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Article

Energy, Entropy and Exergy in Communication Networks

Slavisa Aleksic

Institute of Telecommunications, Vienna University of Technology, Favoritenstr. 9-11/E389, 1040 Vienna, Austria; E-Mail: slavisa.aleksic@tuwien.ac.at; Tel.: +43-158801-38831; Fax: +43-158801-938831

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Abstract: The information and communication technology (ICT) sector is continuously growing, mainly due to the fast penetration of ICT into many areas of business and society. Growth is particularly high in the area of technologies and applications for communication networks, which can be used, among others, to optimize systems and processes. The ubiquitous application of ICT opens new perspectives and emphasizes the importance of understanding the complex interactions between ICT and other sectors. Complex and interacting heterogeneous systems can only properly be addressed by a holistic framework. Thermodynamic theory, and, in particular, the second law of thermodynamics, is a universally applicable tool to analyze flows of energy. Communication systems and their processes can be seen, similar to many other natural processes and systems, as dissipative transformations that level differences in energy density between participating subsystems and their surroundings. This paper shows how to apply thermodynamics to analyze energy flows through communication networks. Application of the second law of thermodynamics in the context of the Carnot heat engine is emphasized. The use of exergy-based lifecycle analysis to assess the sustainability of ICT systems is shown on an example of a radio access network.

Keywords: energy; entropy; exergy; communication networks; lifecycle analysis

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1. Introduction

In the last two decades, the information and communication technology (ICT) sector has been growing very fast. There is no such example in human history that the development of a technology has changed our way of life in such a rapid and fundamental manner. In the meanwhile, ICT has become an integral part of our everyday life, including social interactions, business processes, technology and ecology. Due to the fact that ICT not only promises enormous potentials, but also carries risks, it is extremely important to carefully evaluate and assess ICT systems and applications regarding their sustainability and potential for improving global energy productivity.

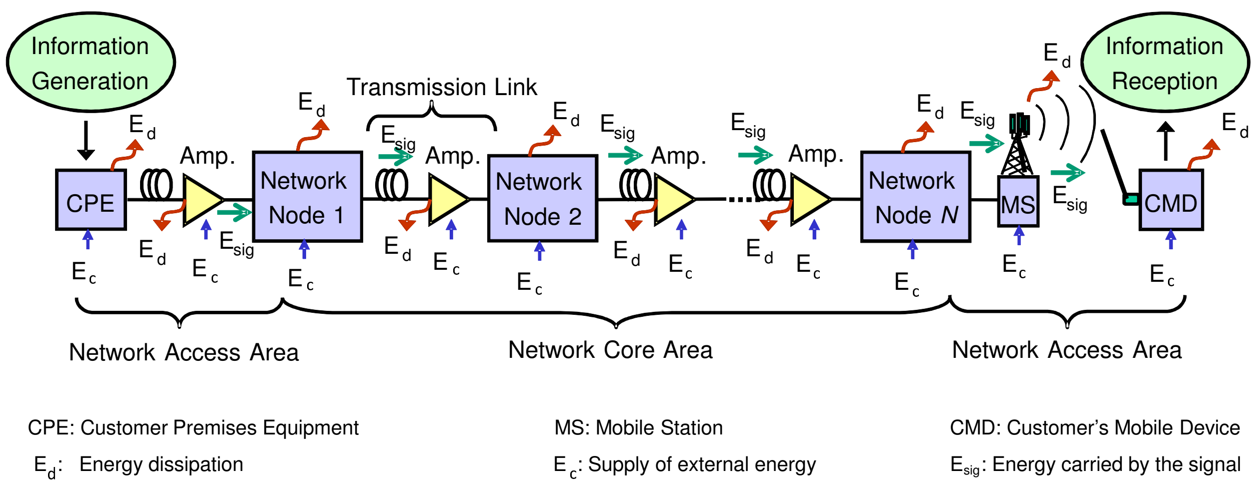
Advanced ICT applications and services can be used to increase the efficiency of resource usage in many areas, such as in transportation, building management, water management, manufacturing, as well as in production, distribution and consumption of electricity (smart grids). In order to assess the sustainability of ICT, one can evaluate the first-order effects that are sometimes referred to as direct effects, which relate to energy consumption and the carbon footprint of ICT hardware. Additionally, environmental impacts resulting from the change in production, transport and consumption processes, due to the application of ICT, are probably even more important. This effect is referred to as the second-order effect. Finally, there are environmental impacts emerging from the medium- or long-term adaptations of behavior and economic structures following from the availability of ICT applications and services, including the rebound effects (third-order effects). Most of current research efforts on energy efficiency in communication networks are concentrated on the direct or first order effects. There have been a number of studies concentrating on potential energy savings in communication networks by using energy-efficient transmission and processing systems, adaptive transmission links, dynamic power management and switching off or putting in sleep mode some of the less utilized transmission links and line cards [1–5]. It has been shown that significant savings in energy consumed by the network infrastructure can be achieved when optimizing both the network concept and the architecture of network elements with regard to energy consumption. Additionally, a high-performance global network infrastructure that is optimized to efficiently support rapid development and broad use of applications and services for improved energy productivity can lead to very large indirect energy savings, *i.e.*, the second order effects. It has been recently estimated that the potential reduction of greenhouse gas (GHG) emissions through the use of advanced ICT applications and services is up to ten times higher than the ICT's own emissions [6]. Thus, complex interactions between the network and various advanced services and applications should be better understood in order to optimize both network infrastructure and applications for maximizing improvements in global energy productivity [7]. Finally, the whole lifecycle of ICT equipment should be considered in order to properly understand and assess the role of ICT in sustainable development.

This paper reviews recent research efforts in treating communication and information processing systems using thermodynamic approaches and tools. Analogies between communication and thermodynamic systems are indicated, and several examples at the device, subsystem and system levels are described. The paper is organized as follows. The next section describes the general idea of applying the thermodynamic laws to analyze energy flow and entropy generation through communication and information processing systems. A particular emphasis is given to the application of the second law of thermodynamics and approaches that use the concept of the Carnot heat engine. Section 3 discuss the use of the exergy concept to assess the sustainability of ICT systems. In this section, exergy flows in a lifecycle perspective are presented for an exemplary radio access network. Finally, Section 4 presents concluding remarks.

2. Analogies between Communication and Thermodynamic Systems

In general, one can define communication as the exchange of meaningful information. A communication system consists of at least three components: a sender, a communication channel over which messages can be transmitted and a recipient. Since all the components of a communication system are physical objects that need energy to function properly, the communication itself is always a dissipative process. Therefore, the perceivable information is physical; we are not able to generate, transmit, receive or process information without its physical representation. Thus, the logical consequence of these facts is that any physical communication system consumes and dissipates energy while transmitting and processing information. Indeed, if we take a look at the current communication networks, we will recognize that, from the thermodynamic point of view, all processes within the network are irreversible (dissipative) processes. As can be seen from Figure 1, all elements on an end-to-end path through communication networks consume energy. Thus, an amount of energy (E_c) must be continuously supplied to active network elements, in which a part of the energy is used to perform the desired function, *i.e.*, useful work, while the rest of the supplied energy is lost due to the inefficiencies of the transforming processes (E_d). The information transmitted through the network is physically represented by means of modulated carrier signals. Although passive elements, such as optical fibers, do not directly consume energy, they are responsible for energy losses, due to the gradual attenuation of the optical signal as it propagates through the transmission line, which must be compensated for by applying an active component, such as an amplifier. Amplification is, in general, a dissipative process that leads to an increase in entropy. During the process of amplification, only a part of the supplied energy is converted into the signal at the output, while another significant portion of the energy is either lost, due to inefficiencies, or converted into noise. Current communication networks are very complex systems that comprise a large number of components and are able to provide a huge number of coexisting end-to-end paths. They are used to exchange information between software applications for various purposes and in different areas of business and society. Since the use of ICT services and applications can influence processes and flows of energy in other different areas, there is a need for a holistic approach that is able to deal with complex interdependencies between heterogeneous systems.

Figure 1. Energy flow in an end-to-end connection through communication networks.



The fundamental laws of thermodynamics were developed many years ago through a combination of observation and experimentation. Although the laws of thermodynamics were developed solely through observations on thermodynamic systems, the main principles and implications of these laws have found a broad application in many other systems and areas of science, such as mechanics, chemistry, biology, genetics, astrophysics and communications. The *first law of thermodynamics* as an expression of the principle of energy conservation defines a state function called internal energy (U), whose change is regarded as being due to a combination of the heat (Q) added to and the work (W) performed by the system to its surroundings, *i.e.*, $dU = \delta Q - \delta W$.

In analogy to thermodynamic systems, one can assume that the processing of data within network elements satisfies the first law. If it would be possible to realize an ideal network element in which no energy is dissipated, then the thermodynamic efficiency of such a system would be 100%. In this hypothetical case, the internal energy would change only due to the transfer of energy from surroundings to the system (supply of electricity) and to the work done by the system on its surroundings while performing the desired data processing function and writing the results at the output. However, the thermodynamic efficiency of network elements is always less than 100%, because dissipation is an integral part of an irreversible change of state in real systems.

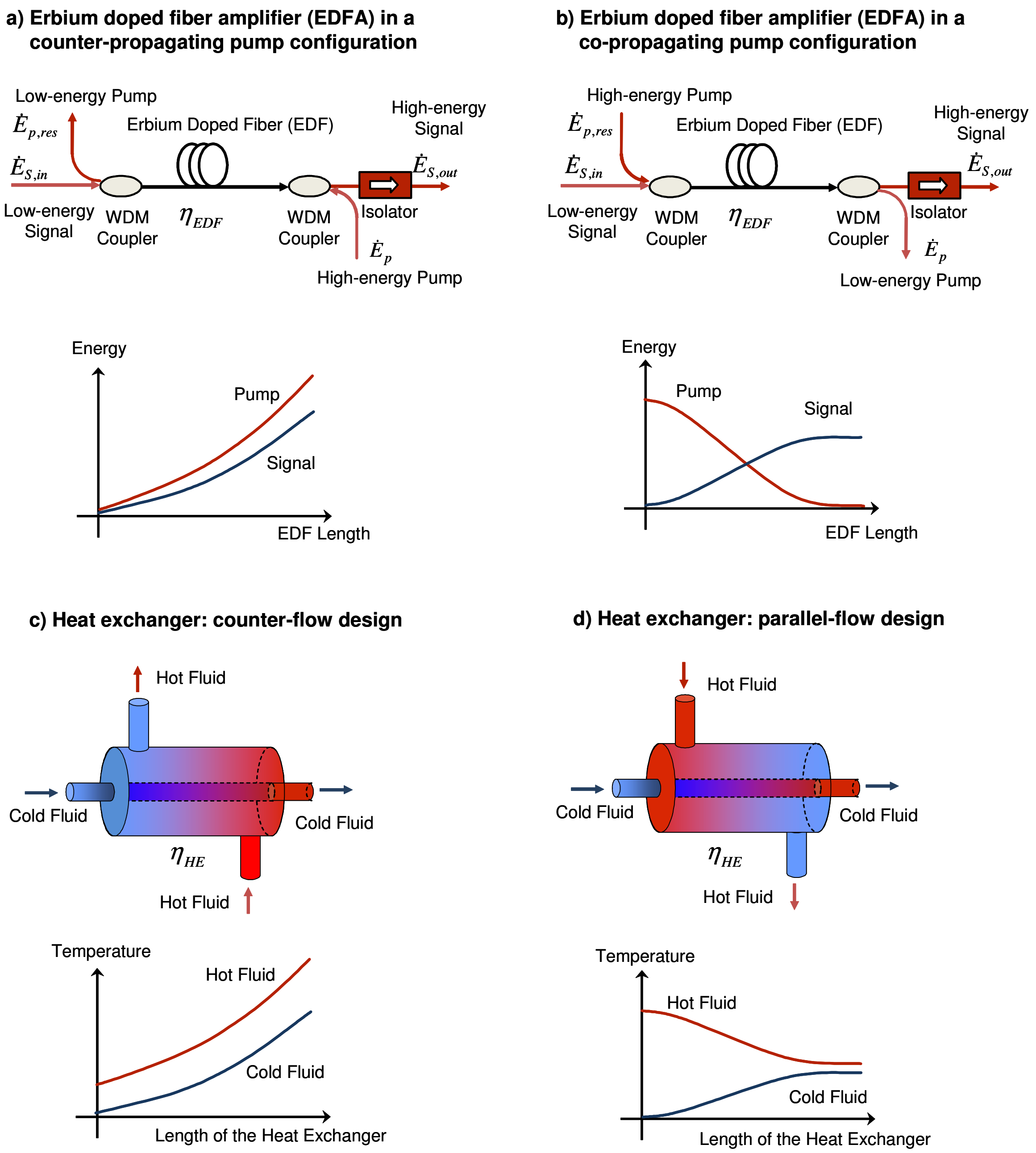
The *second law of thermodynamics* is a basic postulate applicable to any system involving the transfer of energy. It can be expressed as the tendency that over time, differences in temperature, pressure and chemical potential equilibrate in a physical system. That means the differences in energy density in a system will be diminished through a flow of energy in a preferred direction. For example, without applying any external work, heat always spontaneously flows from high-temperature to low-temperature regions. Moreover, the second law of thermodynamics introduces the principle of the increase in *entropy*. Entropy can be seen as the opposite of available energy, *i.e.*, a measure of the energy that is not available for useful work in a thermodynamic process. It can be used to differentiate between the bound and free forms of energy. Rudolf Clausius had already developed the concept of thermodynamic entropy in the early 1850s [8]. According to his definition, the entropy is a state function of a reversible cyclic process, e.g., the Carnot cycle, that satisfies $dS = \delta Q/T$, where T is the absolute temperature. While Clausius considered a reversible process, an increase of entropy is commonly associated with irreversible transformations. For an isolated system undergoing an arbitrary process, entropy can never decrease, *i.e.*, $dS/dt \geq 0$, which is equivalent to the principle of entropy increase. One of the well-known formulations of the second law is that the entropy of the Universe tends to a maximum. There also exist other formulations that can be applied to various systems. For example, Annila *et al.* [9,10] state that wherever there exists a difference in energy density, a flow of energy can appear to diminish that difference, while the flow of energy naturally selects the fastest ways. Similarly, for a communication system, we can say that wherever there exists a difference in information density, a flow of information can appear to diminish that difference. The information flow tends to select the fastest and most energy-efficient ways. It should be noticed here that the latter postulation is an intuitive observation by the current author, which is not going to be proven in this correspondence. Here, we should also underline the difference between *thermodynamic* and *logical* entropy. Thermodynamic entropy, which is mostly associated with Clausius, Lord Kelvin and Carnot, is defined in The American Heritage Dictionary as "the quantitative measure of the amount of thermal energy per unit temperature not available to do work in a closed system". It has the unit of J/K. Logical entropy, also called statistical entropy, first developed by Ludwig Boltzmann in the 1880s [11], is "a measure of disorder or randomness in a closed system" (The American Heritage Dictionary). Logical entropy has been used by Shannon to characterize information coding and properties of communication channels [12]. Since its introduction, entropy has found use in many areas, such as in thermodynamics, communications, statistical mechanics, statistics, quantum mechanics, evolutionary biology, genetics and theoretical astrophysics. Entropy generation analysis has been shown to be an effective tool in optimizing systems and processes [13–16].

A very useful concept for treating many different systems is that of a heat engine first developed by Sadi Carnot [17]. Models based on the Carnot heat engine have been often used to describe thermodynamic cycles of systems, in which some work may be performed by the system on its surroundings [18]. The system is thereby acting as a heat engine that performs work according to the difference in the temperature between the hot and the cold reservoirs. Both the hot and the cold reservoir are assumed to be at thermodynamic equilibrium throughout the process. The flow of heat out of the hot reservoir (Q_H) at the constant absolute temperature, T_H, is the energy supplied to the engine to perform work (W), while Q_C represents the energy flow into the cold sink at the constant equilibrium temperature, T_C, which is the residual energy not used to perform useful work. The Carnot engine is a reversible heat engine with the maximum possible efficiency that is determined only by the temperatures, T_H and T_C. The efficiency of a Carnot engine is given by: $\eta_{max} = 1 - T_C/T_H$.

2.1. An Optical Amplifier As the Carnot Heat Engine

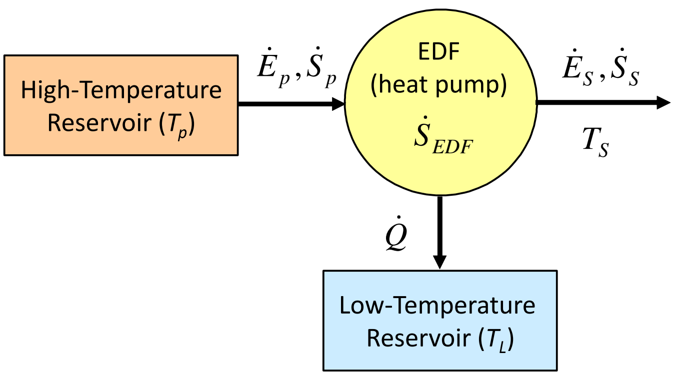
In analogy to thermodynamic systems, it is possible to use the concept of the Carnot heat engine to determine the thermodynamic efficiency of communication systems. For example, the approach presented in [15] introduces a new modeling technique that combines rate and propagation equations with thermodynamic approaches in order to evaluate both energy dynamics and the evolution of thermodynamic entropy within an optical amplifier. When observing the amplification process in an optical amplifier, e.g., in an erbium-doped fiber amplifier (EDFA), one can identify analogies with some well-known thermodynamic systems, such as the heat exchanger (see Figure 2). In an EDFA, the high-energy pump signal transfers a part of its energy to the low-energy data signal. As a result of this amplification process, the energy of the data signal is increased at the output of the device. The efficiency of this process is characterized by the energy conversion efficiency of the amplifier. Similarly, energy transfer occurs in the heat exchanger by the transfer of heat from the high-temperature (hot) fluid to the low-temperature (cold) fluid, which results in an increased temperature of the cold fluid at the output of the device. Thermodynamically speaking, the amplification process in an erbium-doped fiber (EDF) requires external energy to be supplied in the form of the optical pump signal, and the work done on its surroundings is manifested by the increase in energy of the data signal. The internal processes are dissipative and lead to an increase in entropy. In both EDFA and the heat exchanger, higher efficiency is achievable in the counter-propagating (counter-flow) design. In parallel-flow heat exchangers, the cold fluid cannot reach a higher temperature than the hot fluid towards the exit, while at the output of EDFA in the co-propagating configuration, the energy of the signal can exceed that of the residual pump, because EDF is acting as the active medium.

Figure 2. Analogies between erbium-doped fiber amplifier ((**a**) and (**b**)) and the heat exchanger ((**c**) and (**d**)). In general, energy transfer between the high-power pump and the low-power input signal in the erbium-doped fiber amplifier (EDFA) corresponds to the transfer of heat from the hot fluid to the cold fluid in a heat exchanger. Although the background physical processes are different, both systems behave similarly when analyzed from the thermodynamic point of view. Note that since EDFA is an active component that provides amplification, the signal energy can be higher than the residual pump energy at the output of EDFA in the co-propagating pump configuration ((b)). In contrast, in a parallel-flow heat exchanger ((d)), it is not possible to have cold fluid at the output at a higher temperature than the hot fluid.



Considering the analogies described above, we can draw a simple thermodynamic system representing EDFA as a heat pump, as shown in Figure 3. A heat pump usually moves thermal energy in the opposite direction of spontaneous heat flow. It uses an amount of external high-grade energy to accomplish the desired transfer of thermal energy from the heat source to the heat sink. Let us consider a steady-state process in which the pump energy is supplied to the erbium-doped fiber (EDF) at the flux temperature, T_p. Here, we use the so-called effective flux temperature of light, defined as $T_f \equiv \dot{E}/\dot{S}$ [19–23], to introduce the entropy rate via T_f as $\dot{S} \equiv \dot{E}/T_f$. This enables describing light generating and converting devices using thermodynamic quantities, such as temperature and heat, which has led to advances in several areas, such as in luminescence [24,25], the thermodynamics of lasers [26], laser cooling systems [27] and photosynthesis [28,29]. The flux temperature is generally not equivalent to the absolute thermodynamic temperature, T_A, defined by $1/T_A \equiv \partial S/\partial U$. A discussion on the relation between the flux temperature and the absolute thermodynamic temperature can be found in [22]. Now, we can identify the flow of pump energy and associated entropy into the system represented by $\dot{E}_p$ and $\dot{S}_p = \dot{E}_p/T_p$, respectively. The work done by the EDF to its surroundings is performed by the amplification operation that results in the energy flow out of the system ($\dot{E}_s = \dot{E}_{s,out} - \dot{E}_{s,in}$). In a similar way as for the pump light, we can define the net rate at which entropy is carried away from the EDF by the amplified signal light as $\dot{S}_s = \dot{E}_s/T_s$, where the flux temperature of the signal light at the output is denoted by T_s. We assume that for an efficient operation, the power of the pump light is chosen such that the energy of the pump is almost completely used up in the EDF. Consequently, $\dot{E}_{p,res}$ becomes very low and can be neglected, so that energy losses in EDF are mainly due to non-radiative processes, amplified spontaneous emission (ASE) and fiber background loss. These internal processes cause an additional entropy generation that is denoted by S_{EDF}. The accompanying generation and transfer of heat to the surroundings is represented by the heat flow rate, $\dot{Q}$, into the low-temperature reservoir (T_L).

Figure 3. Model of an erbium-doped fiber amplifier using the analogy to a thermodynamic heat pump.



Thus, under the steady-state condition, we can write two basic balance equations for the EDFA model presented in Figure 3 according to the first and the second law of thermodynamics as follows:

$$\dot{E}_p - \dot{Q} - \dot{E}_s = 0 \tag{1}$$

$$\dot{S}_p - \dot{Q}/T_L - \dot{S}_s + \dot{S}_{EDF} = 0 \tag{2}$$

where due to the second law, we have $\dot{S}_{EDF} \geq 0$. When using $\dot{Q} = \dot{E}_p - \dot{E}_s$ from Equation (1) and considering $\dot{E}_{s,p} = \dot{S}_{s,p} T_{s,p}$, where $\dot{E}_{s,p}$ and $T_{s,p}$ represent the energies and flux temperatures of the signal and the pump, respectively, one can rewrite Equation (2) in the following form:

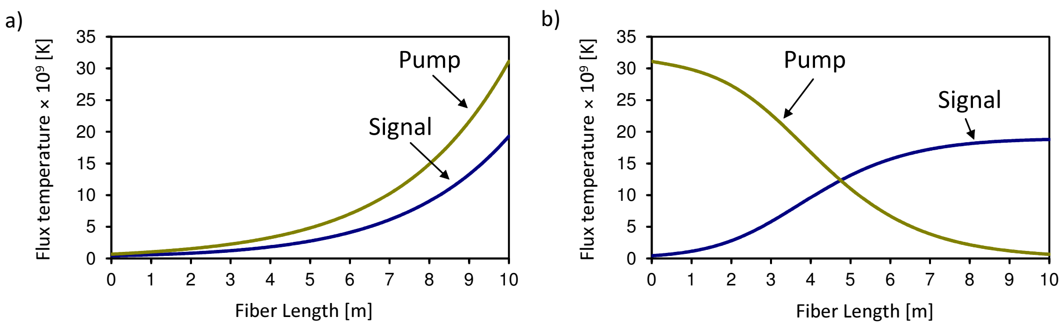
$$\dot{E}_s \frac{T_L}{T_s} + \dot{E}_p - \dot{E}_s - \dot{E}_p \frac{T_L}{T_p} = \dot{S}_{EDF} T_L \geq 0 \tag{3}$$

The quantity of interest in practice is the efficiency of the amplification process that we have defined in the previous section as the EDF efficiency, $\eta_{EDF} = \dot{E}_s / \dot{E}_p$. It can be now obtained from Equation (3) as:

$$\eta_{EDF} = \frac{\dot{E}_s}{\dot{E}_p} \leq \frac{1 - T_L/T_p}{1 - T_L/T_s} \tag{4}$$

It is evident from Equation (4) that the maximum efficiency of an EDF as a heat pump can be determined from temperatures T_L, T_p and T_s only. It is of the same form as the limiting efficiency derived for an optically pumped laser in [19]. Through analyzing Equation (4), one can find out that it represents a ratio of two Carnot efficiencies. Thus, the thermodynamic model of an EDFA presented in Figure 3 is equivalent to a tandem arrangement of two heat engines [30]. In the case of an ideal amplifier, the heat pump reduces to a heat engine, in which no entropy can be associated with output work, *i.e.*, $\dot{S}_s = 0$. Consequently, the system becomes reversible and $T_s \rightarrow \infty$. This is equivalent to the situation where the output signal light is close to perfectly monochromatic and perfectly directional radiation, which carries energy but no entropy. Under such ideal circumstances, the EDF efficiency from Equation (4) becomes the Carnot efficiency, *i.e.*, $\eta_c = 1 - T_L/T_p$, $\eta_{EDF} < \eta_c$.

Figure 4. Evolution of the flux temperatures of signal and pump optical fields for an erbium-doped fiber amplifier in (**a**) counter-propagating and (**b**) co-propagating pump configuration. The curves are obtained using the model from [15].

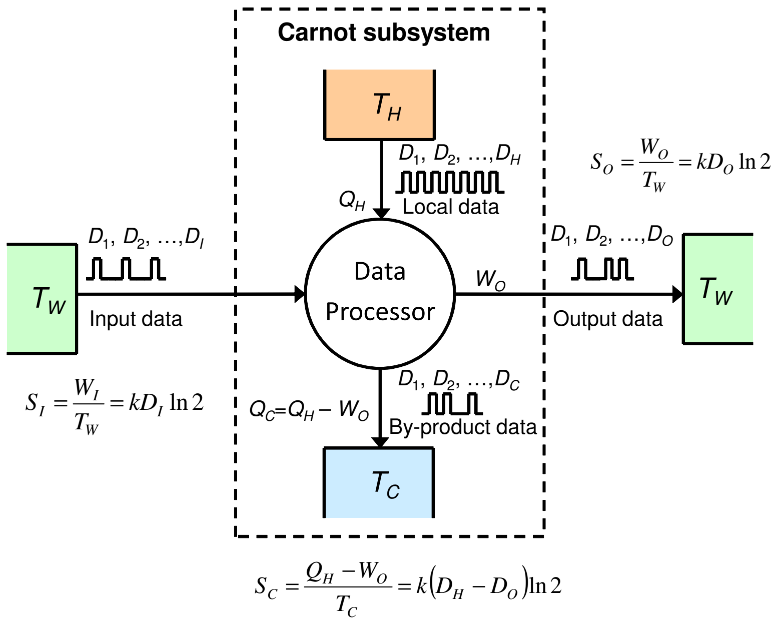


A three-level EDFA model based on rate and propagation equations can be used to effectively model the propagation of optical signals and their interaction with Er^{3+} ions in erbium-doped fibers [15,31,32]. The entropy associated with a radiation field can be found by applying the Bose statistics to a "gas of photons", as has been done by several authors for systems of n discrete quantum states in the past [20–22]. Hence, according to the definition of the effective flux temperature, $T_f \equiv \dot{E}/\dot{S}$, we can calculate the flux temperatures, T_p and T_s, associated with optical pump and signal lights as the ratio between the rates of energy and entropy carried by the light. Figure 4 shows the evolution of the flux temperatures in a typical EDFA [15]. When observing the figure, we can conclude that the flux temperature of the pump decreases with increasing of the fiber length, while the signal temperature increases. Thus, EDF behaves similarly to the heat exchanger.

2.2. Data Processing Systems As a Carnot Heat Engine

Even a more complex network element, such as a switch or a data processing module within a router, can be considered as a Carnot subsystem, as depicted in Figure 5 [33]. Here, the input data represent the work performed on the system by its surroundings, which is characterized by the entropy of the incoming data stream. The entropy of a data stream is associated with the degrees of freedom of the information system used and the corresponding quantity of energy for the particular ensemble. Similarly, the output data represent the work done by the system on its surroundings, which is characterized by its entropy. It has already been shown that the minimum energy required for processing, or, more precisely, deleting, a bit of information in binary systems is $\Delta Q = k_B T \ln 2$ [34], where k_B is the Boltzmann's constant. Thus, the entropy of a binary ensemble composed of D degrees of freedom is given by $S = Dk_B \ln 2$.

Figure 5. A possible representation of a data processing element using the analogy to the Carnot engine [33].



Energy consumption of the system is represented by the flow of heat from the hot reservoir (Q_H) associated with the locally generated array of size D_H, which represents the space in which the data processing operation is performed. The size of the ensemble of the internal degrees of freedom (D_H) must be larger or equal to that of the incoming data, *i.e.*, $D_H \geq D_I$. The data processor makes use of the energy, Q_H, to process input data and to generate results of a length of D_O. The minimum energy dissipated by this process is equal to the energy flow into the cold reservoir $Q_C = Q_H - W_O$, which is determined by the number of by-product bits of the processing operation. Thus, Figure 5 shows an example of a model based on the Carnot heat engine representing a simple data processor with only one input and one output. The efficiency of such a processor is given by $\eta = W_O/Q_H$.

3. Exergy in Communication Networks

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:

$$Ex = U + P_r V - T_r S - \sum_i \mu_{r,i} n_i \tag{5}$$

where extensive system parameters are internal energy (U), volume (V) and the number of moles of different chemical components, i (n_i), while intensive parameters of the reference environment are pressure (P_r), temperature (T_r) and the chemical potential of component i ($\mu_{r,i}$). A useful formula for practical determination of exergy is [35]:

$$Ex = U - U_o + P_r(V - V_o) - T_r(S - S_o) - \sum_i \mu_{r,i}(n_i - n_{o,i}) \tag{6}$$

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, Ex_{mat}, at a constant temperature, $T = T_0$, and pressure, $P = P_0$, can be calculated from:

$$Ex_{mat} = \sum_i n_i(\mu_i^o - \mu_{o,i}^o) + RT_o \sum_i n_i \ln \frac{c_i}{c_{o,i}} \tag{7}$$

In Equation (7), c_i is the concentration of the element i, R is the gas constant, while μ_i^o denotes the chemical potential for the element i, relative to its reference state.

The relation of exergy loss to entropy production is given by:

$$Ex_{loss} = Ex_{in} - Ex_{out} = T_r \Delta S \tag{8}$$

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.*, $Ex_{loss,total} = \sum Ex_{loss,component}$. Exergy analyses have 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.

3.1. Exergy-Based Lifecycle Analysis (E-LCA) of ICT Equipment

Since exergy analysis is a universally applicable method to assess process efficiency, it is well suited to investigate the sustainability of heterogeneous systems. Indeed, there are a number of studies that apply *exergy-based lifecycle analysis (E-LCA)* to assess the sustainability of complex systems and technologies [36–41]. Since recently, E-LCA has also been used by several research groups to assess the sustainability of ICT infrastructure and applications [39–41].

In 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. Two examples of a typical decomposition of a smartphone and tablet PC are given in Table 1.

Table 1. Decomposition of a typical smartphone and tablet PC [42].

Smartphone			Tablet PC		
Material	**Mass [g]**	**Mass [%]**	**Material**	**Mass [g]**	**Mass [%]**
Glass	40.9	30	Glass	140	23
Stainless Steel	38.7	29	Stainless Steel	115	19
Battery	24.7	18	Battery	131	21
Circuit boards	15.4	11	Circuit boards	40	7
Display	7.2	5	Display	142	23
Plastic	3.1	2	Plastic	19	3
Other materials	5	4	Other materials	26	4
Total	135	100	Total	613	100

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 [39,41,43–45]. 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 [38]. The values of specific exergy consumption used to obtain the results presented in this paper are listed in Table 2. 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.

Two examples of exergy lifecycles for a Universal Mobile Telecommunications System (UMTS) radio base station and a smartphone are presented in Figure 6a,b, respectively. 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 values stated in Table 2, which roughly correspond to the current situation in Austria [46].

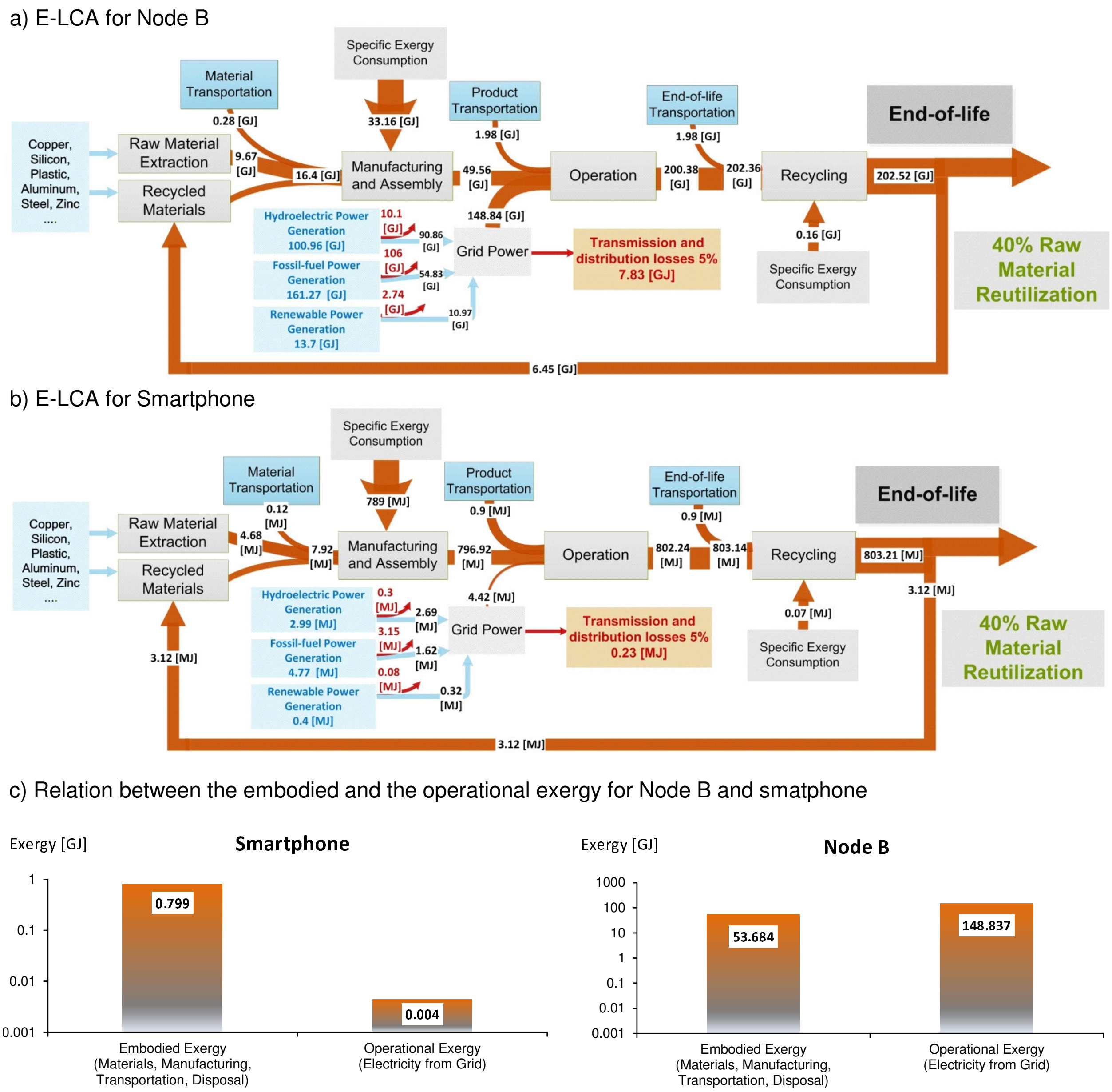
It is evident from Figure 6c that the main contributors to the exergy losses of the entire device lifecycle are the manufacturing and material extraction processes, in the case of a smartphone, and the high operational energy consumption of a radio base station. This difference in the relation of embodied 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.

Table 2. Specific exergy consumptions, as used in this paper [38,39,41,43–45].

Category	**Value**	**Unit**	**Notes**
Embodied exergy in materials (cumulative exergy cost (CExC))			
Aluminum	341.5	MJ/kg	using the Bayer process and Hall Cell, 50% bauxite ore
Steel	52.1	MJ/kg	50% from scrap, electrolytic process
Copper	67	MJ/kg	includes mining, concentrating, smelting and refining
Iron	51.04	MJ/kg	iron casting
Zinc	198.9	MJ/kg	froth flotation, electrowinning and electrolysis
Plastic	92.3	MJ/kg	low-density polyethylene (LDPE) from crude oil
Other	20	MJ/kg	order-of-magnitude estimate
Specific exergy consumption of various manufacturing processes			
Metals	0.28	kJ/kg	machining process
Plastic	14.9	kJ/kg	injection, modeling
Printed Circuit Boards (PCBs)	238.4	MJ/m^2	FR-4, per area
Integrated Circuits (ICs)	12.5	MJ/IC	for an average IC size
Complex Processor	1,242	MJ/processor	including purification of silicon
Exergy consumption of different transportation modes			
Air	22.14	kJ/kg-km	per km and kg of transported goods
Truck	2.096	kJ/kg-km	per km and kg of transported goods
Rail	0.253	kJ/kg-km	per km and kg of transported goods
Ship	0.296	kJ/kg-km	per km and kg of transported goods
Energy source mix for Austria [46] and exergy efficiencies of different electricity generation systems [38]			
Hydroelectric power generation	57.1	%	exergy efficiency 90%
Coal-Fired Power Plant	37.2	%	exergy efficiency 36%
Wind Turbine System	4.2	%	exergy efficiency 88.5%
Solar Photovoltaic System	1.5	%	exergy efficiency 25%

To obtain the results presented in Figure 6, it is 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 a 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.

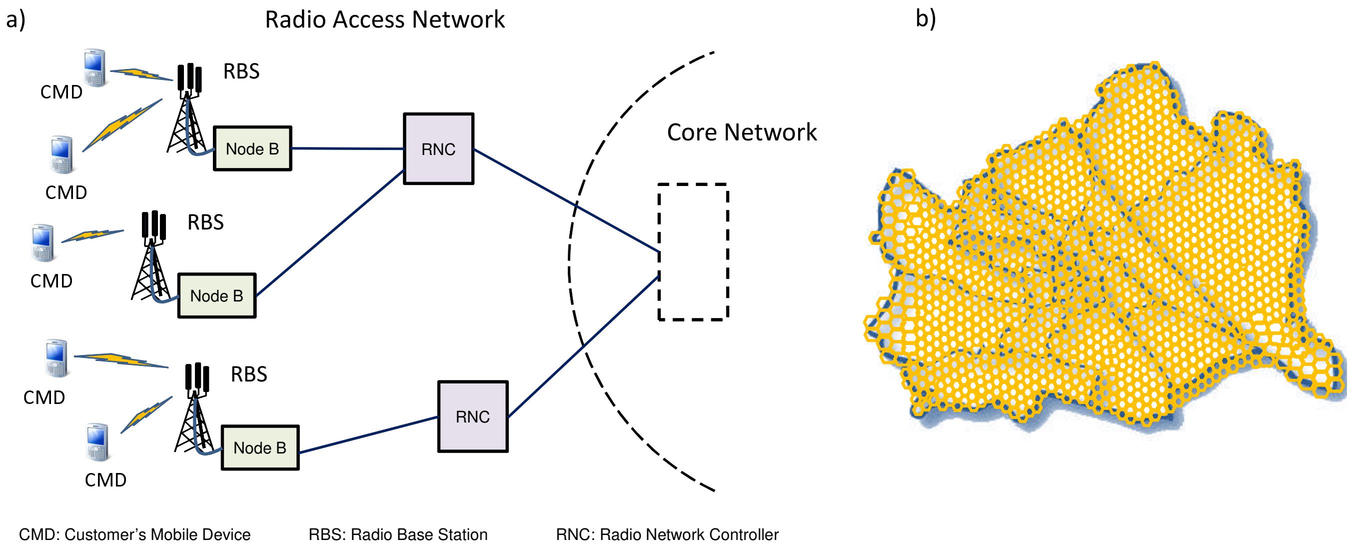
Figure 6. Examples of exergy-based lifecycles for (**a**) a Universal Mobile Telecommunications System (UMTS) base transceiver station and (**b**) a smartphone. (**c**) The relation between the embodied and the operational exergy for Node B and the smartphone [39,40].



3.2. E-LCA of Radio Access Networks

In order to illustrate the use of E-LCA for evaluating the sustainability of communication networks, we consider an exemplary radio access network (RAN). Here, we assume a system as shown in Figure 7a, which represents a generic architecture of a UMTS RAN. The main components of such a network are the base transceiver station (Node B), the radio network controller (RNC) and the connection to the core network that is referred to as the backhaul. The backhaul can be realized in different ways and using different technologies based on radio links, copper cable or optical fiber. Customers use mobile devices (CMD) to connect to radio base stations in order to use various services and applications, such as telephony, classical Internet services or new services, such as videoconferencing, video on demand, file sharing or any kind of cloud service.

Figure 7. (**a**) Generic architecture of UMTS radio access network and (**b**) an exemplary coverage of the City of Vienna by the UMTS macrocell radio access network.



As an example, we model a hypothetical radio access network for the City of Vienna. According to the statistical data on areas and population densities [47] and the typical network configuration and coverage for the City of Vienna, we estimate the required number of base station sites (see Figure 7b) and, consequently, the number of network elements, such as Node B, RNC and backhaul equipment using the tool for the evaluation of the energy efficiency of access networks presented in [48,49]. We also estimate the required total length of copper and fiber cables, as well as the time-of-the-day-dependent traffic profiles. A result of the radio access network model is the overall energy consumption. Hence, knowing the operational energy consumption and the required number of network elements, it is possible to obtain exergy consumptions of different lifecycle phases. The main assumptions we made for the E-LCA of the UMTS radio access network are summarized in Table 3.

Figure 8 shows the estimated values of the embodied material exergy and the exergy consumed during the manufacturing of typical UMTS Node B and RNC racks. For both Node B and RNC, the embodied material exergy is dominated by the housing, *i.e.*, by the material used for racks and enclosures. Differently, the most exergy-intensive components in the manufacturing process of Node B and RNC are radio frequency (RF) amplifier and processor board, respectively.

The lifecycle of a radio access network for the City of Vienna, including the customer's mobile devices, is presented in Figure 9a. Here, we assume a case where all row materials are available within a radius of 1,000 km from the manufacturing location, while the recycling is taking place in China. The raw material reutilization is 40%. All other assumptions regarding network dimensioning and the number of mobile customers are made according to data we obtained from Statistics Austria, the Austrian Regulatory Authority for Broadcasting and Telecommunications (RTR), Austrian network operators and the Forum Mobilkommunikation (FMK); particularly, data on technology penetration, market shares and population statistics. For more detailed information about the assumptions and main modeling parameters, the reader is referred to [39].

Table 3. Main assumptions for the exergy-based lifecycle analysis (E-LCA) of the UMTS radio access network for the City of Vienna.

E-LCA model	**Assumptions for the case with 40% material reutilization**
Raw Material Extraction	Spatial context: southeast Asia/China Material supply: within the radius of 1,000 km 40% of material flows from the recycling phase
Material Transportation	Spatial context: within the radius of 5,000 km Mode of transportation: rail/truck
Manufacturing and Assembly	Spatial context: southeast Asia/China
Product Transportation	From southeast Asia/China to Austria/Vienna Mode of transportation: rail/truck/ship
Operation (Network Design Parameters)	Lifespan: 9 years Area coverage: 95% Backhaul: 95% radio link, 4% fiber, 1% copper Cell diameter: 300 m–500 m Cell type: macro No. of sectors: – 1 sector: 2% – 3 sectors: 97% – 4 sectors: 1% No. of network operators: 3 No. of sites (estimated/actual): 2,385/2,571
End-of-Life Transportation	From northeast Austria/Vienna to southeast Asia/China Mode of transportation:rail/truck/ship
Recycling	Based on the mass of equipment Approximately 520 kJ/kg exergy consumption [7]

The total lifecycle exergy consumption of the radio access network over eight years of service is estimated to be about 10.6 PJ (see Figure 9). Customer's mobile devices contribute by about 6.5 PJ, which is approximately 60% of the total exergy consumption. Hence, although a mobile device (e.g., a smartphone) consumes much less electricity than a network device, such as Node B or RNC, the high number of customer's mobile devices and their relatively short service time lead to a significant contribution of mobile devices to the total system's exergy consumption. The effect of mobile devices on the sustainability of the entire system becomes evident from Figure 9b, which shows the relation between the embodied and the operational exergy for the considered radio access network with (the diagram on the right-hand side) and without (on the left-hand side) mobile devices. Without mobile devices, the operational exergy of the network is 13 times higher than the embodied exergy. When considering mobile devices, the operational exergy becomes lower than the embodied exergy. This result emphasizes the importance of using a holistic approach and considering the entire lifecycle.

Figure 8. Exergy consumption of material extraction and manufacturing processes for the UMTS Node B and the radio network controller (RNC) [39,40].

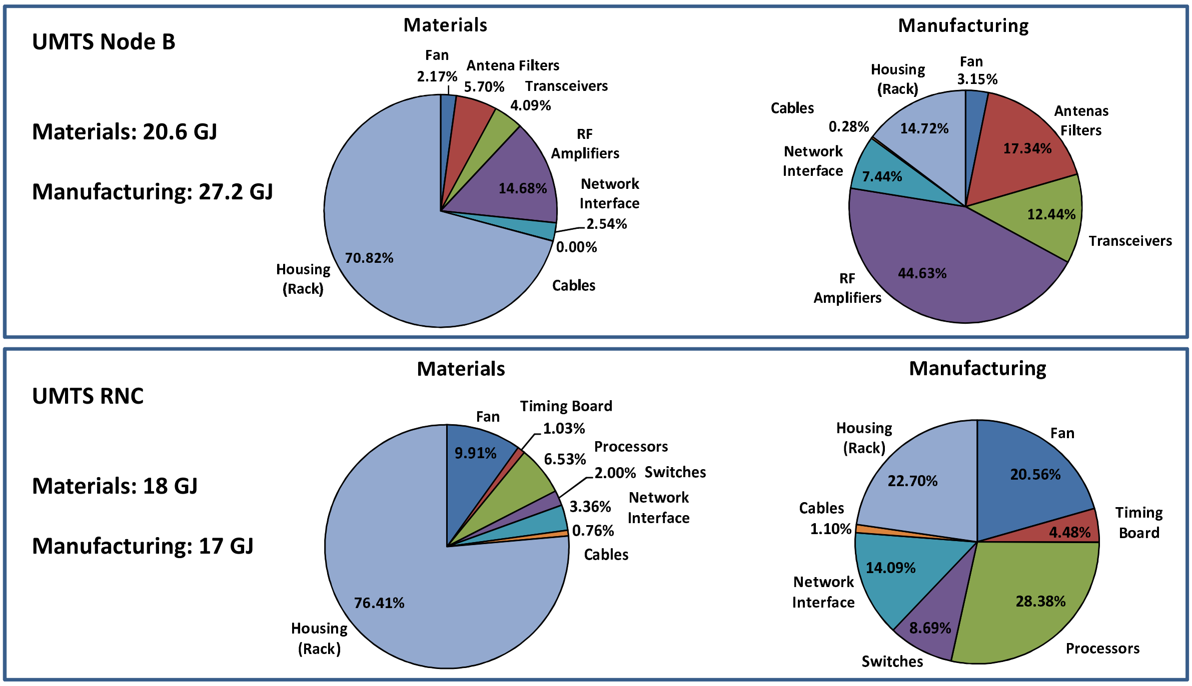
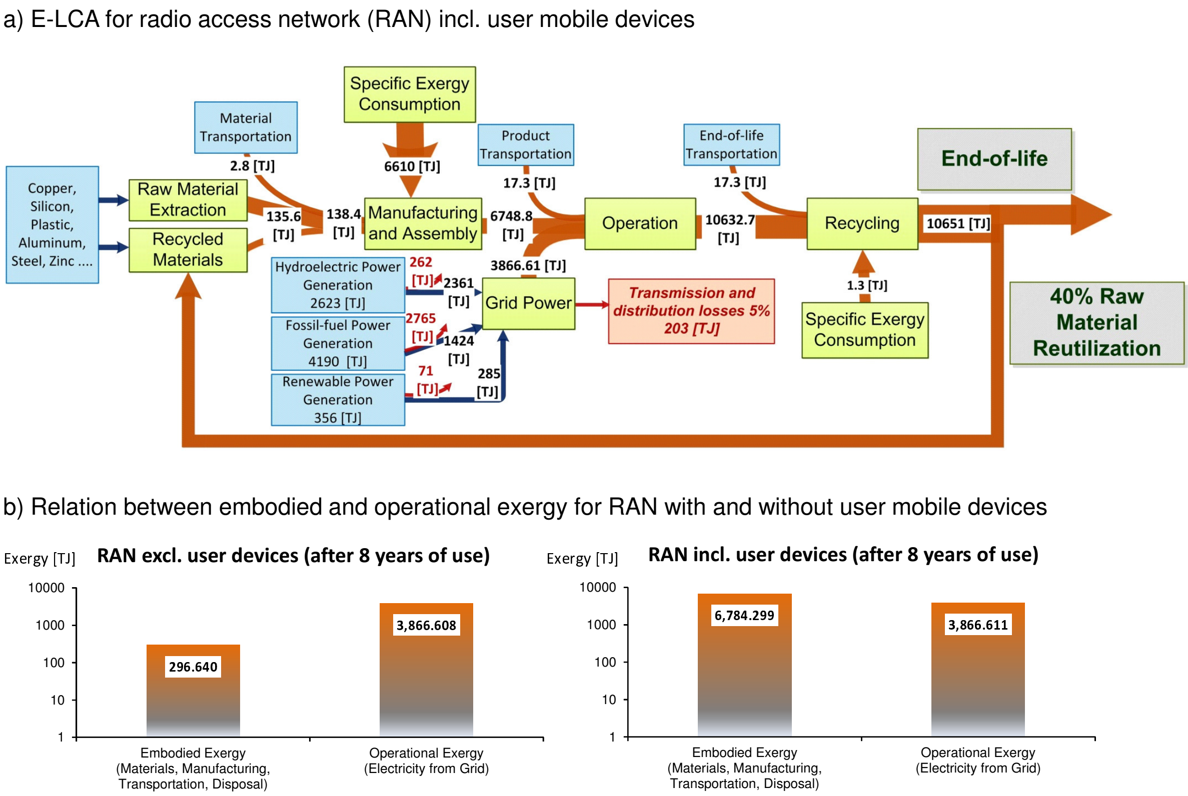


Figure 9. Exergy-based lifecycle assessment of the modeled UMTS radio access network for the City of Vienna [39,40]. The service life of network elements is assumed to be 10 years, while that of smartphones, two years.



4. Conclusions

Recent advances in information and communication technologies (ICT) open new perspectives for optimization in various areas, such as in transportation, building management and manufacturing and in production, distribution and consumption of electricity. However, the ever-increasing amount of ICT equipment results in an increasingly high energy consumption and environmental impairments of the ICT sector itself. Complex interactions between heterogeneous systems interconnected by the global communication network can only been properly analyzed and understood in a holistic framework. Such a holistic framework can be based on universally applicable tools of thermodynamics. Especially the second law of thermodynamics and the concept of entropy are extremely useful tolls. In this paper, various methods for evaluating energy flows and entropy in communication networks are reviewed. In particular, methods based on the Carnot heat engine and the concept of Exergy are illustrated in examples of analyzing optical amplifiers and lifecycles of radio access networks. The exergy-based lifecycle analysis of radio access networks has indicated the importance of a sustainable technological development able to ensure both a high rate of innovations and an increased service lifetime of ICT devices. Even though a fast technological development can lead to both the high performance and high energy efficiency of ICT equipment, the sustainability of the overall system is strongly influenced by the short service life of user devices, which causes a considerable increase in the total embodied exergy and a high environmental impact.

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Conflicts of Interest

The authors declare no conflict of interest.

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