Method for Calculating the Avoided Impact of Specific Information and Communication Technology Services

ANDERS S.G. ANDRAE
Huawei Technologies Sweden AB
Skalholtsgatan 9, 16494 Kista
SWEDEN

Abstract: - Particular Information and Communication Technology (ICT) services can help avoid environmental impact in larger contexts. However, there is no commonly agreed bottom-up methodology for calculation of the total net reduction effect of specific digital ICT services. Life Cycle Assessment (LCA) is a common denominator for most methodologies. The most common method is the Attributional LCA (ALCA), and recently the emerging handprint ALCA estimating so-called positive environmental impacts. Moreover, Consequential LCA (CLCA) can be used to capture market effects. The third conceptual approach is Input-Output LCA. The purpose is to propose and test a new method based on some of the existing ones. The existing concepts are compared and a synthesis is made to create a practical but still useful method. The new method is applied to two illustrative cases in the ICT domain; the introduction of a 5G enabled drone for pipe inspection and the 5G enabled health consultation. Compared to simplified ALCA, the difference between the absolute scores for the baseline system and the target system changes around 10% when the proposed simplified CLCA (SCLCA) method is used. The results show that SCLCA, when combined with analytical methods for expressing digital ICT services' own impact, is a fruitful approach which is both practical and feasible. The new method includes formulae for calculating the total lifetime environmental impact of a specific ICT Equipment when reused or replaced.

Key-Words: - avoided impact, digital, ICT services, life cycle assessment.

Received: January 31, 2024. Revised: March 11, 2024. Accepted: March 12, 2024. Published: March 19, 2024.

1 Introduction

For several years there have been attempts to estimate the potentially avoided, reduced, offset and enabled environmental impact thanks to replacing products/systems/solutions/services with others, mostly using subtracting one attributional LCA (ALCA) [1] from another. ALCA asks the question: What are the absolute environmental impacts of the existing solution and the new solution? Especially digital Information and Communication Technology (ICT) solutions may avoid impacts [2,3] when replacing physical solutions or other digital ones.

The avoided impact is estimated on the level of individual product savings, individual service savings, savings by corporations and savings in society (Figure 1).

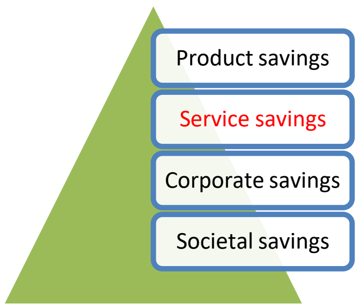

Fig. 1. Categorization for estimation of avoided impact of ICT and the focus of the present research.

Most research in this domain uses simplified ALCA (SALCA) [4-8] of product or service systems to draw conclusions about avoided impact. So far when using ALCA it is clear that comparisons between smart ICT and "physical" is always beneficial for the former. ICT Services have an increasing economic effect on other sectors, in a very intricate and knotted way [9]. That said, more proof is required to show avoided impact in society as a result of using the innovations. Especially knowing the consequences of digital solutions [2,8] replacing each other will be useful. Moreover, the functions and functional units are not described well enough in existing research case studies of avoided impact by ICT Services. Setting an appropriate functional unit is always crucial for comparative LCA, particularly for complex studies which involve ICT Services which help reduce impacts in larger systems.

The existing methods, mainly ALCA, may be able to prove the impact avoidance more or less convincingly and efficiently.

Some macro-perspective studies of societal savings show no [10] or a rather small [9,11] avoidance potential thanks to the introduction of ICT Services while others show very large reduction [12,13]. In this context, the idea of the internet's handprint is based on a top-down macro view of how much general ICT Services (handprint services) can reduce impact in main societal sectors (customers product systems) compared to the baseline systems [13]. The approach asks which fraction of e.g. global electricity generation is applicable for smart facilitation of renewable electricity. Related it also asks which is the reduction potential of smart facilitation of renewable electricity compared to traditional facilitation of renewable electricity. Another example is the fraction of global travel impact that could be addressed by 5G Health Consultation and what is the reduction potential of 5G Virtual Health compared to face-to-face meetings. However, the macro internet handprint approach [13] for societal savings does not account for market and rebound effects.

A similar approach but bottom-up procedure [14] outlines the following steps to estimate the avoided impact by ICT Services: 1) identify the efficiency of the ICT Service, 2) estimate the baseline impact without the ICT Service, 3) estimate the share of population (or other base) that will use the ICT Service, 4) estimate the material and energy savings per quantifiable metric of the ICT Service, and 5) estimate the expected rebound effect.

Still, existing ALCA approaches lack the identification of marginal consumers and complementary production and use.

Advanced ALCA (AALCA) [2], handprint ALCA (HALCA) [15] and consequential LCA (CLCA) [16] are methodological concepts which may help articulate the calculation rationale further beyond just subtracting one ALCA from another. Nevertheless, AALCA can primarily be used [2] if the global sales of relevant sub-materials and sub-parts are available. Hence, AALCA seems only applicable for comparable systems with minor complexity.

The goal of HALCA calculations is to assess the positive impacts that would be achieved when a presumed HALCA solution is used by an existing or potential customer (a customer product system as defined by LCA). In essence HALCA is another way of showing ALCA results.

As it stands, neither HALCA nor (detailed and simplified) CLCA methodologies are used extensively compared to SALCA for estimating impact reductions. Input-Output LCA (IOLCA) is used but mainly so far for top-down reduction studies [9,12,17,18]. HALCA seems clearer than AALCA and CLCA as far as data availability and uncertainty. Anyway, HALCA wants to position itself as a positive footprint referring to the beneficial impacts that organizations can achieve by providing products/services/solutions that reduce the footprints of customer product systems.

CLCA uses different techniques to determine what is expected to happen in the future if the status quo remains compared to introducing a new product. CLCA has two main steps: 1) identify the processes which will change for Baseline System and Target System. More or less electricity consumption and/or transportation are very common for ICT services. 2) identify the consumers of products made available by the change. In this sense the goal of CLCA is noticeably different from the HALCA calculation. CLCA should be used when significant changes in surrounding markets can be assumed to occur as a result of changing technologies. CLCA seems a good fit for those ICT services which have caused, or will cause, relatively large market effects when introduced, e.g. health consultation or flexible mobile office.

Consequential system expansion can be employed to account for secondary functions provided.

In practice, the CLCA methodology often has to be simplified and adapted for practical reasons. The uncertainty is also large and habitually not assessed.

Even so, the role of CLCA is useful in adding some more detail into various rebound effect [19] calculations. In summary avoided impact calculations should contain the impact of the innovation, the rebound effects and the enabling effect. Any reliable methodology for calculating avoided impact needs to be based on bottom-up analysis with immediate and quantifiable aspects

having strong statistical and causal relations to the functions and studied systems
It is somewhat possible to identify the exact unit processes which are affected by the introduced change in the system such as virtual meeting.
The main hotspot in an LCA of a physical meeting is travel. Only the immediate travels will be affected by this change.

The gap found in the literature is that the main approaches for avoiding impact calculations do not provide a practical method for bottom-up estimations for specific digital services. The hypothesis proposed in the present research is that simplified CLCA (SCLCA) can be combined with bottom-up cloud-service LCA estimation methods to estimate the avoided impact. Table 1 shows the main advantages and disadvantages of existing approaches compared to the proposed.

Table 1. Comparison of methodological approaches for quantifying avoided impact of ICT Services.

Methodological approach	**Main advantage**	**Main disadvantage**	**Complexity**	**Data availability**	**Reliability of result**
Attributional LCA (ALCA)	Simplified, direct, fast if streamlined	Market effects excluded	Low	High	Medium
Advanced ALCA	Some market effects included	Data availability, no real added value compared to CLCA	Medium	Medium	Medium
Handprint ALCA	Focus on customer product systems	No real added value compared to ALCA	Medium	Medium	Medium
Detailed Consequential LCA (DCLCA)	High specificity, may include rebound effect	Variable interpretation of marginal data	High	Low	Low
Input-Output LCA	Comprehensive, fast, may include rebound effect	Low specificity	Very Low	Low	Low
Proposed method, Simplified CLCA	High specificity, fast, some market effects included	Not Detailed CLCA	Low	High	High

2 Materials and Methods

Equation (1) describes how the total avoided environmental impact of a specific ICT Service can be calculated.

$$T\_AEI_{(i)} = T\_EI_B - \left(T\_ICT_{(i)} + T\_EI_{RB}\right) \quad (1)$$

where

$T\_AEI_{(i)}$= Total Avoided Environmental Impact (or emissions) from the ICT Service *i* at hand per functional unit.

T_EI_B= Total life cycle Environmental Impact (or emissions) without ICT service *i* in studied product system per functional unit. This is the Baseline system.

$T\_ICT_{(i)}$ = Total life cycle Environmental Impact (or emissions) with ICT service type *i* in studied product system per functional unit. This is the Target system.

i = type of ICT service, e.g. 5G, fixed broadband, cloud.

T_EI_{RB}= Total Environmental Impact (or emissions) for rebound effects.

Equation (2) describes how the total lifetime environmental impact of a specific ICT Equipment when replaced can be calculated.

$$T_{EI(j),replace} = EI_{M,1st} + EI_{D,1st} + EI_{U1,1st} \times Ti_{replace} + \frac{EI_{M,1st,replace}}{Ti_{total}} \times \left(Ti_{total} - Ti_{replace}\right) + EI_{D,1st,replace} + EI_{U1,1st,replace} \times \left(Ti_{total} -\right.$$

$Ti_{replace}) + EI_{EoLt,1st} + EI_{EoLT,1st,replace}$ (2)

Equation (3) describes how the total lifetime environmental impact of a specific ICT Equipment when reused can be calculated.

$$T_{EI_{(j),reuse}} = EI_{M,1st} + EI_{D,1st} + EI_{U1,1st} \times Ti_{reuse} + EI_{M,1st,reuse} + EI_{D,1st,reuse} + EI_{U1,1st,reuse} \times (Ti_{total} - Ti_{reuse}) + EI_{EoLt,1st} + EI_{EoLT,1st,reuse} \quad (3)$$

where

$T_{EI_{(j),replace}}$ = Total environmental impact when Equipment type j is replaced.

$T_{EI_{(j),reuse}}$ = Total environmental impact when Equipment type j is reused.

$EI_{M,1st}$= Environmental impact for manufacturing of the first Equipment.

$EI_{M,1st,replace}$= Environmental impact for manufacturing of the Equipment replacing the first Equipment.

$EI_{M,1st,reuse}$= Environmental impact for manufacturing of the spare parts for the first Equipment.

$EI_{D,1st}$= Environmental impact for distribution of the first Equipment.

$EI_{D,1st,replace}$= Environmental impact for distribution of the Equipment replacing the first Equipment.

$EI_{D,1st,replace}$= Environmental impact for distribution of the first Equipment when reused.

$EI_{U1,1st}$= Annual Environmental impact for use of the first Equipment.

$EI_{U1,1st,replace}$= Annual Environmental impact for use of the Equipment replacing the first Equipment.

$EI_{U1,1st,reuse}$= Annual Environmental impact for use of the first Equipment when reused.

$EI_{EoLT,1st}$= Environmental impact for end-of-life treatment of the first Equipment.

$EI_{EoLT,1st,replace}$= Environmental impact for the end-of-life treatment of the Equipment replacing the first Equipment.

$EI_{EoLT,1st,reuse}$= Environmental impact for end-of-life treatment of the spare parts used for the first Equipment.

Ti_{total}= Total lifetime of first and replacing Equipment.

$Ti_{replace}$=Time when the first Equipment is replaced.

Ti_{reuse}=Time when the first Equipment is reused.

j = type of Equipment.

Equations (2) and (3) are applied to the PCs and Monitors in the examples in sections 2.3 and 2.4. These equations – inspired by [20, 21] - can be used to decide in any situation if a product should be reused or replaced.

2.1 Total Environmental Impact for individual ICT service types

A simplified way to estimate the network share of $T\_ICT_{(i)}$ is to multiply the energy efficiency (μ) of the ICT Service(s) with its bandwidth (B_i) the time of duration (t_h) per session, and the environmental impact intensity of the electricity (See Equations (4)-(6)) [22].

$$\mu = \frac{P}{T_n} \quad (4)$$

$$E_s = \mu \times B_i \times t_h \quad (5)$$

$$T\_ICT_{(i)} = EI_{electricity} \times E_s \quad (6)$$

P = Power usage of specific Network (kW)

T_n = Total specific network traffic (Gb/s)

B_i = Bandwidth for studied ICT service i, (Gb/s)

t_h= Duration of ICT Service {h}.

μ = ICT Service Energy Efficiency (kW/[Gb/s])

E_s = Studied ICT Service energy usage (kWh)

$EI_{electricity}$ = environmental impact intensity of electricity used by studied ICT service (environmental impact/kWh)

A more detailed approach for estimating the energy consumption (E_s) of the use phase for an ICT Service is provided in [23]. The scope consists of the Data transmission (in the Wi-Fi Router&Access Equipment and in the Metro&Core Networks) and the Data processing/storage in the Data Centers. Equations (7) - (10) give the individual electricity use per ICT Service, and Equation (11) gives E_s in a more precise manner than Equation (5). Wireless Access network equipment energy consumption is more data dependent than time-dependent [24] and is therefore modelled as the Metro&Core network Equipment in Equation (8).

$$E(t,V)_{Fixed\&Wireless\ Access\ Customer\ Premise\ Equipment} = t_h \times \sum_j \left(P_j \times PUE_j\right) \quad (7)$$

$$E(t,V)_{Metro\&Core\&Wireless\ Access\ Equipment\ in\ Networks} = V \times \sum_j \frac{P_j}{C_j} \times PUE_j \quad (8)$$

$$P_{glo} \approx \frac{E_{glo}}{8760} \quad (9)$$

$$E(t,V)_{Data\ Centers} = V \times \sum_j \frac{E_{j,Data\ centers}}{P_{Data\ centers}} \times \left(\frac{T_{glo}}{P_{glo}}\right)^{-1} \quad (10)$$

$$E_s = E(t,V)_{CPE\&Fixed\ Access\ Equipment} + E(t,V)_{Metro\&Core\&Wireless\ Access\ Equipment\ in\ Networks} + E(t,V)_{Data\ Centers} \quad (11)$$

$$HW(t,V)_{Fixed\&Wireless\ Access\ Customer\ Premise\ Equipment} = t_h \times \sum_j \left(\frac{HW_{kj}}{L_j}\right) \quad (12)$$

$$HW(t,V)_{Metro\&Core\&Wireless\ Access\ Equipment\ in\ Networks} = \frac{V}{C_j} \times \sum_j \frac{HW_{kj}}{L_j} \quad (13)$$

$$HW(t,V)_{Data\ Centers} = V \times \sum_j \frac{\frac{HW_{kj}}{L_j}}{P_{Data\ centers}} \times \left(\frac{T_{glo}}{P_{glo}}\right)^{-1} \quad (14)$$

$$HW_s = HW(t,V)_{CPE\&Fixed\ Access\ Equipment} + HW(t,V)_{Metro\&Core\&Wireless\ Access\ Equipment\ in\ Networks} + HW(t,V)_{Data\ Centers} \quad (15)$$

where

$E(t,V)_{Fixed\&Wireless\ Access\ Customer\ Premise\ Equipment}$ = Electricity consumption of the Fixed&Wireless Access CPE {kWh per ICT Service}.

P_j = Power consumption of Equipment type j {kW}.

PUE_j = Overhead factor for inclusion of electricity consumption of supporting functions for Equipment type j.

$E(t,V)_{Metro\&Core\&Wireless\ Access\ Equipment\ in\ Networks}$ = Electricity consumption of the Metro and Core and Wireless Access networks {kJ per ICT Service}.

V = data volume processed by the network per functional unit for the ICT service at hand {GB}.

C_j= throughput rate of Equipment j [GB/s, Gb/s divided by 8].

$E(t,V)_{Data\ Centers}$ = Electricity consumption of the Data Centers {kWh per ICT Service}.

$E_{j,Data\ centers}$= Electricity consumption of Equipment j in data centers at hand {kWh/year}.

$P_{Data\ centers}$= Total power consumption of data centers at hand {kW}.

T_{glo}= Total Global Data Center IP Traffic {GB/year}.

P_{glo}= Total Power consumption of Global Data Centers {kW}.

E_{glo}= Total Electricity consumption of Global Data Centers {kWh}.

T_{glo} and E_{glo} estimates can be obtained from [25]. E_{glo} can be used to estimate P_{glo} if P_{glo} data are not available.

HW_{kj}= Consumption of hardware k in Equipment type j {kg}.

L_j= Lifetime of Equipment type j {hours}.

$HW(t,V)_{CPE\&Fixed\ Access\ Equipment}$= Hardware consumption of the Fixed&Wireless Access CPE {kg per ICT Service}.

$HW(t,V)_{Metro\&Core\&Wireless\ Access\ Equipment\ in\ Networks}$ = Hardware consumption of the Metro and Core and Wireless Access networks {kg per ICT Service}.

$HW(t,V)_{Data\ Centers}$ = Hardware consumption of the Data Centers {kg per ICT service}.

HW_s = Studied ICT Service Hardware usage {kg per ICT service}.

The fraction of idle time per day has been removed from Equation (7) compared to [23] (Eq. 1) due to difficulties for a designer to quantify this parameter. Moreover, the redundancy and utilization rate have been removed from Equation (8) compared to [23] (Eq. 2) due to problematic quantifications compared to their relevance for driving $E(t,V)_{Metro\&Core\&Wireless\ Access\ Equipment\ in\ Networks}$.

The wireless networks are modelled as metro and core networks. The impact of producing the hardware is included although it is rather insignificant for ICT Services [23].

As far as data center hardware consumption, [23] (Eq. 6) has here been changed from using material usage per data volume to hardware consumption per lifetime. This is done to mimic the other equipment types (See Equations 12 and 13) and for easier data collection.

2.1 Validation of ICT Service impact with IOLCA

If the cost of delivering the ICT Service at hand is known, the bottom-up results from Equation (11) may be compared to the IOLCA scores in 2009 for EU27, 0.264 kg CO_2e/USD for "Computer and related services" [26].
The corresponding intensity had shrunk to around 0.15 kg CO_2e/USD in 2017 for "Data Processing, Hosting, and Related Services" [27].

Based on literature, cases can be identified in which avoided impacts have occurred and are expected. The comparable product systems are then decided from the existing baseline system and target system (new innovation). The function to be delivered by both systems is identified and then the functional unit for both. Then Equations (1) to (15) are applied as appropriate.

2.2 Cooling of base stations – use of marginal electricity and heat production technologies

The first example is used to show how marginal energy technologies can be identified. This example does not feature any ICT Service.
Base stations can be cooled in different ways, e.g. air cooling or liquid cooling. The latter provides waste heat that is recoverable through the cooling liquid for various heating purposes [15].
The identified function is: providing cooling of base stations.
The functional unit is: "A subsystem providing the cooling to be suited for the needs of one 0.695kW base station in Finland for one year".
Figure 2 shows the CLCA for the baseline system (air cooling).

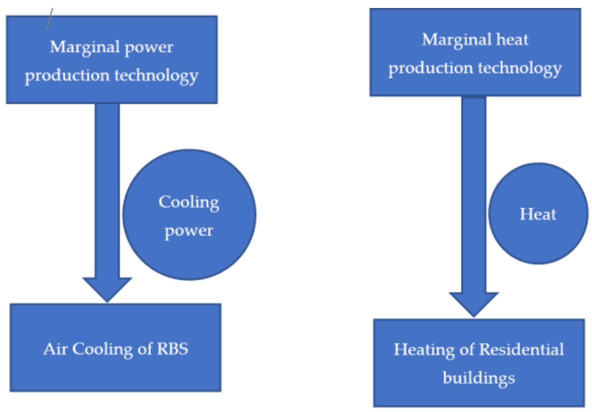

Fig. 2. Scope of baseline system with proposed simplified CLCA method for cooling of base station.

Figure 3 shows the scope of the target system for cooling of base stations.

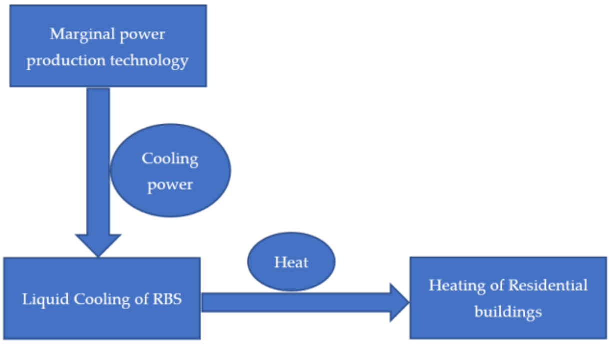

Fig. 3. Scope of target system with proposed simplified CLCA method for cooling of base station.

The numbers in Table 2 for power and heat are based on [15]. The most sensitive process is the most competitive in a situation with an increasing or constant market trend, while it is the least competitive in a situation with a decreasing market trend [28]. Nuclear power is assumed to be the most competitive baseload power production method in Finland and district heat is assumed to be the most competitive heat generation technology for residential houses.

When demand increases, short-term marginal production is the unit with the highest operation costs [29]. Light fuel combustion is assumed to be the costliest way in Finland of producing heat for this application, i.e. light fuel combustion is the marginal heat production technology.

The simplest calculation for avoided impact (or emissions) is subtractive simplified ALCA for the use stage: Baseline System - Target System. The parameters used for the calculation are shown in Table 2.

Table 2. Parameters used in [15] for simplified ALCA baseline and target system for cooling of base stations.

Parameter	**Baseline System**	**Target System**
Power consumption (kW)	0.695	0.591
Heat consumption (kW)	0.4728	
Environmental impact intensity of electricity used ($kgCO_2e/kWh$)	0.164	0.164
Environmental impact intensity of heat used ($kgCO_2e/kWh$)	0.188	
Calculation	0.695 kW × 8760 hours/year × 0.164 $kgCO_2e/kWh$ + 0.591 kW × 0.8 × 8760 hours/year × 0.188 $kgCO_2e/kWh$	0.591 kW × 8760 hours/year × 0.164 $kgCO_2e/kWh$
Total result	1777 kg CO_2e/year	849 kg CO_2e/year
Avoided impact	1777 – 849 = 928 kg CO_2e/year per 0.695 kW base station	

The next simplest calculation for avoided emissions is done with SCLCA:
CLCA (Baseline System) – CLCA (Target System).

The parameters used for the SCLCA calculation are shown in Table 3.

Table 3. Parameters used by proposed simplified CLCA method by baseline and target system for cooling of base stations.

Feature	**Baseline System**	**Target System**
Power consumption (kW)	0.695	0.591
Heat consumption (kW)	0.4728	
Environmental impact intensity of electricity used ($kgCO_2e/kWh$)	0.01 (Nuclear)	0.01 (Nuclear)
Environmental impact intensity of heat used ($kgCO_2e/kWh$)	0.32 (Light fuel combustion)	
Calculation	0.695 kW × 8760 hours/year × 0.01 $kgCO_2e/kWh$ + 0.591 kW × 0.8 × 8760 hours/year × 0.32 $kgCO_2e/kWh$	0.591 kW × 8760 hours/year × 0.01 $kgCO_2e/kWh$
Total result	1386 kg CO_2e/year	52 kg CO_2e/year
Avoided impact	1386 – 52 = 1334 kg CO_2e/year per 0.695 kW base station	

2.3 5G enabled drone for pipe inspection – use of framework and marginal electricity

The first example [30] (pp. 23-25, 41-43) of a case study, which includes an ICT Service which can help avoid impact, is pipe inspection. Such inspection can be done with humans visiting the pipes for inspection or by Unmanned Aerial Vehicle (UAV) in combination with 5G wireless networks. Table 4 shows how the present methodology is applied to pipe inspection.

Table 4. Present proposed methodology applied to pipe inspection in China.

Item	Description	
Goal	Avoided emissions in pipe inspection technology comparison	
Scope	CO_2e emissions resulting from: ▪ driving of the petrol vehicle during human inspection ▪ production of petrol fuel ▪ production of the petrol vehicle. ▪ use of the Unmanned Aerial Vehicle (UAV), including emissions during flight ▪ production of UAV aviation diesel fuel ▪ UAV production ▪ use of personal computers (PCs) – marginal baseload power is used. ▪ production of PCs. ▪ use of wireless networks for 5G on the UAV. The marginal baseload power production technology in China is dependent on province characteristics but is here assumed as coal power [31] with 0.9 kgCO_2e/kWh. End-of-life treatment of e.g. PCs is excluded due to expected low significance [2].	
Function	Providing inspection of gas pipes.	
Functional unit	A subsystem providing the inspection to be suited for the needs of 160 km of gas pipe in China.	
System related avoided emissions		
	Baseline System	Target System
Description	Human inspection	5G-equipped Unmanned Aerial Vehicle (UAVs) inspection
System Boundary	Use and production stages for inspection of 160 km pipe in China on average.	Use and production stage for inspection of 160 km pipe in China on average.
Result of avoided emissions calculations		
Calculation formula: Baseline System - Target System = $T\_AEI_{(i)} = T\_EI_B - (T\_ICT_{(i)} + T\_EI_{RB})$ T_EI_B :160km/250000km × ((8340kWh×0.9 kg CO2e/kWh)+5000)) kg CO_2e/car {Petrol vehicle production} + 26.67dm3×0.73kg/dm3×0.45 kg CO_2e/kg {Petrol production} + 16.66dm^3/100km×2.31 kg CO_2e/dm^3 ×160km {Use of Petrol vehicle} = 81 kg CO2e/160 km. $T\_ICT_{(i)}$: 2months/200months×((609kWh×0.9 kg CO_2e/kWh + 365)) kg CO_2e/UAV {UAV production} + 1month/48months×(202kWh×0.9 kg CO_2e/kWh + 121.4 kg CO2e/PC + 0.01kW×4years×8760hrs/year×0.9 kg CO_2e/kWh) {PC production and use} + 0.7dm3 ×0.45 kg CO_2e/kg {Diesel production} + 160km × 0.16 kg CO_2e/km {UAV use} +1month/12month×{wireless CPE use} $\{t_h \times \sum_j (P_j \times PUE_j)\}$8760hours×0.0075 kW×1.3×0.9 kg CO_2e/kWh = 54 kg CO_2e/160 km. Avoided emissions = 81 – 54 = 27 kg CO_2e per 160 km pipe inspected. Rebound effects are not estimated in this case study. They are discussed in section 4.		

2.4 5G enabled health consultation - use of framework and marginal electricity

The second example [30] (pp. 27-28) involving an ICT Service - potentially avoiding impact - is health consultation. It is a well-established practice for doctors to use computerized tomography (CT) scans to help diagnose patients' conditions and to guide the formulation of suitable treatment plans. Hospitals in smaller cities regularly invite highly experienced medical experts from larger metropolitan cities to carry out on-site consultation and differential diagnosis. The consultation can also be done remotely with 5G which may avoid some travelling. Travelling by aircraft is excluded as the medical experts in this case do not travel by private jets. Regular aircraft cannot be claimed to be immediately avoided.
Table 5 shows how the present methodology is applied to health consultation.

Table 5. Present proposed methodology applied to health consultation in China.

Item	**Description**
Goal	Health Consultation Technology comparison, effect of digitalization
Scope	CO_2e emissions resulting from: ▪ driving of the petrol vehicle during face-to face (F2F) consultation, the petrol fuel supply chain ▪ production of the petrol vehicle. ▪ use of personal computers (PCs) and monitors - marginal baseload power is used. ▪ production of PCs and monitors. ▪ production of wireless equipment ▪ use of wireless networks for 5G for the remote consultation in which the marginal baseload power is used. ▪ production of data centers ▪ use of data centers in which the marginal baseload power is used. The marginal power production technology in China is here assumed as coal thermal power [31] with 0.9 kgCO_2e/kWh. End-of-life treatment of e.g. PCs is excluded due to expected low significance [2].
Function	Providing health consultation of computerized tomography (CT) scans.
Functional unit	A health consultation subsystem for 24 consultations per day involving analysis of CT scans to be suited for the needs of the purchasing customer.

System related avoided emissions		
	Baseline Scenario	Target Product or System
Description	F2F consultation	5G health consultation
System Boundary	Use and production stage for 24 consultations in China on average.	Use and production stage for 24 consultations in China on average.

Result of avoided emissions calculations
Calculation formula: Baseline System - Target System = $T_{AEI_{(i)}} = T_{EI_B} - \left(T_{ICT_{(i)}} + T\_EI_{RB}\right)$ Baseline System, T_EI_B: 320km × (4cars/250000km × ((8340kWh×0.9 kg CO_2e/kWh)+5000) kg CO_2e/car)) {Petrol car production} + 320km× ((5.58dm3/100km×0.73kg/dm3×(0.375kWh×0.9 kg CO2e/kWh + 0.225 kgCO_2e/kg)) {Petrol production} + 320km×(5.58dm3/100km×2.31 kgCO_2e/dm3) {Use of petrol car} + 1 PC×8hours×((202kWh×0.9 kg CO_2e/kWh + 121.4 kg CO_2e/PC))/(4years×8760hours) + 0.01kW×0.9 kg CO2e/kWh) {PC production and use}+ 1 monitor×8hours×((222kWh×0.9 kg CO2e/kWh + 200 kg CO_2e/Monitor))/(4years×8760hours) + 0.01kW×0.9 kg CO_2e/kWh)) {Monitors production and use} = 113 kg CO2e/24 consultations Target System, $T_{ICT_{(i)}}$: 3 PCs×13hours×((202kWh×0.9 kg CO_2e/kWh + 121.4 kg CO2e/PC))/(4years×8760hours)+ 0.01kW×0.9 kg CO_2e/kWh) {PC production and use} + 3 monitors×13hours×((222kWh×0.9 kg CO_2e/kWh + 200 kg CO2e/Monitor))/(4years×8760hours) +0.01kW×0.9 kg CO_2e/kWh)) {Monitors production and use} + {wireless network production + use, data center production + use} 5GB/hour×13hours×200 kg×1/(0.05 GB/s×3600 s/h) ×20 kg CO2e/kg×1/(5 years×8760 hours/year) {5G wireless network production} + 5GB/hour×13hours×7kW/(0.05GB/s)×1/1000 kJ/MJ×1/3.6 MJ/kWh×1.3×0.9kgCO_2e/kWh {5G wireless network use} + 5GB/hour×13hours×10230 kWh/kW/year×0.9 kg CO_2e/kWh × 1/(43762×2^{60}/2^{30}(GB/year)/((350×10^9 kWh /8760 hours/year)) {Data center use} + 5GB/hour×13hours× (1585590 kg/year)/15064.3 kW×10 kg CO_2e/kg × 1/(43762×2^{60}/2^{30}(GB/year)/((350×10^9 kWh /8760 hours/year)) {Data center production} = 5.04 kg CO_2e/24 consultations. Avoided emissions = 113 – 5.04 - T_EI_B = 107.96 kg CO_2e per 24 health consultations. Rebound effects are not estimated in this case study. They are discussed in section 4. The annual material use, its average power consumption and

kWh/kW/year for the data center are obtained from [32].

Applying Equations (2) and (3) to PCs and Monitors using Ti_{total}= 4 years, $Ti_{replace}$=2 years, Ti_{reuse}=2 years increase the production (of PCs and Monitors) emissions by 50% for the replace scenario (Equation (2)) but this does not change the total scores significantly. Interestingly, the reuse scenario (Equation (3)) with these assumptions gives almost the same values as the original.

3 Results

The results show that SCLCA combined with analytical methods for expressing digital services' own impact is a fruitful approach.
Figures 4 to 10 show the comparison between ALCA and the proposed SCLCA method for the case studies in sections 2.2 to 2.4.

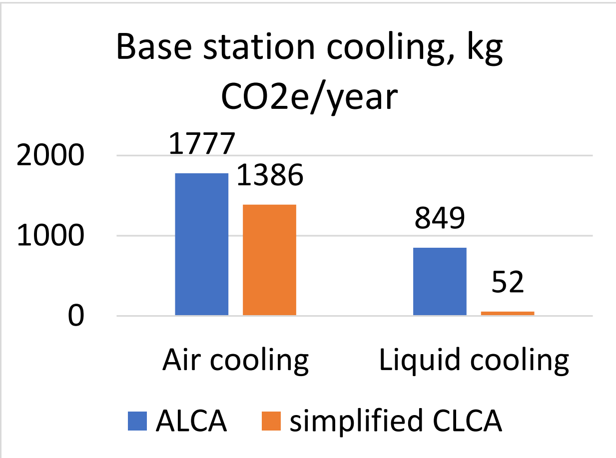

Fig. 4. Difference between ALCA [15] and the proposed simplified CLCA for base station cooling.

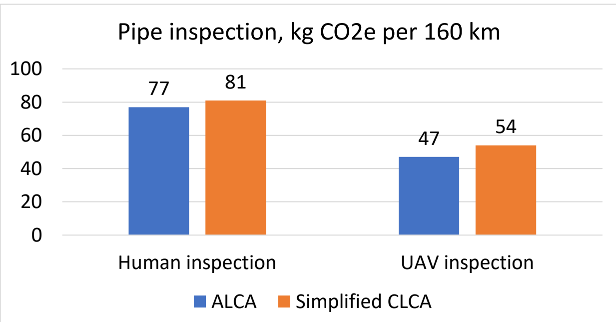

Fig. 5. Difference between ALCA [30] and the proposed simplified CLCA for pipe inspection

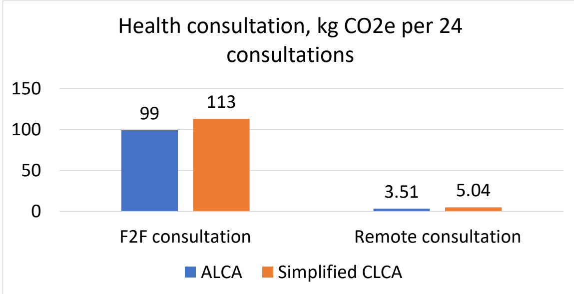

Fig. 6. Difference between ALCA [30] and proposed simplified CLCA for health consultation.

Figure 7 to 10 show the drivers for CO_2 and electricity for the case studies in sections 2.3 and 2.4 using SCLCA.

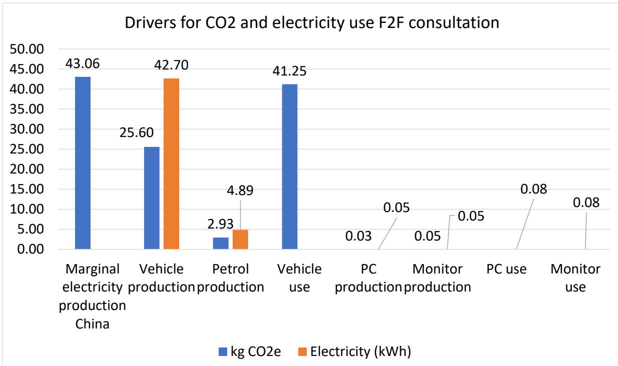

Fig. 7. Drivers for CO_2 and electricity for F2F health consultation.

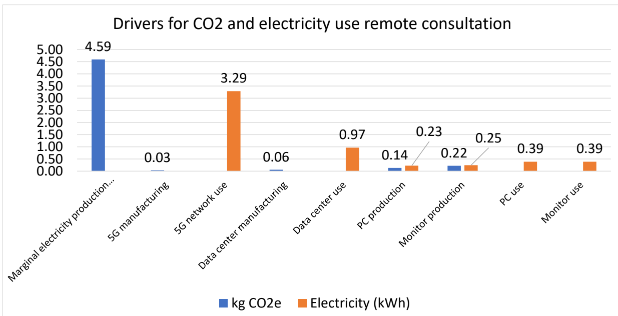

Fig. 8. Drivers for CO_2 and electricity for Remote health consultation.

As shown in Figure 7 and Figure 8, the avoided vehicles use and production explain much of the avoided impact for health consultation.

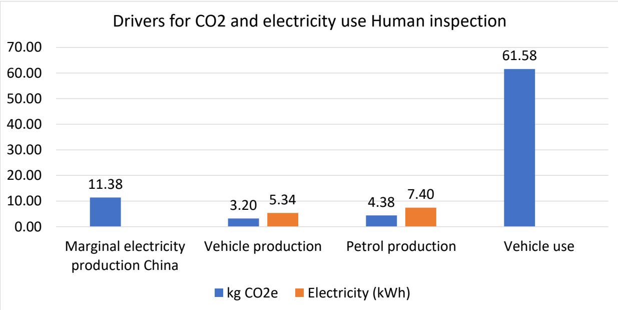

Fig. 9. Drivers for CO_2 and electricity for human pipe inspection.

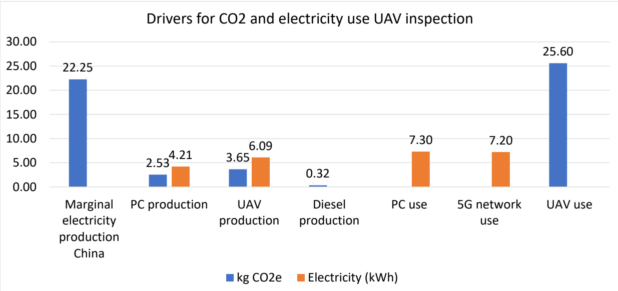

Fig. 10. Drivers for CO_2 and electricity for UAV pipe inspection.

Regarding Figure 9 and Figure 10, the avoided impact thanks to UAV pipe inspection may not be a foregone conclusion due to the rather high uncertainties for Vehicle use emissions and UAV use emissions.

4 Discussion

The topic of avoided impact is both a bottom-up and a top-down issue. It spans from specific ICT Services to ICT's impact on the whole society (Figure 1).

The overall effect of avoided carbon is very complex and more research is necessary on hypotheses to be tested.

For the proposed SCLCA approach, Figures 4 to 6 do not show significant differences for chosen ICT Service systems compared to ALCA. Anyway, the proposed method at least contains the possibility for marginal technologies, data volumes and replace/reuse considerations.

The differences may become larger if marginal fuel type producers are introduced and if the correct marginal consumers could be identified. Hence, the general conclusion that SCLCA will not show considerably different results than SALCA, for bottom-up ICT Service avoided impact calculations, cannot yet be drawn.

Equation (1) does not deal with reductions of total societal sectors like [13] but is a bottom-up approach for non-experts looking at ICT Services.

Corporate annual reporting of avoided impacts refers to impacts of sold products having causation outside Scope 1 and 2 [33]. Apart from the absolute impact, it is logical that Scope 3 Category 11 (use of sold products and services) should also contain the (separately reported) avoided impact from sold products and services. The proposed approach can partly support such corporate calculations. The reason is that the functional units defined for the ICT Services are reflecting the functions sold by each company. However, intermediate products, like e.g. batteries, would need an allocation methodology to be researched.

Furthermore, Detailed CLCA (DCLCA) will need a basic description of the economy in monetary units.

Is it realistic to include higher order effects before very fine granular impact and computable general equilibrium models [12] have been established worldwide? If such databases were available for DCLCA, the consequences of introducing specific technologies in the economies could be more accurately predicted. However, the level of aggregation for such models is still a problem for studying specific systems for which ALCA or SCLCA is more appropriate. Still, databases such as "Full International and Global Accounts for Research in inputOutput analysis' (FIGARO) and EXIOBASE [34] lack the detailed industry, engineering, and household data that are needed for generating emission profiles at the detailed product and service level.

Still the overall reduction potential of ICT in society [13] has been confirmed by [12] and [9].

The rebound effects - which are unknown quantitatively for the present cases studies – would have to be rather large to completely off-set the avoided emissions. Especially for the health consultation.

The uncertainty and sensitivity analyses for the current case studies are not developed extensively. However, as shown in Table 6, adding a 10% uncertainty to the input parameters used in Tables 4 and 5 results in approximate spreads of the output values.

Table 6. Initial uncertainty analysis of present case studies (kg CO_2e)

	SALCA	2 standard deviations,	SCLCA	2 standard deviations,

		spread		spread
F2F health consultation	99	10.4	113	11.9
Remote health consultation	3.51	0.43	5.04	0.64
Human inspection	77	10	81	10.4
UAV inspection	47	3.2	54	3.7

Although the uncertainty calculation and sensitivity assessment methodologies for ICT Services are further work, preliminary a >25% uncertainty for the values 61.58 kg CO_2e in Figure 9 and 25.6 kg CO_2e in Figure 10 would make the results for Human and UAV inspection of pipes equal.
The end-of-life treatment should also be added to the present calculations, as well as reuse and replace modelling of UAV and transport vehicles.
For all methods listed in Table 1 the main issue concerns how far the studied product system needs to be expanded to get useful and informed results.
DCLCA will often lead to complex identifications as it tends to be hard to point out the correct marginal consumers and producers in a ripple effect analysis. A typical example is the physical meeting versus virtual meeting exemplified in section 2.4. A related example is “office work”. A popular dematerialization case is flexible work in which physical meetings/office work are replaced by online meetings/home office, reducing commuting and business travel. Another reduction effect is for the office space.
Both the baseline system and target system can provide space for apartments.
Here the function is: providing area in buildings suitable for office work places and residential apartments. The functional unit is: “A working place subsystem providing the area to be suited for the needs of one employee and one resident for one year”. The baseline system has to provide residential area places by building new ones. On the other hand, the target system can offer office work at home and residential area space by refurbishing office area which is no longer needed. However, here it is not certain which is the marginal consumer of the surplus office space created by smart home offices. In Figure 11 and Figure 12 it is assumed that refurbished apartments area is the marginal consumer.

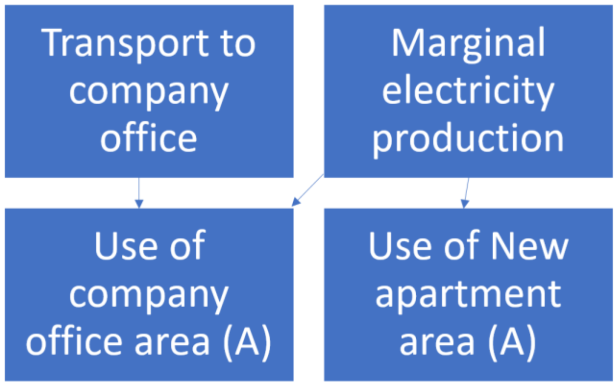

Fig. 11. Scope of baseline system with proposed simplified CLCA method for office work in area (A).

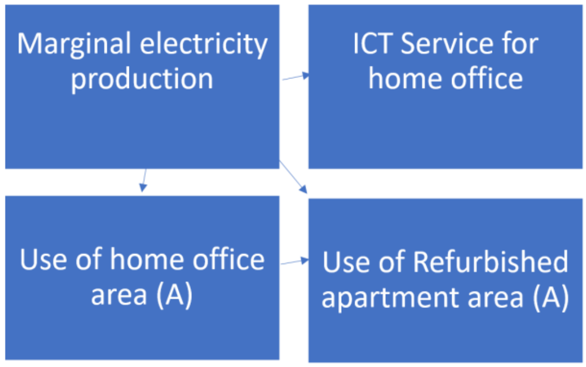

Fig. 12. Scope of target system with proposed simplified CLCA method for office work in area (A).

The SCLCA scenario for avoided impact may look like “Transport to company office plus construction and use (with marginal electricity) of new apartments” minus “Marginal electricity for home office + ICT Service enabling home office”. Still, it should be attempted to make scenarios of (maybe also do modelling of) the plausible avoided impacts with DCLCA and further system expansion. However, when no significant changes in surrounding markets are to be expected, DCLCA is superfluous.
The number of both statistical and causal factors which influence the identification of the marginal technologies in DCLCA should not be underestimated. SCLCA is a practical way forward.
While several efforts are ongoing attempting to standardize the avoided impact calculation, the SCLCA method is rather neglected so far.

5 Conclusions

SALCA would give the same conclusion as SCLCA for the chosen systems of pipe inspection and health consultation. A bottom-up approach of using SCLCA, reuse/replace scenarios and data volume approach is developed which give reasonable results and can be used by non-LCA experts.

6 Next steps

It remains to be researched whether SCLCA is generally applicable to e.g. Smart Energy Systems [35]. The uncertainty assessment, rebound effects and scale-up are next steps methodologically. Moreover, the methodology for calculating the shares of subsystems of the total avoided impacts should be outlined.

References:

[1] R. Heijungs. Identification of key issues for further investigation in improving the reliability of life-cycle assessments. *Journal of Cleaner Production*, Vol.4, No. 3-4, 1996, pp. 159-166. https://doi.org/10.1016/S0959-6526(96)00042-X

[2] A.S.G. Andrae. Method based on market changes for improvement of comparative attributional life cycle assessments. *International Journal of Life Cycle Assessment*, Vol. 20, 2015, pp. 263-275. https://doi.org/10.1007/s11367-014-0830-2

[3] L. Wang, T. Zhu. Will the Digital Economy Increase Energy Consumption?–An Analysis Based on the ICT Application Research. *Chinese Journal of Urban and Environmental Studies*, Vol. 10, No. 1, 2022 p. 2250001. https://doi.org/10.1142/S2345748122500014

[4] R. Hischier, I. Reichart. Multifunctional electronic media-traditional media: The Problem of an Adequate Functional Unit A case study of a printed newspaper, an internet newspaper and a TV broadcast. *International Journal of Life Cycle Assessment*, Vol. 8, 2003, pp. 201-208. https://doi.org/10.1007/BF02978472

[5] H.K. Jeswani, A. Azapagic. Is e-reading environmentally more sustainable than conventional reading?. *Clean Technologies and Environmental Policy*, Vol. 17, 2015, pp. 803-809. https://doi.org/10.1007/s10098-014-0851-3

[6] X. Chavanne, S. Schinella, D. Marquet, J.P. Frangi, S. Le Masson. Electricity consumption of telecommunication equipment to achieve a telemeeting. *Applied Energy*, Vol. 137, 2015, pp. 273-281. https://doi.org/10.1016/j.apenergy.2014.10.027

[7] A. Seidel, N. May, E. Guenther, F. Ellinger. Scenario-based analysis of the carbon mitigation potential of 6G-enabled 3D videoconferencing in 2030. *Telematics and Informatics*, Vol. 64, 2021, p. 101686. https://doi.org/10.1016/j.tele.2021.101686

[8] D. Maga, M. Hiebel, C. Knermann. Comparison of two ICT solutions: desktop PC versus thin client computing. *International Journal of Life Cycle Assessment,* Vol. 18, 2013, pp. 861-871. https://doi.org/10.1007/s11367-012-0499-3

[9] T. Kopp, M. Nabernegg, S. Lange. The net climate effect of digitalization, differentiating between firms and households. *Energy Economics*, Vol. 126, 2023, p. 106941. https://doi.org/10.1016/j.eneco.2023.106941

[10] S. Lange, J. Pohl, T. Santarius. Digitalization and energy consumption. Does ICT reduce energy demand?. *Ecological Economics*, Vol. 176, 2020, p. 106760. https://doi.org/10.1016/j.ecolecon.2020.106760

[11] S. Sorrell. Digitalisation of goods: a systematic review of the determinants and magnitude of the impacts on energy consumption. *Environmental Research Letters*, Vol. 15, No. 4, 2020, p. 043001. DOI 10.1088/1748-9326/ab6788

[12] X. Zhang, M. Shinozuka, Y. Tanaka, Y. Kanamori, T. Masui. How ICT can contribute to realize a sustainable society in the future: a CGE approach. *Environmental Development and Sustainability*, Vol. 24, 2022, pp. 5614-5640. https://doi.org/10.1007/s10668-021-01674-9

[13] A.S.G. Andrae. Internet's handprint. *Engineering and Applied Science Letters*, Vol. 4, No. 1, 2021, pp. 80-97. DOI: 10.30538/psrp-easl2021.0065

[14] J. Bieser, L. Hilty. Assessing indirect environmental effects of information and communication technology (ICT): A systematic literature review. *Sustainability*, Vol. 10, 2018, p. 2662.1. https://doi.org/10.3390/su10082662

[15] H. Kasurinen, S. Vatanen, K. Grönman, T. Pajula, L. Lakanen, O. Salmela, R. Soukka. Carbon handprint: Potential climate benefits of a novel liquid-cooled base station with waste heat reuse. *Energies*, Vol. 12, No. 23, 2019, p 4452. https://doi.org/10.3390/en12234452

[16] Y. Yang, R. Heijungs On the use of different models for consequential life cycle assessment. *International Journal of Life Cycle Assessment*, Vol. 23, 2018, pp. 751-758. https://doi.org/10.1007/s11367-017-1337-4

[17] X. Li, J. Liu, P. Ni. The Impact of the Digital Economy on CO2 Emissions: A Theoretical and Empirical Analysis. *Sustainability*, Vol.13, 2021, p. 7267. https://doi.org/10.3390/su13137267

[18] X. Lei, Y. Ma, J. Ke, C. Zhang. The Non-Linear Impact of the Digital Economy on Carbon Emissions Based on a Mediated Effects Model.

Sustainability, Vol. 15, p. 7438. https://doi.org/10.3390/su15097438

[19] L.H. Shu, J. Duflou, C. Herrmann, T. Sakao, Y. Shimomura, Y. De Bock, J. Srivastava. Design for reduced resource consumption during the use phase of products. *CIRP Annals,* Vol. 66, No. 2, 2017, pp. 635-658. https://doi.org/10.1016/j.cirp.2017.06.001

[20] M.D. Bovea, V. Ibáñez-Forés, V. Pérez-Belis. Repair vs. replacement: Selection of the best end-of-life scenario for small household electric and electronic equipment based on life cycle assessment. *Journal of Environmental Management*, Vol. 254, 2020, p. 109679. https://doi.org/10.1016/j.jenvman.2019.109679

[21] A.S.G. Andrae. From an Environmental Viewpoint Large ICT Networks Infrastructure Equipment must not be Reused. *WSEAS Transactions on Environment and Development*, Vol.19, 2023, pp. 375-382. DOI: 10.37394/232015.2023.19.34

[22] C.A. Chan, E. Wong, A. Nirmalathas, A.F. Gygax, C. Leckie, D.C. Kilper. Towards an energy rating system for telecommunications. *Telecommunications Journal of Australia*, Vol. 62, 2012, pp. 77.1-77.10. DOI:10.7790/TJA.V62I5.377

[23] N. Ullrich, F.M. Piontek, C. Herrmann, A. Saraev, T. Viere. Estimating the resource intensity of the Internet: A meta-model to account for cloud-based services in LCA. *Procedia CIRP*, Vol. 105, 2022, pp. 80-85. https://doi.org/10.1016/j.procir.2022.02.014

[24] L.K. Oxenløwe, Q. Saudan, J. Riebesehl, M. Zahidy, S. Swain. Evaluating Energy Consumption of Internet Services. *IEICE Transactions on Communications,* Vol. E1016.B, No. 11, 2023, pp. 1036-1043. https://doi.org/10.1587/transcom.2022OBI0001

[25] A.S.G. Andrae, T. Edler. On global electricity usage of communication technology: trends to 2030. *Challenges*, Vol. 6, No. 1, 2015, pp. 117-157. https://doi.org/10.3390/challe6010117

[26] J.M. Rueda-Cantuche, J. Beutel, F. Neuwahl, I. Mongelli, A. Loeschel. A symmetric input–output table for EU27: latest progress. *Economic Systems Research*, Vol. 21, No. 1, 2009, pp. 59-79. https://doi.org/10.1080/09535310802703429

[27] W.W. Ingwersen, M. Li, B. Young, J. Vendries, C. Birney. USEEIO v2.0, the US environmentally-extended input-output model v2.0. *Scientific Data*, Vol. 9, 2022, 194. https://doi.org/10.1038/s41597-022-01293-7

[28] M.A. Thomassen, R. Dalgaard, R. Heijungs, I. De Boer. Attributional and consequential LCA of milk production. *International Journal of Life Cycle Assessment*, Vol. 13, 2008, pp. 339-349. https://doi.org/10.1007/s11367-008-0007-y

[29] Ahlgren, S.; Baky, A.; Bernesson, S.; Nordberg, Å.; Norén, O.; Hansson, P.A. Consequential life cycle assessment of nitrogen fertilisers based on biomass–a Swedish perspective. *Insciences Journal*, Vol. 2, No. 4, 2012, pp. 80-101. doi: 10.5640/insc.020480

[30] Analysys Mason. Green 5G: building a sustainable world. https://www.analysysmason.com/research/content/perspectives/green-5g-sustainability-rma18-rdns0/ ; 2020 (Accessed Date: 10 March 2024).

[31] G. Zhao. J.M. Guerrero, Y. Pei. Marginal generation technology in the Chinese power market towards 2030 based on consequential life cycle assessment. *Energies*, Vol. 9, No. 10, 2016, p. 788. https://doi.org/10.3390/en9100788

[32] B. Whitehead, D. Andrews, A. Shah. The life cycle assessment of a UK data centre. *International Journal of Life Cycle Assessment*, Vol. 20, 2015, pp. 332-349. https://doi.org/10.1007/s11367-014-0838-7

[33] A. Kumar Rajesh Jha, A.S.G. Andrae, B. Mainali. Comparison of Methods for Calculating Indirect Upstream Carbon Emissions from Information and Communication Technology Manufacturing. *WSEAS Transactions on Environment and Development*, Vol. 19, 2023, pp. 1045-1097. DOI: 10.37394/232015.2023.19.99

[34] S. Merciai, J. Schmidt. Methodology for the construction of global multi-regional hybrid supply and use tables for the EXIOBASE v3 database. *Journal of Industrial Ecology*, Vol. 22, No. 3, 2018, pp. 516-531. https://doi.org/10.1111/jiec.12713

[35] D. Wohlschlager, H. Bluhm, S. Beucker, J. Pohl, M. Fröhling. Overcoming challenges in life cycle assessment of smart energy systems–A map of solution approaches. *Journal of Cleaner Production*, Vol. 423, 2023, p. 138584. https://doi.org/10.1016/j.jclepro.2023.138584

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)
The author contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself
No funding was received for conducting this study.

Conflict of Interest
The author has no conflict of interest to declare that is relevant to the content of this article.