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Quantification of emissions in the ICT sector – a comparative analysis of the Product Life Cycle Assessment and Spend-based methods.

- *Optimal value chain accounting (Scope 3, category 1)*

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Abstract

Considering the rapid increase in the ICT (Information & Communication Technology) products in use, there is a risk of an increase in GHG emissions and electronic waste accumulation in the ICT sector. Therefore, it becomes important to account for the emissions in the ICT sector in order to take steps to mitigate them. There are several methods put forward under ETSI, ITU-T, GHG protocol, etc., which can be used to measure the emissions in the ICT sector. Two such methods are Product Life Cycle Assessment (PLCA) and Spend-based, which are used in this study to account for scope 3, category 1 emissions in the ICT sector. Scope 3, category 1 emissions are released during the raw material acquisition and part production phase of the ICT product's life cycle and account for a major portion of the overall emissions.

As the ICT sector is a very huge field of study in itself, two ICT products, namely smartphones and laptops, are considered in this study to calculate their overall scope 3, category 1 emissions. A list of influential components in smartphones and laptops is defined to be included in the Excel Management Life Cycle Assessment (EMLCA) tool to calculate the scope 3, category 1 emissions. A comprehensive comparison between PLCA and Spend-based methods is also studied during the process of calculating their emissions. These observations are then used to make critical analyses and compare the two methods under results and discussions based on various parameters described under them. Both the methods were found to be suitable for calculating the emissions, with some uncertainty, although the Spend-based method was a quicker approach to do so. The PLCA method, although more complex, was found to be more suitable for ICT product eco-design. Both methods required a different set of primary data and were sensitive to various components in smartphones and laptops. This study illustrates the parameters that affect PLCA and Spend-based methods and discusses the pros and cons of them depending on the situations they are used in.

Key words

ICT sector, Scope 3 category 1 emissions or Optimal value chain emissions, CO_{2e} emissions, GHG protocol, PLCA, Spend-based, Smartphones, Laptops, Display, Printed Wiring Board, Integrated Circuit, Solid State Drive, EMLCA, Sensitivity analysis & Uncertainty analysis.

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I would like to thank people in set A, where A= {x| x is either an important person in my life or has helped me to finish this thesis or both}.

Jai Shree Ram

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1. Introduction

In today's industrialized world, electronic products have become an integral part of everybody's daily life. The worldwide electronic devices in use have increased by six times in the previous 50 years, whereas the human population has barely doubled during the same time span [1]. The Information and Communication Technology (ICT) sector is not only evolving rapidly but also influencing society's lives along with having a substantial contribution to the overall economic growth [2] [3] [4].

The digital consumer devices under the Communication Technology (CT) devices segment, particularly smartphones, tablets, and Television (TV), overshadow the sales of consumer electronics in the global market for the new communication technology devices [5]. ICT sector consists mainly of computing devices (laptops, smartphones, personal computers, etc.), data centers (servers, storage systems, switches, etc.), communication networks (routers, modems, etc.), and equipment for entertainment and media (television, printers, monitors, etc.). Global sales of Information and Communication Technology (ICT) products are projected to grow immensely in the future as the ICT sector has experienced significant growth in the last few decades. The ICT sector is anticipated to grow even more in the coming decades as significant portions of the world's economy are still not digitized and new economies are entering the market [6]. For instance, the sales of laptops and mobile phones are predicted to increase from around 3 billion to more than 4 billion units each year globally [5] [7] [8]. Due to the short lifetimes of mobile phones and their low rates of recyclability and re-use (less than 10% of all units), this could result in an increase in electronic waste (e-waste) accumulation [9].

Simultaneously, it can also be seen that the awareness of the potential environmental impact of the ICT sector is growing, notably in terms of GHG emissions (e.g., [10], [11], [12], [13], [14]). There is a need to learn more about ICT's carbon footprint. Anyway, ICT is a powerful area in the battle against climate change. But this also comes with a significant cost because ICT products and services use energy, therefore every enabling solution has a carbon cost that must be calculated as a percentage of the reductions achieved in order to evaluate the solution objectively [15].

There are considerably high expectations of the ICT sector in terms of its potential contribution to sustainable development [2] [16]. According to a report from the Global e Sustainability Initiative (GeSI), the ICT sector has the ability to reduce 16.5% of the overall GHG emissions (of the total GHG emissions in 2020) through the applications in a variety of areas which include transportation, energy, land use, agriculture, buildings, consumer, buildings and service sectors [16].

Currently, the ICT sector accounts for approximately 8% of the global electricity usage and also results in nearly 2% of the total global carbon emissions [7] [17]. As in the coming decade, the manufacture of ICT goods is predicted to increase, which could result in increased energy usage and GHG emissions, particularly in the fields where electrical networks have relatively higher carbon intensity [7] [17]. In order to reduce the CO_2 and other GHG emissions, and increase CO_2 sequestration, research is being carried out across the globe in this field [17] [18]. As the ICT sector is sophisticated, disruptive, widespread, and expanding, we also need to learn more about its role as a contributor and off-setter.

"How do we measure the GHG emissions attributable to the ICT sector?", this is a big question. Calculating the answer to this question may take a long time, and even if we succeed, the outcome may not give us the desired information – or more significantly, what we need to know. As a result, it seems logical to state very explicitly what we do want to know, and then assess if the measures taken by us could help us achieve our demand.

The share of the ICT sector of total global GHG emissions can be measured using a carbon footprint, which is a calculation of the amount of GHG generated due to a product or an activity throughout its entire life cycle [19]. This comprises embodied emissions (GHG emissions generated during the extraction of raw materials, manufacture, and transportation to the company or consumer), use phase or operational emissions (from energy usage and maintenance), and the emissions during its end-of-life stage (emissions after disposal) [19].

As the technology is developing rapidly and so is the ICT sector, there is also an increase in the studies that try to assess the environmental impact of the new technologies in the ICT sector. Numerous types of ICT goods/products and their probable environmental impacts are examined in a variety of environmental assessment studies. Several studies [20] [21] [22] [23] have looked into the environmental effects of certain ICT products including phones, laptops, monitors, displays, desktops, etc. There are few studies (e.g., [16] [24]) that look at the ICT sector in a broader sense and give a systematic assessment of the sector's environmental implications and potentials, and while such studies include energy use and carbon footprint and in scope 3, upstream category 1 emissions, they fail to address optimal calculation approaches to be used by the companies according to the GHG protocols.

2. Background review

2.1 Emissions in the ICT sector

The total emissions during the life cycle of an ICT product can be categorized into scope 1, scope 2, and scope 3 emissions according to the Greenhouse Gas Protocol. These three scopes (scope 1, scope 2 & scope 3) have been created for greenhouse gas accounting and reporting in order to assist differentiate direct and indirect emission sources, promote transparency, and offer usefulness for various companies, their business goals, and also climate policies.

Scope 1 consists of the direct greenhouse gas emissions that come from the sources that a firm owns or controls, such as emissions from combustion in owned or controlled boilers, automobiles, etc. Few GHG emissions such as Chlorofluorocarbons (CFCs) and NOx, which are not covered by the Kyoto Protocol, are excluded from scope 1 emissions but they may be reported individually. The indirect GHG emissions caused due to the generation of purchased energy or electricity are included in scope 2 emissions of a company. The electricity that is purchased or otherwise brought into the company's organizational border is referred to as purchased electricity/energy. Emissions under scope 2 are produced at the power plants or facilities where the electricity used by the company is generated. All the indirect emissions, that occur in the reporting company's value chain (including upstream and downstream), which are excluded in scope 2 emissions fall under the category of scope 3 emissions. It is optional to report this category of emissions thereby allowing all additional indirect emissions to be handled. These emissions are generated by the sources that the company does not own or control and are a result of the company's activities or operations. Extraction and manufacturing of purchased resources, transportation of purchased fuels, and usage of paid products and services are all examples of scope 3 activities. Figure 1 shows the outline of the various scopes (scope 1, scope 2 & scope 3) and emissions across the value chain under GHG protocols and also differentiates between upstream and downstream activities along with the emissions related to them. The indirect emissions that are attributed to the acquired or purchased products/services/goods in an organization fall under upstream, scope 3 emissions whereas the downstream scope 3 emissions consist of indirect emissions that are related to products/services/goods that are sold in the market or to a consumer. [25]

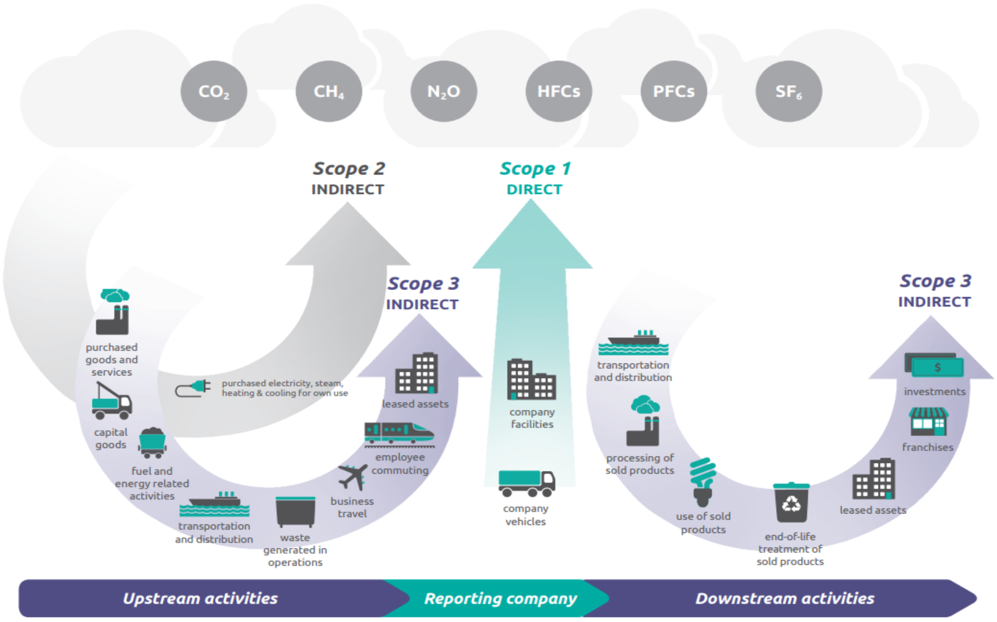

Figure 1: Outline of scopes and emissions across the value chain under GHG protocols [25].

These three scopes (scope 1, scope 2, and scope 3) are further divided into different categories wherein scope 1 has 4 categories, scope 2 has 1 category, and scope 3 has 15 subcategories (the categories in scope 1, scope 2, and scope 3 can be found in Figure 1). The majority of an organization's/company's emissions are attributed to scope 3 emissions and the same goes for the ICT sector too [26] [27].

Usually, scope 3 emissions have the impact scaling several times that of scope 1 and scope 2. As a matter of fact, especially ICT firms/companies cause or influence around 85% of global greenhouse gas emissions only via their purchases (i.e., purchased goods and services – Category 1 in scope 3 emissions) and the products they sell (i.e., consumption of sold items – Category 11 in scope 3 emissions) [28]. As most businesses and companies have greater direct control on scope 1 and scope 2 emissions, they have concentrated their efforts thus far on them [27]. There is an increasing interest to cut down the GHG emissions wherever feasible [27], including lowering emissions across the value chain/scope 3 emissions. Companies can choose whether or not to account for scope 3 emissions under the Corporate Standard. Many firms have been losing out on huge chances for improvement because a significant share of overall company emissions come from scope 3 category 1 sources. This is why Accounting and Reporting for the Corporate Value Chain or scope 3 category 1 emissions are so crucial. [29]

As mentioned, under scope 3 emissions, category 1 (i.e., purchased goods and services) and category 11 (i.e., use of sold items) contribute to about 85% of global GHG emissions in the ICT sector, we aim to concentrate on scope 3, category 1 emissions (cradle-to-gate) in our study and look at the carbon estimation methodologies present in the ICT sector, both on the product (PLCA- Product Life Cycle Assessment) and corporate level (Spend-based method). To further understand the importance of scope 3 category 1 emissions in the ICT sector, Figure 2 shows the emissions related to scope 1, scope 2, and scope 3 of one of the major companies in the ICT sector during the year 2018. It can be clearly seen that the product manufacturing stage under scope 3 category 1 contributed to the CO_{2eq} the most (76%) to the overall corporate emissions. OEM with a different product portfolio may have different trends.

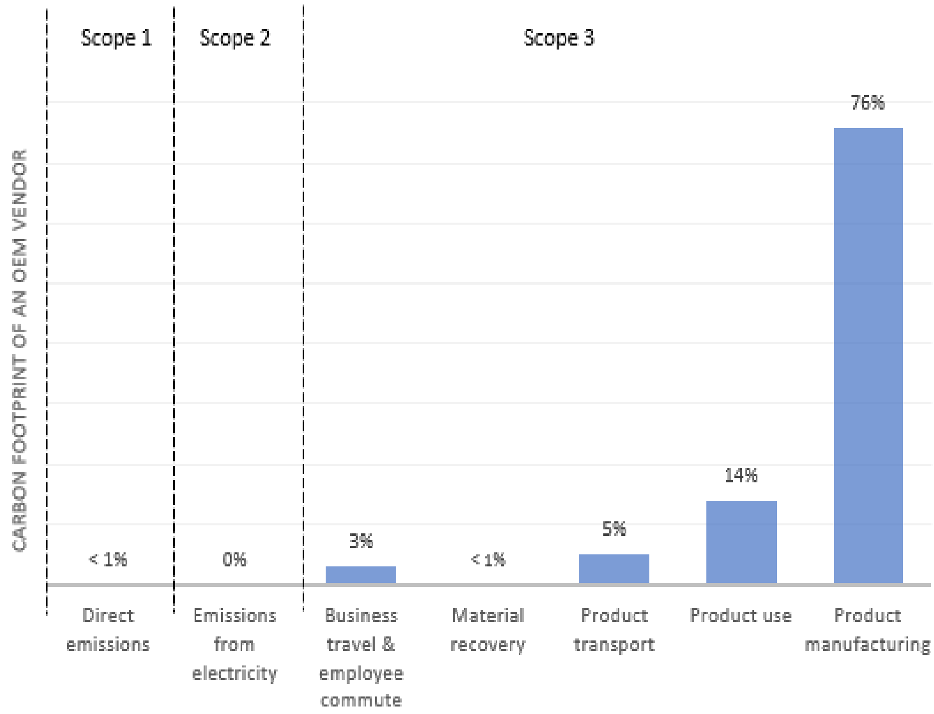

Figure 2: Scope 1,2 & 3 emissions in Apple’s overall carbon footprint during 2018. [30]

3. Literature review

3.1 ICT sector

In this study, the term "ICT sector" covers ICT goods or ICT products. Sometimes, the ICT sector is also referred to as "ICT solutions". ICT products are defined by Organization for Economic Cooperation and Development (OECD) to aid in the compilation of data for the economic analysis [4].

The following categories are included in its definition of ICT products and services [4]:

1. "Computers & peripheral equipment (e.g., desktop computers, laptops, printers, scanners, CPU, photocopy machines, etc.)
2. Leasing or rental services for ICT equipment (e.g., Installation of network towers for signal reception and transmission, etc.)
3. Telecommunications services (e.g., data transmission/reception services, fixed/mobile telephone services, network architecture, etc.)
4. Consumer electronic equipment (e.g., monitors, desktops, TV receivers, projectors, cameras, gaming consoles, microphones, etc.)
5. Information technology consultancy and services (e.g., website designing/hosting and developing services, IT support/consulting/design and development services, etc.)
6. Manufacturing services for ICT equipment
7. Miscellaneous ICT components and goods (e.g., Printed Circuit Boards (PCBs), Integrated Circuits (ICs), transistors, audio equipment, video processing equipment, diodes, etc.)
8. Business and productivity software and licensing services (e.g., database management software, network software, operating systems for computers like windows, mac os, Linux, ubuntu, etc.)
9. Communication equipment (e.g., Television cameras, Set-Top boxes, transmission equipment, ordinary mobile phones, smartphones, etc.)
10. Other ICT services (e.g., quality testing of network equipment, research, and development, measuring, navigating and testing network equipment)."

While discussing ICT's potential for future sustainability, [16] and [31] picked the term 'ICT products', but their definition in the discussion only consists of telecommunication networks (e.g., wireless networks, and fixed-line), end-user devices (e.g., mobile devices, Personal computers, and peripherals) and data centers (storage and cooling systems and servers). The 'ICT sector', according to [24], includes fixed and mobile telecommunications, data centers, personal computers, transport networks, and enterprise/corporate networks. The term 'ICT' is used in European [32] and is defined as a collection of all the technical means that handle the information in the network and also support communication (i.e., computer and network hardware and their software).

3.2 Global ICT carbon footprint

As the global Greenhouse Gas Emissions have increased historically, so did the emissions from the ICT sector. There have been several studies [24] [33] [7] that aimed at calculating the carbon footprint of the ICT sector during the period 2015 to 2020 and estimating the emissions thereafter. Figure 3 shows the estimated ICT sectors' global Carbon footprint in 2015 and Figure 4 shows the same for the year 2020 based on the studies [24] [33] [7]. The minimum estimated GHG emissions in the year 2015 were 775 $MtCO_2eq$ [33] and the maximum estimation for the same was 2,257 $MtCO_2eq$ in the worst-case scenario as shown in [7]. The average estimated GHG emissions from all the studies shown in Figure 3 for the year 2015 stand at approximately 1,250 $MtCO_2eq$. The minimum estimated GHG emissions in the year 2020 were 887 $MtCO_2eq$ in the best-case scenario as shown in [7] whereas, the maximum estimation for the same was 3,634 $MtCO_2eq$ in the worst-case scenario as shown in [7]. The average estimated GHG emissions from all the studies shown in Figure 4 for the year 2020 stand at approximately 1,620 $MtCO_2eq$ which is an increase of about 400 $MtCO_2eq$ in 5 years.

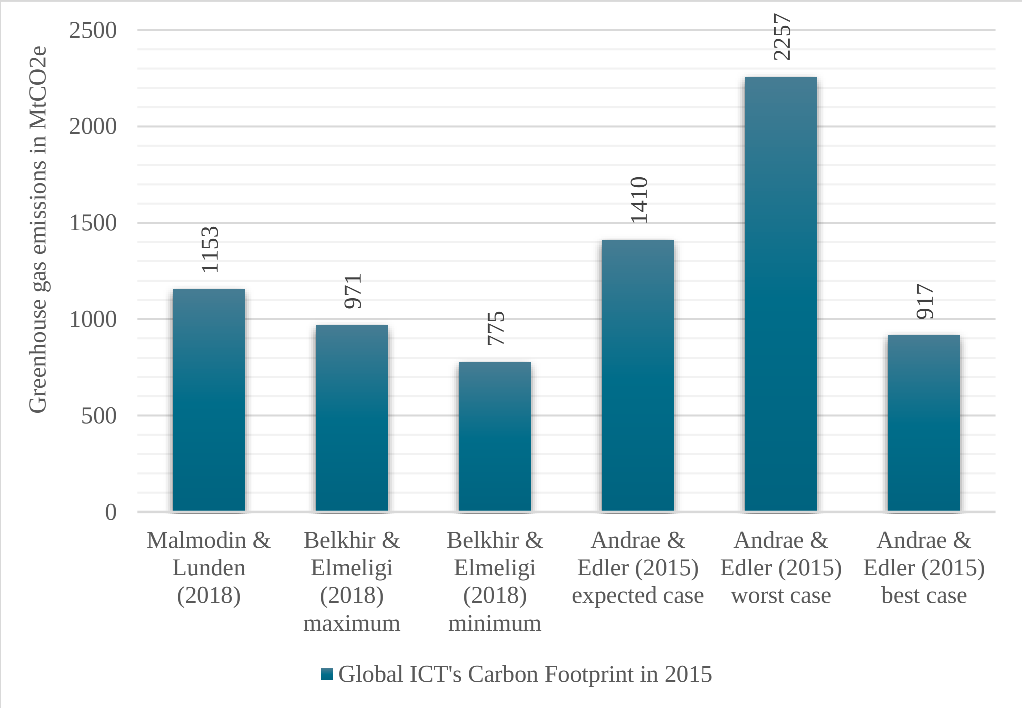

Figure 3: Estimation of ICT’s global Carbon footprint in 2015 [24] [33] [7] [26]

Currently, the leading research groups that are evaluating the energy use in the Information and Communication Technology sector are Ericsson with partners [24], [34], [35], [36], [37]; several Japanese organizations that are situated in Japan [38], [39]; University of Ghent [40], [41], [42], [43]; Global e-Sustainability Initiative [44]; University of Melbourne/Centre for Energy-Efficient Telecommunications [45], [46]; National University of Ireland, Galway [47], [48], [49]; The European Commission/ Öko-institute in Europe [50] and Alcatel Lucent/Bell Labs [51]. Furthermore, the University of Zurich and the Swiss Federal Laboratories for Materials Science and Technology are two of the most prominent institutions that describe the total sustainability footprint of the ICT sector [52].

In the study [24] ’s estimates, the ICT product, Television (TV) includes television networks and also a few other consumer electronic products where as in the study [7], they have estimated only Televisions themselves alongside including television peripherals. The study [24] does not include televisions and [24] ‘s original estimations for the ICT sector also took into account the paper media.

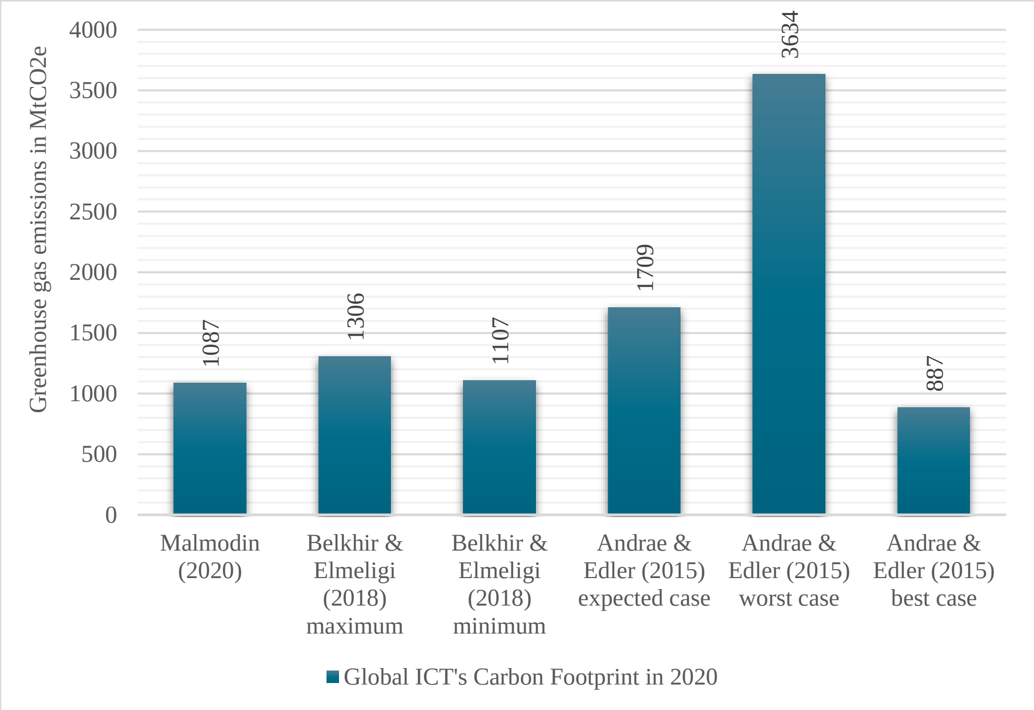

Figure 4: Estimation of ICT's global Carbon footprint in 2020 [24] [33] [7] [26].

3.3 Measuring the carbon footprint and scope emissions in the ICT sector

The GHG emissions released during the entire life cycle of an ICT product can be calculated using various existing methodologies in the market such as Product Life Cycle Assessment (PLCA0, Spend Based method, Hybrid method, Supplier Specific method, Average-data method, etc. To understand these methodologies and know how they work in detail and how they are interrelated, it is also important to know the life cycle phases and their relative scope emissions of an ICT product present in the ICT sector. These life cycle stages are briefed and not discussed in detail here as it is not the main focus of our study.

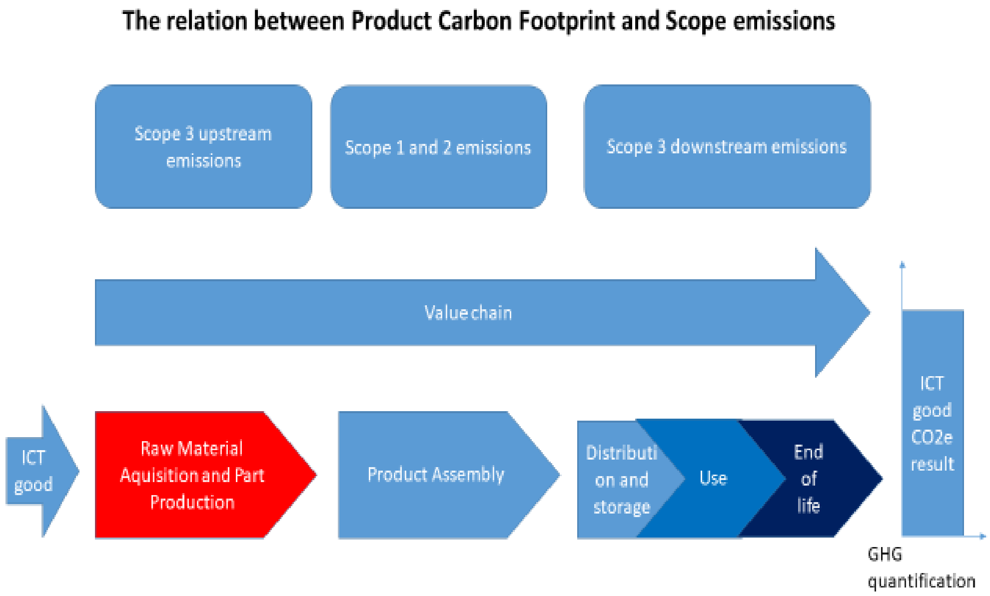

Figure 5: Life Cycle Stages of an ICT product and their relative emissions.

As shown in Figure 5, the life cycle of an ICT product can be divided into 5 stages namely Raw Material Acquisition and Part Production, Product Assembly, Distribution and Storage, Use phase of the product, and the End-of-life stage. Under the Raw material acquisition phase, the raw materials required for the manufacturing of the parts for the ICT product are extracted and processed to make them compatible with the further processes of part production. During the part production phase, the raw materials extracted and processed in the previous steps are used to manufacture the parts for the ICT products. These parts can then be assembled in the further phase called Product Assembly and a final, useable ICT product is obtained at the end of this phase. After an ICT product is manufactured, they are distributed to the retailers or consumers during the next phase in which retailers, sometimes, store the products in large quantities before shipping them to the consumers based on the demand of the product. The use phase of an ICT product is where consumers experience the product in person during which they operate, charge, get them repaired if any issue arises in the product, replace, etc. During the End-of-life phase of the ICT product, the devices are either reused, recycled, or processed further depending on the condition and functionality of the ICT product and its parts.

Figure 5 also shows the scope emissions related to their respective life cycle phase. The scope 3 upstream emissions, which come under the indirect emissions category, are attributed to the Raw Material Acquisition and part production stage whereas the indirect emissions under scope 3 downstream emissions come under the distribution and storage, use, and end-of-life phases of the ICT product. The direct emissions under the scope 1 emissions are released during the ICT product’s assembly stage whereas another category of indirect emissions, which is scope 2 emissions are also attributed to the product assembly phase of an ICT product. As mentioned in the introduction section under 1.2, most of the ICT companies concentrate their efforts on scope 1 and scope 2 emissions due to the fact that they have more control over them, they often choose to ignore the efficient calculation or inclusion of scope 3 categories of emissions in their product carbon footprint study. By doing this and not reporting their scope 3 emissions (as they are optional to be reported as per the GHG protocol), they also miss on a greater chance of reducing their overall GHG emissions and improving their overall product carbon footprint. It is also important to note that about 85% of the global GHG emissions in the ICT sector are attributed to scope 3 category 1 (i.e., purchased goods and services) and scope 3 category 11 (i.e., use of sold items) emissions. Therefore, I try to dig deeper into scope 3, category 1 emissions in the ICT sector, and focus my study on scope 3, category 1 (cradle-to-gate) emissions, and try to answer the question “Which corporate carbon foot printing method is more suitable to evaluate the upstream scope 3 category 1 emissions for the ICT sector?” Methodologies for Scope 3 category 1 are less clear and more likely challenging than those for Category 11.

3.4 Overview of various categories under the Scope 3 emissions

This section lists down all the categories under Scope 3 and throws extra light on Scope 3, category 1 as it is the main focus of our study.

Scope 3 emissions include all indirect emissions that occur in the reporting company's value chain (including upstream and downstream) and are not included in scope 2 emissions. It is optional to report this category of emissions, allowing for the handling of all additional indirect emissions. These emissions are a result of the firm's activities or operations and are created by sources that the company does not own or control.

The scope 3 emissions in the ICT sector are divided into upstream and downstream categories where the upstream scope 3 emissions and the downstream scope 3 emissions have 8 and 7 categories respectively. Hence, in total, the scope 3 emissions have 15 categories which are depicted in Table 1.

Table 1: List of upstream and downstream scope 3 emission categories [25].

Upstream/Downstream emissions	Categories under Scope 3 emissions
Upstream Scope 3 emissions	1. Purchased goods and services 2. Capital goods 3. Fuel and energy-related activities (not included in scope 1 or scope 2) 4. Upstream transportation and distribution 5. Waste generated in operations 6. Business travel 7. Employee commuting 8. Upstream leased assets
Downstream Scope 3 emissions	9. Downstream transportation and distribution 10. Processing of sold products 11. Use of sold products 12. End-of-life treatment of sold products 13. Downstream leased assets 14. Franchises 15. Investments

The description of Scope 3, category 1 emission alongside its minimum boundary is shown in Table 2. These details help to define the scope of the study and describe the boundary which is necessary for further evaluation of the carbon footprint of the ICT sector.

Table 2: Scope 3 category 1 description and minimum boundary [25].

Category	Description of the category	Minimum boundary
1. Purchased goods & services	Extraction, production, and transportation of goods and services purchased or acquired by the reporting company in the reporting year, not otherwise included in Categories 2 - 8	All upstream (cradle-to-gate) emissions of purchased goods and services.

3.4.1 Scope 3, category 1 emissions – Purchased goods and Services.

In this section, we discuss in detail the scope 3, category 1 emissions which is the main focus of our study due to the fact that it (scope 3 category 1) along with scope 3 category 11 contribute – from the viewpoint of the OEM vendors - to about 85% of global GHG emissions in the ICT sector [28].

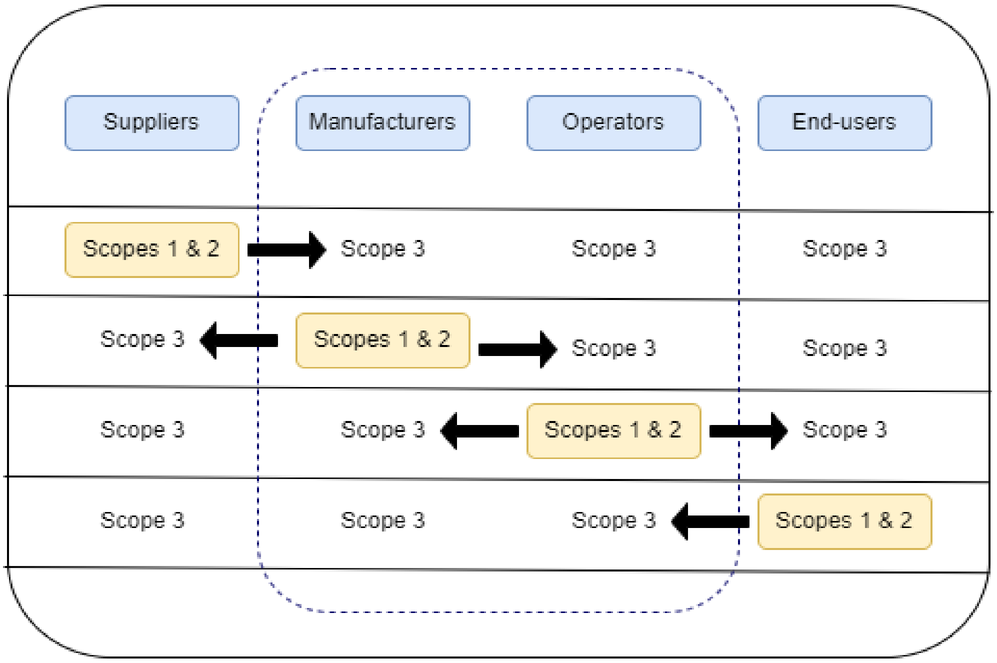

Figure 6: Relation between scope 1,2 & 3 emissions along the ICT value chain [28].

Figure 6 depicts how the different scopes (Scope 1,2 & 3) under ICT companies at various points throughout the ICT value chain are connected to each other and demonstrates the complexity of the idea of scope emissions. Our section of interest for this study is “Manufacturers”. It can be seen from Figure 6 that the scope 1 & 2 emissions from the suppliers contribute to the scope 3 emissions of the manufacturers and hence are termed as “indirect emissions” as they are not directly responsible for those emissions. Similarly, the scope 1 & 2 emissions of the manufacturers become scope 3 emissions for the “Operators” group and their scope 1 & 2 emissions become the scope 3 emissions of the “End-users”.

All the upstream emissions (1.e., cradle-to-gate) that occur due to the manufacturing/production of the goods that are purchased or acquired by the reporting organization during the reporting year are included in scope 3, category 1 emissions. Goods (products that are tangible) and services (products that are intangible) are both included in the product category. The emissions from all the purchased products and services that are excluded from all the other upstream scope 3 emission categories (i.e., from category 2 to category 8) are included in the upstream scope 3, category 1 emissions. In order to improve the transparency and consistency of scope 3 reporting, specific categories of upstream emissions are reported individually under scope 3, category 2 through scope 3, category 8. All the emissions that are emitted along the life cycle of the purchased goods, until the moment the reporting company receives it, are included in cradle-to-gate emissions. But in a reporting company, they do not take into account those emissions that come from sources which are owned/controlled by them. [25]

The cradle-to-gate emissions under scope 3 category 1 may include [25]:

1. “Extraction of raw materials
2. Agricultural activities
3. Manufacturing, production, and processing
4. Generation of electricity consumed by upstream activities
5. Disposal/treatment of waste generated by upstream activities
6. Land use and land-use change5
7. Transportation of materials and products between suppliers

8. Any other activities prior to acquisition by the reporting company Emissions from the use of products purchased by the reporting company are accounted for in either scope 1 (e.g., for fuel use) or scope 2 (e.g., for electricity use), rather than scope 3."

3.5 Measuring and reporting the scope 3, category 1 emissions

There are various measuring techniques or methodologies used to measure the emissions from different categories under scope 3. This section sheds light on a few of the popular techniques that are used in the corporate ICT sector. These techniques are used in the corporate value chain accounting and reporting in order to know the corporates' GHG emissions which can be beneficial for them to later implement mitigation measures or get an environment certificate, etc. The two main focused methods in this section (for this study) are Product Life Cycle Assessment (PLCA) and Spend-based methods. Hence, they are explained in detail for better understanding.

3.5.1 Product Life Cycle Assessment (PLCA)

a) International Telecommunication Union – Telecommunication (ITU-T L.1410 and L.1420)

The International Telecommunication Union's Telecommunications (ITU-T) standardization sector is in charge of organizing worldwide telecommunications standards and is also an agency of the United Nations (UN). The L-1410 and L-1420 are the two standards under ITU-T which are a growing set of standards dealing with the carbon footprint of the Information and Communication Technology sector. These standards are Greenhouse Gas focused Life Cycle Analysis (LCA) strategy that is compliant with ISO 14040 and 14044 which are internationally recognized LCA standards. ITU, in essence, is adapting the existing techniques in the ICT sector by regulating the processes and trying to minimize the existing uncertainties and the possibility of outcome variation. "L1400 provides an introduction, L1410 covers goods, networks, and services, L1420 covers ICT in organizations, L1430, L1440 and L1450 will cover ICT in projects, cities, and countries respectively". [53]

b) European Telecommunication Standards Institute (ETSI ES 203 199)- LCA of ICT equipment

The European Telecommunication Standards Institute or ETSI is a non-profit standardization organization which is situated across five continents. The goal of this standard is to concentrate on the need for uniformity in the Life Cycle Analysis (LCA) findings obtained in the ICT sector while staying consistent with widely recognized techniques like ISO 14040 and 14044 and the (International Reference Life Cycle Data System) ILCD handbook. Through a more regulated approach, the goal is to remove uncertainty and enhance the uniformity and transparency of the findings. Although the ETSI standard, which began in 2008 and was finished by 2011, is more particular to the ICT sector than the general standards, it is less detailed than the product category regulations for the ICT devices. [53]

The ICT product manufacturers intend to understand how they can reduce the environmental effects caused by every product as much as feasible. The Life Cycle Assessment or LCA is the main technique/methodology and instrument for meeting this demand today. The International Organization for Standardization has standardized the LCA method for all sorts of goods [7] while the European Telecommunications Standards Institute has standardized LCA for Electronics [54]. Regardless of the standardization of the LCA methodology, the LCA studies of similar consumer electronics (e.g., laptops, smartphones, etc.) are still variable and inconsistent which, in the present times, is a major challenge for the LCA methodology [55].

The LCA is a systematic analytical approach or a method and a model for estimating the Eco environmental impacts/effects of production systems with an order of magnitude ten times precision [54]. This method is primarily used for identifying the momentous Eco environmental features in the life cycle of the product, to be able to market the products with minimal environmental impacts, compare and contrast the new product concepts, achieve competitive advantages, and manage the risks [56].

The initial step in an LCA is to define the goal and scope, followed by gathering emissions and resource consumption data for the product or the service. The midpoint categories and midpoint category indicators are used in the impact assessment which is the third step in the LCA process. One of the midpoint categories and its respective midpoint category indicators are Ozone Depletion (OD) and UV-B radiation where the UV-B radiation is represented as Ozone Depletion Potential (ODP). Typically, ODP is measured in mass chlorofluorocarbon 11 equivalents (CFC-11e). Climate Change (CC), land use, and acidification are examples of additional midpoint categories [54]. Researches try to assign an economic cost (end-point modeling) to the final results of the assessed Eco environmental consequences in the fourth phase of the LCA study [57] [58] [59]. Product pricing that considers the costs of environmental impacts, if effective, is beneficial to the producers and also the policymakers. To limit the effects, it seems logical to support the use of best-practice manufacturing. LCA is a strong method that is becoming increasingly and commonly acknowledged and employed in planning and strategic thinking.

LCA is highly valuable as a “Compass”, primarily for internal reasons [60]. Figure 7 shows the Life Cycle stages of electronic products as defined by the ETSI. These stages are prior explained in section 3.3 Measuring the carbon footprint and scope emissions in the ICT sector.

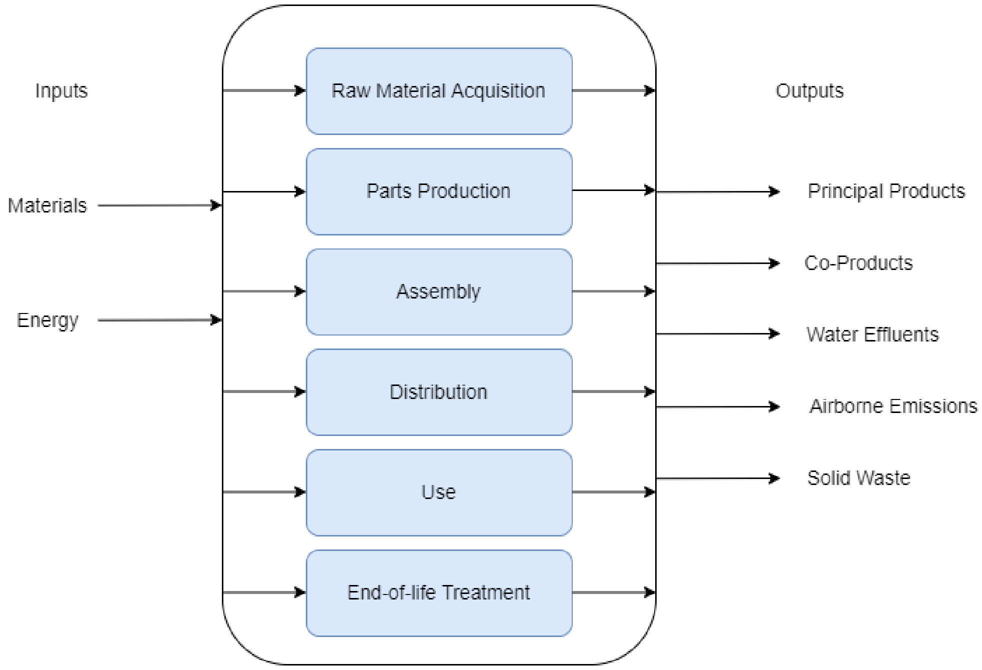

Figure 7: Life Cycle stages of electronic products as specified by the ETSI [54].

PLCA may not only be used for product eco-design, but also for corporate GHG accounting. The present thesis will deal with this topic.

3.5.2. Methodologies under Greenhouse Gas (GHG) Protocol for corporate carbon accounting of Scope 3 Category 1 emissions

There are four major methods under the GHG protocol that use different data types to measure and report the emissions from purchased goods and services (scope 3, category 1 emissions). Two types of data that are used in these methods include data collected from the supplier and secondary data (i.e., industry average data). The four different methods are the Supplier-specific method, Hybrid method, Average-data method, and Spend-based method. The Technical Guidance for Calculating Scope 3 emissions, Greenhouse Gas Protocol [62] defines the required activity data, emission factors, and data collection guidance for all the four methods which are mentioned further in this section. This section also explains, in brief, the Hybrid and Average-data methods whereas explains in detail the Supplier-specific and Spend-based methods which are further used in this study to measure and report the scope 3, category 1 emissions in the ICT sector.

1. Supplier-Specific method

The supplier-specific method uses data from the suppliers which are collected by the reporting company. This data is generally the GHG inventory data at the product level (cradle-to-gate) from the goods or services suppliers. Due to the fact that this method refers to the specific good/service acquired by the reporting company thereby avoiding the need for allocation, it is considered to be the most accurate among all the four methods [62]. The required activity data for this method is “Quantities or units of goods or services purchased” [62] and the emission factor needed is “Supplier-specific cradle-to-gate emission factors for the purchased goods or services” [62]. The data collection guidance for the supplier-specific method is explained in detail in the Greenhouse Gas Protocol under the Technical Guidance for Calculating Scope 3 emissions [62].

Companies should also seek information about the ratio of primary data to secondary data used to compute the emission factor when collecting emission factors from their suppliers. This data from the suppliers will show how much primary data was utilized by the suppliers to determine the emission factor for the products supplied by them. The amount of original data used to compute emissions factors are projected to rise as suppliers grow more sophisticated in their GHG assessments. This ratio may be monitored and tracked over time if the information on the ratio of primary and secondary data is collected. [62]

The formula to calculate the CO_2 equivalent emissions for purchased goods/services from their suppliers is given in GHG protocol as [62].

“CO_2e Emissions for Purchased goods/services =

Sum across purchased goods/services.

i.e., ∑ (Quantities of good purchased (e.g., kg) × supplier-specific product emission factor of purchased good or service (e.g., kg CO_2e/kg)).”

The supplier-based method seems challenging and burdensome for ICT OEM vendors.

2. Hybrid method

The reporting company, under the hybrid method of GHG protocol scope 3 emission measuring and reporting, requires to collect the data from their suppliers. Reporting firms should gather as much of the following activity data as possible for each supplier, pertaining to the good or service acquired [62]:

- “Allocated scope 1 and scope 2 data
- Mass or volume of material inputs
- Quantities of waste output other emissions”

The data collection guidance and the required emission factors for the hybrid method are explained in detail in the Greenhouse Gas Protocol document under the Technical Guidance for Calculating Scope 3 emissions [62].

The formula to calculate the CO_2 equivalent emissions for purchased goods/services in the Hybrid method where supplier-specific activity data is available for all activities that are associated with producing the purchased goods is given in GHG protocol as [62].

“CO_2e emissions for purchased goods and services =

the sum across purchased goods and services.

i.e., ∑ scope 1 & scope 2 emissions of tier 1 supplier relating to purchased good or service (kg CO_2e)

+

the sum across material inputs of the purchased goods and services

i.e., ∑ (mass or quantity of material inputs used by tier 1 supplier relating to purchased good or service (kg or unit) × cradle-to-gate emission factor for the material (kg CO_2e/kg or kg CO_2e/unit))

+

the sum across a transport of material inputs to tier 1 supplier

i.e., ∑ (distance of transport of material inputs to tier 1 supplier (km) × mass or volume of material input (tonnes or TEUs) × cradle-to-gate emission factor for the vehicle type (kg CO_2e /tonne or TEU/km))

+

the sum across waste outputs by tier 1 supplier relating to purchased goods and services

i.e., ∑ (mass of waste from tier 1 supplier relating to the purchased good or service (kg) × emission factor for waste activity (kg CO_2e /kg))

+

other emissions emitted in the provision of the good or service as applicable.”

The formula to calculate the CO_2 equivalent emissions for purchased goods/services in the Hybrid method was only allocated scope 1 and scope 2 emissions and waste data available from the supplier is given in GHG protocol as [62].

“CO_2e emissions for a purchased good where the supplier can only provide scope 1 and scope 2 emissions data and waste generated in operations data =

the sum across purchased goods and services

i.e., ∑ scope 1 & scope 2 emissions of tier 1 supplier relating to purchased good or service (kg CO_2e)

+

∑ (mass of waste from tier 1 supplier relating to the purchased good (kg) × emission factor for waste activity (kg CO_2e/kg))

+

∑ (mass or quantity of units of purchased good or service (kg) × emission factor of purchased good excluding scope 1, scope 2, & emissions from waste generated by the producer (kg CO_2e/kg or unit or $))"

The supplier-based method seems challenging and burdensome for ICT OEM vendors due to the number of assumptions for materials.

3. Average-data method

The CO_2 equivalent emissions for purchased goods and services in this method are determined by the product of data on the mass or other relevant units of purchased products/services (gathered by the reporting company) and their relevant secondary (e.g., industry average) cradle-to-gate emission factors. Process-based life cycle inventory databases may contain secondary emission factors [62]. The required activity data for this method is "Mass or number of units of purchased goods or services for a given year" [62] and the emission factor needed is "Cradle-to-gate emission factors of the purchased goods or services per unit of mass or unit of product" [62]. The data collection guidance for the average-data method is explained in detail in the Greenhouse Gas Protocol document under the Technical Guidance for Calculating Scope 3 emissions [62].

The formula to calculate the CO_2 equivalent emissions for purchased goods/services in the Average-data method is given in the GHG protocol as [62].

"CO_2e emissions for purchased goods or services =

the sum across purchased goods or services *i.e., ∑ (mass of purchased good or service (kg) × emission factor of purchased good or service per unit of mass (kg CO_2e/kg))*

or

∑ (unit of purchased good or service (e.g., piece) × emission factor of purchased good or service per reference unit (e.g., kg CO_2e/piece))"

The Average-data method seems similar to PLCA and will not be analyzed in detail in terms of benefits and drawbacks.

4. Spend-based method

The Spend-based method is elaborated in detail in this section as it is used further in our study to evaluate Scope 3, category 1 emissions in the ICT sector alongside the PLCA method. The data sources required for the activity data, emission factors, and the formula for the Spend-based method are also described below.

Companies should use the average spend-based method if the supplier-specific, hybrid, or average-data method is not suitable (which could occur due to limitations of required data/information). The CO_2 equivalent emissions for purchased goods and services in this method are determined by the product of collected data on the economic value of purchased goods and services by the reporting company and the relevant Environmentally-extended input-output (EEIO) emission factors [62]. The activity data needed for this method are "1. Amount spent on purchased goods or services, by product type, using market values and 2. Where applicable, inflation data to convert market values between the year of the EEIO emissions factors and the year of the activity data (e.g., dollars)" [62], and the emission factor needed is "Cradle-to-gate emission factors of the purchased goods or services per unit of economic value (e.g., kg CO_2e/$)" [62].

For data collection under this method, companies can suggest to include the following data which is mentioned in the GHG protocol guidance [62]:

"Data sources for activity data:

1. Internal data systems (e.g., Enterprise Resource Planning (ERP) systems)
2. Bill of materials (BOM)

3. Purchasing records.

Data sources for emission factors:

1. Environmentally extended input-output (EEIO) databases
2. Industry associations."

The formula to calculate the CO_2 equivalent emissions for purchased goods/services in the spend-based method is given in the GHG protocol as [62].

"CO_2e emissions for purchased goods or services =

the sum across purchased goods or services

i.e., ∑ (value of purchased good or service ($) × emission factor of purchased good or service per unit of economic value (kg CO_2e/$))"

The spend-based method seems to have good possibilities and advantages for Scope 3 Category 1 accounting. This method is also a key focus point in this study while comparing it with the PLCA method.

Figure 8 sums up all the different data types used for the various calculation methods under the GHG protocol (Supplier-specific method, Hybrid method, Average-data method, and Spend-based method) in relation to the product life cycle stages. This includes all other upstream emissions from the production of product and supplier's scope 1 and scope 2 emissions. Figure 9 provides GHG Protocol's generic decision tree to choose a calculation method for calculating the scope 3, category 1 emissions. For the ICT OEM vendor, Figure 9 may not be directly applicable.

There are different sources of variation which affect the PLCA scores of ICT goods. This is important as some companies use PLCA for Scope 3 Category 1 estimation while others use supplier-based, hybrid, average or spend-based, or others. The implications of different methods are not understood well at the corporate and ICT Sector levels. These implications are the target of the present thesis on corporate scope 3 category 1 accounting in the ICT Sector.

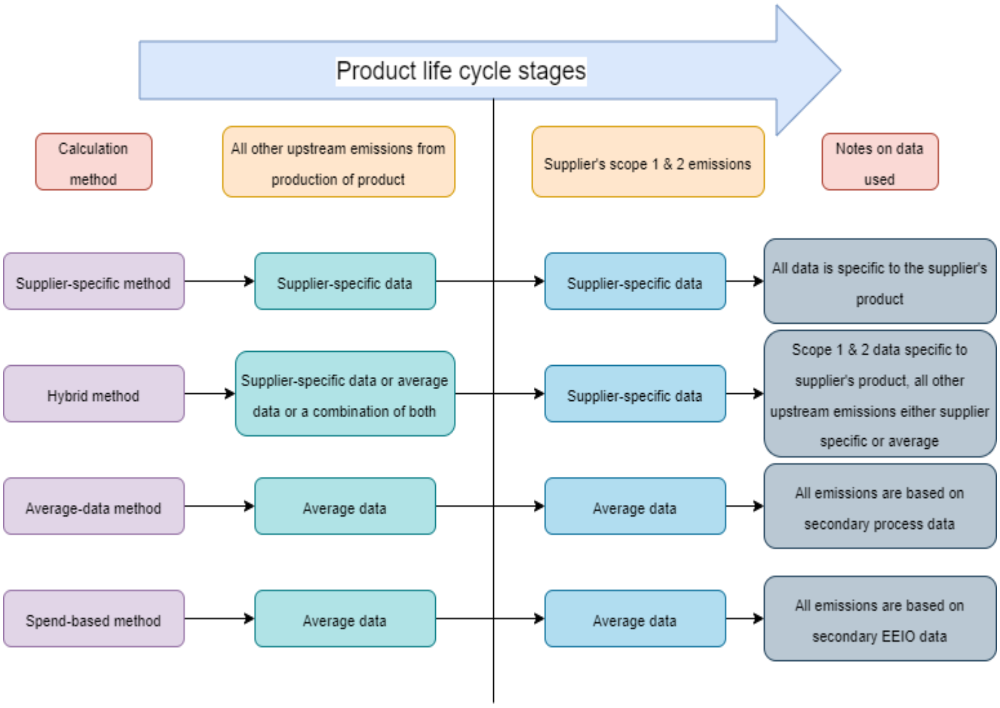

Figure 8: Data types used for various calculation methods under GHG protocol [62].

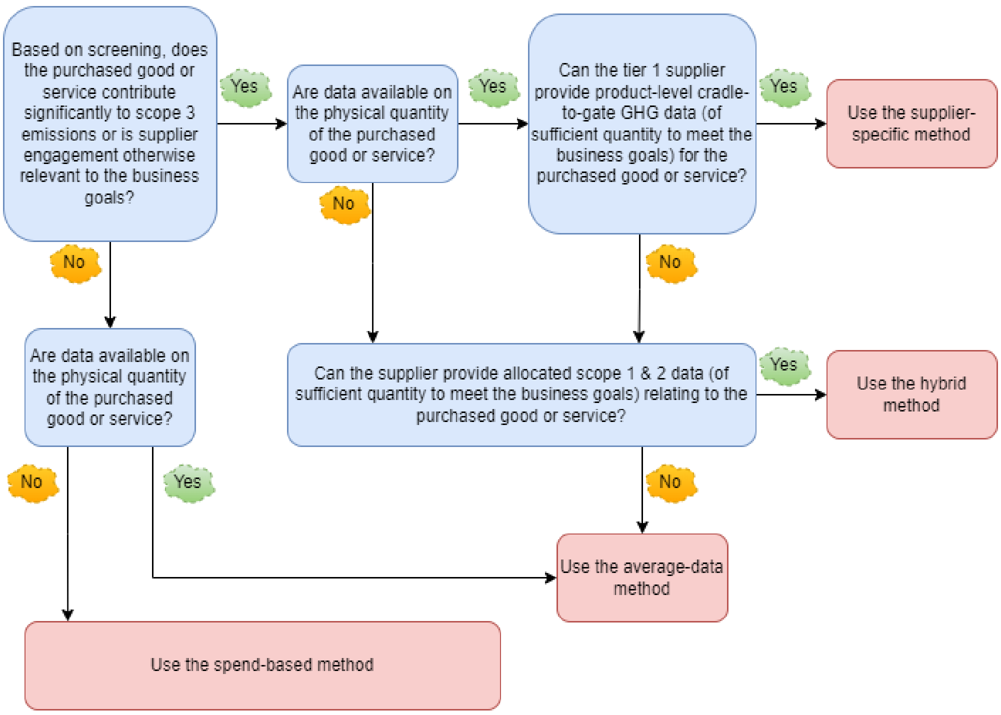

Figure 9: Choosing a technique for calculating emissions from scope 3, category 1 using a decision tree [62].

The objectives of this study are:

- To analyze the sensitivity and uncertainty of main parameters for ICT Sector carbon footprint level/Corporate level (Scope 3 Category 1) depending on which method is used to estimate (PLCA method or Spend-based method).
- To analyze the cost, speed, data availability, learning curve, future proof, number of assumptions, applicability, the feasibility of PLCA method and Spend-based method, respectively, for ICT Corporate and ICT Sector carbon footprint level Scope 3 Category 1 estimations.
- To analyze if PLCA can replace other approaches, for corporate/sector level carbon footprint with regards to data accuracy, data collection, and target setting for Scope 3, category 1 emissions.

4. Methodology

This section details the method used to attain the answers to the research questions of this study. A detailed literature review of the articles, papers, newsletters, and other literary works had to be done in order to understand the ICT sector, its significance in the overall global GHG emissions, scope 3 category 1 emissions in the ICT sector, and the methods used to account for these emissions. Figure 10 shows the method flow of this study.

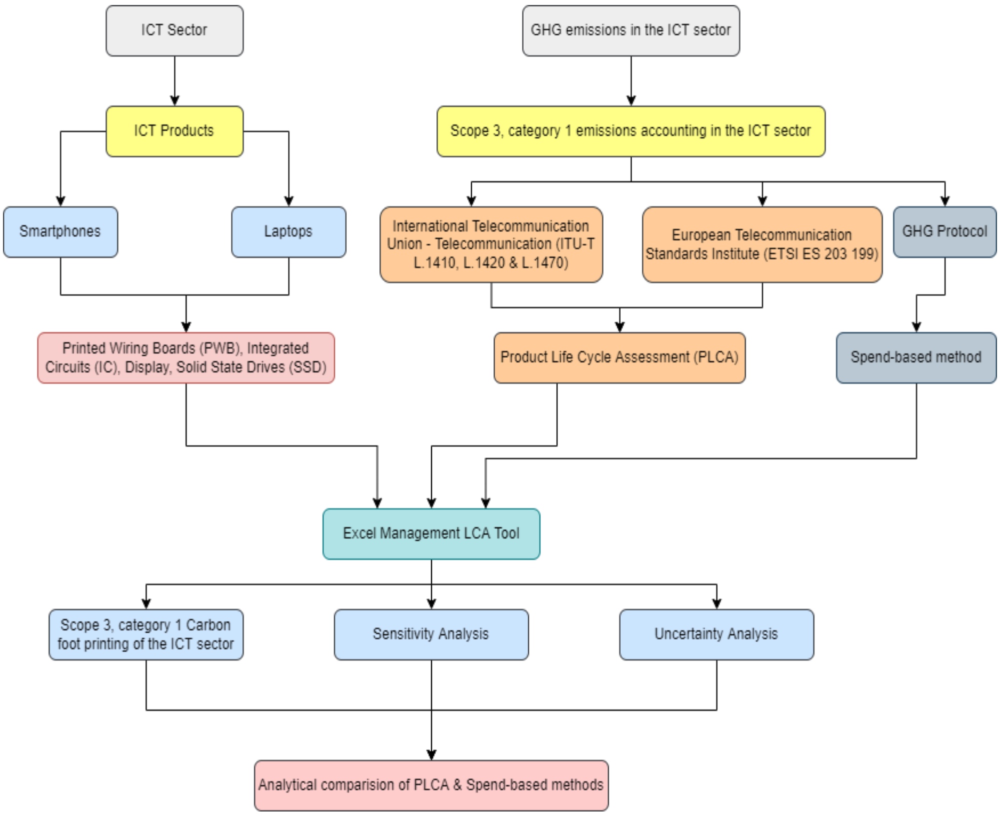

Figure 10: Methodology flowchart of this study.

This study can be branched into two parts:

1. Calculating Scope 3, category 1 emissions in the ICT sector using PLCA and Spend-based methods.
2. Performing a comparative analysis between PLCA & Spend-based based on the process and findings from them.

4.1 Calculating the Scope 3, category 1 emissions in the ICT Sector

One of the crucial steps in Carbon estimation using PLCA is the Life Cycle Inventory Analysis as it involves the collection of data and calculation processes to quantify a product system's (ICT sector in our case) relevant inputs and outputs. The use of resources in the company may be included in these inputs and outputs. As mentioned in the Spend-based method under section 3.5.2. Methodologies under Greenhouse Gas (GHG) Protocol for corporate carbon accounting of Scope 3 Category 1 emissions, the activity data needed in this method are "1. Amount spent on purchased goods or services, by product type, using market values and 2. Where applicable, inflation data to convert market values between the year of the EEIO emissions factors and the year of the activity data (e.g., dollars)" [62]. This means, Spend-based method takes into account the inventory of purchased goods or resources that go into the making of the product of the company. As it is about having an inventory of products/resources to calculate the emissions of a product, we choose a method that helps us to perform the Life Cycle Inventory Analysis (LCIA).

4.1.1 Excel Management Life Cycle Assessment (EMLCA) tool.

There are various techniques that can help us to perform the LCIA, namely, the Process flow diagram method, the Matrix-based LCIA method, Input-Output Analysis (IOA) method, the Hybrid LCIA method, etc. Heijungs was the first to introduce the matrix-based LCIA approach to Life Cycle Inventory (LCI) computation and he later also developed the comprehensive computational methods and skills of the matrix method [63] [64]. To solve the problem of inventory, the matrix method uses a system of linear equations. Matrix algebra operations are used in this method to calculate the final cumulative environmental loads after arranging the economic and environmental flows in the matrix form. The matrix method, in comparison to other methods, is better at dealing with the LCA system with internally recurring unit processes [65] [66].

One such tool which uses the matrix technique is the Excel Management Life Cycle Assessment Tool (EMLCA) [67] which is used in this study to perform the calculation required to determine the Scope 3, category 1 emissions in the ICT sector using the PLCA and the Spend-based methods.

The steps on how the EMLCA tool uses the matrix method to calculate the emissions by using the inventory data are [67].

Step 1: The calculation procedure begins with the collection of necessary process data.

Step 2: Under every unit process, a functional flow is defined and then the concerned environmental flows are identified and noted down.

Step 3: The defined functional flows make up the coefficient matrix. The processed vector is then calculated after composing the system boundary vector.

Step 4: The final environmental load vector is calculated after composing the environmental load matrix, in the meantime, the surplus flow matrix is constructed, and the final surplus flow vector is computed simultaneously.

Step 5: If necessary, allocation is carried out based on the final surplus flow vector.

Step 6: The gathered Life Cycle Inventory (LCI) result is then finally interpreted.

Figure 11 shows the process flow of the working EMLCA tool for the LCI analysis. This is also the general process of how the matrix method for the LCI analysis works.

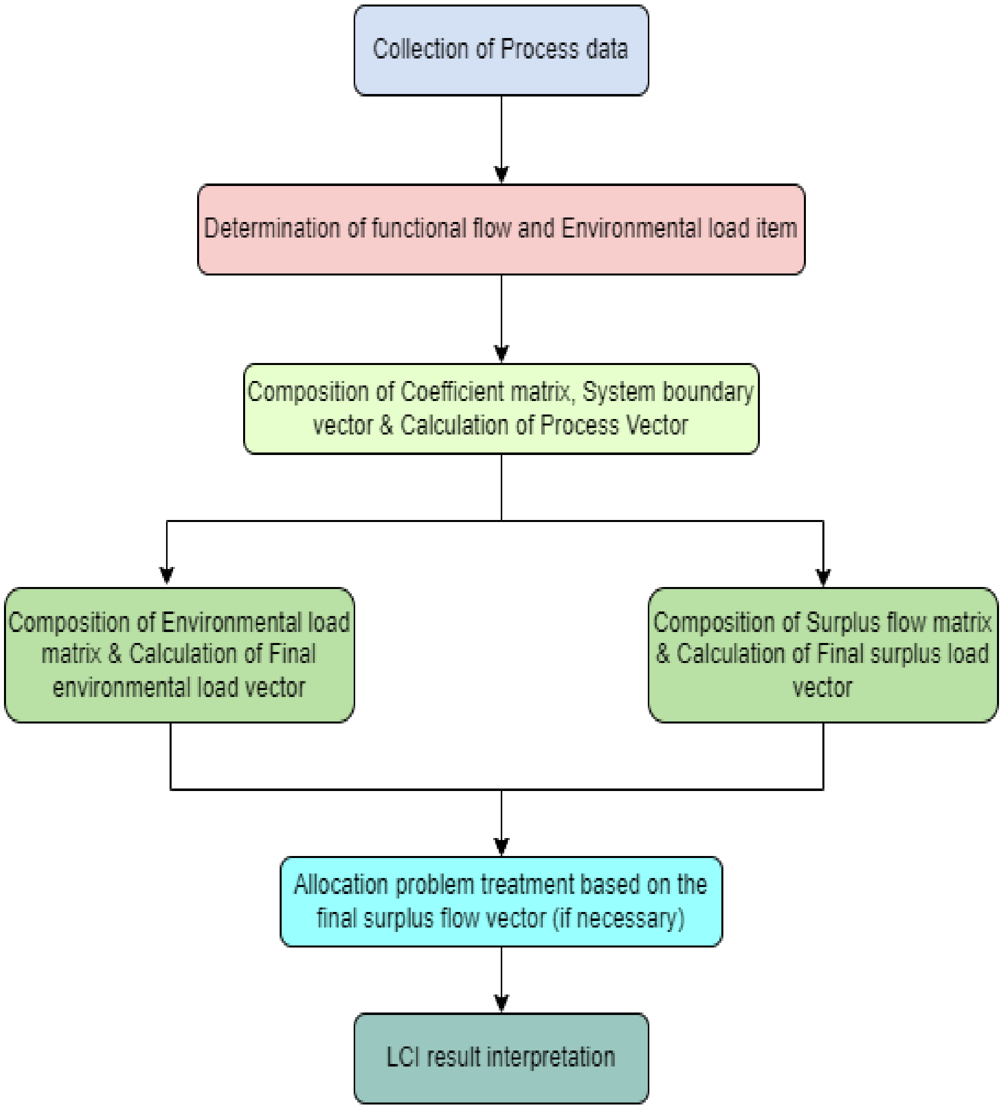

Figure 11: Procedure of the EMLCA tool for LCI analysis [67]

The ICT products being considered in this study are smartphones and laptops due to the predicted increase in their number of users as mentioned in the 1. Introduction section. Figure 12 shows the Global Warming Potential (GWP) contribution of various modules from the part production phase of the laptop considered for this study. It can be seen from Figure 12 that the GWP contribution is dominated by PWB (47%), followed by SSD (17%), and has significant shares of Display and other electronics (which consists of IC). The IC, Display, PWB, and SSDs are among the components that are considered to be vital for smartphones and laptops.

The components considered for EMLCA under these products are as follows:

For smartphones

1. Integrated Circuits (IC)
2. Displays
3. Printed Wiring Boards (PWB)

For laptops

1. Integrated Circuits (IC)
2. Displays
3. Printed Wiring Boards (PWB)
4. Solid State Drives (SSDs)

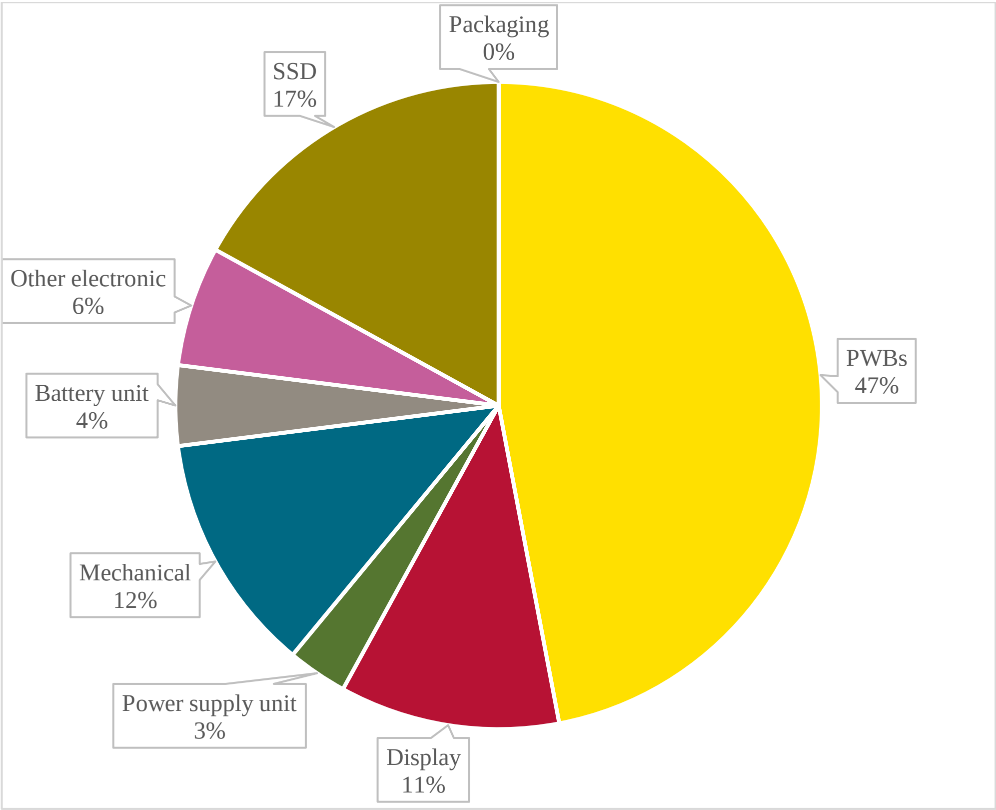

Figure 12: Global Warming Potential (GWP) of various components from the part production phase of the laptop considered for this study [68].

4.2 Performing a comparative analysis between PLCA & Spend-based methods

During the process of the calculation of scope 3 category 1 emissions in the ICT sector using PLCA & Spend-based methods in the EMLCA tool, the entire process was analyzed deeply to make an analytical comparison between both methods. This analysis takes into account the parameters such as cost, speed, data availability, learning curve, future proof, number of assumptions, applicability, and the feasibility of the PLCA method and Spend-based method, respectively, for ICT Corporate and ICT Sector carbon footprint level Scope 3 Category 1 estimations. This analysis derives the sensitivity, uncertainty, reliability, applicability, etc., of the methods under various circumstances which are discussed briefly in the 5. Results and 6. Discussion sections.

While the manufacturing of these components using electricity from the global average emissions (CO_{2e} in tonnes/kWh of global average) was taken into account, three other hypothetical situations were also considered wherein the production of the components for laptops and smartphones (from cradle-to-gate) is expected to take place in high CO_{2e} emission for electricity production country (India), low CO_{2e} for electricity production emission country (Norway) and production of these components in China.

5. Results

5.1 Input process data for PLCA

Under the PLCA method, the size of the components (IC, PWB, Display, and SSD in our case) are taken in terms of "cm^2" as input process data for the EMLCA tool. For the Integrated Circuits, the die area is being taken into account for the process data. Electricity consumption for these components is taken in terms of "kWh/cm^2" and the environmental load is taken as "CO_{2e} in $tonnes/cm^2$" of the components used.

The following information shows the data used as input for the EMLCA tool under the PLCA method [68] [69] [70].

- Number of smartphones in use = 1774 million units (As of 2020)
- Number of laptops in use = 785 million units (As of 2020)

The above values are used in the EMLCA tool for the PLCA method with 5% uncertainty.

✓ Area of the components considered for smartphones

1. Die area of the IC = 7.221806 cm^2
2. Are of the PWB = 70 cm^2
3. Area of the display = 81.9 cm^2

The above values are used in the EMLCA tool for the smartphones for the PLCA method with 50% uncertainty.

✓ Area of the components considered for laptops

1. Die area of the IC = 1.26 cm^2
2. Area of the PWB = 93.55 cm^2
3. Area of the display = 485.41 cm^2
4. Area of SSD = 196.76 cm^2

The above values are used in the EMLCA tool for the laptops for the PLCA method with 5% uncertainty.

The environmental load item considered in this study for PLCA is "CO_{2e} in tonnes/cm^2" of the components used. The values, hence used are:

- ✓ Environmental load item considered for components
  1. For IC = 0.000782 CO_{2e} in tonnes/cm^2 (25% uncertainty)
  2. For PWB = 0.0000116841 CO_{2e} in tonnes/cm^2 (5% uncertainty)
  3. For Display = 0.0000051 CO_{2e} in tonnes/cm^2 (20% uncertainty)

5.2 Input process data for Spend-based method

Under the Spend-based method, the value of the components (IC, PWB, Display, and SSD in our case) are taken in terms of "Dollars ($)" as input process data for the EMLCA tool. For the Integrated Circuits, the die area is being taken into account for the process data. Electricity consumption for these components is taken in terms of "kWh/dollar ($)" and the environmental load is taken as "CO_{2e} in tonnes/dollar ($)" of the components used.

The following information shows the data used as input for the EMLCA tool under the Spend-based method [70] [71] [72] [73].

- Number of smartphones in use = 1774 million units (As of 2020)
- Number of laptops in use = 785 million units (As of 2020)

The above values are used in the EMLCA tool for the Spend-based method with 5% uncertainty.

- ✓ Price of the components considered for smartphones
  1. Price of the IC = 14.9 $
  2. Price of the PWB = 20 $
  3. Price of the display = 25 $

The above values are used in the EMLCA tool for the smartphones for the Spend-based method with 50% uncertainty.

- ✓ Price of the components considered for laptops
  1. Price of the IC = 20 $
  2. Price of the PWB = 55 $

3. Price of the display = 10 $

The above values are used in the EMLCA tool for the laptops for the Spend-based method with 5% uncertainty.

The environmental load item considered in this study for PLCA is "CO_{2e} in tonnes/cm^2" of the components used. The values, hence used are:

- ✓ Environmental load item considered for components
  1. For IC = 0.00024254 CO_{2e} in tonnes/$
  2. For PWB = 0.00042744 CO_{2e} in tonnes/$
  3. For Display = 0.00065067 CO_{2e} in tonnes/$

The above values are used in the EMLCA tool for the Spend-based method with 5% uncertainty.

The emissions in terms of "CO_2e in tonnes/kWh" for the production of chosen components (IC, PWB, Display) under PLCA & Spend-based methods are [70] [74]:

1. For Global Average = 0.000588392 CO_{2e} in tonnes/kWh
2. For Low Carbon Country Case (Norway)= 0.00003655 CO_{2e} in tonnes/kWh
3. For High Carbon Country case (India) = 0.0008108 CO_{2e} in tonnes/kWh
4. For China = 0.00069675 CO_{2e} in tonnes/kWh

The above values are used in the EMLCA tool for the PLCA & Spend-based method with 5% uncertainty.

After inserting the above respective values for PLCA and Spend-based methods in the EMLCA tool, we can then calculate the overall Scope 3, category 1 emissions for the smartphones and laptops. Figure 13 shows the total scope 3, category 1 emissions under PLCA and Spend-based for smartphones and laptops. The total scope 3, category 1 emissions for the smartphones and laptops, when considering the electricity production from the global average are 195.45 MT CO_{2e} and 224.01 MT CO_{2e} under PLCA and Spend-based respectively. Similarly, Figure 13 also illustrates how the value of these emissions would differ depending on where the raw materials required for them are extracted and the components are manufactured. As mentioned in the section, 4.2 Performing a comparative analysis between PLCA & Spend-based methods, the chosen cases are global average emission value for electricity production, high carbon emission value for electricity production (India), low carbon emission value for electricity production (Norway) and the last one chosen is China.

The vertical error bars on the rectangular bars in Figure 13 represent the uncertainty of the data used for the calculation in the EMLCA tool for the information regarding the components, electricity use for their raw material extraction, and production for the smartphones and laptops. It is also quite obvious that the higher the carbon content in the fuel used for electricity production, which is used for the raw material extraction and part production for the components in smartphones and laptops, the higher will be the overall CO_{2e} emissions. Hence, Figure 13 shows that the highest overall CO_{2e} emissions are from the country which uses high Carbon for its electricity production (India in this case), whereas, the lowest overall CO_{2e} emissions are from the country which uses low Carbon for its electricity production (Norway in this case). The CO_{2e} emissions under the global average remain in between high Carbon and low Carbon electricity use and so do the total CO_{2e} emissions in the ICT sector. For PLCA, the uncertainty was mainly attributed to the size of the components used under smartphones and laptops whereas, for Spend-based, it was the cost of the components used under smartphones and laptops. It can also be seen from Figure 13 that the total scope 3, category 1 emissions is always higher in PLCA when compared to that off Spend-based. This is further discussed in the 6. Discussion section.

Figure 14 shows the Scope 3, category 1 emissions on an individual device basis for smartphones and laptops under the PLCA method. When considering the electricity production from the global average, the emissions per smartphone are calculated to be 48.47 kilograms whereas the emissions per laptop are 139.43 kilograms. Similarly, Figure 15 shows Scope 3, category 1 emissions on an individual device basis for smartphones and laptops under the Spend-based method. When considering the electricity production from the global average, the emissions per smartphone are calculated to be 61.6 kilograms whereas the emissions per laptop are 147.28 kilograms. This shows that the emissions per laptop are always significantly higher than the emissions per smartphone in all the global/various country cases. It is also self-evident that the higher the carbon content of the fuel used to generate electricity, the higher will be the CO_{2e} emissions per unit device.

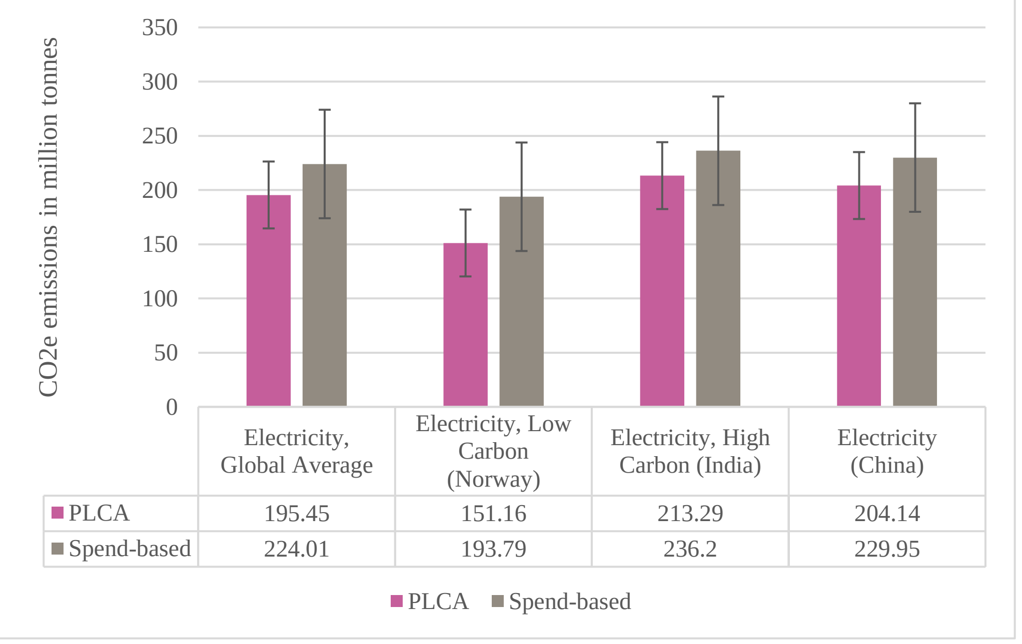

Figure 13: Scope 3, category 1 emissions for smartphones & laptops from global/various country cases.

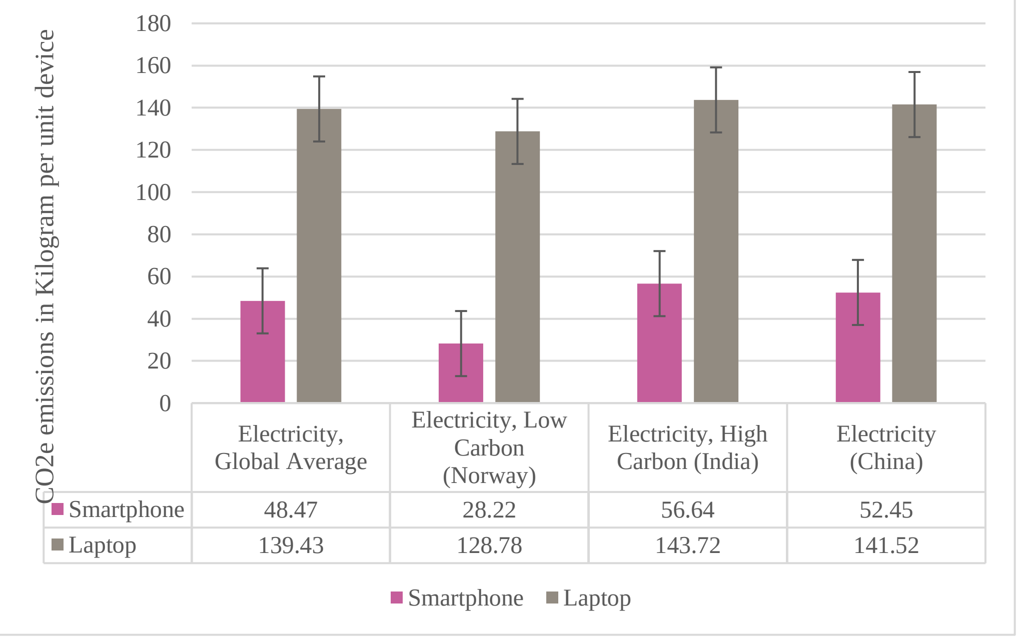

Figure 14: Scope 3, category 1 emissions per unit device from global/various country cases (PLCA)

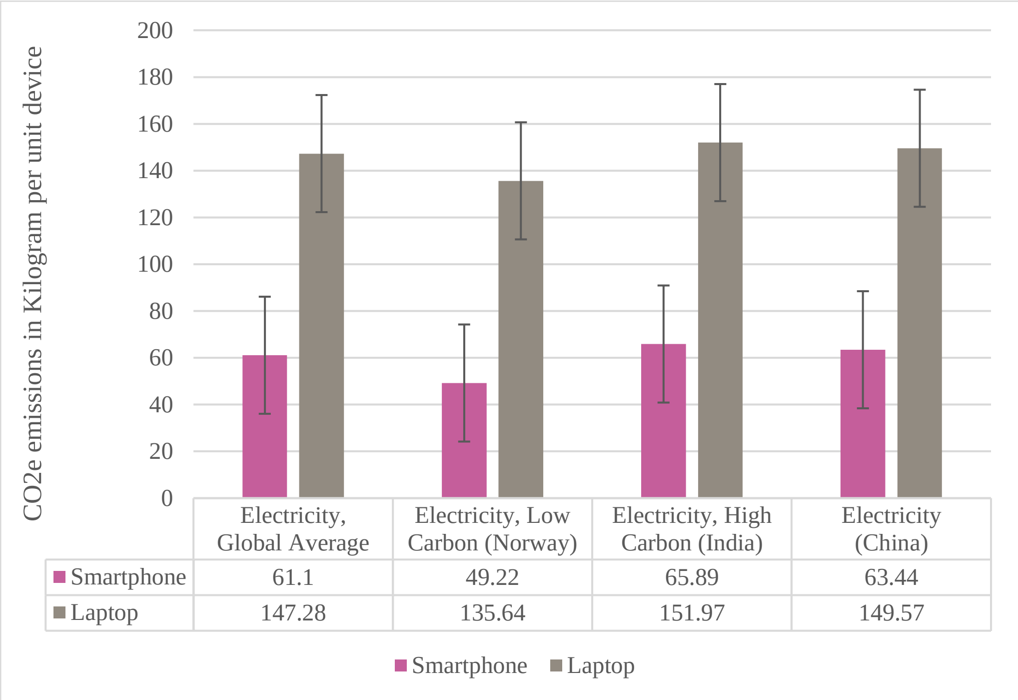

Figure 15: Scope 3, category 1 emissions per unit device from global/various country cases (Spend-based)

5.3 Result validation

In this section, the result obtained in this study is validated by using the scope 3, category 1 emissions of an OEM vendor (Original Equipment Manufacturer) from the ICT industry [77] [78]. To compare, we take into account the Scope 3, category 1 emissions of a laptop and a smartphone manufactured by them in 2020 as shown in Table 3. The results of this study are also internally verified. The verification is as follows:

Table 3: Comparison of CO_{2e} emissions per unit device from this study and an OEM vendor.

ICT product	PLCA	Spend-based	OEM vendor
Per smartphone (CO_{2e} emissions)	49 kg	61 kg	58 kg
Per laptop (CO_{2e} emissions)	139 kg	147 kg	164 kg

6. Discussion

6.1 Comparative analysis between PLCA & Spend-based methods

This section deals with the analytical comparison between PLCA & Spend-based based on their sensitivity, uncertainty to the input/output values (of the components & electricity mix and the overall Scope 3, category 1 CO_{2e} emissions) in the EMLCA, and a few other parameters which are mentioned in the 6.2 Further discussions about PLCA & Spend-based methods section.

6.1.1 Sensitivity analysis

Sensitivity analysis is used to determine how the changes in input data/variable affect the target variable or output data. It is a method of predicting the outcome of a choice (overall Scope 3, category 1 CO_{2e} emissions for smartphones and laptops in our case) based on a set of input variables (inputs for PLCA & Spend-based used in the EMLCA tool). This method can be used to determine how the changes in one or more input variables can affect the output by creating a set of input variables/data. The sensitivity study uses rate sensitivity and is used in this study to investigate the impact of each input process data on the final cumulative environmental loads quantitatively.

Figure 16 and Figure 17 show the sensitivity analysis for the smartphones under the PLCA and Spend-based methods respectively. It can be seen from Figure 16 that, in terms of components under smartphones, for PLCA, IC is the most influential parameter/component followed by PWB and Display whereas Figure 17 shows that the most influencing parameter/component for smartphones under the Spend-based method is Display followed by PWB and IC. Similarly, in the case of components under laptops, Figure 18 shows that the IC along with SSD influence the overall CO_{2e} emissions at the highest rate under the PLCA method followed by Display and PWB, whereas, when it comes to the Spend-based method, it is PWB the most influential parameter/component followed by Display and IC. It is also vital to note that, under PLCA for laptops, IC and SSD need to be combined as one single unit and then compared to IC under laptops for the Spend-based method. The IC under Spend-based for laptops includes SSD in itself. The conducted sensitivity analysis for both the methods can be interpreted as follows:

For Smartphones

1. Under PLCA – Figure 16
   I. 1% change in input IC value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.5%.
   II. 1% change in input PWB value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.05%.
   III. 1% change in input Display value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.03%.
2. Under Spend-based – Figure 17
   I. 1% change in input Display value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.4%.
   II. 1% change in input PWB value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.18%.
   III. 1% change in input IC value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.09%.

For Laptops

1. Under PLCA – Figure 18
   I. 1% change in input IC (IC+SSD) value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.2%.
   II. 1% change in input Display value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.06%.
   III. 1% change in input PWB value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.02%.
2. Under Spend-based – Figure 19
   I. 1% change in PWB input value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.2%.
   II. 1% change in input Display value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.07%.

III. 1% change in input IC value/data will affect the overall output value (Scope 3, category 1 CO_{2e} emissions) by 0.05%.

It is interesting to note that none of the methods have a common most influential component/input parameter when it comes to both, smartphones and laptops. This shows that it greatly depends on the primary input data provided to both the methods related to the specifications of the input parameters whether it is their size or their value.

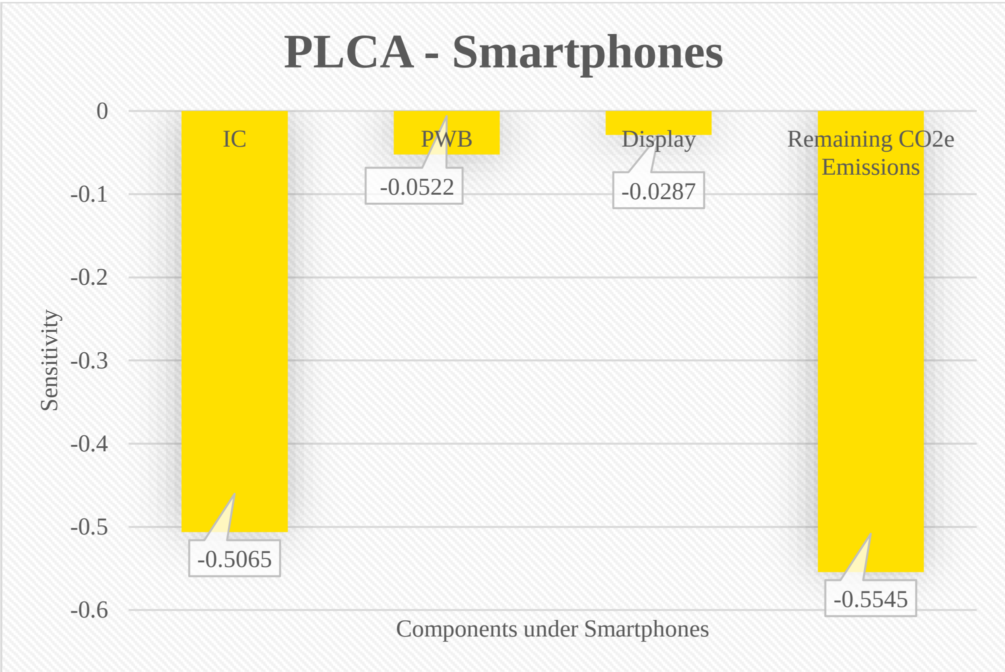

Figure 16: Sensitivity analysis for Smartphones – PLCA

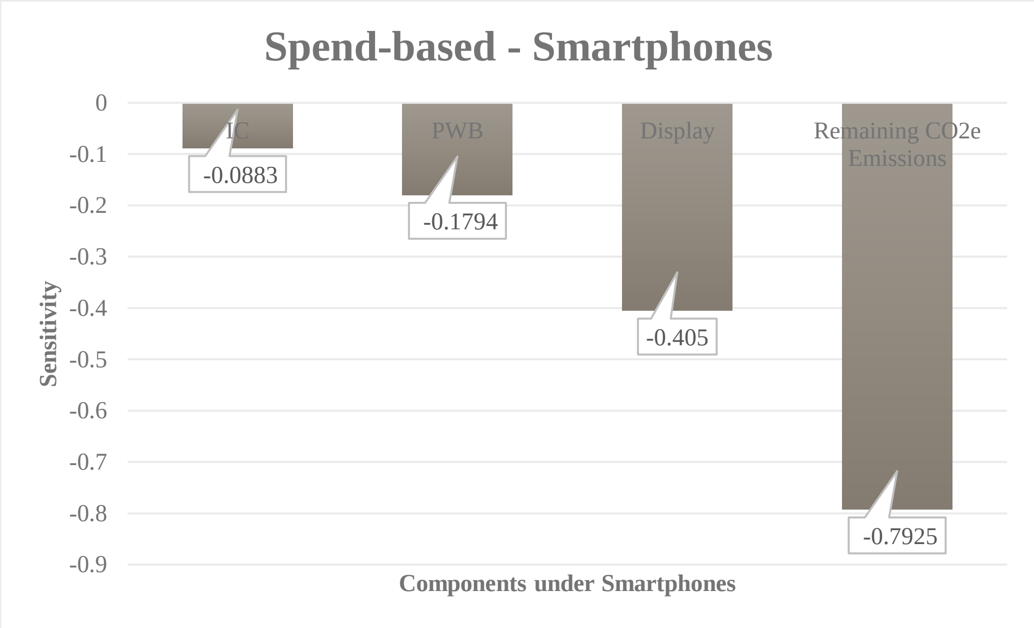

Figure 17: Sensitivity analysis for Smartphones – Spend-based

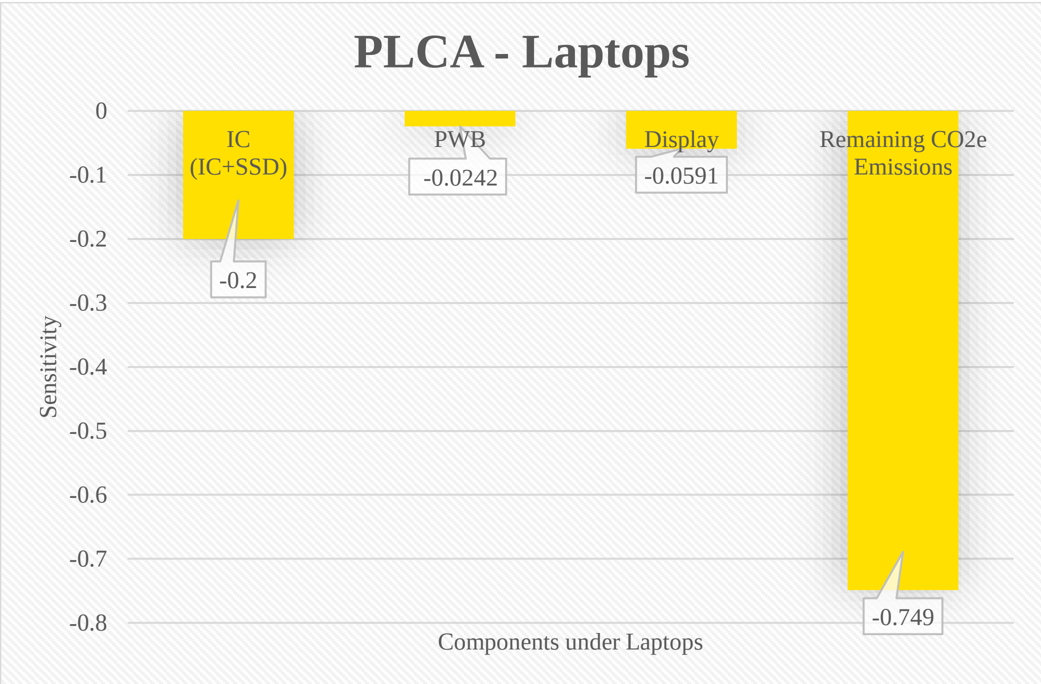

Figure 18: Sensitivity analysis for Laptop - PLCA

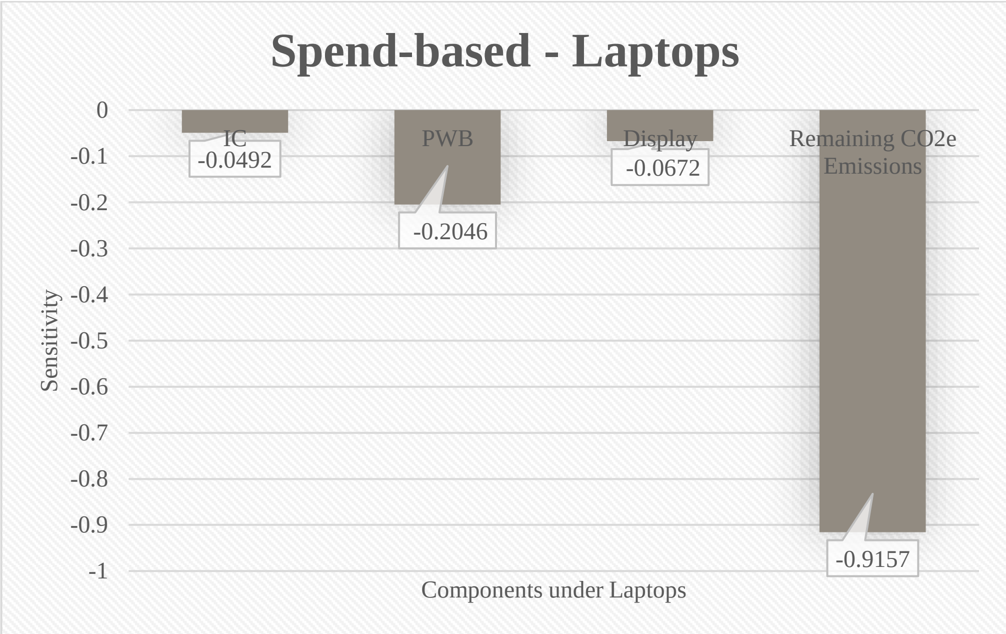

Figure 19: Sensitivity analysis for Laptops – Spend-based.

It can be seen from Figures 16-19 that under different methods (PLCA & Spend-based), smartphones & laptops are sensitive to different components. This shows that the influencing parameters can differ based on the method used to calculate the overall scope 3, category 1 CO_{2e} emissions. This sensitivity fluctuation is even more when it comes to the Spend-based method as strong or constant variations in the price of the components used to make the ICT product can result in different sensitivity order but despite that, the emissions should remain constant [75] as seen in our case that the overall emissions and the individual product level emissions (for smartphones and laptops) are similar although they have different order of sensitivity for the components in them. Similar case is found in [76] where two LCA methods (OLCA – Open Eco Rating LCA & FLCA – Full LCA) were analyzed to look at the GWPI (Global Warming Potential Indicator) of various smartphones. Although the overall GWPI scores of OLCA & FLCA for all the phones were similar when calculated, the repartition of GWPI scores of OLCA & FLCA for individual phones were noticeably different [76].

6.1.2 Uncertainty analysis

The uncertainty analysis helps us to examine the scale of the uncertainty of the final output (overall scope 3, category 1 CO_{2e} emissions in our case) which results due to the uncertainties from the input process data (information related to the components for smartphones & laptops and the electricity mix in our case). The uncertainty in the output value arising due to the uncertainties in the input parameters is shown in Figure 13 in terms of error bars under the 5. Results section. The uncertainty analysis performed in this study has the standard deviation values for PLCA & Spend-based under a 95% confidence interval.

In other words, Figure 13 shows the uncertainty values for Scope 3, category 1 CO_{2e} emissions for a combination of smartphones & laptops under PLCA and Spend-based with a 95% probability that the values would be as follows:

1. Scope 3, category 1 emissions for the Smartphones & Laptops under PLCA method = 194±31.3 Mt CO_{2e} emissions.
2. Scope 3, category 1 emissions for the Smartphones & Laptops under PLCA method = 224±50.3 Mt CO_{2e} emissions.

Interestingly, unlike the sensitivity analysis, the order of high to low uncertainties for Smartphones and Laptops under PLCA & Spend-based, follow almost the same trend (except for the laptops). The order of uncertainties in the input parameter (components) is as follows:

1. For Smartphones
    a) Under PLCA: Displays > PWB > IC
    b) Under Spend-based: Displays > PWB > IC
2. For Laptops
    c) Under PLCA: Displays > IC+SSD > PWB
    d) Under Spend-based: PWB > IC > Displays

6.2 Further discussion about PLCA & Spend-based methods

Apart from sensitivity analysis (order of influencing components) & the uncertainty analysis, PLCA & Spend-based methods can be further compared and analyzed using other parameters mentioned in Table 4.

1. Speed:

When it comes to the optimal value chain accounting in the ICT sector, the Spend-based method is quicker than PLCA due to the fact that most part of the primary data required for the Spend-based method (amount spent on every component/product by the emissions calculating company) is available internally in the ICT company and hence is much easier to access. Whereas, for the PLCA, the ICT company would require to access data such as their component supplier's scope 1 & 2 emission data which is not internally available making it more complex and a time-consuming process.

2. Cost:

The cost of performing PLCA or Spend-based methods with the same data quality depends on the availability of primary and secondary data. In fact, the cost of both methods depends highly on how much the company is spending on its resources to gather the primary/secondary data required for both methods. If the primary data for the Spend-based method for all the required components/products are available, then the Spend-based method is more cost-effective than the PLCA. It is very difficult in the long-term to have the "CO_{2e} emissions per Sq Unit (cm or m)" from the supplier and hence, it would always be some average data in the end from the supplier making the PLCA costlier to perform due to the regular change in the input primary data.

3. Precision:

The precision is high for the Spend-based method as can be seen in the 5. Results section. The scope 3, category 1 emissions for a smartphone from one of the popular ICT vendors in 2020 is about 58 kg CO_{2e} emissions which is closer to Spend-based's CO_{2e} emissions for smartphone value of 61 kg CO_{2e} emissions [77], and this data is also internally cross-checked. Similarly, for the laptops, the scope 3, category 1 emissions for a laptop from one of the popular ICT vendors in 2020 is about 165 kg CO_{2e} emissions which is closer to Spend-based's CO_{2e} emissions for laptop value of 147 kg CO_{2e} emissions [78] and this data is also internally cross-checked. The precision for Spend-based is quite high when compared to that of PLCA's for the included scope.

4. Likelihood of being able to have cradle-to-gate coverage:

PLCA approach is more preferred when it comes to the likelihood of being able to have better coverage from cradle-to-gate emission accounting. In the present times, PLCA has a collection of a better and more detailed database for their primary input information which other approaches lack at the moment. PLCA also has more coverage over the different life cycle stages of the product.

5. Acceptance by standards and industry as Scope 3 Category 1 approach:

According to ETSI (European Telecommunication Standards Institute) & ITU-T (International Telecommunication Union – Telecommunication), PLCA is recognized for emission accounting in the ICT sector. On the other hand, Spend-based is one of the five optimal value chain accounting methods recognized under the GHG protocol. Hence, as of now, it can be said that both the methods are accepted by standards and industry for the Scope 3 category 1 emission accounting approach.

Table 4: List of parameters for PLCA & Spend-based comparison.

Parameters	PLCA	Spend-based
1. Speed		✓
2. Cost		✓
3. Precision		✓
4. Likelihood of being able to have cradle-to-gate coverage	✓	
5. Acceptance by standards & industry as Scope 3, category 1 approach	✓	✓
6. Ability to show reductions year by year	✓	✓
7. Ability to reflect regional differences		✓
8. ICT product eco-designing	✓	

6. Ability to show reduction year by year and reflect regional differences:

Both PLCA & Spend-based methods have the ability to show a reduction in scope 3, category 1 emissions in the ICT sector on a yearly basis whereas, when it comes to the reflection of regional differences, the Spend-based method has an upper hand over

PLCA. This is due to the limitations in the PLCA where the ability to map the component's data with the Life Cycle Inventory (LCI) database is more challenging.

7. Product eco-designing:

Although it takes more time to perform the PLCA for each and every product in the ICT company under the ICT sector, PLCA is overall a better option for comparing complicated product designs, especially with recycled materials. Hence, this makes PLCA a more suitable option for product eco-designing. The primary Spend-based data can also be used inside the PLCA to make even better and more comprehensive product designing ideas.

7. Conclusion

In the ICT sector, from a company's perspective, if they are required to calculate/quantify their scope 3, category 1 emissions, then the PLCA method becomes a laborious task due to the fact that they would then need to perform the PLCA for all of their products theoretically to capture their scope 3, category 1 emissions. For instance, while performing the PLCA of the laptop or smartphone or routers etc., they would need to have emissions of them all by performing product LCA for all the individual components in the product. It is quite a challenging task to provide or perform the LCA of all the products in the ICT sector for the company. Hence, the Spend-based approach seems quicker and more cost-effective. On the other hand, it is simpler to quantify the input parameters for both the methods provided that we define the scope and account for the remaining emissions. If a company depends to a higher extent on their tier-1 supplier, then the data sources are limited and the result can have higher uncertainty.

PLCA has complex and comprehensive uses in corporate accounting in the ICT sector and is also not mentioned under any of the methods for corporate value chain emissions accounting. But it is still a more preferred option in the telecommunication industry to use PLCA to solve the corporate emissions accounting problem. There is an ICT company with significant stature in the ICT sector which has been using the PLCA for a very long time and defined it as "The most important methodological platform for environmental prioritization and understanding" [79]. PLCA can be a more suitable option for product design and improvement but it is also vital to implement the design and not just provide design improvement solutions. Having a design rule to implement the design improvements/changes can be a viable option in the future.

In order to calculate Scope 3, category 1 emissions, and understand the environmental impact of diverse product systems under the ICT sector, both (PLCA & Spend-based methods) seem to be suitable. As a result, they are shown to be a strong foundation for prioritizing a company's environmental activity. However, it is important to note that the conclusions from PLCA & Spend-based methods are always model-based approximations of the environmental impact in real-life. Calculation of the absolute impact of any ICT product is unattainable. Only under a study's assumptions are these results (from PLCA & Spend-based methods) valid and they still come with a degree of uncertainty that must be taken into account to the extent necessary to comprehend the study's findings.

8. References

[1]. Wann, D. 2011. “The New Normal: an Agenda for Responsible Living. Macmillan”. [Online]. Available at: https://books.google.com/books?hl=en&lr=&id=HaWHFAsodd8C&oi=fnd&pg=PT7&ots=hNIzfyjayw&sig=a8xkZ_u9REf-HmxArZsx29csXvQ

[2]. Plepys, A. 2002. “The grey side of ICT. Environmental Impact Assessment Review 22 (5)”, 509–523.

[3]. Berkhout, F., Hertin, J. 2004. “De-materialising and re-materialising: digital technologies and the environment”, Futures 36, 903–920.

[4]. OECD. 2011. OECD Guide to Measuring the Information Society 2011, OECD Publishing. [Online]. Available at: https://www.oecd-ilibrary.org/science-and-technology/oecd-guide-to-measuring-the-information-society-2011_9789264113541-en

[5]. Shapiro, G. 2012. “America’s comeback starts with American innovators soapbox”, IEEE Consum. Electron. Mag, 1, 19–24.

[6]. The Economist. 2020. How to make sense of the latest tech surge. [Online]. Available at: https://www.economist.com/leaders/2020/02/20/how-to-make-sense-of-the-latest-tech-surge.

[7]. Andrae ASG, Edler. 2020. “T. On Global Electricity Usage of Communication Technology: Trends to 2030”, *Challenges*; 6(1):117-157. [Online]. Available at: https://doi.org/10.3390/challe6010117.

[8]. Andrae, Anders & Xia, Mengjun & Zhang, Jianli & Tang, Xiaoming. 2016. “Practical Eco-Design and Eco-Innovation of Consumer Electronics—the Case of Mobile Phones”, Challenges. 7. 3. 10.3390/challe7010003.

[9]. Geraldo T.R. Silveira, Shoou-Yuh Chang. 2010. “Cell phone recycling experiences in the United States and potential recycling options in Brazil, Waste Management”, Volume 30, Pages 2278-2291, ISSN 0956-053X. [Online]. Available at: https://doi.org/10.1016/j.wasman.2010.05.011.

[10]. Kaapa, P. 2017. “It’s time to start thinking about our digital carbon footprint. The Conversation”. [Online]. Avaialable at: https://theconversation.com/its-time-to-start-thinking-about-our-digital-carbon-footprint-81518.

[11]. Guardian Environment Network. 2017. ‘Tsunami of data’ could consume one fifth of global electricity by 2025. The Guardian. [Online]. Available at: https://www.theguardian.com/environment/2017/dec/11/tsunami-of-data-could-consume-fifth-global-electricity-by-2025.

[12]. Belkhir, L. and Elmeligi, A. 2018. “Assessing ICT global emissions footprint: Trends to 2040 & recommendations”, Journal of Cleaner Production, 177: p. 448-463.

[13]. Tarnoff, B. 2019. “To decarbonize we must decomputerize: why we need a Luddite revolution”, The Guardian. [Online]. Available at: https://www.theguardian.com/technology/2019/sep/17/tech-climate-change-luddites-data.

[14]. BBC iPlayer. 2020. The internet's big secret. [Online]. Available at: https://www.bbc.co.uk/news/av/stories-51742336/dirty-streaming-the-internet-s-big-secret.

[15]. International Telecommunication Union. 2014. Evaluating the carbon impact of ICT or The answer to life, the universe and everything, 2014. [Online]. Available at: https://www.techuk.org/asset/3BF53A90-6AB0-430E-9473884D05DD9017/.

[16]. GeSI. 2012. GeSI SMARTer 2020: The Role of ICT in Driving a Sustainable Future. [Online]. Available at: http://gesi.org/portfolio/project/71.

[17]. Andrae, Anders & Hu, Ling & Liu, Long & Spear, John & Rubel, Keagan. 2017. “Delivering Tangible Carbon Emission and Cost Reduction through the ICT Supply Chain”, International Journal of Green Technology.

[18]. Fistarol GO, Farias M, Salomon PS. 2016. “Viability of using flue gases as carbon source for microalgae cultivation. Int J Green Technol”.

[19]. C. Freitag, M. Berners-Lee, K.V. Widdicks, B.H. Knowles, G. Blair, A. Friday. 2020. “The climate impact of ICT: A review of estimates, trends and regulations”. [Online], Available at: https://arxiv.org/pdf/2102.02622

[20]. Williams, E. 2004. “Energy intensity of computer manufacturing: Hybrid assessment combining process and economic Input - Output methods”, Environmental Science and Technology 38 (22), 6166–6174.

[21]. Choi, B.-C., Shin, H.-S., Lee, S.-Y., Hur, T. 2006. “Life cycle assessment of a personal computer and its effective recycling rate”, International Journal of Life Cycle Assessment. 11 (2), 122– 128.

[22]. Eugster, M., Hischier, R., Duan, H. 2007. “Key Environmental Impacts of the Chinese EEE-Industry: A Life Cycle Assessment Study”, Empa, Switzerland and Tsinghua University, China.

[23]. Bergelin, F. 2008. “Life cycle assessment of a mobile phone - a model on manufacturing, using and recycling”, Uppsala university, Uppsala.

[24]. Malmodin, J., Moberg, A.S., Lundén, D., Finnveden, G., Lövehagen, N. 2010. ”Greenhouse gas emissions and operational electricity use in the ICT and entertainment & Media sectors”, Journal of Industrial Ecology 14 (5), 770-790.

[25]. Greenhouse Gas Protocol. 2004. Corporate Value Chain (Scope 3) Accounting and Reporting Standard.

[26]. Charlotte F, Mike B, Kelly W, Bran K, Gordon B, Adrian F. 2020. “The climate impact of ICT: A review of estimates, trends and regulations”, (Lancaster University).

[27]. Alexander Farsan, Andres Chang, Annemarie Kerkhof, Navigant Bence Cserna, Chendan Yan, Fernando Rangel Villasana, Nicole Labutong. 2018. “Best Practices in Scope 3 Greenhouse Gas Management”. [Online]. Available at: https://sciencebasedtargets.org/resources/files/SBT_Value_Chain_Report-1.pdf

[28]. ITU-T L.1470. 2020. Greenhouse gas emissions trajectories for the information and communication technology sector compatible with the UNFCCC Paris Agreement.

[29]. Jyoti Banerjee, Cristina Bueti. 2012. "Assessment framework for environmental impacts of the ICT sector", International Telecommunication Union (ITU).

[30]. Environmental Responsibility report. 2019. Progress Report, covering fiscal year 2018, Apple. [Online]. Available at: https://www.apple.com/environment/pdf/Apple_Environmental_Responsibility_Report_2019.pdf.

[31]. GeSI. 2008. SMART 2020: Enabling the low carbon economy in the information age. [Online]. Available at: http://www.smart2020.org/publications/

[32]. Eurostat. 2013. "Information and communication technology (ICT)". [Online]. Available at: http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Glossary:ICT

[33]. Lotfi Belkhir, Ahmed Elmeligi. 2018. "Assessing ICT global emissions footprint: Trends to 2040 & recommendations, Journal of Cleaner Production", Volume 177, Pages 448-463, ISSN 0959-6526. [Online]. Available at: https://doi.org/10.1016/j.jclepro.2017.12.239.

[34]. Fehske, A.; Fettweis, G.; Malmodin, J.; Biczok. 2011. "G. The global footprint of mobile communications: The ecological and economic perspective". IEEE Commun, 49, 55–62.

[35]. Malmodin, J.; Bergmark, P.; Lundén, D. 2013. "The future carbon footprint of the ICT and E&M sectors", In Proceedings of ICT4S, Zurich, Switzerland.

[36]. Malmodin, J. 2013. "European Telecommunication Standards Institute". [Online]. Available at: http://docbox.etsi.org/Workshop/2013/201310_EEWORKSHOP/S05_Environ.alImpactAssessm entsofICT/ERICSSON_Malmodin.pdf

[37]. Malmodin, J.; Lundén, D.; Moberg, Å.; Andersson, G.; Nilsson, M. 2014. "Life cycle assessment of ICT: carbon footprint and operational electricity use from the operator, national, and subscriber perspective in Sweden", 829–845.

[38]. Ishii, K.; Okazaki, F.; Kurumida, J.; Mizutani, K.; Takeshita, H.; Kobayashi, K.; Kudoh, T. 2013. “Unified aroach of top-down and bottom-up methods for estimating network energy consumption. In Proceedings of 39th European Conference and Exhibition on Optical Communication”, London, UK.

[39]. Kuroda, K.; Kishita, Y.; Yamaguchi, Y.; Umeda, Y.; Hara, M.; Oka, H.; Nakamura, J. 2016. “Scenario Analysis of the electricity consumption in the Japanese information and communications sector toward green of ICT”. In Proceedings of Going Green CARE Innovation, Vienna, Austria. [Online]. Available at: https://www.mdpi.com/2071-1050/8/1/52/htm.

[40]. Pickavet, M.; Vereecken, W.; Demeyer, S.; Audenaert, P.; Vermeulen, B.; Develder, C.; Colle, D.; Dhoedt, B.; Demeester, P. 2008. “Worldwide energy needs for ICT: The rise of power-aware networking. In Proceedings of 2nd International Symposium on Advanced Networks and Telecommunication Systems”, Mumbai, India. [Online]. Available at: https://biblio.ugent.be/publication/867344

[41]. Lambert, S.; Van Heddeghem, W.; Vereecken, W.; Lannoo, B.; Colle, D.; Pickavet, M. 2012. “Worldwide electricity consumption of communication networks”. Opt. Express, 20, B513–B524.

[42]. Van Heddeghem, W.; Lambert, S.; Lannoo, B.; Colle, D.; Pickavet, M.; Demeester, P. 2014. “Trends in worldwide ICT electricity consumption from 2007 to 2012”, Comp. Commun, 50, 64–76.

[43]. Van Heddeghem, W.; Lambert, S.; Vereecken, W.; Lannoo, B.; Colle, D.; Demeester, P.; Pickavet, M. 2012. “Modelling of the worldwide electricity consumption of ICT”. In Proceedings of MMB & DFT, Bamberg, Germany.

[44]. Global e-Sustainability Initiative - The Role of ICT in Driving a Sustainable Future, 2012. [Online]. Available at: http://gesi.org/assets/js/lib/tinymce/

[45]. Tucker, R.S.; Hinton, K.; Ayre. 2012. “Energy Efficiency in Cloud Computing and Optical Network”, University of Melbourne. [Online]. Available at: http://people.eng.unimelb.edu.au/rtucker/talks/files/Tucker_ECOC_Tutorial.pdf

[46]. Tucker. 2014. “R.S. Towards an energy-efficient Internet. In Proceedings of Optical Instrumentation for Energy and Environ.al Applications”, Canberra, Australia. [Online]. Available at: https://opg.optica.org/ViewMedia.cfm?uri=E2-2014-EF3A.1&seq=0

[47]. Corcoran, P.M. 2012. “Cloud computing and consumer electronics: A perfect match or a hidden storm?”, IEEE Consum. Electron. Mag., 1, 14–19.

[48]. Corcoran, P.M.; Andrae, A.S.G. 2013. “Emerging Trends in Electricity Consumption for Consumer ICT”. [Online]. Available at: http://aran.library.nuigalway.ie/xmlui/handle/10379/3563

[49]. Corcoran, P.M.; Andrae, A.S.G. 2014. “On thin-clients and the cloud; can smartphones and tablets really reduce electricity consumption?”, In Proccedings of 2014 IEEE International Conference on Consumer Electronics (ICCE), Las Vegas, NA, USA.

[50]. European Commission. 2014. [Online]. Available at: http://ec.europa.eu/information_society

[51]. Alcatel-Lucent. 2015. pages/ 20150114_1907/GWATT_WhitePaper.pdf. [Online]. Available at: https://media-bell-labs-com.s3.amazonaws.com

[52]. Aebischer, B.; Hilty, L. M. 2015. “The energy demand of ICT: A historical perspective and current methodological challenges. In ICT Innovations for Sustainability”; Springer International Publishing: Berlin, Germany; Volume 1, pp. 71–103.

[53]. The UK Technology Industry - Evaluating the carbon impact of ICT, 2014. [Online]. Available at: https://www.techuk.org/asset/3BF53A90-6AB0-430E-9473884D05DD9017/

[54]. M. Finkbeiner, A. Inaba, R. Tan, K. Christiansen, and H. J. Klüppel. 2006. “The new international standards for life cycle assessment: ISO 14040 and ISO 14044,” Int. J. Life Cycle Assess., vol. 11, no. 2, pp. 80–85.

[55]. A. S. G. Andrae and M. S. Vaija. 2014. “To which degree does sector specific standardization make life cycle assessments comparable? —The case of global warming potential of smartphones”, Challenges, vol. 5, no. 2, pp. 409–429.

[56]. A. S. G. Andrae. 2016. “Life-Cycle Assessment of Consumer Electronics: A review of methodological approaches”, in *IEEE Consumer Electronics Magazine*, vol. 5, no. 1, pp. 51-60, doi: 10.1109/MCE.2015.2484639.

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

[58]. C. Monfreda, M. Wackernagel, and D. Deumling. 2004. “Establishing national natural capital accounts based on detailed ecological footprint and biological capacity assessments”, Land Use Policy, vol. 21, no. 3, pp. 231–246.

[59]. N. Itsubo, M. Sakagami, K. Kuriyama, and A. Inaba. 2012. “Statistical analysis for the development of national average weighting factors— visualization of the variability between each individual’s environmental thoughts”, Int. J. Life Cycle Assess., vol. 17, no. 4, pp. 488–498.

[60]. G. Van Hoof, A. Weisbrod, and B. Kruse. 2004. “Assessment of progressive product innovation on key environmental indicators: Pampers Baby Wipes from 2007–2013”, Sustainability, vol. 6, no. 8, pp. 5129–5142.

[62]. Greenhouse Gas Protocol: Technical Guidance for Calculating Scope 3 emissions, 2004.

[63]. Reinout Heijungs. 1994. “A generic method for the identification of options for cleaner products, Bcological Economics”, 10(1), Pages 69-81.

[64]. Reinout Heijungs and Sangwon Suh. 2002. “The Computational Structure of Life Cycle Assessment”, Published by Kluwer Academic Publishers,The Netherlands.

[65]. Jong Myung Gwak, Mi-Ryang Kim, Tak Hur. 2003. “Analysis of internally recurring unit processes in life cycle assessment”, Journal of Cleaner Production,11, Pages 787-795.

[66]. Reinout Heijungs and Sangwon Suh. 2006. "Reformulation of matrix-based LCI: from product balance to process balance", Journal of Cleaner Production, 14(1), Pages 47-51.

[67]. Weizhe LU. 2006. "Study on The Advanced Technique of Environmental Assessment Based On Life Cycle Assessment Using Matrix Method".

[68]. Andreas Busa. 2019. "Life Cycle Assessment of Dell Latitude 7300 25th Anniversary Edition", Dell Technologies.

[69]. Environmental Impacts of Modular Design - Life Cycle Assessment of the Fairphone 3., 2020. [Online]. Available at: https://www.fairphone.com/wp-content/uploads/2020/07/Fairphone_3_LCA.pdf.

[70]. Andrae, Anders S.G., and Tomas Edler. 2015. "On Global Electricity Usage of Communication Technology: Trends to 2030 Challenges 6", no. 1: 117-157.

[71]. Yi Yang, Yujin Park, Timothy M. Smith, Taegon Kim, and Hung-Suck Park. 2002. "High-Resolution Environmentally Extended Input–Output Model to Assess the Greenhouse Gas Impact of Electronics in South Korea".

[72]. Song Su-hyun. 2020. "What makes up smartphone prices?", The Jakarta Post. [Online]. Available at: http://www.thejakartapost.com/life/2020/06/08/what-makes-up-smartphone-prices.html

[73]. Aaron See, Gian de Jesus, and Zeilord Wee Ebol. 2018. "Dell-a Cost-a: The True Cost of a Dell PC". [Online]. Available at: https://thehappyandgayexperience.wordpress.com/2018/05/02/dell-a-cost-a-the-true-cost-of-a-dell-pc/

[74]. Ge Zheng, Zhijun Peng. 2021. "Life Cycle Assessment (LCA) of BEV's environmental benefits for meeting the challenge of ICExit (Internal Combustion Engine Exit)", Energy Reports, Volume 7, Pages 1203-1216, ISSN 2352-4847. [Online]. Available at: https://doi.org/10.1016/j.egyr.2021.02.039.

[75]. Manuel Gaber. 2021. "Spend-based carbon accounting – A useful or oversimplified methodology?". [Online]. Available at: https://dfge.de/spend-based-carbon-accounting/

[76]. Andrae, Anders S. G., and Mikko Samuli Vaija. 2017. "Precision of a Streamlined Life Cycle Assessment Approach Used in Eco-Rating of Mobile Phones" *Challenges* 8, no. 2: 21. [Online]. Available at: https://doi.org/10.3390/challe8020021

[77]. Apple: Product Environmental Report, iPhone 12, 2020. [Online]. Available at:https://www.apple.com/environment/pdf/products/iphone/iPhone_12_PER_Oct2020.pdf

[78]. Apple: Product Environmental Report, 13-inch MacBook Pro, 2020. [Online]. Available at: https://www.apple.com/environment/pdf/products/notebooks/13-inch_MacBookPro_PER_May2020.pdf

[79]. Fredrik Guldbrandsson, Pernilla Bergmark. 2012. “Opportunities and Limitations of Using Life Cycle Assessment Methodology in the ICT Sector”, Ericsson AB, Stockholm, Sweden.