Ensuring that components from different manufacturers remain interchangeable and repairable.
- **Software and firmware updates**: Enabling devices to stay functional through software reconfigurability, improving longevity without hardware replacements.
- **Repairability metrics**: Adopting rating systems, such as the French repairability score, to encourage manufacturers to design more repair-friendly products.

Promoting repairability reduces e-waste, conserves valuable resources, and extends product life, making it a critical aspect of sustainable electronics.

3.6.3 Design for Refurbish

The **Refurbish** strategy focuses on restoring outdated or defective electronics to a functional state, ensuring they remain useful rather than becoming waste. This process involves upgrading, reconditioning, and reusing old components to extend product lifespans. Essential aspects include:

- **Component replacement and performance enhancement**: Upgrading outdated parts to meet modern standards and efficiency requirements.

- **Testing and quality assurance**: Ensuring that refurbished devices comply with safety and performance regulations.
- **Remanufacturing techniques**: Reusing core components of defective or discarded products in new systems to reduce material waste.
- **Digital product passports**: Implementing tracking systems to monitor a device's lifecycle and refurbishment history for better circular economy management.

  By refurbishing electronics, manufacturers and consumers can contribute to **sustainable consumption** by reducing the demand for new raw materials, preventing excessive landfill waste, and promoting a circular economy.

3.7 Design Policies and Strategies for Green Electronics

The application of the Life Cycle Assessment (LCA) to the production of green electronic devices is required for the call for sustainability in the electronics sector. Several draft policies and rules are under discussion to prevent any harm to the environment, save the resource from depletion, and increase the lifespan of the product [81]. These methods emphasize the used energy that is utilized efficiently and the material that is reduced in type, waste manipulated and recycling, which ensures electronic devices will be in accordance with environmental sustainability goals. The creators adhere to a circular economy and regulations concerning electronics and carbon emissions but would like to do their part in these as well.

Eco-design, where the use of sustainable materials is the selection of materials, optimized energy usage, and product design for disassembly and recycling, is among the primary practices of green electronics [82]. Modular design, the third key practice, allows replacement of different parts rather than the entire device discarded, hence cutting down on electronic wastes.

Furthermore, energy-efficient design highlights the reduction in power use, achieved using advanced semiconductor technology and low-power circuit styles. The incorporation of non-toxic materials which can be easily broken down through natural processes is also on the rise to avoid creating harmful waste. In addition, the extended producer responsibility (EPR) laws which compel producers to take responsibility for the recycling and disposal of the device at the end of the device's lifecycle exist [83]. Such measures adhere to some standards in which the gadgets utilized will not be polluted and schools are likely to be an environment where the young ones will not be treated badly.

Table 3.4. Design Policies and Strategies for Green Electronics

Design Policy/Strategy	Description
Eco-Design	Incorporates sustainable materials, energy efficiency, and end-of-life management into product development.
Modular Design	Designs products with easily replaceable components to extend lifespan and minimize e-waste.
Energy-Efficient Design	Focuses on reducing power consumption through low-energy components and circuit optimizations.
Use of Non-Toxic Materials	Avoids hazardous substances, favoring biodegradable and recyclable materials.
Extended Producer Responsibility (EPR)	Encourages manufacturers to take responsibility for the entire product lifecycle, including recycling and disposal.
Design for Disassembly and Recycling	Ensures that products can be easily dismantled for material recovery and recycling.
Lightweight and Minimalist Design	Reduces raw material usage by optimizing product design without compromising functionality.
Smart Manufacturing Techniques	Uses AI, IoT, and automation to minimize waste and improve resource efficiency.

By integrating these approaches into electronic device design, companies can substantially mitigate environmental effects, encourage resource use efficiency, and enhance global efforts at sustainability. LCA-based integration into decision-making offers an evidence-based solution for evaluating and enhancing the environmental performance of electronic products across their life cycle.

3.8 Chapter Summary

In summary, these low-power design strategies are foundational to the development of energy-efficient, high-performance electronic systems. By reducing both static and dynamic power dissipation, these techniques directly impact device power consumption, extending battery life, reducing heat generation, and improving overall system reliability. These approaches also play a critical role in minimizing operational costs, enhancing device performance, and supporting environmentally sustainable electronics manufacturing. Furthermore, integrating design for 3R (Reduce, Repair, Refurbish) principles ensures that electronics have a reduced ecological footprint over their lifecycle, promoting the reuse of resources and contributing to a circular economy. As technology continues to evolve, these strategies will remain essential for achieving the next generation of green, energy-efficient electronics.

Chapter 4

Data Analysis and Interpretation

4.1 Power Dissipation and its Environmental Implication

The focus of the previous chapter was low power design approaches, stressing methods to reduce power consumption at several levels of electronic design. Although these strategies are necessary to improve efficiency and prolong device lifetime, the wider influence of power consumption goes much beyond only technical performance. It directly affects the carbon footprint of electronic systems, so greatly increasing world greenhouse gas emissions.

This chapter addresses the important link between power dissipation and its environmental effects—more especially, the relationship between power consumption and equivalent CO_2 emissions. The energy needed to run electronic devices—often derived from carbon-intensive energy grids—along with the demand for these devices keeps rising. By raising the carbon footprint of digital technologies, this reliance not only increases running costs but also speeds up climate change.

Development of more sustainable electronics depends on an awareness of this link. This chapter seeks to assess the environmental effect of power dissipation, investigate the elements controlling CO_2 emissions, and investigate possible approaches to lower this carbon footprint. This study offers a whole picture of the environmental consequences of power consumption in contemporary electronics by bridging the gap between low power design and sustainable practices.

The below table shows the Regional Variations in Electricity Carbon Intensity for the year 2023. One must *take into account* the carbon intensity of the power grid in addition to the electricity mix if one is to fairly evaluate the environmental impact of semiconductor use across different areas. Expressed in grams of CO_2 emitted per kilowatt-hour (gCO_2/kWh), carbon intensity offers a direct indicator of the environmental cleanliness or pollution level of a nation's electrical supply.

Table 4.1. Regional Variations in Electricity Carbon Intensity (2023)

Entity	**Code**	**Year**	**Carbon intensity of electricity - gCO_2/kWh**
Australia	AUS	2023	548.69226
China	CHN	2023	582.31696
France	FRA	2023	56.03859
Germany	DEU	2023	380.95047
India	IND	2023	713.4407
Italy	ITA	2023	330.71823
Japan	JPN	2023	485.39236
Norway	NOR	2023	30.080084
Russia	RUS	2023	441.03885
Switzerland	CHE	2023	34.842716

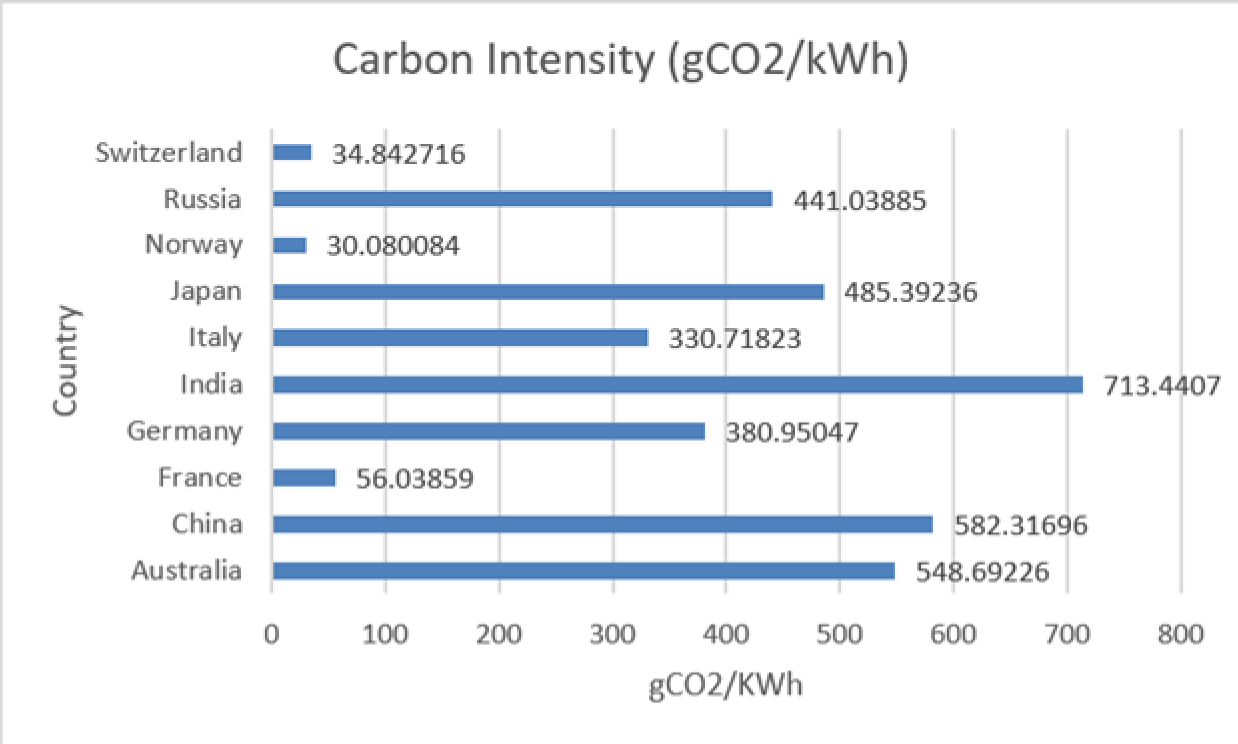

Figure 4.1. Carbon Intensity of Electricity generation, 2023

Data Source : Ember(2024); Energy institute – Statistical Review of World Energy (2024) [84].

Reflecting India's great reliance on coal and other fossil fuels, India boasts the highest carbon intensity—713 gCO_2/kWh [83] . Thanks to its mostly renewable energy mix—mostly hydropower—Norway has the lowest carbon intensity (30 gCO_2/kWh). Given its great nuclear power capacity, which generates zero direct CO_2 emissions, France also ranks low (56 gCO_2/kWh). Despite rising investments in renewable energy, nations including Australia, China, and Russia remain high because of their continued reliance on fossil fuels.

4.2 Calculating Device CO_2 Emissions for One Hour of Usage

I show in this part the projected CO_2 emissions from one hour of use for several digital devices, including data centers, laptops, and cell phones. Reflecting the variations in energy production techniques and efficiency, this computation considers the carbon intensity of electricity across many nations. The aim is to underline how device use affects the environment and stress the need of sustainable energy sources in lowering the general carbon footprint of our digital infrastructure.

The calculations are based on the following factors:

- **Power Consumption of the Device (Watt-hour)**: The average power required to operate each device for one hour.
- **Carbon Intensity (gCO_2/kWh)**: The amount of CO_2 emitted per unit of electricity consumed, varying significantly by country based on their energy mix.
- **Total Emissions ($gCO_2/hour$)**: The resulting emissions calculated by multiplying the power consumption by the carbon intensity.

CO_2 Emissions per Device (India - 2023)

Table 4.2. CO_2 Emission Table (1 Hour Usage in gCO_2)

Country	**Carbon Intensity (gCO_2/kWh)**	**Laptop (gCO_2)**	**Mobile (gCO_2)**	**Data Center (gCO_2)**
Australia	548.69226	13.7173	2.7435	274.3461
China	582.31696	14.5579	2.9116	291.1585
France	56.03859	1.4010	0.2802	28.0193
Germany	380.95047	9.5238	1.9048	190.4752
India	713.4407	17.8360	3.5672	356.7204
Italy	330.71823	8.2680	1.6536	165.3591
Japan	485.39236	12.1348	2.4270	242.6962
Norway	30.080084	0.7520	0.1504	15.0400
Russia	441.03885	11.0260	2.2052	220.5194
Switzerland	34.842716	0.8711	0.1742	17.4214

- Country: India
  Carbon Intensity: 713.44 gCO_2/kWh
  Usage Duration: 1 Hour

Formula for Calculating Emissions:

- The total CO_2 emissions generated by an electronic device can be calculated using the following formula:

$$\text{Emissions (gCO}_2) = \frac{\text{Power (W)} \times \text{Carbon Intensity (gCO}_2\text{/kWh)}}{1000}$$

- To convert this to kilograms of CO_2, divide by 1000 again:

$$\text{Emissions (kgCO}_2) = \frac{\text{Power (W)} \times \text{Carbon Intensity (gCO}_2\text{/kWh)}}{1000000}$$

- **Detailed Hand Calculations(For Country-India)**:

- Laptop (25W): $(25 \times 713.44) / 1000 = 17.836$ gCO_2
  $17.836 / 1000 = 0.01784$ $kgCO_2$

- Mobile Phone (5W): $(5 \times 713.44) / 1000 = 3.567$ gCO_2
  $3.567 / 1000 = 0.00357$ $kgCO_2$

- Data Center (500W): $(500 \times 713.44) / 1000 = 356.72$ gCO_2
  $356.72 / 1000 = 0.35672$ $kgCO_2$

  These calculations illustrate the varying carbon emissions associated with different power consumption levels, providing a quantitative foundation for evaluating the environmental impact of electronic devices. The same calculation has been performed for other countries too.

Table 4.3. CO_2 Emission Table (1 Hour Usage in $KgCO_2$)

Country	Carbon Intensity (gCO_2/kWh)	Laptop ($kgCO_2$)	Mobile ($kgCO_2$)	Data Center ($kgCO_2$)
Australia	548.69226	0.013717307	0.002743461	0.27434613
China	582.31696	0.014557924	0.002911588	0.29115848
France	56.03859	0.001400965	0.000280193	0.028019295
Germany	380.95047	0.009523762	0.001904752	0.190475235
India	713.4407	0.017836018	0.003567204	0.35672035
Italy	330.71823	0.008268196	0.001653591	0.165359115
Japan	485.39236	0.012134809	0.002426962	0.24269618
Norway	30.080084	0.000752002	0.0001504	0.015040042
Russia	441.03885	0.011026571	0.002205194	0.220519425
Switzerland	34.842716	0.000871068	0.000174214	0.017421358

The above table presents the CO_2 emissions associated with the same set of electronic devices, calculated using the carbon intensity values for various countries, providing a broader context for understanding the global environmental impact of power consumption.

It is evident that countries relying heavily on renewable energy sources, like **Norway** and **Switzerland**, exhibit substantially lower emissions per device compared to coal-dependent regions such as **China** and **India**.

This table emphasizes the critical role of energy sources in determining the carbon footprint of electronic devices, reinforcing the importance of transitioning to cleaner energy systems to reduce global carbon emissions. It also underscores the need for localized power efficiency strategies to further minimize the environmental impact of digital technologies.

Here's a full breakdown of CO_2 emissions (in grams) produced by using a laptop, mobile phone, and data center server for 1 hour across different countries, based on their 2023 carbon intensity values. **Data Centers**, as the largest CO_2 contributors due to their intense power requirements, with a single data center in India emitting 356.72 $\mathbf{gCO_2}$, compared to just 15.04 $\mathbf{gCO_2}$ in Norway.

Devices in countries like Norway (30.08 $\mathbf{gCO_2/\ kWh}$) and Switzerland (34.84 $\mathbf{gCO_2/\ kWh}$) have significantly lower emissions compared to high-intensity regions like India (713.44 $\mathbf{gCO_2/kWh}$).

To further enhance the clarity of this data and provide a more intuitive understanding of the variations in CO_2 emissions across different countries, the bar chart has been included.

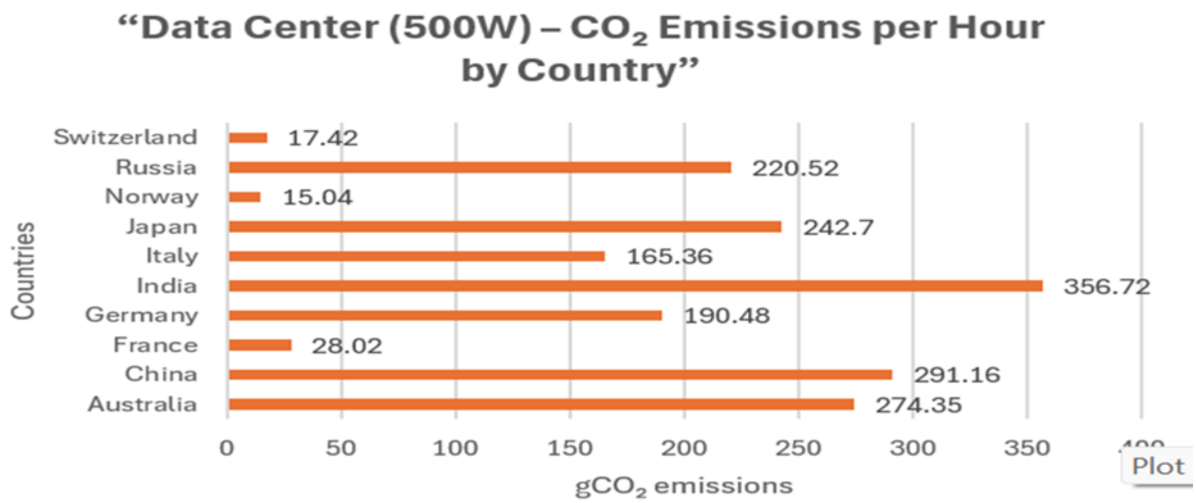

Figure 4.2. Data Center (500W)-CO_2 Emissions per hour by Country

Data Centers as the largest CO_2 Contributors-due to their intense power requirements, with a single data center in India emitting 356.72 gCO_2 compared to just 15.04 gCO_2 in Norway.

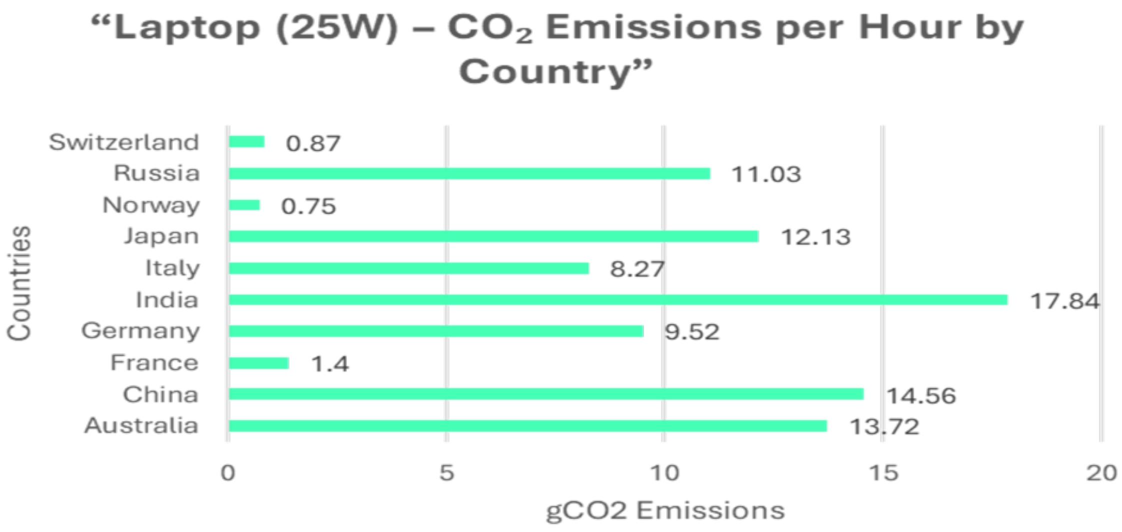

Figure 4.3. Laptop (25W)-CO_2 Emissions per hour by Country

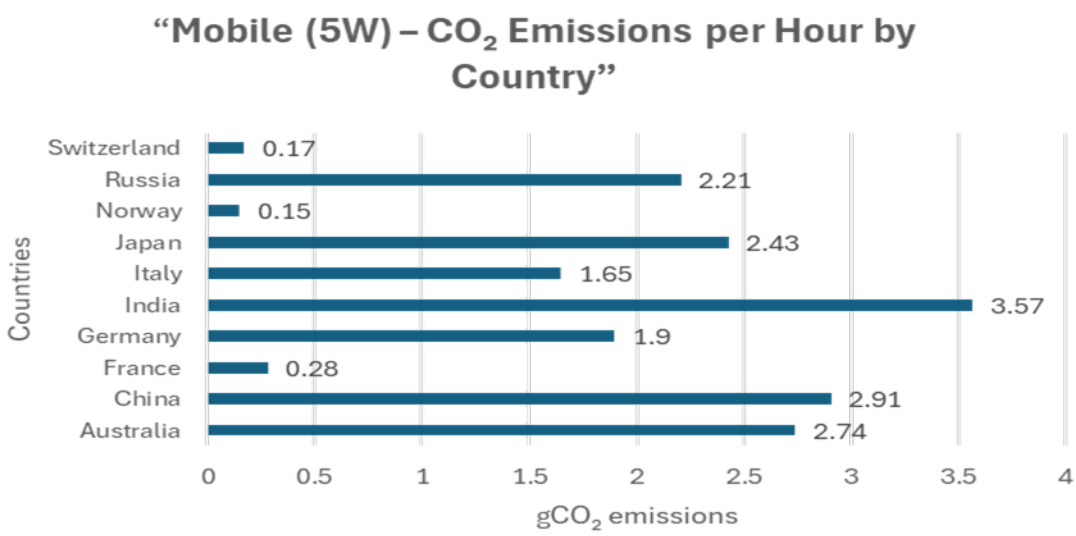

Figure 4.4. Mobile (5W)-CO_2 Emissions per hour by Country

4.3 Electricity Source Composition by Country and Its Impact on IC Power Sustainability:

Table 4.4. Electricity Production By Source (Measured in terawatt-hours)

Entity	Code	Year	Electricity from Renewables (TWh)	Electricity from Nuclear (TWh)	Electricity from Fossil Fuels (TWh)
Australia	AUS	2023	96.16	0	175.73
China	CHN	2023	2902.24	418.91	6125.6
France	FRA	2023	135.16	335.65	47.65
Germany	DEU	2023	246.66	61.43	263.76
India	IND	2023	344.01	49.74	1357.57
Italy	ITA	2023	114.8	0	427.78
Norway	NOR	2023	151.35	0	7.72
Russia	RUS	2023	260.84	217.47	753.16
Switzerland	CHE	2023	44.96	24.19	7.72

Examining national sources of electricity reveals important new information about the carbon footprint of semiconductor use[81]. For example, Norway and Switzerland produce very low operational CO_2 emissions by almost entirely depending on renewable and nuclear energy. On the other hand, nations like China and India, with great renewable capacity, still rely mostly on fossil fuels, so seriously compromising the environmental advantages of energy-efficient hardware. This emphasizes the need of taking geographic energy context into account in evaluating actual sustainability in addition to technical efficiency. Furthermore, nuclear-heavy systems like France show a reasonable middle ground for efficient running. Thus, sustainable deployment should coincide with regional electricity profiles and stress clean grid availability as much as hardware developments.

Table 4.5. Technology Node Scaling vs. Regional CO_2 Emissions: A 2-Year Impact Analysis

Technology Node (nm)	Typical Power Usage (W)	Manufacturing Energy (kWh)	Manufacturing CO2 (kg)	2-Year Operational Energy (kWh)
180	25	1000	400	438
130	18	2000	800	315.36
90	15	2000	800	262.8
65	13	2500	1000	210.24
45	10	3000	1200	175.2
32	8	3000	1200	140.16
22	6	3000	1200	105.12
14	5	3500	1400	87.6
10	4	3500	1400	70.08
7	3	5000	2000	52.56
5	2	7000	3000	35.04

Operational CO2 (Italy, kg)	Total 2-Year CO2 Impact (Italy, kg)	Operational CO2 (India, kg)	Total 2-Year CO2 Impact (India, kg)	Operational CO2 (Norway, kg)	Operational CO2 (Switzerland, kg)	Total 2-Year CO2 Impact (Norway, kg)	Total 2-Year CO2 Impact (Switzerland, kg)
102.054	502.054	310.104	710.104	13.17504	15.25992	413.17504	415.25992
73.47888	673.47888	223.27488	823.27488	9.4860288	10.9871424	609.4860288	610.9871424
61.2324	861.2324	186.0924	986.0924	7.896072	9.155592	807.896072	809.155592
40.8576	1040.8576	124.992	1124.992	5.26016	6.103968	1005.26016	1006.103968
40.8576	1240.8576	124.992	1344.992	5.26016	6.103968	1205.26016	1206.103968
20.44896	1420.44896	62.496	1462.496	2.63008	3.051984	1402.63008	1403.051984
20.44896	1620.44896	62.496	1662.496	2.63008	3.051984	1602.63008	1603.051984
20.44896	1820.44896	62.496	1862.496	2.63008	3.051984	1802.63008	1803.051984
16.37232	2416.37232	49.9776	2449.9776	2.105472	2.442816	2402.105472	2402.442816
12.24648	2512.24648	37.41264	2537.41264	1.5810048	1.8311056	2501.581005	2501.831106
8.16432	3008.16432	24.80832	3024.80832	1.0540032	1.2207936	3001.054003	3001.220794

Particularly for advanced nodes like 7 nm and 5 nm, manufacturing CO_2 emissions becomes the main determinant of semiconductor sustainability over a 2-year lifetime. Under these circumstances, over 90% of total emissions come from manufacturing; operational emissions have a negligible impact except in nations with high carbon intensity. This emphasizes the crucial need of strategically deploying energy-efficient hardware in clean-energy areas as well as, more crucially, extending device lifetime to enhance carbon amortizing. A brief two-year lifetime drastically reduces the environmental advantages of more recent nodes, hence sustainability becomes more about sensible consumption and regional energy policy than about only technological development.

4.4 Interpreting CO_2: From Abstract Figures to Tangible Impacts

Abstract carbon data (e.g., 18 gCO_2) often fails to evoke an emotional or practical response. To improve understanding, this study compares emissions from electronic devices with the CO_2 emitted by an average gasoline car. As shown in Table 4.5, using a laptop for one hour in India (2023) is equivalent to driving a car for approximately 93 meters, while using a data center for the same duration equals nearly 1.9 km of driving. This approach makes emissions more relatable and highlights the hidden environmental cost of routine digital actions.
Estimated CO_2 emissions and equivalent driving distances for typical digital device usage in India (2023), based on an electricity carbon intensity of 713.44 gCO_2/kWh and a vehicle emission factor of 0.192 $kgCO_2$/km (U.S. EPA) [85]. Estimated CO_2 emissions and equivalent driving distances for typical digital device usage in Norway (2023), based on an electricity carbon intensity of 30.08 gCO_2/kWh and a vehicle emission factor of 0.192 $kgCO_2$/km . Estimated CO emissions and equivalent driving distances for typical digital device usage in Norway (2023), based on an electricity carbon intensity of 30.08 gCO/kWh and a vehicle emission factor of 0.192 kgCO/km (U.S. EPA) [85].

Table 4.6. Device CO_2 Emissions and Car Distance Equivalent (India, 2023)

Device	Emissions (gCO_2)	Emissions ($kgCO_2$)	Car Distance Equivalent (km)
Laptop (25W)	17.84	0.01784	0.093
Mobile (5W)	3.57	0.00357	0.019
Data Center (500W)	356.72	0.35672	1.86

Table 4.7. Device CO_2 Emissions and Car Distance Equivalent (Norway, 2023)

Device	Emissions (gCO_2)	Emissions ($kgCO_2$)	Car Distance Equivalent (km)
Laptop (25W)	0.75	0.00075	0.004
Mobile (5W)	0.15	0.00015	0.001
Data Center (500W)	15.04	0.01504	0.078

A study of CO_2 emissions from digital devices in India and Norway reveals substantial discrepancies, primarily attributable to the carbon intensity of the energy grid. One hour of laptop usage in India, where fossil fuels predominate energy production, emits 0.01784 kg of CO_2, comparable to operating a gasoline vehicle for 93 meters. In Norway, where renewable hydropower prevails, laptop usage produces merely 0.00075 kg of CO_2, comparable to driving 4 meters.

All sorts of gadgets exhibit this trend. In India, smartphones emit 0.00357 $kgCO_2$ per hour, whereas in Norway, they emit 0.00015 $kgCO_2$ per hour. The carbon footprints of data centres differ markedly: in India, one hour of 500W use results in 0.35672 $kgCO_2$ emissions (equivalent to 1.86 km driven), whereas in Norway, it produces merely 0.01504 $kgCO_2$ (equivalent to 78 meters driven).

These discrepancies indicate that the environmental impact of digital technology is contingent upon location. The carbon intensity of the electricity utilised to operate gadgets dictates their "green" or "dirty" classification. User conduct can lead to CO_2 emissions that vary by a factor of 200, contingent upon the geographical location.

Regardless of the nation, data centres generate the highest amount of digital carbon emissions. Their substantial energy use renders them noteworthy even in low-emission nations such as Norway. As digitalisation advances, the demand for sustainable energy grids and enhanced energy-efficient computer infrastructure increases.

4.5 Quantitative Country-Wise Analysis of Laptop CO_2 Emissions and Real-World Environmental Equivalents:

From table 4.3 we have already calculated the CO_2 emissions in kgCO_2 for all three devices: laptop, mobile and data centre. If we consider that the entire population of the below-mentioned countries uses laptops for an hour, we can estimate the total CO_2 emissions for each country, and based on that, real-world equivalence has been computed . The country population data has been extracted from [86]. And all necessary calculations have been performed based on the methods defined below:

Table 4.8. One-Hour Laptop CO_2 Emissions by Entire Population

Country	Population	Total_Laptop_CO2_tons	Total_Mobile_CO2_tons	Total_DataCenter_CO2_tons
Australia	26451124	362.8381884	72.5676271	7256.763504
China	1422584933	20709.88	4141.976952	414197.6668
France	66438822	93.07846426	18.61569285	1861.150388
Germany	84548231	805.2172296	161.0434121	16104.34417
India	1438069596	25649.4352	5129.887615	512988.6896
Italy	59499453	491.9388594	98.38775999	9838.776891
Japan	124370947	1509.217687	301.8435623	30184.35374
Norway	5519167	4.150424622	0.830082717	83.00850349
Russia	145440500	1603.622735	320.724518	32072.54543
Switzerland	8870561	7.726681829	1.545375914	154.5372188

Table 4.9. Real-World Equivalents for 1-Hour Laptop Operation by Entire Population

Country	Total_Laptop_CO2_tons	Km driven by an average gasoline-powered passenger vehicle in one year	Homes' energy use for one year	Propane cylinders used for home barbeques	gasoline-powered vehicles driven for one year
Australia	362.84	1487012.46	48.7	16668	84.6
China	20709.88	84874903.4	2781	951393	4831
France	93.08	381461.86	12.5	4276	21.7
Germany	805.22	3300060.39	108	36991	188
India	25649.44	105118570.8	3445	1178131	5983
Italy	491.94	2016103.9	66.1	22599	115
Japan	1509.22	6185197.93	199	68232	352
Norway	4.15	17009.11	0.557	191	0.968
Russia	1603.62	6572095.55	213	73669	373
Switzerland	7.73	31666.98	1.2	355	1.8

The greenhouse gas equivalence calculator was used in order to calculate the equivalence mentioned in the table above.

Calculations:

1.km driven by an average gasoline powered passenger vehicle in an year:
The typical gasoline-powered passenger car's mileage
3.93 x 10-4 metric tonsCO_2e/mile [85, 87]

2. Home energy use:
Total CO_2 emissions for energy use per home 7.45 metric tons CO_2 per home per year [88, 89]

3. Propane cylinders used for home barbecues:
0.022 metric tons CO_2/cylinder[90, 88]

4. Gasoline-powered passenger vehicles per year:
4.29 metric tons CO_2e/vehicle /year [85, 87]

Observations:

1. Vehicle Distance Equivalent:
India leads with over 105 million km, more than China's 84.8 million km. France (381,461 km)

and Germany (3.3 million km) highlight a higher footprint for developed nations per unit CO_2. Norway's equivalent: 1,709 km — showcases the benefits of clean digital infrastructure.

2. Home Energy Use Equivalence:
India (3,445 homes) and China (2,781 homes) dominate, with Japan also high at 203 homes. This metric reflects how much total CO equals annual electricity use per average household.

3. Propane Cylinder Equivalence:
India: 1.17 million tanks
China: 951,393
Germany: 36,991
Norway: only 191, reinforcing its extremely low impact.

4. Vehicles Driven per Year:
India's emissions equate to 5,983 cars, and China's to 4,831 cars.
Germany: 188; Italy: 115; Japan: 352
Norway: <1 car, again showing excellent per-capita environmental performance.

India and China lead in emissions attributable to their substantial populations and elevated carbon intensity.
One hour of national laptop usage generates emissions equivalent to over 6,000 vehicles or the annual energy consumption of nearly 3,000 residences. European nations, such as France, Switzerland, and Norway, exhibit far lower emissions.Owing to more environmentally friendly electrical grids (reduced carbon intensity).Despite their populations, Switzerland and Norway produce nearly insignificant emissions.Mid-range nations like as Germany, Japan, and Italy continue to make substantial contributions (hundreds of homes or vehicles) owing to either moderate population levels or carbon intensity.

Summary:
India leads in vehicle distance equivalent, home energy use equivalent, and propane cylinder equivalent. India and China have the highest emissions due to their large populations and high carbon intensity. One hour of national laptop usage in India generates emissions equivalent to driving 653,178,14 miles or operating 5,983 vehicles for one year. European nations like France, Switzerland, and Norway have lower emissions due to more environmentally friendly electrical grids. Mid-range nations like Germany, Japan, and Italy contribute significantly due to their moderate population levels or carbon intensity.
This analysis highlights the critical significance of demographic size, carbon intensity of the electrical grid, and device energy efficiency in evaluating overall emissions. Even low-energy devices like laptops, when utilised on a national scale, can generate considerable environmental impacts within a mere hour.

4.6 Impact of Carbon Intensity on CO_2 Savings:

4.6.1 Introduction: Why Carbon Intensity Matters

Reducing the power consumption of electronic devices is an important step toward sustainability, but the environmental benefits depend significantly on where the devices are used. This is because the carbon intensity of electricity production—the amount of CO_2 emitted per kilowatt-hour—varies greatly by country. As a result, the same energy-saving technique may lead to vastly different emissions reductions in different regions.
This section explores the relationship between carbon intensity and CO_2 savings derived from low-power circuit design techniques. The goal is to show how much CO_2 can be avoided in

countries with varying energy profiles when deploying energy-efficient integrated circuits (ICs).

4.6.2 Methodology

We modeled a standardized scenario where a device saves 100 kWh of energy through low-power techniques. Using national carbon intensity values (Table 4.1), we calculated CO2 savings as follows:
Formula:

$$CO_2 \text{ Saved (g)} = \text{Energy Saved (kWh)} \times \text{Carbon Intensity } (gCO_2/\text{kWh}) \quad [91]$$

For ease of interpretation, we converted grams to kilograms and compared savings across seven power-saving techniques, such as clock gating, power gating, and subthreshold logic.

So if two identical chips save the same energy:

- In **India:** 100 kWh $\times$ 713 gCO_2/kWh = 71.3 kg CO_2 saved
- In **Norway:** 100 kWh $\times$ 30 gCO_2/kWh = 3.0 kg CO_2 saved

Same energy savings $\rightarrow$ dramatically different CO_2 impact depending on the grid.

4.6.3 Results and Discussion

All power-saving techniques (like DVFS, clock gating, subthreshold logic) work by reducing energy consumption of the IC.
Table 4.10 has been prepared taking into consideration the resulting power savings by employing various power reduction techniques as shown in Table 1.1.Also in the calculation the carbon intensity has been considered for different countries.It illustrates the estimated CO_2 savings for each technique in ten countries. In high-carbon countries like India and China, subthreshold operation results in savings of over 64 and 52 kg CO_2, respectively. In contrast, countries with clean grids like Norway and Switzerland yield savings of just 2–3 kg for the same energy reduction.
These results highlight the strategic value of deploying low-power designs in countries with fossil-fuel-heavy electricity. For example, optimizing ICs in Indian data centers offers far greater emissions reductions than similar deployments in Norway.

Table 4.10. Estimated CO_2 Emissions Saved (kg) by Low-Power Design Techniques across Different Countries (Based on 100 kWh Operational Reduction)

Country	Clock Gating (kg)	Power Gating (kg)	DVFS (kg)	MTCMOS (kg)	Body Biasing (kg)	Subthreshold Operation (kg)	Capacitance Reduction (kg)
Australia	13.717305	27.434613	21.9476904	21.9476904	16.4607678	49.3823034	8.2308339
China	14.557924	29.115848	23.2967824	23.2967824	17.4695088	52.4085624	8.7374544
France	1.400096475	2.8019295	2.2415436	2.2415436	1.6811577	5.0434731	0.84057885
Germany	9.523876175	19.047235	15.238018	15.238018	11.428511	34.2855423	5.71425705
India	17.8360175	35.672035	28.537628	28.537628	21.403221	64.209663	10.7016105
Italy	8.268795575	16.5359115	13.228792	13.228792	9.621593	29.4646407	4.96077345
Japan	12.134809	24.269618	19.4156944	19.4156944	14.5617198	44.1208732	7.28014854
Norway	0.7520021	1.5040042	1.20320336	1.20320336	0.90240252	2.70720756	0.45120126
Russia	11.02597125	22.0519425	17.641554	17.641554	13.2311655	39.6934695	6.61582575
Switzerland	0.8710679	1.7421358	1.39370864	1.39370864	1.04528148	3.13584444	0.52264074

4.6.4 Summary:

The effectiveness of low-power design techniques in reducing CO_2 emissions is strongly influenced by the carbon intensity of the electricity grid where the integrated circuit (IC) is operated. Carbon intensity, expressed in grams of CO_2 per kilowatt-hour (gCO_2/kWh), reflects how polluting a region's energy supply is. In countries such as India (713 gCO_2/kWh) and China (582 gCO_2/kWh), electricity is predominantly generated from fossil fuels, resulting in a high carbon footprint per unit of energy. Consequently, any reduction in power consumption due to techniques like dynamic voltage and frequency scaling (DVFS), power gating, or subthreshold operation translates into substantial CO_2 savings.

For instance, a 100 kWh energy reduction in India prevents over 71 kg of CO_2 emissions, whereas the same saving in Norway, with its clean hydropower-based grid (30 gCO_2/kWh), yields only 3 kg of savings. This contrast highlights that while energy efficiency is universally beneficial, its climate impact is maximized in high carbon intensity regions. Thus, sustainable chip deployment should strategically prioritize the use of power-efficient ICs in countries with carbon-heavy grids to amplify global emission reductions.

Power optimization offers the greatest CO_2 benefit in regions with high carbon intensity. Therefore, environmentally responsible hardware deployment should prioritize such regions to maximize global carbon mitigation. This geographic optimization aligns hardware efficiency with sustainability goals.

4.7 Technological Strategy: Material Substitution for Low-Carbon Dielectric Processing

Dielectric materials, essential in ICs, contribute significantly to lifecycle CO_2 emissions due to their high-temperature fabrication processes and influence on power consumption. Traditional materials like silicon dioxide (SiO_2) require processing at temperatures up to 900°C and support higher operating voltages, which increase energy use.

This section investigates replacing SiO_2 with high- materials such as tantalum pentoxide (Ta_2O_5), hafnium dioxide (HfO_2), and zirconium dioxide (ZrO_2) to reduce both manufacturing and operational emissions.

4.7.1 Comparative Performance Analysis

Table 4.11 compares key properties of four dielectric materials. Ta_2O_5 stands out with the highest dielectric constant, lowest threshold voltage, and superior mobility. These properties result in lower dynamic power consumption and support energy-efficient operation at reduced voltages. Conversely, SiO_2 necessitates gate voltages exceeding 18 V and leads to increased dynamic power dissipation [92].

Table 4.11. Dielectric Material Performance Comparison

Material	Deposition Temp (°C)	Threshold Voltage (V)	Mobility ($cm^2/V{\cdot}s$)	Power Reduction (%)
SiO_2	900	18.4	1.62	—
HfO_2	500	1.17	1.02	∼90%
ZrO_2	500	1.03	0.38	∼90%
Ta_2O_5	200	1.00	2.97	∼95%

4.7.2 Use-Phase CO_2-Equivalent Reduction Estimation

Given a decrease in power usage from 100 mW (SiO_2) to 5 mW (Ta_2O_5), and a device lifespan of 5 years (43,800 hours), the energy conserved per device is given by:

$$\Delta E = \Delta P \times \mathrm{t} \qquad [93]$$

where,
ΔE : Total energy saved (in watt-hours or kilowatt-hours)
ΔP : Difference in power consumption between two technologies or configurations (e.g., SiO_2 vs. Ta_2O_5)
t : Time of operation (in hours)

$$\Delta E = (0.1 - 0.005)\,\mathrm{W} \times 43800\,\mathrm{h} = 4.161\,\mathrm{kWh}$$

Utilising a global average grid emission ratio of 0.5 kg CO_2/kWh [94]:

$$\mathrm{CO_2\text{-eq\ Saved}} = 4.161 \times 0.5 = 2.08\,\mathrm{kg\ CO_2\text{-eq\ per\ device}}$$

This saving scales linearly with production volume:

Table 4.12. CO_2-eq Savings by Production Volume

Production Volume	**CO_2-eq Saved**
1,000 devices	∼2,080 kg
1 million devices	∼2,080 metric tons
1 billion devices	∼2.08 million metric tons

The results in Table 4.12 are obtained by multiplying the per-device CO_2-equivalent savings by the total number of devices manufactured. The savings per device, derived from a decrease in operational power (from 100 mW to 5 mW) over a 5-year period, is roughly 2.08 kg CO2-eq.The scaling is linear and adheres to this relationship:

$$\mathrm{Total\ CO_2\text{-eq\ Saved}} = \mathrm{Number\ of\ Devices} \times 2.08\ \mathrm{kg\ CO_2\text{-eq}}$$

Using Ta_2O_5 instead of SiO_2 can reduce operational power from 100 mW to 5 mW. Over 5 years (43,800 hours), this saves 4.161 kWh per device. At a global average carbon intensity of 0.5 kg CO_2/kWh, the reduction is approximately 2.08 kg CO_2-eq per device. Table 4.12 extrapolates this to production scales, showing potential savings of 2.08 million metric tons for 1 billion devices.

Besides the energy savings in the operating phase, the selection of dielectric material also significantly determines carbon dioxide emissions in the fabrication step. Classic dielectrics, such as silicon dioxide (SiO_2), require processing at high temperatures—commonly between 800 and 1,000 °C—with methods like thermal oxidation or low-pressure chemical vapor deposition (LPCVD). Advanced high-k dielectrics like tantalum pentoxide (Ta_2O_5), on the other hand, can be deposited at much lower temperatures (200-300 °C) using methods like sputtering or atomic layer deposition (ALD) [95]. The reduction of the thermal requirements results in less energy consumption per step and, accordingly, lower CO_2-equivalent emissions.

Thus, the replacement of SiO_2 by Ta_2O_5 yields a double environmental benefit:

- reduced CO_2 emissions in the production process.
- reduced power consumption in use due to Ta_2O_5's improved electrical characteristics.

The combination of these lifecycle benefits makes Ta_2O_5 an attractive material choice for green integrated circuitry development.

4.7.3 Manufacturing-Phase CO_2 Reduction

The energy to heat a 300 mm wafer from 200°C to 900°C can be estimated as below:
To estimate the energy:

$$Q = m \times C_p \times \Delta T \qquad [96]$$

Where:
Q = energy required to heat the wafer (in joules or kWh)
m = mass of the wafer (kg)
C_p = specific heat capacity (J/kg · K)
T = temperature difference (K or °C)

$$Q = 0.2\,\text{kg} \times 700\,\frac{\text{J}}{\text{kg} \cdot \text{K}} \times 700\,\text{K} = 98{,}000\,\text{J} = 0.0272\,\text{kWh}$$

CO_2-eq saved per wafer:

$$0.0272\,\text{kWh} \times 0.5\,\frac{\text{kg CO}_2}{\text{kWh}} = 0.0136\,\text{kg CO}_2\text{-eq} \qquad [94]$$

The per-wafer reduction is minimal, although it becomes substantial at elevated volumes:

- 1,000 wafers: approximately 13.6 kg CO_2
- 1 million wafers: approximately 13.6 **tonnes** of CO_2
- 1 billion wafers: approximately 13,600 **tonnes** of CO_2

Therefore, substituting Ta_2O_5 also reduces emissions during wafer processing. Lower deposition temperatures (200°C vs. 900°C for SiO_2) result in energy savings per wafer of 0.0272 kWh. Though small individually, this adds up across mass production: 1 million wafers save 13.6 metric tons CO_2 as shown above.

4.7.4 Summary

Transitioning from SiO_2 to solution-processed Ta_2O_5 has the advantages of decreased deposition temperature and substantially lower operational power, resulting in considerable CO_2-equivalent reductions during both production and utilisation. This corresponds with overarching decarbonisation objectives in the electronics industry and illustrates the capacity of material innovation to diminish lifecycle emissions of semiconductor devices.

4.8 Chapter Summary

The chapter explores the relationship between power dissipation in electronic systems and its environmental impact, focusing on carbon emissions. It begins with a regional comparison of electricity carbon intensity, revealing disparities in grid cleanliness across nations. Countries like India and China, which heavily rely on coal-based energy, have significantly higher carbon intensity than countries like Norway and Switzerland, which predominantly use hydropower or nuclear energy. A quantitative evaluation of CO_2 emissions for one hour of usage across various digital devices was conducted, showing how identical device usage can lead to vastly different emissions based on geographical energy sources. Emissions were translated into relatable metrics, such as car distance equivalents, to bridge the gap between abstract emission figures and user comprehension. The chapter also assesses nationwide CO_2 impacts by scaling device usage to each country's population, emphasizing the importance of aligning digital infrastructure strategies with local grid realities.
The chapter also examines the effect of carbon intensity on CO_2 savings from low-power design

techniques. Energy-efficient integrated circuits (ICs) yield more significant carbon reductions in high carbon intensity regions than in clean grid countries like Norway. A material-level strategy is proposed to further cut emissions: substituting traditional dielectrics like SiO with low-temperature, high-κ alternatives such as TaO. This transition could save 2.08 kg CO_2-equivalent per device and up to 13,600 tonnes of CO_2 per billion wafers during manufacturing.

Chapter 5

Conclusion Future Scope

5.1 Overview

This study presents a comprehensive examination of the environmental implications associated with the lifecycle of electronic devices, utilizing Life Cycle Assessment (LCA) as the principal analytical framework. LCA, governed by ISO 14040 and ISO 14044 standards, serves as a methodological foundation for quantifying environmental burdens from raw material extraction to end-of-life disposal. The investigation addresses both static and dynamic power consumption, evaluates cross-layer low power design techniques, and explores regional variations in electricity grid carbon intensity as a determinant of device-related CO_2 emissions.
By integrating technical analysis with sustainability strategies—such as design for 3R (Reduce, Repair, Refurbish), modularity, and energy-efficient architectures—the study advances the discourse on environmentally responsible electronics. Case studies of European firms engaged in green electronics provide practical insights into the implementation of sustainable design principles and the promotion of a circular economy. Furthermore, the research contextualizes CO_2 emissions by translating them into tangible equivalents, such as vehicle kilometers and ecological losses, enhancing interpretability for policy and design applications.

5.2 Conclusion

The results discussed in this dissertation highlight the importance of integrating sustainable factors in the early design stage of electronic products. The wide-scale utilization of Life Cycle Assessment (LCA) helps to determine key environmental hotspots along the entire life cycle of a product, hence providing a basis for decision-making which can help limit ecological footprints without diminishing performance functionality.

One of the key findings of this research involves the environmental trade-offs related to scaling technology. By and large, while smaller process nodes drive performance improvement and energy efficiency in operation, they simultaneously involve significantly higher CO_2-equivalent emissions through the fabrication process. The increased emissions are due to greater complexity, more material usage, and increased energy used over the course of manufacturing. The impact of manufacturing, which results due to scaling, is significant as chip sizes get smaller and integration densities get higher. Accordingly, under conditions where performance requirements permit, the use of larger technology nodes can result in lower lifecycle emissions, thus opposing the assumption that smaller nodes are always more sustainable.

The research shows that energy expenditures towards environmental sustainability in the electronics industry incur a significant rise at both the utilization and manufacture stages, specifically when the carbon intensity of the supply grid is high. It becomes necessary to adopt energy-efficient design practices like Dynamic Voltage and Frequency Scaling, power gating, and subthreshold logic in order to see energy savings and curb CO_2 emissions, the effects of which are particularly remarkable in regions depending on fossil fuel-based power sources. The life cycle analysis, which considers the energy conditions prevailing at specific localities, highlights the importance of local conditions in determining sustainable performance. The consideration of aspects like upgradeability, repairability, and recyclability can assist in steering towards circular economics and improved product lifecycles. Industry-led initiatives prove economic and operational viability; however, such approaches are optimal when supplemented by product return policies and modular-design principles. In summary, this research stresses the fact that environmental sustainability in the electronics industry is feasible through the concurrent convergence of life cycle assessment, green design, chosen technological nodes, and location-specific approaches.

5.3 Future Scope

Building on the current work, several avenues for future research and development are identified:

Integration of Artificial Intelligence in LCA

The use of artificial intelligence in the improvement of Life Cycle Assessment has the potential to significantly streamline the process. Through data management and analysis automation, AI can improve accuracy, reduce human input, and allow more dynamic appraisals during the initial stages of product design. Additionally, machine learning algorithms have the capability to predict the environmental impacts before the prototyping stage, hence making the factors of sustainability more manageable.

Expansion to Life Cycle Sustainability Assessment (LCSA)

Future research should explore the expansion of traditional Life Cycle Assessment (LCA) into the broader framework of Life Cycle Sustainability Assessment (LCSA). It means integrating environmental, social, and economic dimensions—combining approaches like Social-LCA and Life Cycle Costing (LCC) to evaluate trade-offs in a more integrated manner. It could lead to the understanding of the true implications of a product under real situations.

Development of Design-Integrated LCA Tools

The need for life cycle assessment tools goes beyond basic analysis capability to include interactivity and integration within the design environment. The integration of sustainability feedback within electronic design automation tools can help engineers make better decisions about material selection and architectural choices early on—when such decisions have the largest impact.

Material Substitution and Green Chemistry

Material selection remains the key means of reducing lifecycle effects. There is a need for research and development programs to identify alternative, safer, biodegradable, or recyclable substitutes to conventional materials, particularly for substrates and components. The application of green chemistry principles can help ensure such alternatives create no additional environmental or health risks.

Policy-Oriented LCA Applications

As policy platforms advance, the role of Life Cycle Assessment (LCA) in informing policy is expected to become more prominent. Results based on LCA can enhance approaches such as eco-labeling, extended producer responsibility, and border carbon adjustments. Combining LCA approaches with policy systems can help link technical analysis to legislative actions.

Consumer-Centric Environmental Metrics

In the end, the translation of complex environmental information into useful indicators—like the estimated carbon savings of each appliance—could enhance consumer understanding and encourage more sustainable behavior. Such transparency has the ability to shape market forces by making sustainability increasingly salient and valuable as a product feature.

In conclusion, this research contributes to the foundational understanding of sustainable electronics design and highlights the role of LCA as a transformative instrument for environmental stewardship in the electronics industry.

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