HOLISTIC VIEW ON THE ROLE OF ICT IN ENVIRONMENTAL SUSTAINABILITY

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Abstract: Information and communication technology (ICT) has become an integral part of our everyday life including social interactions, business processes, technology and ecology. However, its potential benefits and risks for the environment are still not sufficiently explored. This is mainly because of the complex interdependencies between ICT and different other areas of business and society that together build a very complex ecosystem. In this paper, a holistic approach that treats ICT as a part of the global ecosystem is introduced. This approach combines data-centric methods that are typically used to analyze communication networks with widely applicable thermodynamic tools. The proposed approach is well suited to investigate complex heterogeneous systems and assess their environmental sustainability. Within this holistic framework, the whole lifecycle of ICT components and systems is considered. In particular, we briefly discuss the application of the presented approach on evaluating the sustainability of smartphones, notebooks, data centers, switches and access network equipment. Additionally, preliminary results of an exemplary model of cloud computing use in Austria are presented.

1. INTRODUCTION

Although information and communication technology (ICT) has been making an enormous progress for more than thirty years and has already influenced many areas of our everyday life, its potential benefits and risks for the environment have gained the interest of the scientific research and broad community only since recently. Even though many extensive studies on energy efficiency of ICT systems have been carried out during the last several years, the influence of ICT on the environment has still not been sufficiently assessed and understood.

On the one hand, broad and intensive use of advanced ICT applications and services promises substantial improvements in many branches such as in industry, logistics, trade, healthcare, and education as well as in society. Furthermore, ICT applications can be used to optimize various processes and, consequently, to support new strategies and mechanisms for a sustainable exploitation of natural resources.

On the other hand, the ever increasing number of ICT equipment and intensive usage of ICT services lead to a continuous increase of ICT-related energy consumption. Additionally, the short lifetime of devices and services cause an increased usage of resources, production intensification, and more hazardous e-waste, which can harm the environment.

The aim of this paper is to present a holistic approach that can be used to evaluate ICT systems and applications as well as their impacts on the environment. To illustrate the application of the presented approach, we show exemplary results for some selected ICT devices and systems. In particular, we show and discuss the results obtained by a model of cloud computing use in Austria.

2. THE CONCEPT OF EXERGY

A very useful quantity that stems from the second law of thermodynamics is *exergy*. It can be used to clearly indicate the inefficiencies of a process by locating the degradation of energy. In its essence, exergy is the energy that is available to be used, i.e., the portion of energy that can be converted into useful work. In contrast to energy, it is never conserved for real processes because of irreversibility. Any exergy loss indicates possible process improvements. The exergy of a macroscopic system is given by:

$$E_x = U + P_r V - T_r S - \sum_i \mu_{ri} n_i \ , \qquad (1)$$

where extensive system parameters are internal energy (U), volume (V) and the number of moles of different chemical components i , i.e., n_i, while intensive parameters of the reference environment are pressure (P_r), temperature (T_r) and the chemical potential of component i, i.e., $\mu_{r;i}$. A useful formula for practical determination of exergy is [1].

$$\begin{aligned} E_x &= U - U_0 + P_r (V - V_0) \\ &\quad - T_r (S - S_0) - \sum_i \mu_{ri} (n_i - n_{0,i}) \ , \end{aligned} \qquad (2)$$

where the relatively easily determined quantities denoted by “o” in the subscript are related to the equilibrium with the environment. The exergy content of materials, $E_{x,mat}$, at a constant temperature, $T = T_0$, and pressure, $P = P_0$, can be calculated from:

$$E_{x,mat} = \sum_i (\mu_i^0 - \mu_{o,i}^0) n_i + RT_0 \sum_i n_i \ln \frac{c_i}{c_{o,i}} \qquad (3)$$

In the above Equation, c_i is the concentration of the element i, R is the gas constant, while μ_i^0 denotes the chemical potential for the element i relative to its reference state. The relation of exergy loss to entropy production is given by:

$$E_{x,loss} = E_{x,in} - E_{x,out} = T_r \Delta S \ , \qquad (4)$$

where ΔS is the entropy (irreversibility) generated in a process or a system. In other words, for processes that do not accumulate exergy, the difference between the total exergy flows into and out of the system is the exergy loss due to internal irreversibilities, which is proportional to entropy creation. The overall exergy loss of a system is the sum of exergy losses in all system components, i.e., $E_{x,loss,total} = \Sigma E_{x,loss,component}$.

Exergy analysis has been performed in industrial ecology to indicate the potentials for improving the use of resources and minimizing environmental impact. The higher the exergy efficiency is, i.e., the lower exergy losses, the better the sustainability of the considered system or approach.

Life cycle assessment (LCA) is a technique to evaluate environmental impacts of a product or a process over its entire life cycle (i.e., raw material extraction, manufacture, transportation, operational, maintenance, and recycling phases). LCA analysis provides a system perspective across the whole life time to define the system boundaries and aid decision making for system optimization and product selection.

An approach that combines the exergy concept with the LCA analysis we refer here to as the *exergy-based LCA* (ELCA). Fig. 1 visualizes the approach of E-LCA across the whole product’s or system’s lifetime. Since the E-LCA approach considers all exergy inputs during the whole life cycle and we assume here that there is no accumulation of exergy, the overall exergy losses accumulated during the product’s or system’s lifetime equals the total exergy consumption. Thus, the overall lifetime exergy consumption is an effective measure of product’s or system’s environmental sustainability. Since exergy-based analysis is a universally applicable method to assess process efficiency, it is well suited to investigate the sustainability of heterogeneous systems [2-4]. Since recently, E-LCA has also been used to assess the sustainability of ICT infrastructure and applications [5-9].

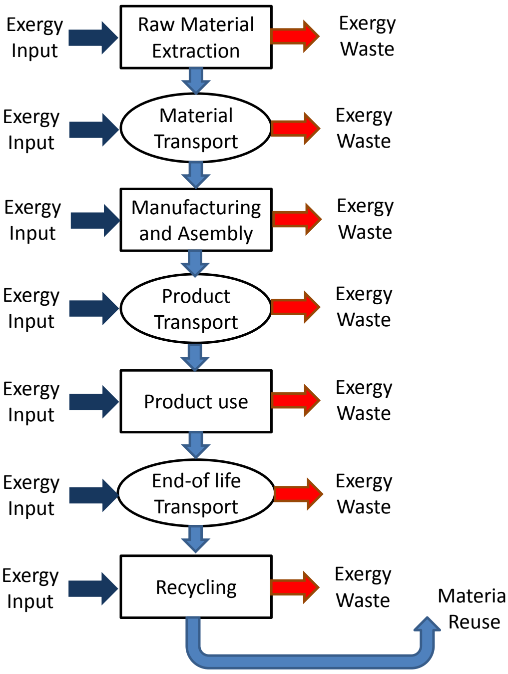

Fig. 1: Illustration of the exergy-based life cycle assessment (E-LCA): lifetime exergy consumption flow.

In general, the exergy consumed over the entire lifetime of the system (i.e., the total cumulative exergy) can be divided into two components. The first component is related to the so called *embodied exergy*, which is the exergy used for material extraction, transportation, manufacturing and recycling. The second component is composed of the electricity consumption of ICT equipment, which is referred to as *operational exergy*.

3. E-LCA OF ICT DEVICES

In an E-LCA, the flow of exergy is determined for each phase of a device lifecycle. First, the embodied exergy of materials used to manufacture the device is determined. This embodied material exergy acts as the input into the system. In the study presented in this paper, the material inventory is performed by surveying the raw material composition of different components. Examples of a typical decomposition of a smartphone and a tablet PC are shown in Fig. 2 [6,9].

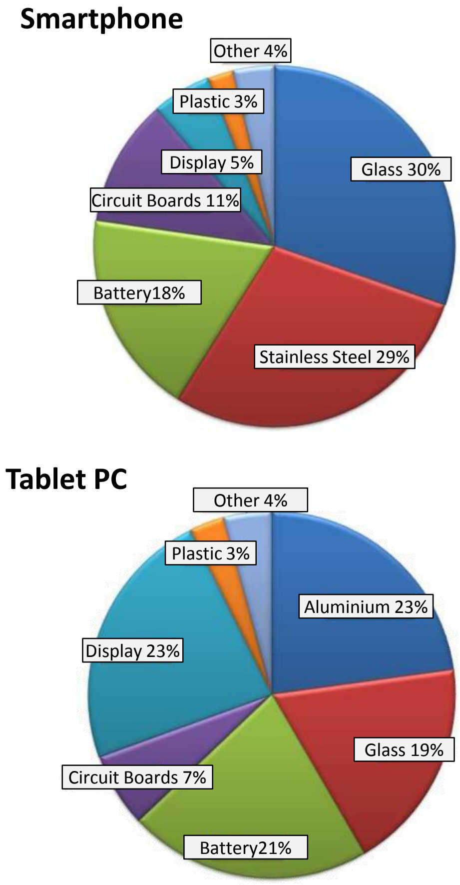

Fig. 2: Typical material decomposition of a smartphone and a tablet PC.

The estimation of exergy consumption for the raw material extraction phase is performed on a per-mass basis and according to the exergy contents of different materials. The values of mass-specific exergy for various materials are mainly taken from [5, 8, 10-12]. Then, we calculate the amounts of exergy destructed during various LCA phases, including material extraction, transportation, manufacturing, use and disposal. Furthermore, the exergy content and conversion efficiencies of different energy sources are considered [3]. As a result of the E-LCA, one can determine exergy-based sustainability indicators that can be used to easily compare the sustainability of different concepts, technologies and approaches.

An example of exergy lifecycle of a smartphone is presented in Figs. 3. A reutilization of recycled materials of 40 % has been assumed in both cases, and the mix of electricity generation sources is chosen according to the current situation in Austria [13]. Similarly, we can calculate the exergy lifecycle of network equipment. An exemplary result obtained by applying E-LCA to a Universal Mobile Telecommunications System (UMTS) base transceiver station (Node B) is shown in Fig. 4.

Fig. 5 illustrates the relation between the embodied and the operational exergy for Node B and smartphone. It becomes evident when comparing the overall embodied and operational exergy consumptions that the main contributors to the exergy losses of the entire device lifecycle are the manufacturing and material extraction processes, in the case of a smartphone, and the high operational energy consumption when considering a radio base station. This difference in the relation of embodied to operational exergy for radio base stations and smartphones is mainly due to the fact that radio base stations have several times longer lifecycles than modern mobile devices and that mobile devices are optimized for low energy consumption. To obtain the results presented in Fig. 5 it has been assumed that the lifecycle of a smartphone is two years, while that of a base station is 10 years. Thus, the specific issue in modern ICT systems is that new generations of devices and technologies are launched within short cycles of only a few years. Even if new technologies are usually more energy efficient, both processing power and use intensity increase, which consequently lead to more or less constant power consumption despite the continuous improvements in energy efficiency. Another important issue is the increased resource exploitation and environmental pollution, due to ever-increasing production volumes and decreasing lifetime, as well as inadequate disposal of ICT hardware. These issues can only be properly addressed using a holistic approach that considers the whole lifecycle of products and services.

4. E-LCA OF ICT SYSTEMS

Additional to investigating sustainability of ICT devices, E-LCA can be applied to analyze complex ICT systems that include a large number of interconnected elements. As an example of such an analysis, we present the a model that has been used to estimate the lifecycle exergy consumption related to the introduction and use of cloud computing in Austria within the time period from 2012 to 2020. The model comprises several submodels such as those for core networks, access networks, data centers as well as different scales of enterprise computing infrastructures for small, medium and large scale enterprises including IT equipment, network infrastructure and end-user equipment.

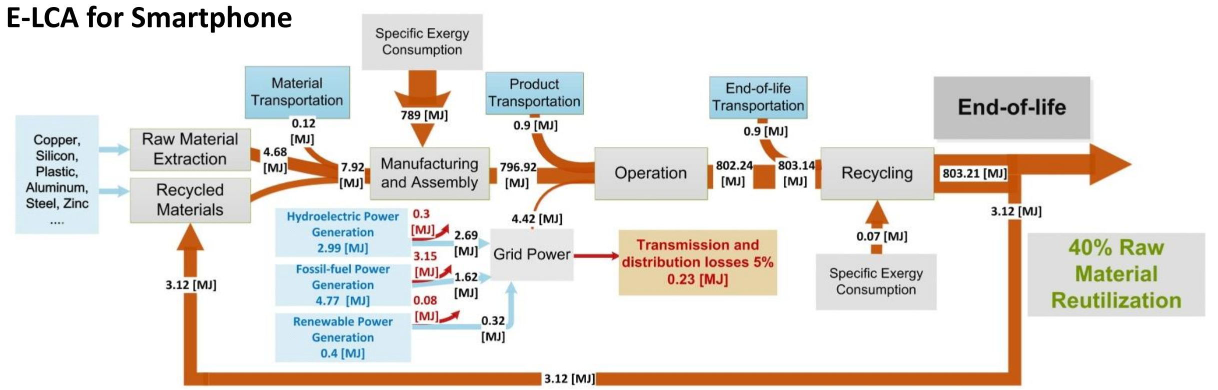

Fig. 3: An example of exergy-based lifecycle for a smartphone.

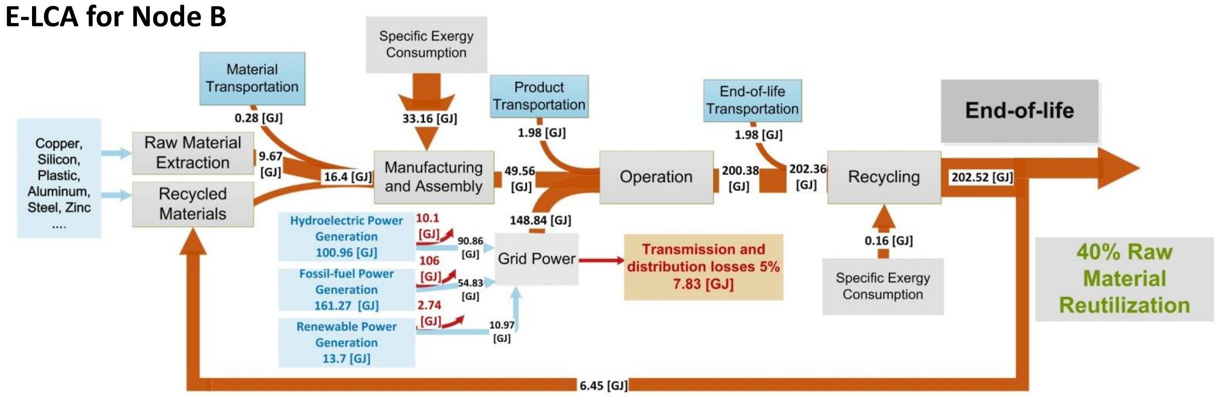

Fig. 4: An example of exergy-based lifecycle analysis (E-LCA) for a Universal Mobile Telecommunications System (UMTS) base transceiver station (Node B).

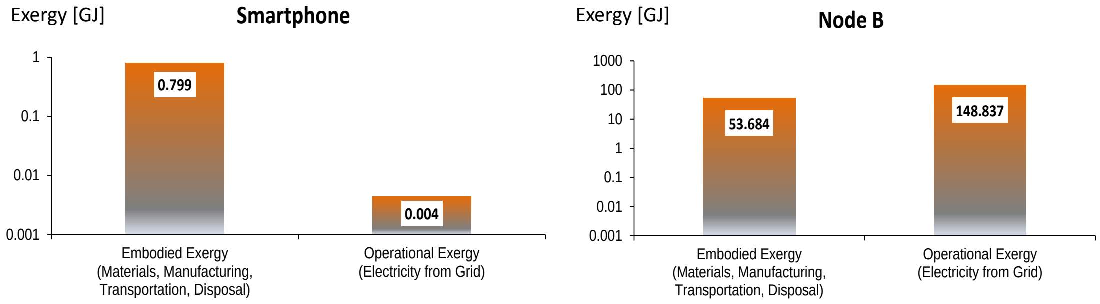

Fig. 5: The relation between the embodied and the operational exergy for Node B and smartphone.

4.1 Network Model

The network core model includes core switches and routers having capacity of about 1 Tb/s, which are placed across Austria and connected through fiber cables. As regards the operational phase of access networks, we used a model that has been developed and used to estimate the energy consumption of an Austria-wide network [14]. To provide mobile access to cloud users, we modeled a UMTS radio access network comprising base transceiver stations (Node B) and radio network controllers (RNC) as well as serving GPRS support nodes (SGSN) and gateway GPRS support nodes (GGSN). We assumed that the wireless backhaul is realized mostly using microwave links (95%), but also copper cables (4%) and optical fibers (1%) are considered for the backhaul.

The network model considers various data on technology penetration, market shares and population densities as well as typical core and access network architectures. The statistical data for Austria are obtained from several sources such as the Statistics Austria, the Austrian Regularity Authority for Broadcasting and Telecommunications (RTR), Austrian network operators and the Forum Mobilkommunikation (FMK). For a more complete description of the access network model and the main assumptions made for E-LCA of RAN, the reader is refereed to [5,6,14].

4.2 Electricity Generation

While estimating the total exergy consumption of the operational (use) phase, we assumed three different electricity production sources as typically used in Austria [13]. The considered sources include hydroelectric power plants, fossilfuel power plants and renewable (i.e., photovoltaic and wind turbine) power plants. In particular, hydropower plants play a substantial role in the Austrian energy sector. As reported in [13], around 58% (41 GWh) of the total electricity produced in Austria was originating from hydroelectric power stations in 2010. Hence, we assume that 58% of the total electrical energy consumed by the ICT equipment is generated by hydroelectric power plants, 35% by fossil-fuel power plants and 7% by renewable energy sources. Additionally, we considered the specific exergy losses for different electricity generation methods, both the waste of exergy due to the transmission losses and internal exergy destruction due to irreversibilities of the energy conversion. The considered energy efficiencies of hydroelectric power plants, fossil-fuel power plants, wind turbine systems and solar photovoltaic systems are 90%, 36%, 88.5% and 25%, respectively [3,6,8].

4.2 Model of Data Centers

For the cloud model for Austria, we assume that there are 10 medium-scale data centers, of which 4 are located in Vienna [15], and one large cloud data center. We considered a typical realization of data centers using the three-tier architecture. Based on the forecasts in [16-18] we defined scenarios for the development of cloud computing in Austria from 2012 until 2020 that include the predicted trends in network traffic, number of users and usage intensity.

Here, we apply E-LCA to assess two types of data centers. First, we consider a cloud data center with 20,000 servers, which includes corresponding network equipment (switches, routers and cabling) and *N* + 1 redundancy in case of power outage. There is an air-cooling system that has a roughly constant electricity consumption of about 2.75 MW [14]. In this case study, the area floor of the data center is assumed to be 4,645 m^2. The second model is for a medium-scale data center with 185 servers and 567 kW of the total electricity consumption. The medium-scale data center consists of rack mounted servers and an air distribution systems.

In the estimation of the embodied exergy, we consider additionally to the rack mounted servers also cables, switches, routers and server cabinets. The main assumptions made for both the cloud center and the medium-scale data center model can be found in [8]. While the total cumulative exergy consumption of the considered large cloud data center with 20,000 enterprise servers and assuming a lifetime of 9 years, is estimated to be around 1.5 PJ, the embodied exergy is approximately 209 TJ. Similarly, total exergy consumption of the medium-scale data center is calculated to be around 20 TJ and the contribution of the embodied exergy is about 2.3 TJ.

The manufacturing and assembly phases contribute mostly to the total embodied exergy. For instance, in case of the large data center, these two phases contribute by approximately 130 TJ, which is more than 70% of the entire embodied exergy consumption. Similarly, an exergy consumption of 1.4 TJ has been calculated for manufacturing and assembly phases of the medium-scale data center, which is approximately 60% of the total embodied exergy.

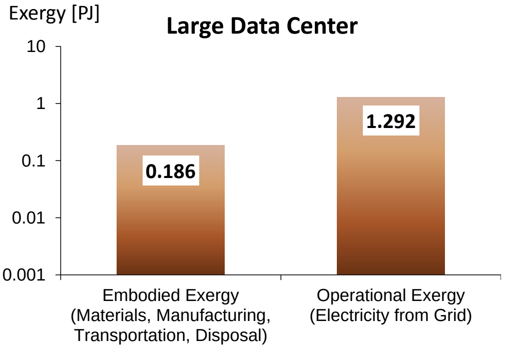

Fig. 6: The relation between the embodied and the operational exergy for the large data center with 20,000 enterprise servers and assuming 40% of recycled resources being reused.

The embodied exergy loss of the large data center can be reduced to about 186 TJ by reusing 40% of the recycled materials and to 145 TJ if 60% of the recycled materials are reused. However, the most exergy is consumed during the operational phase, which accounts for about 1.3 PJ or 87% of the total. The operational exergy is for almost a factor of 7 larger than the embodied exergy as it is evident from Fig. 6, which shows the relation between the embodied and the operational exergy for the large data center with 40% of materials being recycled. Hence, the best improvements can be achieved by applying techniques aimed at reducing the operational energy consumption of data centers.

4.2 Overall Model

The main components of the overall model are briefly described in previous sections. It comprises data centers, access networks, core network as well as devices of private and business users. The embodied exergy consumption (EEC) refers to the sum of exergy consummations of different phases such as raw material extraction, transportation between different phases, manufacturing/assembly and disposal/recycling. For all end-user devices as well as network and processing elements, we define a specific service lifetime. For instance, we assume that a smartphone will be replaced by a new device after 2 years of operation, while a PC is used for 4 years. A longer service lifetime of 9 years is assigned to the network equipment.

5. SUSTAINABILITY OF CLOUD COMPUTING

In this section, we present some preliminary results obtained by the model for cloud computing use in Austria that has been briefly described in Section 4. The cumulative exergy flow from 2012 to 2020 is graphically presented in Fig. 7. The figure shows the flow of exergy for all phases of the system's life cycle including the raw material extraction, transportation, manufacturing, operation and disposal. The exergy values presented include data centers and networks as well as devices of private and business users. In this particular example, 40% of material reutilization is assumed. The total cumulative exergy consumption has been estimated to be 222.5 PJ, of which 82.1 PJ (22.8 TWh of electricity) is consumed during the operational phase. Thus, the main part of the total exergy is related to the embodied exergy, which accounts for about 140.5 PJ or 65% of the total (see Fig. 8). This result is different from the result obtained when considering data centers only, where 87% of the total exergy is consumed during the operational phase. This is mainly because in the overall model, end-user devices contribute significantly to the increase of the embodied exergy due to their high quantity and short service lifetime. On the other hand, material reutilization plays less significant role in reducing the total exergy consumption. The total cumulative exergy consumption assuming 40% material reutilization is 222.5 PJ (see Fig. 7) and in case of 60% reutilization we obtained a value of 216 PJ. With no material reutilization at all, the estimated total exergy consumption is 233 PJ. Hence, material reutilization has a moderate saving potential of less than 10%.

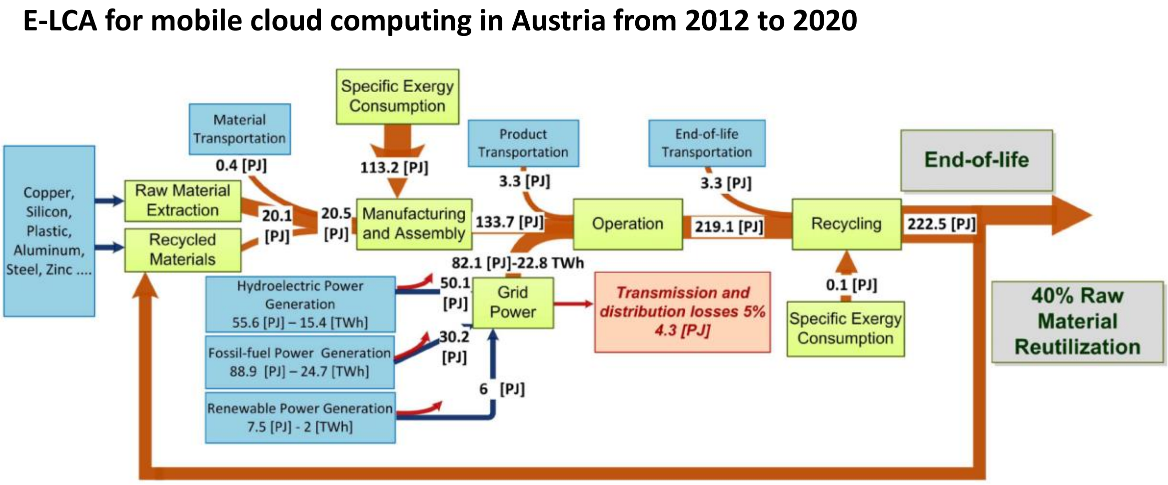

Fig. 7: E-LCA for cloud computing in Austria from 2012 to 2020. Exergy flow inclusive private and business user devices, data centers, UMTS RAN, and core network and assuming 40% material reutilization.

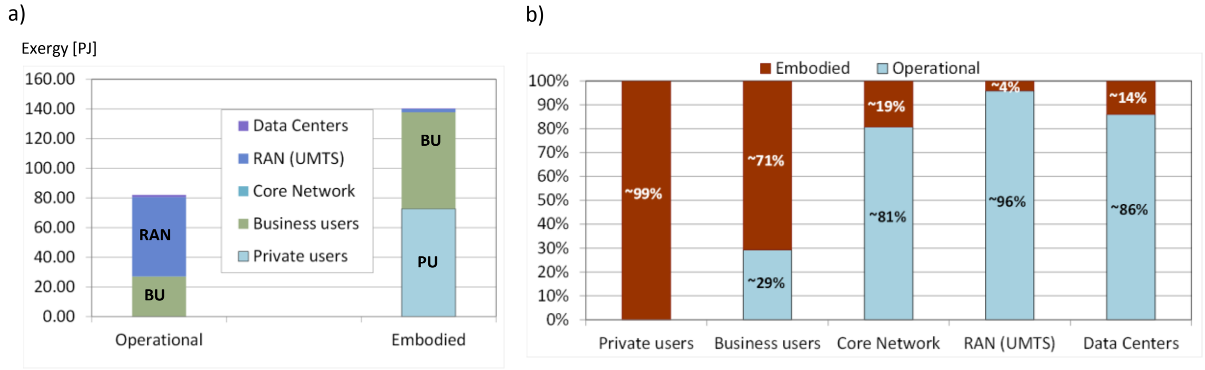

Fig. 8: Break down of the cumulative exergy consumption of cloud computing use in Austria from 2012 to 2020.

Fig. 8 shows a breakdown of the cumulative exergy consumption of the modelled cloud computing use in Austria. From Fig. 8a is evident that the main contributors to the embodied exergy are business and private end-user devices, while radio access network (RAN) contributes most to the operational exergy. Embodied exergy is counting for about 99% of the total cumulative exergy consumed by private user devices and for about 71% by business user devices as evident from Fig. 8b. Differently, exergy consumption of the core network, RAN and data centers is strongly dominated by the operational exergy, namely 81% of cumulative exergy is operational exergy in case of the core network, 96% in case of UMTS RAN and 86% in data centers. Thus, it is clear that in order to achieve maximum improvements in the entire system, one should concentrate on techniques for reducing operational energy consumption in networks and data centers, while considering potentials for minimizing the embodied exergy of end-user devices.

CONCLUSIONS

Modern information and communication technologies (ICT) are affecting our everyday business and social life. They also influence the environment due to the broad use of ICT applications, ICT-related energy consumption and an ever increasing number of electronic devices.

In this paper, we presented a holistic approach based on a combination of the exergy concept and life cycle assessment (LCA), which we applied to study the sustainability of ICT devices such as end-user devices and network equipment as well as of cloud computing on an example of a model made for Austria. Our results have shown that the impact of ICT on the environment grows with time and that there is a potential to slow down this trend. It should be noted that we concentrated here on the impacts related to the life cycle of ICT hardware and not on impacts that result from the change in production, transport, and consumption processes due to the applications of ICT.

Nevertheless, the obtained results clearly show the need for a holistic approach that take into consideration the whole system, which includes additionally to data centers also the interconnecting network and end-user devices. In order to achieve maximum improvements in the entire system, one should concentrate on techniques for reducing operational energy consumption in networks and data centers, while considering potentials for minimizing the embodied exergy of end-user devices. Even though an optimized design and management of data centers is an important step towards a sustainable cloud, the huge number of end-user devices and their short service time have much higher impact on the overall system's exergy consumption. It is mainly because end-user devices contribute most to the high embodied exergy consumption that is related to the material extraction, transportation, manufacturing and recycling processes.

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