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# Environmental Impact of Information and Communication Equipment for Future Smart Grids

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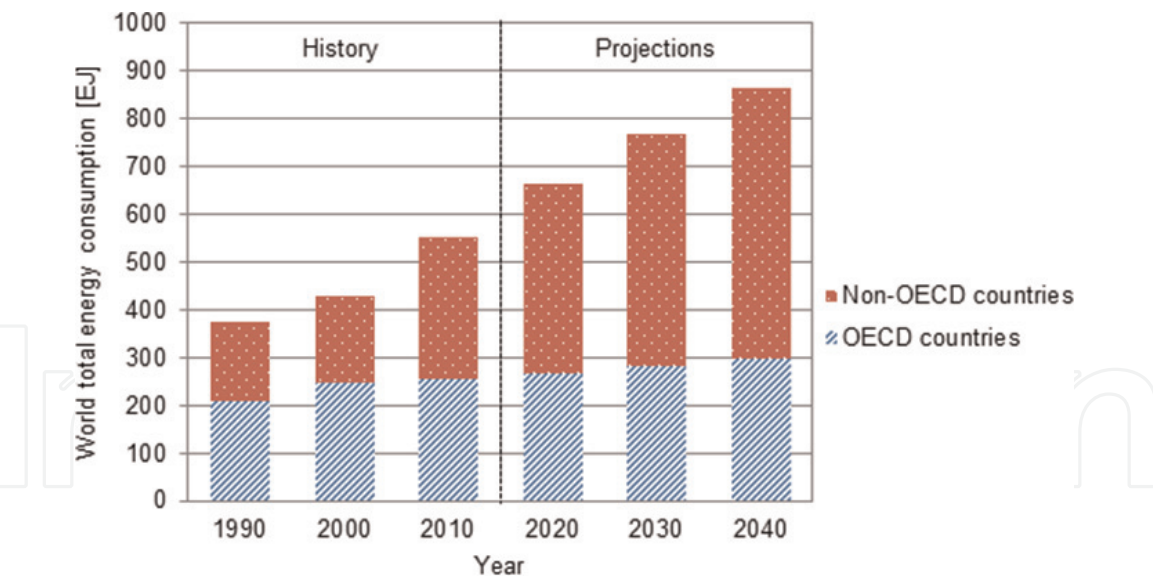
## Abstract

The realization of the smart grid will require a deployment of additional information and communication technology (ICT) equipment in various domains but mostly the customer and distribution domains. All of these ICT equipment will unavoidably lead to an increase in electricity consumption and consequently to increased environmental sustainability issues and thus an overall environmental sustainability analysis if the future smart grid has to be performed. In order to obtain a meaningful environmental sustainability analysis, additionally to the operation phase, various other ICT equipment life cycle stages, i.e., raw material extraction and processing, manufacturing and assembly, recycling and disposal, as well as transportation, have to be included in the assessment as well. This chapter addresses the environmental sustainability of ICT equipment for smart grids involved in the advanced metering infrastructure (AMI) and home area network (HAN) smart grid applications. The environmental sustainability is analyzed by means of the exergy-based life cycle assessment (E-LCA) that is based on the second law of thermodynamics and takes the entire lifetime of ICT equipment into consideration. Some selected results of the E-LCA study are briefly presented and discussed. They have shown that the environmental impact of the additional ICT equipment cannot be neglected and has to be taken into account when assessing the environmental overall sustainability of smart grids.

**Keywords:** smart grids, advanced metering infrastructure (AMI), home area network (HAN), information and communication technology (ICT), exergy-based life cycle assessment (E-LCA), environmental sustainability

## 1. Introduction

The global energy demand has continuously been increasing over the last years and is expected to increase further at an average of 1.5% per year until 2040 [1]. The strongest increase is observed in countries which do not belong to the Organisation for Economic Co-operation and Development (OECD), known as non-OECD countries. The demand for energy in those countries is mainly caused by a strong economic growth, but also the growth in population has a remarkable contribution to this fact [1]. As opposed to this, most OECD countries have a slower economic growth, and also the growth in population in those countries is not that significant compared to non-OECD countries. **Figure 1** illustrates this development. Based on



**Figure 1.**  
World total energy consumption between 1990 and 2040 (modified from U.S. Energy Information Administration [1]). OECD, Organisation for Economic Co-operation and Development.

that, the world total energy consumption amounted 552.82 EJ in 2010 is expected to increase to 664.65 EJ in 2020 and further to 865.1 EJ in the year 2040. This corresponds to an approximately 56% increase between 2010 and 2040 [1].

Exploitation of fossil resources, like carbon and oil, for energy (e.g., electricity) generation satisfies about 70% of the global energy demand [2–5]. However, fossil resources are the main causes of greenhouse gas (GHG) emissions, which poses a detrimental effect on the environment. The combustion of fossil fuels (i.e., coal, oil, natural gas) leads also to pollution of water and land resources in the course of sulfur and nitrogen oxide emissions (e.g., acid rain) [4]. Besides pollution, these resources are also not available in unlimited quantities. The deployment of renewable energy sources, like sunlight and wind, for energy production is seen as an alternative to fossil resources. However, these energy sources are not always available, which makes it difficult to follow the variable load and meet the ever-increasing energy demand [3, 5]. Still, energy production by means of renewable energy sources is seen as a part of the future electricity grid, mostly referred to as smart grid, which will coexist as a decentralized energy source alongside with the traditional centralized power plants. The smart grid can be understood as a constant improvement of the current electricity grid. It will enable not only transport of electricity but also information, which will, on the other hand, result in a more efficient grid management, and facilitate a large-scale deployment of distributed renewable energy sources.

The realization of the smart grid, with the mentioned features, i.e., two-way information exchange in a timely manner and integration of renewable energy sources, will only be possible by a pervasive deployment of information and communication technologies (ICTs) on top of it [3]. It is the information and communication technology in the smart grid which will improve the efficiency of current electricity production, distribution, and consumption, as well as its management, and allow the integration of distributed renewable energy sources. This fact gives ICTs a very important role in smart grids, making them a very involved part of the overall electricity supply system. ICT represents the most important part in the shift from the current electricity grid to the future smart grid and will be the engine for its realization. The future electricity grid will be augmented by a magnitude of additional ICT components and devices, i.e., ICT equipment. Smart meters, power line communication (PLC) modems, data concentrators, data and control center (DCC) servers, switches, and routers are just some of them. All of these

components and devices will lead to a further increase in electricity consumption, which should be taken into account in an overall, holistic analysis of environmental impacts of smart grids.

Energy efficiency is an important design parameter, and new systems should be designed with optimized energy consumption requirements in mind. Even though the operation (or use) phase of ICT equipment is important, it is only a part of the entire “story.” In order to design an energy-efficient and environmentally sustainable system, other life cycle phases of ICT equipment such as raw material extraction and processing, manufacturing and assembly, recycling and disposal, as well as transportation have also to be taken into account [6]. An exergy-based life cycle assessment (E-LCA) makes such a life cycle assessment possible, as it allows an exergy consumption evaluation across the entire ICT equipment lifetime [7], which serves as a measure for the attained environmental sustainability. Exergy can be understood as the amount of energy that can be transformed into useful work, i.e., the quantity of energy available to be consumed [6]. An exergy analysis provides the means to evaluate and compare various systems with regard to their environmental sustainability. For that reason, it can be concluded that the environmental sustainability of ICT equipment relies upon its lifetime exergy (i.e., available energy) consumption and not just the electricity consumption during operation [8]. The exergy concept will be explained in more detail in the next section.

It is also worth noticing that the deployment of ICTs in various other sectors will be responsible for great emission reductions. Smart grids are just one but maybe the most promising of them [9]. Others include, e.g., smart transportation, smart infrastructure, smart production, and smart buildings. According to the Global e-Sustainability Initiative [9], ICT has the potential to enable 7.8 gigatons (Gt) of carbon dioxide equivalent (CO<sub>2</sub>e) emission abatements by the year 2020. Smart grids will allow 2 Gt CO<sub>2</sub>e emission abatements, which represents the strongest reduction potential of all the considered technologies. Although ICT’s own footprint is expected to increase from 0.5 Gt CO<sub>2</sub>e in 2002 to 1.4 Gt CO<sub>2</sub>e in 2020, the enabled abatements achieved by its introduction in the different sectors will be greater. They will account for five times of ICT’s own footprint, which equals to 15% of the projected total global CO<sub>2</sub>e emissions [10]. The findings provided in the Global e-Sustainability Initiative [9] suggest that the realization of the smart grid from an environmental aspect is justified, as its potential to improve the overall environmental sustainability will overcome the environmental sustainability issues associated with the introduction of additional ICT equipment in its various domains. However, the study presented in the Global e-Sustainability Initiative [9] did not address explicitly the environmental impact of ICT for smart grids. Additionally, it used traditional LCA approaches and energy analysis. An energy analysis tracks material and energy flows of a process, enabling a complete assessment of a system [7]. Even though mass and energy conservation are included, it does not consider the second law of thermodynamics. This fact is the main drawback of an energy analysis, since different forms of energy cannot be directly compared [7].

A life cycle assessment (LCA) represents a framework for indicators that can be used to assess how various products or processes impact the environment [7]. For that purpose, all inputs and outputs of a product or process during its considered lifetime are analyzed, i.e., the evaluation takes the entire product or process life cycle under consideration. There are a lot of variants of a LCA, but most of them base their assessment on emissions. A LCA provides a thorough assessment of environmental effects but has also a few drawbacks. The most important one is that it does not produce a simple and unambiguous outcome, which could be used for easy and meaningful comparison purposes between various potential approaches. The other one is its time exposure and accomplishment expenses [7].



An exergy-based life cycle assessment (E-LCA), on the other hand, tracks the lifetime exergy consumption and considers the second law of thermodynamics. Exergy is defined as the maximum amount of useful work that can be attained from a system when brought into thermodynamic equilibrium with its reference environment [10]. Exergy can be understood as the amount of energy that can be used, i.e., the quantity of energy that can be transformed into useful work. Due to irreversibilities (i.e., inefficiencies) attributed to real processes, it is never conserved. This is the main characteristic which distinguishes exergy from energy [6]. An exergy analysis eliminates the main drawbacks of an energy analysis and a LCA. In contrast to an energy analysis, exergy analysis allows different forms of energy to be directly compared, since it makes use of the second law of thermodynamics. It does not allow a detailed assessment of environmental effects of ICTs, but it produces a simple (i.e., a single) outcome, which can be more easily computed and compared with other approaches [7]. An E-LCA is also not that time-consuming and costly to accomplish like a LCA. All of these benefits make E-LCA the best candidate for the evaluation of the environmental sustainability of ICTs for smart grids, and this thermodynamic-based indicator [7] will therefore be used as the environmental sustainability indicator of choice for the study presented in this chapter.

## **2. Framework for environmental sustainability analysis**

This section provides the framework for the environmental sustainability analysis of information and communication technologies (ICTs). Since a large amount of additional ICT equipment is expected to become part of the future smart grid, the means to provide useful and meaningful information on the environmental sustainability of this equipment would prove beneficial. Exergy-based life cycle assessment (E-LCA) provides such means, as it allows various approaches to be compared with each other based on their exergy consumption in their different lifetime or life cycle stages, i.e., raw material extraction and processing, manufacturing and assembly, operation, recycling and disposal, as well as transportation. The obtained exergy consumption serves thereby as a measure for the attained environmental sustainability. Moreover, specific electrical generation systems and their respective energy and exergy efficiencies can be considered as well.

### **2.1 Classification of sustainability indicators**

Before the discussion of sustainability indicators, a definition of sustainability deems appropriate. According to the Report of the World Commission on Environment and Development: Our Common Future [11, 12], the sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” However, this definition of sustainability exhibits two major shortcomings, namely the terms needs and future generations, which are not precisely specified [13]. There are also other definitions for sustainability, but they all fail to give a clear understanding if a product, system, process, or approach is sustainable or not. For that reason, the existence of a sustainability indicator, which could be used for comparison purposes between different approaches, would prove beneficial. Such an indicator could be used to evaluate which of the various approaches under consideration is the most sustainable one. With this in mind, a strict definition for sustainability would not be needed and could be replaced with a more easily attainable approach for sustainability analysis and evaluation [13].

There are several sustainability indicators in existence. Many of them have been introduced and recommended over the last years [14]. According to a report published by the Scientific Committee on Problems of the Environment (SCOPE), sustainability indicators can be categorized into three “pillars” (also called the triple bottom line), which classify sustainability into social, environmental, and economic indicators [14]. An example of a social indicator is the human development index (HDI), which evaluates the development of a country based on people and their capabilities [15]. The gross domestic product (GDP), which indicates the economic condition of a country, is an example of an economic indicator [16]. ICTs may have an influence on the entire triple bottom line of sustainability. Introduction of ICTs may lead to an improved access to education and its quality and also to more profitable markets, which will, on the other hand, result in an increase of a country’s HDI (i.e., social sustainability) and the GDP (i.e., economic sustainability), respectively [14].

To obtain a useful indicator, a few requirements have to be fulfilled. First, it has to be interchangeable so that it can be modified when new data becomes available or some new processing techniques are applied. Further, the difficulty to obtain the indicator should be kept within bounds. Finally, a considerable and most desired indicator should at best provide a single value (i.e., outcome), which could be utilized to compare different approaches with each other, with the aim to obtain the most sustainable one [13].

In the following two subsections, only sustainability indicators associated with environmental effects will be considered and further discussed. After a brief discussion of environmental sustainability indicators, thermodynamic-based environmental sustainability indicators applicable to ICTs will be discussed in more detail. The most promising of them will be chosen as the environmental sustainability indicator for the assessment of ICTs in this study.

### *2.1.1 Environmental sustainability indicators*

Environmental sustainability indicators are used to estimate the influence of human actions (i.e., their behavior) on the environment. They can be used for environmental impact assessment purposes, allowing different approaches to be compared with regard to environmental sustainability. As an example, the environmental sustainability index (ESI) represents an environmental sustainability indicator [17]. By weighing 76 different variables, a single value for a country’s environmental sustainability is derived [13, 17]. The main drawback of the ESI is the fact that it is obtained based on subjective assumptions and conclusions, which lead to inaccuracies. Hence, basing the various variables of the ESI on other assumptions would most probably result in a different outcome. This leads to the conclusion that a more meaningful, unambiguous, and reliable indicator is needed, one that is based on scientifically accurate estimations, and not on vague assumptions [13].

The fundamental laws of thermodynamics, which allow assessing mass and energy transfers attributed to various processes, make such accurate estimations possible. Mass conservation and the first law of thermodynamics provide means to evaluate mass and energy transfers. The second law of thermodynamics enables a further estimation of the exploited energy, i.e., a determination of the energy being utilized [13]. It can be concluded that thermodynamic theory exhibits important advantages for an environmental sustainability analysis, e.g., evaluation of materials needed by a process and those generated due to its existence and determination of the energy demanded by the process. Moreover, it is possible to provide information on how efficiently the energy is being exploited by the process. Based on that, an evaluation of different approaches is facilitated. Even though a

thermodynamic analysis may not always provide a simple value (i.e., outcome) for straightforward and uncomplicated comparison purposes, it is still possible to estimate and evaluate all inputs and outputs to and from a process, respectively. Other thermodynamic indicators, like exergy consumption, serve as a single value, i.e., a simple indicator, which allows an easy comparison between competing approaches.

In order to distinguish between various thermodynamic indicators, two main framework conditions exist [7]. The first one considers the thermodynamic quantity assessed by the indicator. Thermodynamic quantities, which can be assessed by an indicator, include, e.g., mass flow, energy flow, and exergy flow. The second parameter considers the scope of the study, which is, moreover, related to its objectives [7]. Indicators may take only a part of a device's life cycle into consideration, like the operation, manufacturing and assembly, or the recycling and disposal stage. That means, the life cycle of a device is not strictly defined. On the other hand, the cradle-to-grave approach includes raw material extraction and processing, manufacturing and assembly, operation, recycling and disposal, as well as the transportation between the various process stages. These life cycle stages can in general be seen as the most important and significant ones. The cradle-to-grave life cycle approach is commonly viewed as an entire life cycle and will therefore be adapted as the ICT component and device (i.e., ICT equipment) life cycle in this study. Thermodynamic-based environmental sustainability indicators that will be considered in the following include [9]:

- Energy analysis
- Life cycle assessment (LCA)
- Exergy-based life cycle assessment (E-LCA)

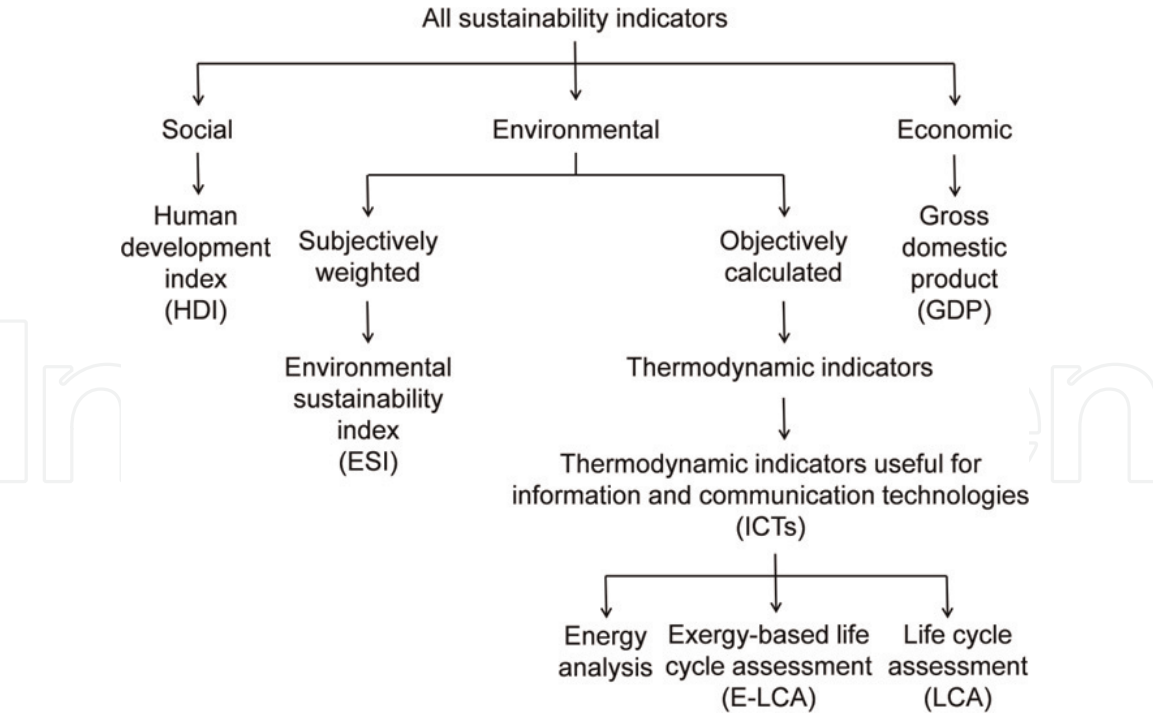
These thermodynamic-based environmental sustainability indicators will be discussed in more detail in the following subsection. A comparison between them is provided with the aim to derive the most suitable one for the environmental sustainability analysis of ICTs. **Figure 2** summarizes the discussion about sustainability indicators and depicts their classification.

### *2.1.2 Thermodynamic indicators suitable for sustainability analysis of ICT*

In the following few parts of this subsection, energy analysis, LCA, and E-LCA will be discussed. Advantages and disadvantages of these thermodynamic indicator types are presented. In addition, basic theory behind energy, exergy, and entropy will be provided. A comparison between LCA and E-LCA for the environmental sustainability analysis of ICT equipment is presented. Further, the relation between environmental impact, exergy efficiency, and environmental sustainability is briefly studied.

#### *2.1.2.1 Energy analysis*

It is a matter of common knowledge that it is possible to store energy within systems (e.g., in batteries). Moreover, it is possible to convert energy from one form to another (e.g., coal energy to electrical energy) and to transfer it from one system to another. In the course of all the storages, conversions, and transfers, the entire quantity of energy must be conserved [18]. This fact is embodied in the first law of thermodynamics, which states that the change of the internal energy ( $U$ ) of a



**Figure 2.**  
*Classification of sustainability indicators (modified from Lettieri et al. [7]).*

system is equal to the sum of heat ( $Q$ ) supplied to the system and work ( $W$ ) done by the same system on its surroundings [6], i.e.

$$dU = \delta Q - \delta W. \tag{1}$$

Therefore, the energy balance of an entire process or system is equal to zero [19]:

$$En_{in} - En_{out} = 0. \tag{2}$$

According to energy balance, input and output energies of a process or system are equal. A portion of the energy at the output may be converted, e.g., into waste heat. This waste heat may as well have a positive side effect, since it could be exploited for, e.g., heating purposes. Nevertheless, the total amount of energy is conserved in all the storages, transfers, and conversions. Using an energy balance, it is possible to assess the energy demanded by a system. However, it does not tell us how well the energy is being exploited by the same system. With an energy analysis, it is not possible to determine the true thermodynamic inefficiencies related to an energy transformation system [18]. An energy analysis can identify merely the inefficiencies arising due to energy transfers out of a system that cannot be exploited anymore in the considered or some other system.

This leads to the conclusion that utilizing energy as an indicator for the assessment of energy system advantages and imperfections can be quite unclear and inaccurate [10]. An energy analysis enables quantifying energy flows. For that reason, a complete assessment of a system is facilitated. Nevertheless, even a complete life cycle energy analysis exhibits considerable disadvantages [7]. The main reason for this is the fact that an energy analysis does not consider the second law of thermodynamics. Because of that, it is not possible to directly compare distinct forms of energy with each other. However, an exergy-based life cycle assessment (E-LCA) provides means to estimate the exergy consumption over the entire considered lifetime of a system and takes the second law of thermodynamics under consideration. Based on that, it is further possible to provide information on the



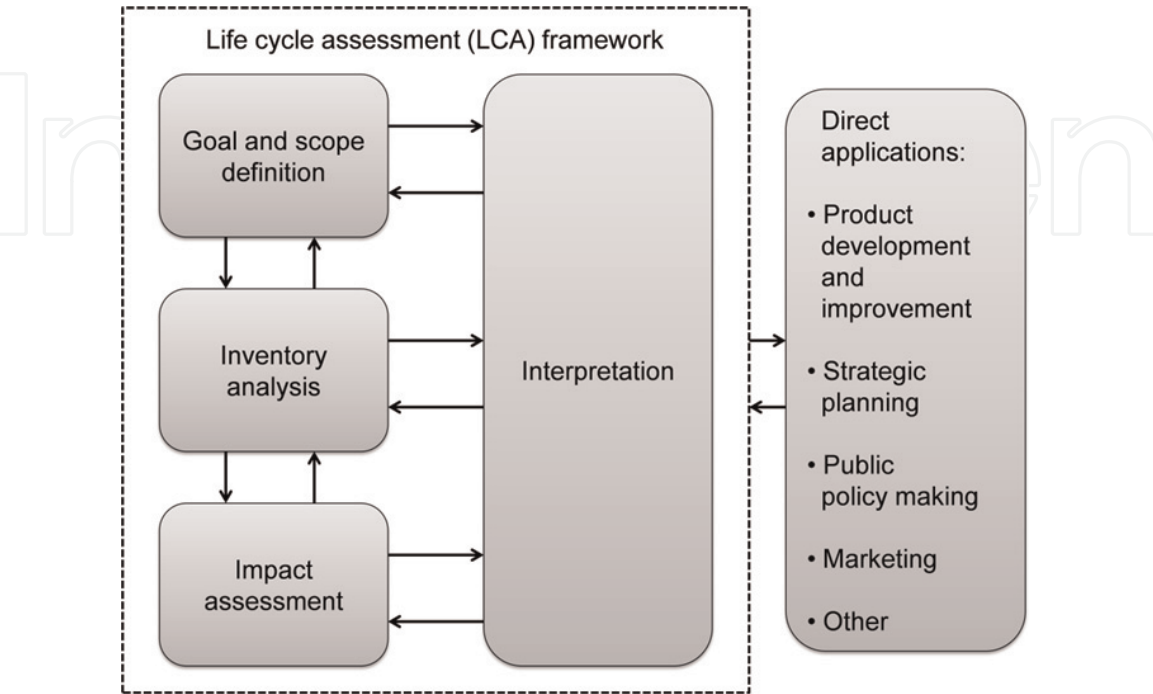
quality of energy, i.e., how efficiently the energy is being utilized by a system. E-LCA will be given its own discussion, and its benefits will be explained in more detail.

2.1.2.2 Life cycle assessment (LCA)

A life cycle assessment (LCA) provides means to estimate environmental effects of a product, process, or system over its respective lifetime, i.e., under consideration of its entire life cycle [20]. It was specified by the International Organization for Standardization (ISO) 14040 family of standards [14, 15]. LCA cannot be directly or precisely considered as an indicator. It rather defines a framework for indicators that can be used to evaluate how various products, processes, or systems impact the environment during their entire lifetime [13]. Based on that, various production approaches and techniques may be analyzed with regard to their environmental effects, with the aim to indicate the most efficient (i.e., environmentally sustainable) one [19]. The evaluation of environmental effects can be accomplished by capturing all inputs and outputs of a product, process, or system during its considered lifetime. Even though there are many variants of a LCA, most of them are based on emissions [13]. **Figure 3** depicts schematically the life cycle assessment (LCA) framework, which is accomplished in four phases [15]:

- 1. Goal and scope definition
- 2. Inventory analysis
- 3. Impact assessment
- 4. Interpretation

The goal and scope definition phase considers the aims of the assessment and the constraints that have to be taken into consideration. The goal definition includes



**Figure 3.** Life cycle assessment (LCA) framework (modified from ISO 14040 [15]).

further the purpose of the assessment and defines the group of people potentially interested in the LCA outcomes. The scope definition defines additionally, e.g., the functional unit, data specifications, assumptions, and constraints of the assessment [15, 19]. The inventory analysis considers all inputs and outputs related to the various processes of the considered system. Inputs and outputs of the processes can be divided into economic and environmental flows [19]. Environmental inputs and outputs, which either come from, or are emitted (i.e., released) to, the environment, are considered as environmental flows. The result of the inventory analysis can be found in the inventory table. This table comprises all the resources and toxic substances that are captured or released during the considered lifetime, i.e., during the entire life cycle. Impact assessment represents the third phase of the LCA framework. During this phase the data in the inventory table is evaluated. For this purpose, impact categories are deployed, e.g., climate change, human toxicity, ozone layer depletion, and ecotoxicity [19]. In the final, i.e., interpretation, phase of a LCA, the obtained outcomes are evaluated and clarified. Based on this assessment, it is possible to suggest further improvement potentials.

A LCA provides a thorough assessment of environmental effects but has also a few drawbacks because of such a complete analysis. The first, and probably the main, disadvantage of a LCA is the lack of a simple (i.e., single) outcome which could serve as the basis for assessment and evaluation purposes between various approaches. For that reason, a direct comparison between different impact categories shows to be not that easy (e.g., ecotoxicity vs. global warming potential) [7]. Even though collections of standardized impact factors are available, the estimation of diverse environmental effects, caused from various processes, is still based on subjective assumptions and conclusions [7]. The inaccuracies introduced in the course of such vague assumptions may not be tolerable and would most probably lead to uncertain or even useless results. The second disadvantage of a LCA relates to its time exposure and accomplishment expenses. LCA software tools are existent and in use (e.g., SimaPro, GaBi Software, EarthSmart) [13, 16, 21, 22]. Still, other environmental sustainability indicators are easier to generate compared to a LCA. Exergy-based life cycle assessment (E-LCA) is an example of such an environmental sustainability indicator and will be discussed in the following part of this subsection.

#### *2.1.2.3 Exergy-based life cycle assessment (E-LCA)*

Exergy is defined as “the maximum theoretical useful work, which can be obtained from a system when brought into thermodynamic equilibrium with its environment while the system interacts with this environment only” [18]. The environment required for computing the exergy values is known as the exergy reference environment or thermodynamic environment. It is free from any irreversibility. Moreover, the exergy value of this environment must be zero. The natural environment does not meet the needs of the exergy reference environment, since it is not in equilibrium. For that reason, a model for the thermodynamic environment is always presumed. In most cases, the actual local environment is chosen as the exergy reference environment. In other words, exergy can be understood as the quantity of energy that can be utilized to perform useful work, i.e., the amount of energy available to be consumed [6]. The theory behind exergy, its characteristics, and benefits are defined by the first and second law of thermodynamics. The first law of thermodynamics defines the concept of energy conservation (see Energy Analysis). The second law of thermodynamics introduces additionally the concept of non-conservation of entropy [10, 19], i.e., the concept of entropy increase. For that reason, an exergy analysis may be utilized to evaluate,

construct, and upgrade various systems. Before further discussing exergy, a few words will be addressed to entropy.

In conjunction with thermodynamic processes, entropy may be understood as the amount of energy deficiency present to perform useful work. As characterized by Rudolf Clausius, entropy can be considered as a state function of a reversible cyclic process, known as the Carnot cycle, which states that the change of entropy ( $S$ ) is proportional to the heat ( $Q$ ) divided by the absolute temperature ( $T$ ), i.e.

$$dS = \frac{\delta Q}{T}. \quad (3)$$

It is important to underline that the process assumed in Clausius definition is a reversible one. However, irreversible processes usually lead to an increase of entropy. Assuming an isolated system is subjected to some process, entropy can only be greater or equal to zero:

$$\frac{dS}{dt} \geq 0. \quad (4)$$

This relation is satisfied with equality only for a reversible process, whereas for an irreversible process, the entropy will be greater than zero. One further aspect with regard to entropy should be mentioned. It is possible to distinguish thermodynamic entropy from logical entropy [6]. According to The American Heritage Dictionary, thermodynamic entropy (expressed in Joule per Kelvin, i.e., J/K) is formulated as “the quantitative measure of the amount of thermal energy per unit temperature not available to do work in a closed system.” Logical entropy, on the other hand, can be understood as “a measure for randomness in a closed system.” The entropy concept can be applied in many fields of research, e.g., thermodynamics, communications, and statistics [6]. Even though an entropy balance provides information on inefficiencies associated with a considered system based on entropy creation, it fails to communicate the precise amount of energy being exploited by the system. The entropy concept does not provide any information about the quality of energy, just like an energy analysis. However, an exergy analysis eliminates this drawback related to an energy analysis and the entropy concept. This is because exergy allows evaluating the quality of an energy carrier (i.e., its ability to perform useful work) [18].

Using an exergy analysis instead of an energy analysis, a more thorough assessment of a system can be accomplished [20]. The data obtained from an exergy analysis contains more valuable and relevant information than the one gained from an energy analysis. Further, an increase of efficiency and means to decrease thermodynamic losses may as well be realized and determined using an exergy analysis. Moreover, an exergy analysis allows different forms of energy (i.e., with different qualities) to be compared directly with each other, as the main criterion is the capability to perform useful work. For that reason, an evaluation of various systems can be accomplished in a more accurate and meaningful way. Environmental effects and improvement potentials may as well be analyzed and assessed with the use of an exergy analysis [10]. In contrast to energy, exergy is destructed and never conserved for a majority of real processes because of irreversibilities. As opposed to an energy analysis, where the energy balance for an entire process equals zero (see the paragraph Energy analysis), the exergy balance corresponds to irreversibilities related to the process under consideration [19], so that

$$Ex_{in} - Ex_{out} > 0. \quad (5)$$

According to the energy balance, the difference between input and output energy is zero, i.e., they are equal (see Eq. (2)). The exergy balance, on the other hand, defines a decrease of the quality of energy (i.e., exergy) during a process [10]. This fact is obvious from Eq. (5), according to which the exergy at the input of a system is greater than the exergy at its output. The exergy balance, which corresponds to irreversibilities associated with the considered process, is proportional to the creation of entropy ( $\Delta S$ ) weighted by the temperature of the exergy reference environment ( $T|0$ ) [6, 19]:

$$Ex_{\text{loss}} = \Delta Ex = Ex_{\text{in}} - Ex_{\text{out}} = T_0 \Delta S > 0. \quad (6)$$

This relation is also known as the law of exergy loss, or the law of Gouy-Stodola [19]. The exergy loss of a complete system can be obtained by assessing and summing up the exergy losses of its corresponding subsystems or components, i.e.

$$Ex_{\text{loss, system}} = \sum Ex_{\text{loss, component}}. \quad (7)$$

Exergy losses can be divided into internal and external exergy losses. External exergy losses are composed of waste and exergies emitted (i.e., released) from a system. They encompass the amount of exergy that cannot be exploited to perform useful work. Internal exergy losses are losses related to internal inefficiencies (i.e., irreversibilities) of processes, which lead to a decrease of energy quality. They can further be classified into technical and structural exergy losses [19]. Technical exergy losses originate from system inefficiencies, while structural exergy losses are defined by various system assumptions, its composition, and features. Technical exergy losses can be minimized by applying improvement procedures. A decrease of structural exergy losses may only be achieved by modification and upgrading measures of the considered system [23].

The exergy-based life cycle assessment (E-LCA) takes all exergy inputs to a system or process during its entire lifetime into account, i.e., it includes all exergy inputs over the entire system or process life cycle [24]. Moreover, an accumulation (i.e., conservation) of exergy during the considered life cycle exergy assessment is excluded [25]. For that reason, it can be concluded that the life cycle system or process exergy losses have to be proportional to the overall exergy consumption [19, 25]. This total exergy consumption can be further used to assess and interpret the environmental sustainability of different approaches, systems, and processes.

In the following few lines, the composition of the total exergy of a system is presented. If electrical, magnetic, nuclear, and surface tension effects can be excluded, then it is possible to divide the total exergy of a system ( $Ex_{\text{system}}$ ) into four components, namely, physical exergy ( $Ex_{\text{physical}}$ ), chemical exergy ( $Ex_{\text{chemical}}$ ), kinetic exergy ( $Ex_{\text{kinetic}}$ ), and potential exergy ( $Ex_{\text{potential}}$ ) [18], i.e.

$$Ex_{\text{system}} = Ex_{\text{physical}} + Ex_{\text{chemical}} + Ex_{\text{kinetic}} + Ex_{\text{potential}}. \quad (8)$$

The physical exergy can be calculated according to Frangopoulos [18]:

$$Ex_{\text{physical}} = (U - U_0) + p_0(V - V_0) - T_0(S - S_0). \quad (9)$$

Here,  $U$ ,  $V$ , and  $S$  are internal energy, volume, and entropy of the system, in that order. The subscript 0 in Eq. (9) indicates the state of the considered system at temperature  $T_0$  and pressure  $p_0$  related to the exergy reference environment. The physical exergy of a system can be further divided into thermal exergy ( $Ex_{\text{thermal}}$ ) related to the system's temperature change from the temperature of the exergy



reference environment and mechanical exergy ( $Ex_{\text{mechanical}}$ ) introduced because of a difference of the system's pressure from the pressure of the exergy reference environment [18], i.e.

$$Ex_{\text{physical}} = Ex_{\text{thermal}} + Ex_{\text{mechanical}}. \quad (10)$$

In analogy to this, it is also possible to split the chemical exergy into reactive exergy ( $Ex_{\text{reactive}}$ ) and nonreactive exergy ( $Ex_{\text{nonreactive}}$ ) [18], i.e.

$$Ex_{\text{chemical}} = Ex_{\text{reactive}} + Ex_{\text{nonreactive}}. \quad (11)$$

The chemical exergy can be understood as the hypothetical maximum of useful work that can be attained from a system as this chemically equilibrates with its exergy reference environment. In order to determine the chemical exergy, it is not sufficient to define just the temperature  $T_0$  and pressure  $p_0$  but also the chemical consistency of the exergy reference environment. Finally, the kinetic and potential exergies can be calculated according to the following Eqs. (10):

$$Ex_{\text{kinetic}} = \frac{mv^2}{2} \quad (12)$$

$$Ex_{\text{potential}} = mgh. \quad (13)$$

As can be seen from Eqs. (12) and (13), kinetic and potential exergies are equal to kinetic and potential energies. The variables  $v$  and  $h$  correspond to the velocity and height relative to that of the exergy reference environment ( $v_0 = 0, h_0 = 0$ ) [18].

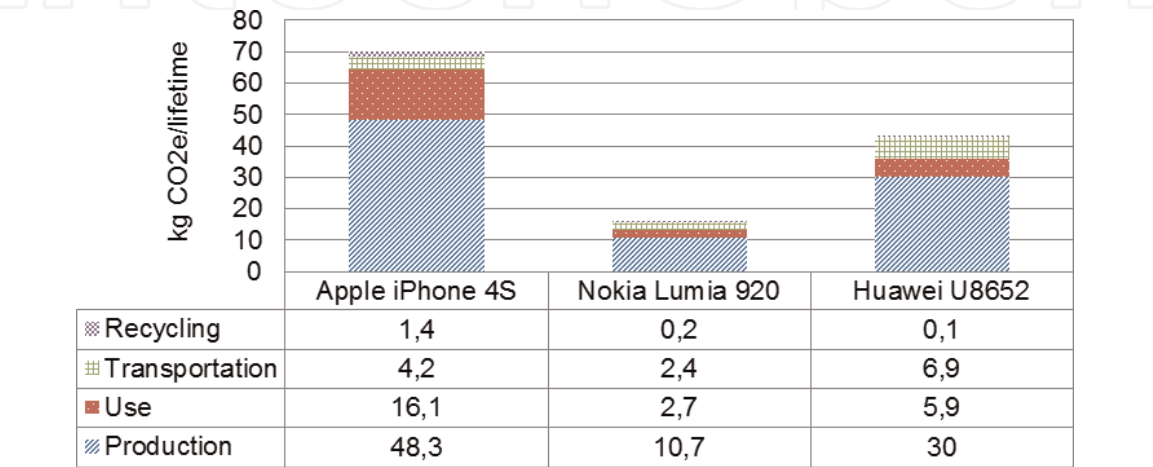
The preceding two parts of this subsection elaborated in detail two important but different approaches for an environmental sustainability analysis of ICTs, namely, the life cycle assessment (LCA) and the exergy-based life cycle assessment (E-LCA). In the following part of this subsection, a comparison between them is provided with the aim to point out the advantages of E-LCA for the assessment and evaluation of environmental effects, i.e., the environmental sustainability, associated with various ICT equipment.

#### 2.1.2.4 LCA vs. E-LCA

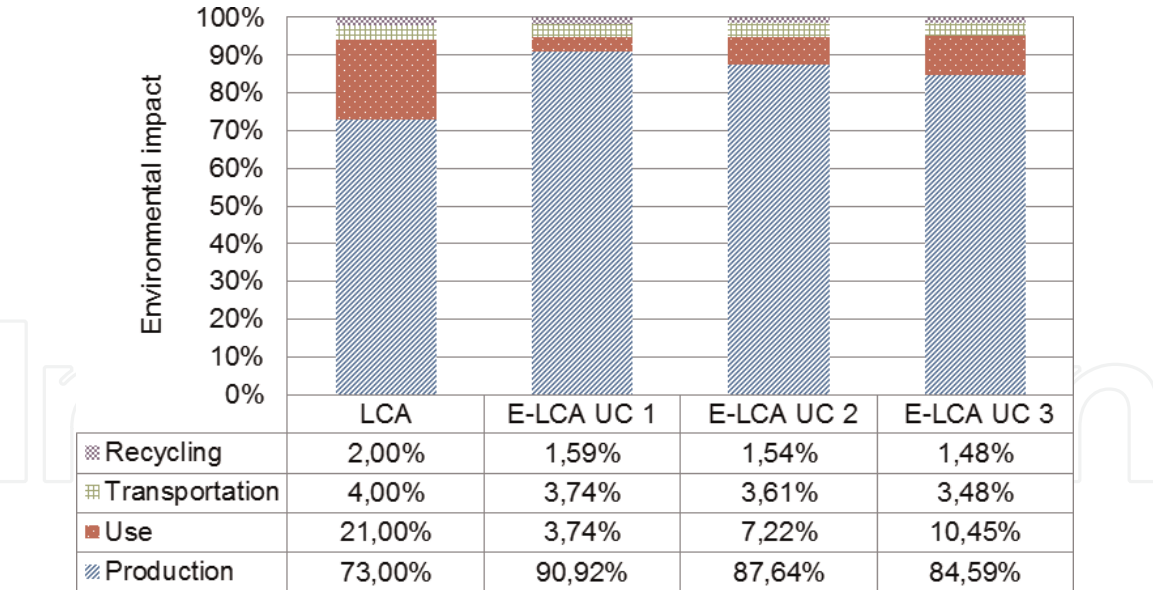
A life cycle assessment (LCA) enables a thorough assessment of environmental effects related to ICT equipment, by capturing all inputs and outputs during its considered lifetime [26–28]. Most LCA approaches base their analysis of environmental effects on emissions, which pose a potential to negatively impact the environment, e.g., greenhouse gas (GHG) emissions. However, such an analysis brings also considerable drawbacks with it, like time exposure, accomplishment expenses, and, more importantly, the absence of a simple and unambiguous outcome for meaningful comparison purposes between different approaches. The exergy-based life cycle assessment (E-LCA), on the other hand, represents a sound approach for the environmental sustainability analysis of ICT equipment, based on its lifetime exergy consumption, which serves as a measure for the attained environmental sustainability. The major benefit of E-LCA is the fact that it leads to a single outcome (i.e., an exergy consumption value) that can be easily compared with various other potential approaches. Moreover, the quite moderate time exposure, accomplishment expenses, as well as the update and expandability features of E-LCA make this thermodynamically based indicator the best choice for the environmental sustainability analysis of ICTs.

The conclusions drawn from the E-LCA do not differ much from those of a LCA. Actually, they coincide quite well in all life cycle stages of the considered ICT equipment, the only difference being the relative scales and the quantity characterizing the environmental effects (e.g., GHG emissions vs. exergy consumption). **Figure 4** shows the results of a LCA of three different smartphones, namely, an Apple iPhone 4S, a Nokia Lumia 920, and a Huawei U8652 [29]. The contribution of the different smartphone life cycle stages to the climate change, attributed to GHG emissions, over a lifetime of 3 years, is expressed in kilograms of carbon dioxide equivalents (kg CO<sub>2</sub>e) [29, 30]. The production stage accounts for raw material extraction and processing, manufacturing and assembly, as well as the transportation during these two processing phases; the use phase is based on a 3-year operation of the smartphones; the transportation stage includes the transport of the products to their distribution location, while the recycling stage includes the transport of products to recycling plants, their separation, and shredding. It is evident that the use of a LCA for the assessment of environmental effects, even for the three considered smartphones, leads to relatively different outcomes (ranging between 16 and 70 kg CO<sub>2</sub>e), which is a result of the quite different assumptions made for each of these approaches and LCA tools used for their assessment. Even this simple example illustrates the underlying ambiguity of a LCA. However, the conclusions drawn from each of these approaches suggest that the most dominant life cycle stage of a smartphone relates to its production stage, i.e., its raw material extraction and processing, as well as its manufacturing and assembly (including transport).

The same conclusions on the environmental sustainability are provided by means of the E-LCA. **Figure 5** depicts the LCA and three E-LCA use cases (UCs) of an Apple iPhone 5C, respectively [31]. The assumptions provided in Ref. [31], i.e., those concerning the production, transportation, customer use, as well as recycling, have been adapted to a good degree into the E-LCA framework, in order to obtain a more meaningful comparison between these two environmental sustainability analysis approaches. The three depicted E-LCA UCs assume different usage intensities and therefore different daily smartphone charging durations. The first UC assumes a daily charging duration of 4 h, the second UC of 8 h, and the third UC of 12 h. An operational duration of 3 years is assumed. It should be noted that the environmental impact of the different smartphone life cycle stages in **Figure 5** is given in percentage of the lifetime GHG emissions in the case of the LCA and in percentage of the lifetime exergy consumption in the case of the E-LCA for easier comparison purposes. **Figure 5** suggests that for both the LCA and the E-LCA approach, the most dominant (i.e., environmentally relevant) life cycle stage of the



**Figure 4.**  
*Life cycle assessment (LCA) of three different smartphones (modified from Andrae and Vaija [29]).*



**Figure 5.** Life cycle assessment (LCA) and three exergy-based life cycle assessment (E-LCA) use cases (UCs) of an Apple iPhone 5C.

smartphone relates to its production. The contribution of the use phase to environmental effects is more pronounced in the case of the LCA than in the case of the E-LCA. This is mainly related to the power grid mix assumed in Ref. [31] (which is accounted at a continent level), as well as the deployed LCA tool. Such an approach underlines again the ambiguity of a LCA, as different power grid mix assumptions and LCA tools will unavoidably lead to different relative outcomes (compare also the use phases of the three different smartphones depicted in **Figure 4**). E-LCA, on the other hand, bases its assessment of the use phase on the operational exergy consumption, leading to a more scientifically reasonable and justified approach. The difference between the use phases of the LCA and E-LCA becomes smaller assuming a longer daily charging duration (i.e., usage intensity).

For that reason, it can be argued that the conclusions drawn from a LCA and the E-LCA coincide to a good degree with each other. The main benefit of E-LCA, however, is the fact that it leads to a simple and unambiguous outcome, useful for easy and meaningful comparison purposes between various potential approaches. Such a feature lacks in a LCA, as each environmental sustainability assessment approach includes different assumptions, as well as LCA tools, leading to relatively different results (see **Figure 4**). Therefore, E-LCA is chosen as the environmental sustainability indicator of choice for the assessment of ICT equipment in the scope of this study.

To summarize the discussion regarding the thermodynamically based environmental sustainability indicators that can be applied to ICTs, **Table 1** provides a comparison between the discussed indicator types. It can be concluded that the environmental sustainability of ICTs may at best be assessed and evaluated using the E-LCA approach. E-LCA proved to be the best choice among the other discussed thermodynamically based environmental sustainability indicators, namely energy analysis and LCA. It allows assessing the lifetime exergy consumption of various ICT approaches, which will, on the other hand, serve as an indicator for the attained environmental sustainability. Even though E-LCA does not provide detailed information of environmental effects like a LCA, it derives at a simple outcome (i.e., a single value) that can be used to compare different approaches, systems, and processes. If more information of a particular system is needed, and a more thorough assessment deems appropriate, a LCA can be applied [7]. Moreover, E-LCA satisfies the requirements defined by SCOPE for useful and applicable indicators.

Indicator type	Advantage	Disadvantage
Energy analysis	Enables energy assessment and evaluation by the use of the first law of thermodynamics	Different forms of energy cannot be directly compared; environmental effects cannot be directly assessed
Life cycle assessment (LCA)	Allows a very detailed and thorough assessment of environmental effects	Difficult to derive; lack of a simple and unambiguous outcome for easy comparison purposes
Exergy-based life cycle assessment (E-LCA)	Different forms of energy can be directly compared; simpler to obtain than a LCA; leads to a single value for easy comparison purposes	Does not allow a direct, i.e., a thorough, assessment of environmental effects

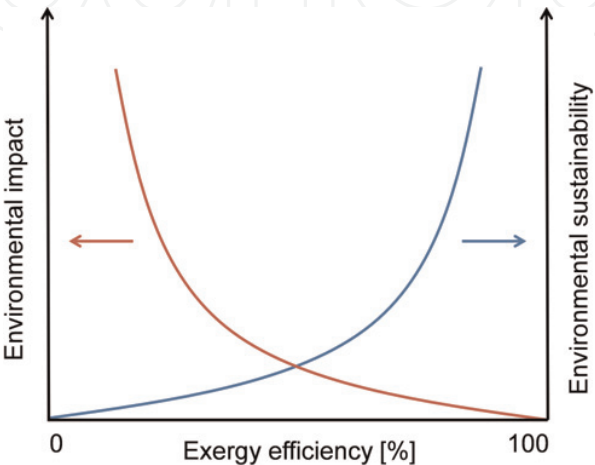
**Table 1.**  
*Advantages and disadvantages of thermodynamic indicators [9, 14].*

E-LCA has the major benefit of being “flexible,” as it can be modified and changed when, e.g., manufacturing techniques are changed. The new data can be quite easily incorporated into the existing assessment framework. Exergy analysis can be used to assess and analyze heterogeneous systems. Since recently, E-LCA has also been used to analyze and evaluate the environmental sustainability of ICTs [7, 8, 13, 25, 32, 33].

As the final topic in this section, the relation between environmental impact, exergy efficiency, and environmental sustainability will be discussed. There are a few ways to define exergy efficiency. One of them, known as the simple efficiency, is given by the exergy at the output divided by the exergy at the input of a system or process [19], i.e.

$$\eta_{\text{ex, simple}} = \frac{Ex_{\text{out}}}{Ex_{\text{in}}} = 1 - \frac{\Delta Ex}{Ex_{\text{in}}} = 1 - \frac{Ex_{\text{loss}}}{Ex_{\text{in}}} . \tag{14}$$

There are also other definitions for the exergy efficiency. However, the simple exergy efficiency defined by Eq. (14) serves quite well for elaboration and assessment purposes in the scope of this study. It can be argued that an increase of exergy efficiency, i.e., a decrease of exergy losses (see also Eq. (6)), is an important step toward the improvement of the environmental sustainability of a system, process, or approach. Moreover, such an improvement would most probably lead to a reduction of the environmental impact associated with the considered system,



**Figure 6.**  
*Relation between environmental impact, exergy efficiency, and environmental sustainability (modified from Rosen et al. [10]).*



process, or approach. **Figure 6** illustrates the relation between environmental impact, exergy efficiency, and environmental sustainability. An increase of the exergy efficiency is accompanied by a decrease of the environmental impact and at the same time by an increase of the environmental sustainability. Therefore, measures to increase the exergy efficiency, or equivalently decrease the exergy losses (i.e., exergy consumption), are desirable to achieve more environmentally sustainable systems or processes. This will, moreover, result in a decrease of environmental effects.

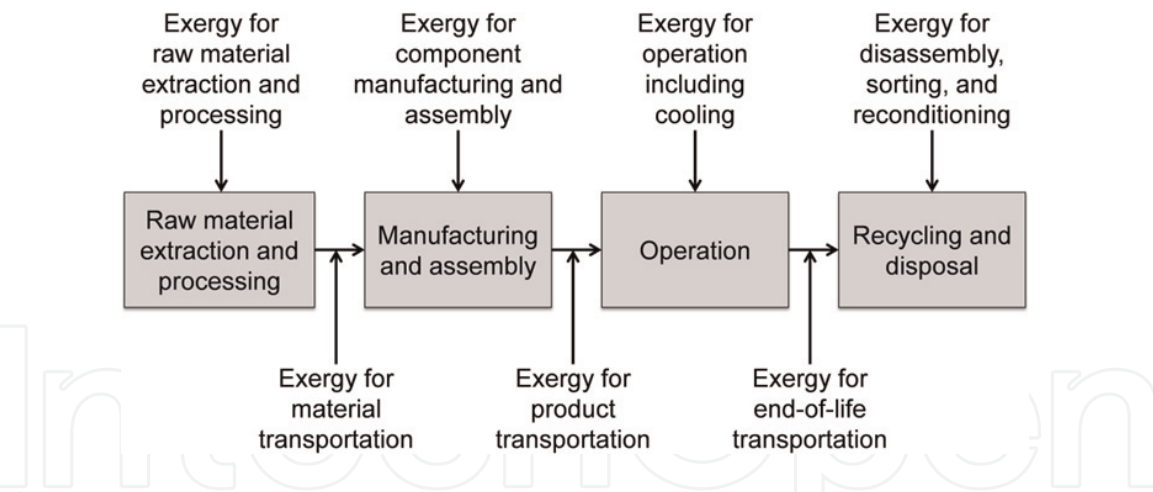
Even though E-LCA does not provide detailed information on environmental effects in comparison to a LCA, it can be argued that a low-exergy consumption (i.e., low-exergy losses or equivalently a high-exergy efficiency) leads to less environmental effects and, more importantly, to an increase of the environmental sustainability of the considered system, product, or approach. This observation will serve as the basis for the assessment and evaluation of the attained environmental sustainability of ICT equipment deployed in the various smart grid domains. It has to be mentioned that the relation between environmental impact, exergy efficiency, and environmental sustainability depicted in **Figure 6** does not hold for all processes. For instance, if a process deploys specific pollution control methods, it is possible to observe a decrease of environmental effects, even in the course of a reduction of the exergy efficiency, i.e., an increase of exergy losses or equivalently an increase of the exergy consumption.

## 2.2 Exergy consumption in different life cycle stages

In this section, the exergy consumption values for various processes (needed to estimate and analyze the environmental sustainability of ICT equipment deployed in the different smart grid domains) will be presented. Furthermore, the framework required for the evaluation of the operational exergy consumption of ICT equipment will be provided. As already mentioned in Section 1, a lot of additional ICT equipment will become part of the future electricity grid, the smart grid. The environmental sustainability of this ICT equipment will be analyzed using the exergy-based life cycle assessment (E-LCA), as this indicator type proved to be the most suitable one for the assessment and evaluation of the environmental sustainability of ICTs.

Life cycle stages that will be considered in the environmental sustainability analysis of ICT equipment include raw material extraction and processing, manufacturing and assembly, operation, recycling and disposal, as well as the transportation between the different process stages. The exergy consumed in all of these life cycle stages will be estimated and will serve as an indicator for the attained environmental sustainability of various systems and approaches. The research focus of most studies on energy efficiency and environmental sustainability of ICT equipment considers mainly their use phase, i.e., their respective power consumption during operation [8]. However, such an approach takes only a portion of the entire ICT equipment life cycle into account, since the majority of its lifetime is not included in the estimation of the overall exergy, i.e., useable energy, consumption. In order to obtain a more thorough environmental sustainability assessment, the whole life cycle of ICT equipment needs to be considered, i.e., from cradle to grave. This approach is schematically depicted in **Figure 7**, which shows the different lifetime exergy consumption stages that will be taken into account for the environmental sustainability assessment of ICT equipment deployed in the various domains of the overall model.

For this purpose, the considered overall model will be divided into submodels for the home area network (HAN)/building area network (BAN), neighborhood



**Figure 7.**  
*Life cycle exergy consumption stages of ICT equipment (modified from Aleksic [6]).*

area network (NAN), access network (AN), core network (CN), and finally the data and control center (DCC). ICT equipment deployed in the HAN/BAN includes smart meters and power line communication (PLC) modems, as well as user devices (UDs) like smartphones, tablets, notebooks, digital subscriber line (DSL) modems, and home energy management systems (HEMSs). This ICT equipment will enable various monitoring and control functions and allow an easy and efficient management of customers' electricity consumption.

A few HANs/BANs are considered a NAN. Equipment in the NAN includes, additionally to the ICT equipment of HANs/BANs, also data concentrators. Smart meters, PLC modems, and data concentrators, referred here to as utility equipment (UE), will be responsible for the collection of various quantities (e.g., electricity consumption data), their management, processing, and forwarding to the DCC where they will be further analyzed. This will enable an efficient management and control of the electricity grid. But also other benefits for the user will emerge, e.g., diverse demand response (DR) methods [3]. The Global System for Mobile Communications (GSM) and the Universal Mobile Telecommunications System (UMTS) radio access network (RAN) compose the considered AN. Components of the AN (more precisely the RAN) include base transceiver station (BTS) and base station controller (BSC) racks for the GSM RAN and Node B and radio network controller (RNC) racks for the UMTS RAN. Further, for a more complete and accurate assessment, optical fiber cables and cat5e cables will be included in the evaluation of the RAN. The CN includes serving General Packet Radio Service (GPRS) switching node (SGSN) and gateway GPRS switching node (GGSN) racks. Cables will be included in the CN as well. The DCC comprises not only a number of servers (including cooling exergy consumption), switches, routers, modems, and cables, but also notebooks, tablets, and smartphones, which represent an important part of the control center (CC), will be included as well. The total exergy consumption of the ICT equipment deployed in these various submodels will be estimated separately. Moreover, the exergy consumption in all the different life cycle stages of this ICT equipment will be evaluated, in order to see where the largest exergy consumption occurs, i.e., in which life cycle stage. Finally, the total exergy consumption of the overall system will be estimated and further analyzed. Additionally, the most dominant ICT equipment category groups (i.e., those with the largest exergy consumption), as well as the most important smart grid domains (i.e., those closely associated with environmental sustainability issues) will be indicated.

Here, a distinction will be made between embodied and operational exergy consumption. Embodied exergy consumption (EEC) refers to the exergy consumed

during raw material extraction and processing, manufacturing and assembly, recycling and disposal, as well as the transportation between the various process stages. Operational exergy consumption (OEC) refers to the power consumed by the considered system during operation, called operational power consumption, and the power needed by the cooling infrastructure (if present), called cooling exergy consumption [6]. This distinction of the exergy consumption will prove beneficial for the assessment of the environmental sustainability of ICT equipment, its deployment in the various submodels of the smart grid, and finally the environmental sustainability assessment of the overall system.

### *2.2.1 Requirements on data for environmental sustainability analysis*

Before we can start with the environmental sustainability assessment of ICT equipment, the following data has to be made available [13]:

- Mass of materials that compose the various ICT components and devices
- Exergy consumption values for extraction and processing of various raw materials
- Amount and dimensions of printed circuit boards (PCBs), integrated circuits (ICs), and processors
- Exergy consumption values for various manufacturing and assembly processes
- Operational specifications of the considered system (i.e., ICT equipment), such as peak power consumption, average load, uptime (i.e., daily operation time), operational (i.e., use) duration, and cooling characteristics
- Exergy consumption value for recycling and disposal processes of ICT equipment
- Locations of raw material extraction and processing, manufacturing and assembly, operation, recycling and disposal, and the transportation mode between these locations
- Exergy consumption values for various transportation modes

In the following few parts of this subsection, the exergy consumption values required for the ICT equipment exergy consumption (i.e., environmental sustainability) estimation in the different process stages as well as the framework for the calculation of the operational exergy consumption, will be presented and discussed in more detail. These exergy consumption values as well as the operational exergy consumption framework form the basis for the assessment of the environmental sustainability of the ICT equipment.

#### *2.2.1.1 Raw material extraction and processing*

Before going into the examination of the various exergy consumption values, it will be repeated what is understood under exergy consumption. Exergy can be understood as the amount of energy available to perform useful work. For example, high-concentration ores possess an exergy value in comparison to the Earth's crust [13]. The extraction of these ores for manufacturing and assembly (i.e., production)

purposes is related to an exergy loss from the environment, i.e., exergy consumption. The estimation of the raw material extraction and processing exergy consumption of ICT equipment is achieved by using mass-specific exergy consumption values for different materials obtained from Refs. [8, 13]. For that reason, the mass of various materials, which make up the different components and devices, needs to be provided. The mass-specific exergy consumption values for raw material extraction and processing of different materials are given in **Table 2**.

The energy required for mining, transporting, and refining defines, among others, these raw material extraction and processing exergy consumption values. The exergy required for the extraction of materials or ores with high concentrations, compared to that of the Earth's crust, is also included in this process stage [13]. For a lot of materials, characterized by a minor weight, mass-specific exergy consumption values were not available. For that reason, an order of magnitude estimate approach deemed appropriate and was applied to those materials in order not to magnify their share to the overall exergy consumption in this particular life cycle stage [6]. Because of the low weight of many of these materials, the deviation from the true or exact raw material extraction and processing exergy consumption value is assumed to be very low, i.e., negligible [8].

*2.2.1.2 Manufacturing and assembly*

The manufacturing and assembly exergy consumption is composed of the energy required by the machinery and procedures for manufacturing and assembly purposes and the exergy contained in the resulting material waste streams. It is estimated that the waste stream for metals and plastics corresponds to 10 and 50%, respectively [13]. Mass-specific exergy consumption values for the manufacturing and assembly of metals and plastics are taken from Refs. [8, 13]. The manufacturing and assembly of printed circuit boards (PCBs), integrated circuits (ICs), and processors involves very complex and more profound energy-related techniques and procedures than those applied to metals and plastics. The exergy consumption values for the manufacturing and assembly procedures of these components are as well taken from Refs. [8, 13]. The exergy consumption expended on the manufacturing and assembly of PCBs is determined and provided on a per area basis, which is based on an average dimension assumption of PCB. The manufacturing and assembly exergy consumption of ICs is determined and provided on a per IC basis, which is based on an average dimension assumption of ICs. The manufacturing and assembly of processors relies upon highly purified silicon wafers and is accompanied by large amounts of water and chemicals. This leads further to various side product waste streams and explains, moreover, the high

Material	Specific exergy (kJ/kg)
Aluminum	341,500
Steel	52,100
Plastic	92,300
Copper	67,000
Iron	51,040
Glass	33,400
Epoxy, ceramics, and others	20,000

**Table 2.**  
*Mass-specific exergy consumption values for raw material extraction and processing [6, 14].*



quantity of this exergy consumption value. The overall manufacturing and assembly exergy consumption of a system, component, or device is composed of the exergy consumption portions of the various processes involved in its production. The exergy consumption values for the different manufacturing and assembly processes can be found in **Table 3**.

As can be seen from **Table 3**, the most complex manufacturing and assembly procedures (i.e., processes with the highest exergy consumption expenditure) are those for PCBs, ICs, and processors. For that reason, the estimation of the manufacturing and assembly exergy consumption of metals and plastics can be neglected for devices with a low mass, e.g., smartphones, tablets, power line communication (PLC) modems, and data concentrators, since the portion of the more complex processes is expected to dominate.

As these devices are, furthermore, considered to be equipped with quite a few ICs and processors (i.e., higher-exergy consumption-related components), the deviation from the true or exact exergy consumption in this particular process stage is expected to be very low.

2.2.1.3 Operation

The operational exergy consumption is composed of the operational power consumption, i.e., the electricity required to power the various ICT equipment, and the cooling exergy consumption, i.e., the electricity demanded by the cooling infrastructure, if present. The framework for the evaluation of the operational power consumption and the cooling exergy consumption will be discussed in more detail in the following two segments.

1. Power consumption of the networking equipment

The operational power consumption takes only the electric power (i.e., electricity) demanded by the system (i.e., some ICT equipment) into consideration, including the cooling requirements within the considered system, i.e., internal fans. The operational power consumption of a system, expressed in joule (J), can be calculated according to the following relation (modified from Hannemann et al. [8]):

$$Ex_{\text{operational}} = P_{\text{system, peak}} \cdot \hat{L}_{\text{system}} \cdot t_{\text{up}} \cdot t_{\text{operational}} \cdot C, \tag{15}$$

where  $P_{\text{system, peak}}$ , given in watts (W), denotes the system’s peak electricity consumption.  $\hat{L}_{\text{system}}$  represents the average load of the system during its use. It is expressed in % of the peak system load.  $t_{\text{up}}$  is the system’s daily operation time and is expressed in % of the time it is deployed.  $t_{\text{operational}}$  denotes the system’s total

Material/component (unit)	Specific exergy
Metals (kJ/kg)	0.28
Plastics (kJ/kg)	14.9
PCBs (kJ/m <sup>2</sup> )	238,400
ICs (kJ/IC)	12,500
Processors (kJ/processor)	1,242,000

*PCBs, printed circuit boards; ICs, integrated circuits.*

**Table 3.**  
Exergy consumption values for manufacturing and assembly [8, 13].

usage time, expressed in years. Finally,  $C$  represents a constant required for a correct unit conversion. It is important to mention that the operational power consumption, described by Eq. (15), takes the entire exergy that enters the considered system during its use into account. It does not depict its actual destruction. Even though the heat emitted from the system may be exploited to perform useful work (e.g., for heating purposes), most systems, however, discard this emitted heat. For that reason, Eq. (15) defines the total exergy loss (i.e., exergy consumption), which is related to the electricity consumption of the considered system.

## 2. Power consumption of the equipment for cooling

The cooling exergy consumption may represent a major part of the operational exergy consumption. It is important for the analysis of data centers, which house a large number of servers and other equipment (e.g., switches, routers). Its power consumption is defined by the electricity demanded by, e.g., the computer room air conditioning (CRAC) units, in general cooling equipment required for a data center's proper operation. According to Hannemann et al. [8], the cooling peak power consumption can be considered to be approximately proportional to the server's peak power consumption. The cooling exergy consumption, expressed in joules (J), can be calculated using the following relation (modified from Hannemann et al. [8]):

$$Ex_{\text{cooling}} = P_{\text{CRAC, peak}} \cdot [1 - \delta_{\text{dynamic}} \cdot (1 - \bar{L}_{\text{CRAC}})] \cdot t_{\text{up}} \cdot t_{\text{operational}} \cdot C. \quad (16)$$

$P_{\text{CRAC, peak}}$ , given in Watt (W), denotes the CRAC units' peak power consumption.  $\delta_{\text{dynamic}}$  denotes a binary indicator, which is used to indicate if a linear adjustment of the CRAC units' electricity consumption to that of the servers is in force, i.e., active. If it is, it is equal to one (i.e.,  $\delta_{\text{dynamic}} = 1$ ); otherwise it is zero (i.e.,  $\delta_{\text{dynamic}} = 0$ ).  $\bar{L}_{\text{CRAC}}$  represents the average CRAC load. It is expressed in % of the peak CRAC load. This factor is needed just in the case of a dynamic cooling system (i.e., for  $\delta_{\text{dynamic}} = 1$ ), where an adjustment of the cooling electricity consumption to that of the servers is in force.  $t_{\text{up}}$  corresponds to the CRAC units' daily operation time and is expressed in % of the time it is deployed.  $t_{\text{operational}}$  denotes the CRAC units' total usage time, expressed in years.  $C$  also denotes here a constant needed for a correct unit conversion [6]. Equation (16) considers also here, equivalently to Eq. (15), the entire exergy that enters the considered cooling system (e.g., CRAC units) during its use, not its actual destruction. Even though the exergy contained in the CRAC unit waste emissions may be exploited to perform useful work, this amount is considered to be negligible and will not be considered in further assessments [6].

### 2.2.1.4 Recycling and disposal

It is not an easy task to obtain the exact amount of exergy consumed during the recycling and disposal (i.e., dismantling, shredding, separating, and recovering useful materials) of a particular ICT device. The main reason for this is the fact that accurate and trustworthy information on the goods (e.g., notebooks, smartphones) delivered to the recycling plants is not available. In Hannemann et al. [8], an order of magnitude estimate approach was assumed, according to which the amount of exergy expended on the recycling of a server (relative to its mass) corresponds to approximately 520 kilo joules per kilogram (kJ/kg). This value is assumed to be reasonable and will, therefore, be used in this correspondence as the reference for the evaluation of the recycling and disposal exergy consumption of ICT equipment.

2.2.1.5 Transportation

In order to make the exergy-based life cycle assessment (E-LCA) complete, the exergy consumed during the transportation between the various life cycle stages needs to be included in the analysis as well. After raw material extraction and processing, the materials have to be transported to the manufacturing and assembly location. From there, the final products will be transported to the location where they will be operated (or used). The final stage is the transportation of used up, damaged, or outdated components and devices to recycling plants. Three different transportation stages in the life cycle of ICT equipment will be considered, and these are material transportation, product transportation, and end-of-life transportation to recycling plants. The transportation exergy consumption does not only depend merely on the mass of the materials but also on the distance between the different process stages and the transportation mode [13]. **Table 4** shows the mass (and distance)-specific exergy consumption values for the different transportation modes.

One further important fact, which concerns the provided exergy consumption values, has to be pointed out. A lot of manufactured and assembled (i.e., produced) ICT components and devices, for which diverse raw materials (e.g., aluminum, steel, plastic, copper; see also **Table 2**) need to be extracted and processed, will not be used for smart grid applications only. Therefore, the total estimated raw material extraction and processing exergy consumption are weighted by a usage factor (UF) of the considered ICT component or device. This is done with the aim not to overestimate the impact of the considered ICT component or device to the total exergy consumption in this particular life cycle stage. For the same reason, the estimated exergy consumption in the other process stages (i.e., life cycle stages) needs to be weighted by such a UF as well, including manufacturing and assembly, operation, recycling and disposal, as well as transportation. User devices (UDs) represent such devices, since smartphones, tablets, and notebooks will be used for other applications as well. In fact, they will be used for other purposes most of the time (e.g., various Internet services, telephony, mobile and video games). They will be used for home energy management purposes, e.g., in average only 2 h daily. To account for this fact, the consumption of smartphones, tablets, and notebooks will be multiplied by their respective UF, referred to as home energy management usage factor (HEMUF). The UF of home energy management systems (HEMSs), on the other hand, is accounted for through its daily uptime. Other examples of ICT equipment in the smart grid, which will be used for only a few minutes daily, are the Global System for Mobile Communications (GSM) and Universal Mobile Telecommunications System (UMTS) radio access network (RAN) components, i.e., base transceiver station (BTS), base station controller (BSC), Node B, and radio network controller (RNC) racks, as well as cables connecting these racks. These components will be multiplied by their respective UF as well, termed smart grid application usage factor (SGAUF), accounting for the time they are used for the

Mode of transportation	Specific exergy (kJ/kg km)
Air	22.41
Truck	2.096
Rail	0.253
Ship	0.296

**Table 4.** Mass (and distance)-specific exergy consumption values for different transportation modes [8, 13].

advanced metering infrastructure (AMI) smart grid application (AMI will be discussed in Section 3.1.1 in more detail). The same UF will be used for core network (CN) components, i.e., serving General Packet Radio Service (GPRS) support node (SGSN) and gateway GPRS support node (GGSN) racks, core switches, as well as cables connecting this equipment. Utility equipment (UE), i.e., smart meters, power line communication (PLC) modems, and data concentrators, will be used for the AMI smart grid application only, so their respective UF is one. The same holds for the data and control center (DCC) equipment (i.e.,  $UF = 1$ ), which manages and controls the entire electric power grid.

### 3. Sustainability analysis of ICT for smart grids

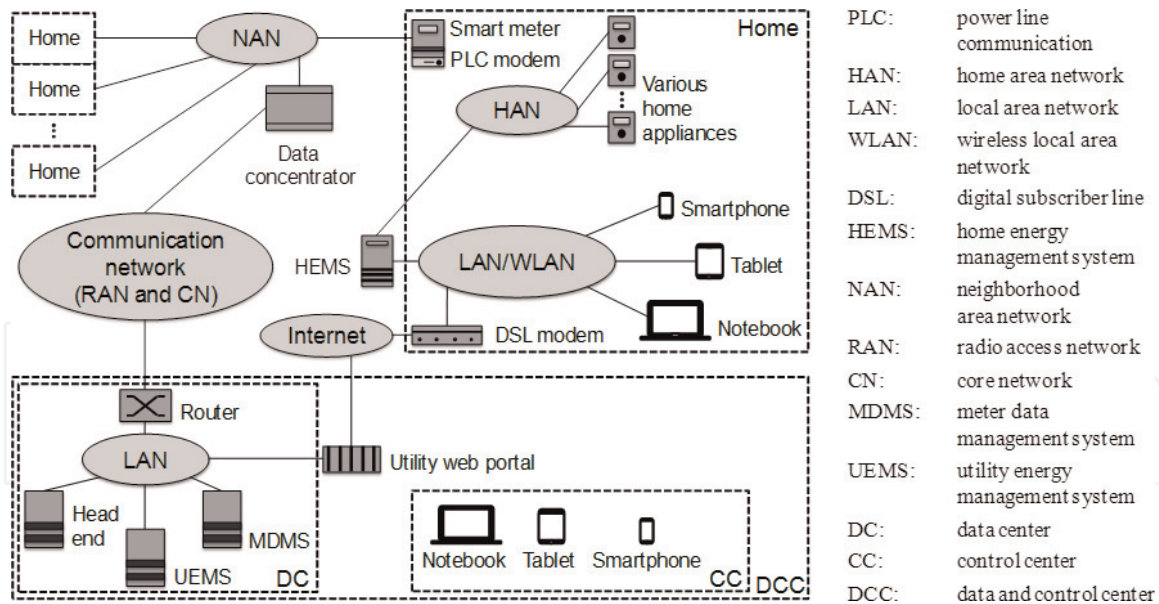
This section presents the environmental sustainability analysis of the overall system. The exergy-based life cycle assessment (E-LCA) is used as the environmental sustainability indicator of choice for the assessment and evaluation of information and communication technology (ICT) equipment, crucial for a proper operation of the advanced metering infrastructure (AMI) and home area networks (HANs). For that purpose, the overall model, developed for the environmental sustainability analysis of ICTs for smart grids, will be divided into submodels for the home area network (HAN)/building area network (BAN), neighborhood area network (NAN), radio access network (RAN), core network (CN), and the data and control center (DCC). The exergy consumption of ICT equipment deployed in the various submodels will be estimated and analyzed using the E-LCA framework. Moreover, the considered ICT equipment will be categorized into five different category groups, namely, utility equipment (UE), user devices (UDs), radio access network (RAN), core network (CN), as well as data and control center (DCC) equipment. Such an approach provides the means to indicate the most exergy consumption-related ICT equipment categories, as well as the most dominant domains of the smart grid. Based on that, ICT equipment categories and smart grid domains closely associated with environmental sustainability issues can be indicated.

#### 3.1 Description of the overall system

We present first an ICT equipment inventory required for the E-LCA of the overall system. The considered ICT equipment defines the basis for a correct and reliable functioning of the advanced metering infrastructure (AMI) and home area networks (HANs). Further, the submodels for the home area network (HAN)/building area network (BAN), neighborhood area network (NAN), radio access radio network (RAN), core network (CN), and the data and control center (DCC), as well as the ICT equipment included in these submodels, are provided. Finally, the assumptions and models required for the environmental sustainability analysis of ICT equipment involved in AMI and HANs are outlined.

The overall model, developed for the assessment of ICT equipment involved in AMI and HANs, is composed of submodels for the HAN/BAN, NAN, RAN, CN, and the DCC. This overall system is schematically depicted in **Figure 8**. The HAN/BAN equipment includes smart meters and power line communication (PLC) modems, as well as user devices (UDs) like smartphones, tablets, notebooks, digital subscriber line (DSL) modems, and home energy management systems (HEMSs), required for a proper utilization of the HAN application. The HEMS in **Figure 8** is placed out of the home, as it is assumed that the HEMS can support energy management requirements of a certain number of households (more precisely





**Figure 8.** Overall model considered for the environmental sustainability analysis of information and communication technology (ICT) equipment for smart grids (modified from Budka et al. [34]).

between 10 and 100). NAN equipment includes additionally to those of the HAN/BAN also data concentrators, required for data collection, processing, and forwarding purposes, and represents a very essential component of the smart grid. RAN equipment includes the Global System for Mobile Communications (GSM) and Universal Mobile Telecommunications System (UMTS) equipment, i.e., base transceiver station (BTS), base station controller (BSC), Node B, and radio network controller (RNC) racks. The CN comprises serving General Packet Radio Service (GPRS) support node (SGSN) and gateway GPRS support node (GGSN) racks, as well as core switches. Copper and optical fiber cables, required to link RAN and CN equipment, are included in the overall system as well. The DCC comprises not only servers (including cooling exergy consumption), switches (i.e., core, aggregation, and rack/edge switches), routers, modems, and cables but also notebooks, tablets, and smartphones, which represent an important part of the control center (CC). Such a holistic approach allows us to obtain more meaningful conclusions on the environmental sustainability of ICT equipment associated with the advanced metering infrastructure (AMI) and home area networks (HANs). Lifetime assumptions of the ICT equipment deployed in the RAN, CN, as well as the DCC are provided in **Table 5**.

These lifetime characteristics are assumed to be fixed during the E-LCA of the overall system. The ICT equipment lifetime listed in **Table 5** is, moreover, weighted by its respective usage factor (UF), termed smart grid application usage factor (SGAUF), accounting for the time it is used for the AMI and HAN smart grid applications. The listed ICT equipment lifetime assumptions are partly based on analytical conclusions as well as the information provided in Refs. [32, 35]. Lifetime assumptions as well as various other parameter assumptions of utility equipment (UE) and user devices (UDs) will be provided in the respective scenario considered.

### 3.1.1 Models for AMI and HANs

The advanced metering infrastructure (AMI) represents the basic infrastructure of the future smart grid. It includes smart meters, PLC modems, data concentrators, and DCC equipment, as well as communication network equipment, i.e., RAN and CN equipment (see **Figure 8**). It is assumed that the smart meter measurements are

ICT equipment	ICT equipment category group	Lifetime (years)
BTS rack	RAN	7
BSC rack	RAN	8
Node B rack	RAN	8
RNC rack	RAN	9
SGSN rack	CN	10
GGSN rack	CN	10
Core switch	CN/DCC	3
Aggregation switch	DCC	3
Rack/edge switch	DCC	3
Server	DCC	4
Notebook (15-inch)	DCC	3
Notebook (13-inch)	DCC	3
Tablet	DCC	2
Smartphone	DCC	2
Router	DCC	3
DSL modem	DCC	3
Cat5e cable	RAN/CN/DCC	>20
Optical fiber cable	RAN/CN/DCC	>20

*BTS, base transceiver station; BSC, base station controller; Node B, Universal Mobile Telecommunications System (UMTS) base station; RNC, radio network controller; SGSN, serving General Packet Radio Service (GPRS) support node; GGSN, gateway GPRS support node; DSL, digital subscriber line.*

**Table 5.**  
*Lifetime assumptions of ICT equipment deployed in the radio access network (RAN), core network (CN), and the data and control center (DCC) (based on analytical conclusions and [32, 35]).*

delivered to the data concentrator by means of the PLC technology. The forwarding of data from the data concentrator toward the DCC is accomplished by means of cellular mobile communication systems, i.e., GSM and UMTS, for further evaluation and processing purposes. AMI is expected to bring a huge number of advantages with it, like increased reliability and energy efficiency, as well as a thorough insight into the condition of the entire smart grid. This will provide the staff at the DCC with advanced management and monitoring opportunities and enable important remote control functions essential in the course of unusual or unexpected events [34].

The home area networks (HANs) considered here can be seen as an enhancement of the advanced metering infrastructure (AMI). They extend the smart grid idea into the home and enable important home energy management functions. The HAN is used to link various consumer appliances with the home energy management system (HEMS) by means of PLC or, e.g., a low-rate wireless personal area network (LR-WPAN) communication technology like ZigBee. The communication technology deployed will highly depend on the location of the HEMS, i.e., the distance between the HEMS and the various monitored and managed consumer appliances. UD, i.e., smartphones, tablets, notebooks, DSL modems, and HEMSs, provide users with real-time electricity consumption information by means of a local area network (LAN) and/or wireless local area network (WLAN). This gives them the opportunity to see where and when their electricity consumption is at its

peak, providing a way to cut down electricity bills. The link between the HEMS and the utility energy management system (UEMS) is achieved by means of the Internet and the utility web portal [34].

### **3.2 Description of the scenarios**

This section considers various scenarios defined for the environmental sustainability assessment of ICT equipment involved in AMI and HANs. Different assumptions and parameter alterations are defined with the aim to gain more insight into the distribution and development of the ICT equipment exergy consumption. Based on that, meaningful and useful conclusions on the environmental sustainability of the ICT equipment are provided.

The presented scenarios are based on a model developed for the city of Vienna. The embodied exergy consumption (EEC) and operational exergy consumption (OEC) are assessed over a time period from 2020 to 2040, i.e., an operational duration of 20 years is considered. The main assumption is that by the year 2020, the city of Vienna will be equipped with appropriate smart metering, data processing, and forwarding equipment (i.e., smart meters, PLC modems, and data concentrators), required for a correct operation of the AMI application [46]. The equipment needed for an appropriate functioning of the HAN application, e.g., smartphones, tablets, notebooks, digital subscriber line (DSL) modems, and personal computer (PC) towers, is already in existence and widely utilized for various other purposes in almost every (if not every) household. These devices may as well be utilized for a multitude of different home energy management applications in connection with the smart grid concept. The PC tower, for example, may provide the functionality of a home energy management system (HEMS). For that purpose, adequate software programs would be required. Here, however, the HEMS is assumed to be implemented in the form of a server, which is able to support energy management applications of more than one household. The HEMS will most likely be placed with many others near a few houses and/or buildings and will be responsible for the energy management of their various households. This HEMS service could be offered by, e.g., some third-party service provider. It is further assumed that in 2020 only 20% of all households in Vienna will make use of HANs. This percentage is, moreover, assumed to grow to 80% in 2040, as it is expected that not all consumers will agree to deploy HANs in their households. Smartphones, tablets, and notebooks could be equipped with suitable mobile applications and software programs as well, enabling users to visualize their electricity consumption. This would, moreover, lead to an increased energy consumption awareness and enable a greater involvement of consumers in the smart grid concept.

Information on the number of households in Vienna, their expected development, as well as the average number of persons per household is obtained from Statistics Austria. The number of households in Vienna is expected to increase from 927,905 in 2020 to 1,027,846 in 2040 [36]. This corresponds to a yearly average household increase of 4997.05 households. The average number of persons per household during this time period is assumed to be equal to 2. Based on this (and the assumptions regarding the development of HANs between 2020 and 2040 described above), the average yearly increase of households that make use of HANs between 2020 and 2040 is estimated to be approximately equal to 31,834.8. That is, the number of households that deploy HANs will increase from 185,581 in 2020 to 822,277 in 2040. The total traveled distance of extracted and processed raw materials to their manufacturing and assembly location in Shenzhen, Guangdong, in China, is assumed to be equal to 5000 km. From there, the final products are transported over Shanghai, China, and Hamburg, Germany, to the location where



they will be deployed, namely, to Vienna, Austria. The total traveled distance of these products was estimated to be equal to 22,403 km. For the end-of-life transportation, a recycling plant in Berlin, Germany, is assumed. The total traveled distance of used up, damaged, and outdated ICT equipment to this location was estimated to be equal to 675 km. The provided distances between the different ICT equipment life cycle stages (i.e., raw material extraction and processing, manufacturing and assembly, operation, recycling and disposal) were estimated by means of the Google Maps route planner. Moreover, various transportation modes (i.e., truck, rail, and ship) between these different locations are considered.

Exergy consumption data of utility equipment (UE), i.e., smart meters, PLC modems, and data concentrators, as well as user devices (UDs), i.e., smartphones, tablets, notebooks (13-inch), and HEMSs, was presented and analyzed in Refs. [37, 38]. The estimation of the exergy consumption of the Apple 15-inch MacBook Pro with Retina Display (w/RD) notebook was based on analytical conclusions as well as the data and information provided in Refs. [39–41]. Exergy consumption data of RAN and CN equipment (including copper and optical fiber cables), as well as that of routers and switches (i.e., rack/edge, aggregation, and core switches), was obtained from Refs. [25, 32, 33]. Network configuration parameters of RAN and CN equipment were based on the data and information provided in Refs. [25, 35]. The evaluation of the exergy consumption of the DSL modem was based on an analytical analysis as well as the information provided in Refs. [42, 43]. Exergy consumption data of the server was based on the data provided in Refs. [8, 13]. The lifetime of BTS and BSC racks is assumed to be equal to 7 and 8 years, respectively, and that of Node B and RNC racks to 8 and 9 years, in that order. The lifetime of both the SGSN and GGSN racks is assumed to be equal to 10 years. The lifetime of DCC routers, CN/DCC switches, and DCC DSL modems is assumed to be equal to 3 years (see also **Table 5**). Data on technology penetration was based on the information obtained from Statistics Austria as well as the forecasts provided in Safaei [32].

### *3.2.1 Scenario 1: deployment of AMI*

This scenario analyzes the environmental sustainability of ICT equipment involved in the advanced metering infrastructure (AMI). The first part of this scenario, i.e., Scenario 1.a, investigates how different utility equipment (UE) lifetime assumptions influence the cumulative embodied exergy consumption (EEC) of the overall model developed for the city of Vienna, over an operational duration of 20 years. The second part of this scenario, i.e., Scenario 1.b, analyzes how the number of smart meters connected to a data concentrator impacts both the cumulative EEC and operational exergy consumption (OEC).

#### *3.2.1.1 Scenario 1a: influence of the utility equipment (UE) lifetime*

As the customer and distribution domains of the smart grid will be equipped with a huge number of utility equipment (UE), namely, smart meters, power line communication (PLC) modems, and data concentrators, the means to gain insight into the exergy consumption of this equipment in connection with different lifetime assumptions would prove beneficial. For that purpose, three different use cases (UCs) are defined which assume different lifetimes of the considered UE. The assumptions for these three UCs are listed in **Table 6**.

UC 1 assumes a short lifetime of UE, i.e., smart meters and PLC modems are replaced every 5 years, and the data concentrator even every 3 years. UC 2 and UC 3, on the other hand, assume a longer lifetime of UE. UC 2 defines, moreover, the



UC	UE lifetime (years)		
	Smart meter	PLC modem	Data concentrator
UC 1: short lifetime	5	5	3
UC 2: medium lifetime	15	10	7
UC 3: long lifetime	20	15	10

PLC, power line communication.

**Table 6.**  
Use case (UC) assumptions for the utility equipment (UE) lifetime.

UC	Number of smart meters per DC
UC 1: 150 smart meters per DC	150
UC 2: 2000 smart meters per DC	2000

**Table 7.**  
Use case (UC) assumptions for different data concentrator (DC) configurations.

basis for Scenario 1.b, which analyzes how the number of smart meters that can be served by a single data concentrator influences the cumulative embodied and operational exergy consumption. It should be noted that the assumed number of smart meters connected to a data concentrator for the present Scenario 1.a equals to 150, which corresponds to the number provided by UC 1 of the following Scenario 1.b (see also UC 1 in **Table 7**). Information on the amount of data traffic per data concentrator, required for the assessment of AMI, was obtained from Luan et al. [44].

3.2.1.2 Scenario 1b: influence of the data concentrator (DC) configuration

The number of smart meters that can be served by a data concentrator can be very high. Up to 2000 smart meters can be linked to a single data concentrator [45]. The present scenario analyzes how the number of smart meters connected to a data concentrator relates to the distribution and development of the cumulative embodied exergy consumption (EEC) and operational exergy consumption (OEC) of the overall system. Two use cases (UCs) with different assumed numbers of smart meters linked to a data concentrator are considered. **Table 7** provides the assumptions for these two UCs. This scenario is based on UC 2 of Scenario 1.a, according to which the lifetime of smart meters, PLC modems, and data concentrators equals to 15, 10, and 7 years, respectively (see also UC 2 in **Table 6**).

UC 1 assumes that 150 smart meters are linked to a data concentrator, whereas UC 2, with 2000 smart meters per data concentrator, represents the upper limit. This scenario will give more insight into the cumulative EEC and OEC in the case of these two UCs. Moreover, UC 1 of the present Scenario 1.b (with 150 smart meters per data concentrator) defines the basis for Scenario 2 described in the following subsection.

3.2.2 Scenario 2: deployment of AMI and HANs

This scenario assesses the environmental sustainability of ICT equipment involved in both the advanced metering infrastructure (AMI) and home area networks (HANs). The first part of this scenario, i.e., Scenario 2.a, analyzes how different lifetimes of utility equipment (UE) as well as user devices (UDs) influence the cumulative embodied exergy consumption (EEC) of the overall system.

Scenario 2.b, on the other hand, investigates how various parameter alterations, e.g., daily charging durations and home energy management usage factors (HEMUFs) of smartphones, tablets, and notebooks, as well as daily uptimes and average loads of home energy management systems (HEMSs), influence the cumulative EEC and operational exergy consumption (OEC) of the overall system. The assumed parameters of these UD define, thereby, the utilization intensity of HANs. Finally, Scenario 2.c analyzes how the number of households that can be served by a single HEMS, i.e., its configuration, influences the total cumulative exergy consumption of the overall system.

3.2.2.1 Scenario 2.a: influence of the devices’ lifetime

The present scenario can be seen as the enhancement of Scenario 1.a, as it considers additionally to utility equipment (UE) also user devices (UDs), i.e., smartphones, tablets, notebooks, home energy management systems (HEMSs), and digital subscriber line (DSL) modems, essential for a proper and easy utilization of home area networks (HANs). As in the case of Scenario 1.a, three use cases (UCs) are defined, which assume different lifetimes of the considered UD. Each UC of Scenario 2.a is, moreover, related to the respective UC of Scenario 1.a. This can be seen in **Table 8**, which provides the assumed lifetimes for both the UD and UE for the three considered UCs.

The first UC assumes a short lifetime of UD as well as UE. UC 2 defines the most probable case considering the lifetimes of UD and UE. UC 3 assumes an extended lifetime for both the UD and UE, i.e., their replacement period is longer than that of the first two UCs. Based on these UCs, more information on the exergy consumption distribution and its development will be provided. UC 2 defines, moreover, the basis for Scenario 2.b as well as Scenario 2.c, which assess how different UD’s parameters, e.g., daily charging durations and home energy management usage factors (HEMUFs) of smartphones, tablets, and notebooks, daily uptimes and average loads of HEMSs, as well as HEMS configurations, influence the cumulative embodied and operational exergy consumption. It should be noted that the assumed daily charging durations and HEMUFs of smartphones, tablets, and notebooks, daily uptimes and average loads of HEMSs, as well as HEMS configurations for the present Scenario 2.a correspond to those of UC 2 of Scenario 2.b as well as Scenario 2.c discussed in the following two parts of this subsection.

UC	Lifetime of the user devices (UDs) (years)				
	Smartphone	Tablet	Notebook	HEMS	DSL modem
UC 1: short lifetime	1	1	2	2	3
UC 2: medium lifetime	2	2	3	4	5
UC 3: long lifetime	4	4	6	6	10
UC	Lifetime of utility equipment (UE) (years)				
	Smart meter	PLC modem		Data concentrator	
UC 1: short lifetime	5	5		3	
UC 2: medium lifetime	15	10		7	
UC 3: long lifetime	20	15		10	

HEMS, home energy management system; DSL, digital subscriber line; PLC, power line communication.

**Table 8.**  
Use case (UC) assumptions for the user devices (UDs) and utility equipment (UE) lifetime.

3.2.2.2 Scenario 2.b: influence of the home area network (HAN) utilization

This scenario analyzes how different daily charging durations and home energy management usage factors (HEMUFs) of smartphones, tablets, and notebooks, as well as daily uptimes and average loads of home energy management systems (HEMSs), influence the exergy consumption of the overall system. For that purpose, three use cases (UCs) are defined which assume different utilization intensities of home area networks (HANs). The assumed daily charging durations and HEMUFs of smartphones, tablets, and notebooks, as well as the daily uptimes and average loads of HEMSs for these three UCs, are provided in **Tables 9–11**. This scenario is based on UC 2 of Scenario 2.a, according to which the lifetime of smartphones tablets, notebooks, HEMSs, and DSL modems equals to 2, 2, 3, 4, and 5 years, respectively, and that of smart meters, PLC modems, and data concentrators to 15, 10, and 7 years.

UC 1 corresponds to a high utilization of HANs, which is associated with longer smartphone, tablet, and notebook daily charging durations and higher HEMUFs, as well as a higher average HEMS load. UC 3, on the other hand, is associated with a low utilization of HANs. UC 2 represents the most probable usage pattern of HANs. Moreover, UC 2 of the present scenario defines the basis for Scenario 2.c described in the following part of this subsection. The daily uptime of HEMSs and DSL modems is set to 100% (i.e., 24 h) for all three UCs, however, with varying average loads (see **Table 11**). Further, the average load of the DSL modem is assumed to be proportional to that of the HEMS for all the three considered UCs. It is important to

UC	Daily charging duration (h)		
	Smartphone	Tablet	Notebook
UC 1: high utilization	4	4	6
UC 2: medium utilization	2	2	3
UC 3: low utilization	1	1	2

**Table 9.**  
Use case (UC) assumptions for daily charging duration.

UC	HEMUF (h)			Daily uptime (%)	
	Smartphone	Tablet	Notebook	HEMS	DSL modem
UC 1: high utilization	4	4	4	100	100
UC 2: medium utilization	2	2	2	100	100
UC 3: low utilization	1	1	1	100	100

**Table 10.**  
Use case (UC) assumptions for the home energy management usage factor (HEMUF) as well as HEMS and DSL modem daily uptime.

UC	Average HEMS load (%)
UC 1: high utilization	80
UC 2: medium utilization	50
UC 3: low utilization	20

**Table 11.**  
Use case (UC) assumptions for the average home energy management system (HEMS) load.

UC	Number of households per HEMS
UC 1: 10 households per HEMS	10
UC 2: 20 households per HEMS	20
UC 3: 100 households per HEMS	100

**Table 12.**  
*Use case (UC) assumptions for different home energy management system (HEMS) configurations.*

mention that the assumed number of households that can be served by a single HEMS for the present Scenario 2.b equals to 20 households, which corresponds to the number provided by UC 2 of the following Scenario 2.c (see also UC 2 in **Table 12**).

3.2.2.3 Scenario 2.c: influence of the configuration of the home energy management system (HEMS)

The last scenario analyzes how the number of households that can be served by a single home energy management system (HEMS) influences the cumulative embodied exergy consumption (EEC) and operational exergy consumption (OEC) of the overall system. As already mentioned several times across this chapter, the HEMS is assumed to be implemented in the form of a 2-unit (2 U) rack-mounted server, which is placed at a convenient location near the various homes and/or buildings it is responsible for to manage. Moreover, the HEMS is considered to be equipped with all the necessary software programs required for a correct and reliable functioning of home energy management applications, i.e., home area networks (HANs). Three different use cases (UCs) are considered which assume different HEMS configurations, i.e., numbers of households it can serve. The assumptions for this three UCs are provided in **Table 12**. This scenario is based on UC 2 of Scenario 2.a as well as Scenario 2.b, which assume a medium lifetime of user devices (UDs) and utility equipment (UE), as well as a medium utilization intensity of HANs.

UC 1 and UC 2 assume that the HEMS can support home energy management applications of 10 and 20 households, respectively. UC 3, on the other hand, assumes that 100 households can be served by a single HEMS. Based on this scenario, more information on the cumulative EEC and OEC for the three defined UCs will be provided. This provides, moreover, means to indicate the most exergy consumption-related category in the case of these three UCs, i.e., whether the EEC or OEC dominates over the considered operational duration of 20 years.

4. Major findings of the E-LCA study

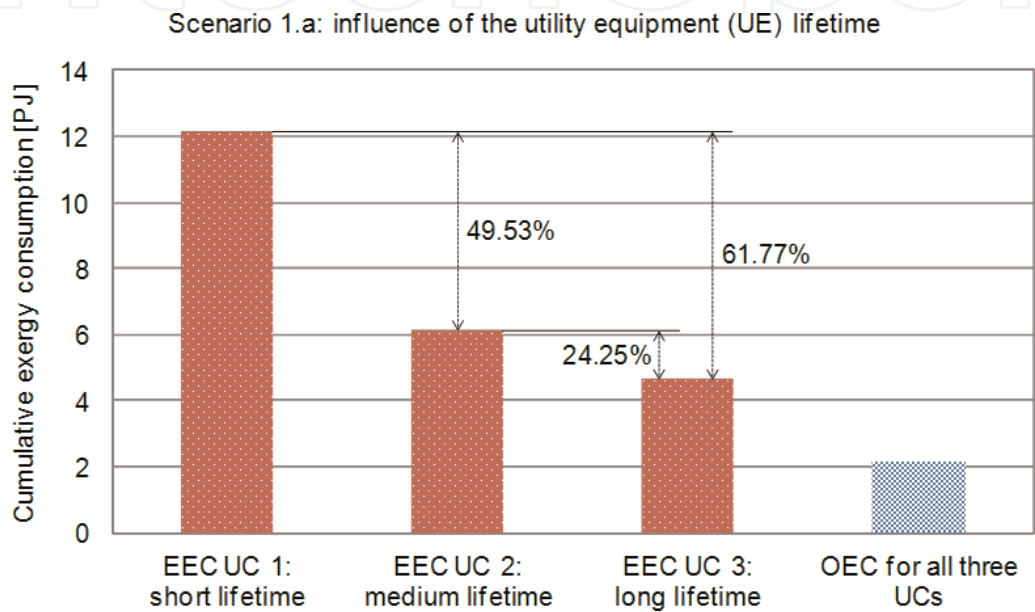
It can be argued that for all of the considered scenarios, the customer and distribution domains are the most exergy-consuming domains. For that reason, they have the highest potential to negatively impact the environment, i.e., they are closely associated with environmental sustainability issues.

Considering only the advanced metering infrastructure (AMI) scenarios (i.e., Scenarios 1.a and 1.b), the utility equipment (UE) was ascertained to be the ICT equipment category group related to the highest cumulative embodied exergy consumption (EEC) as well as operational exergy consumption (OEC). The contribution of the data and control center (DCC) equipment to the total cumulative OEC was determined to be relatively high (i.e., about 20%), taking into account that the

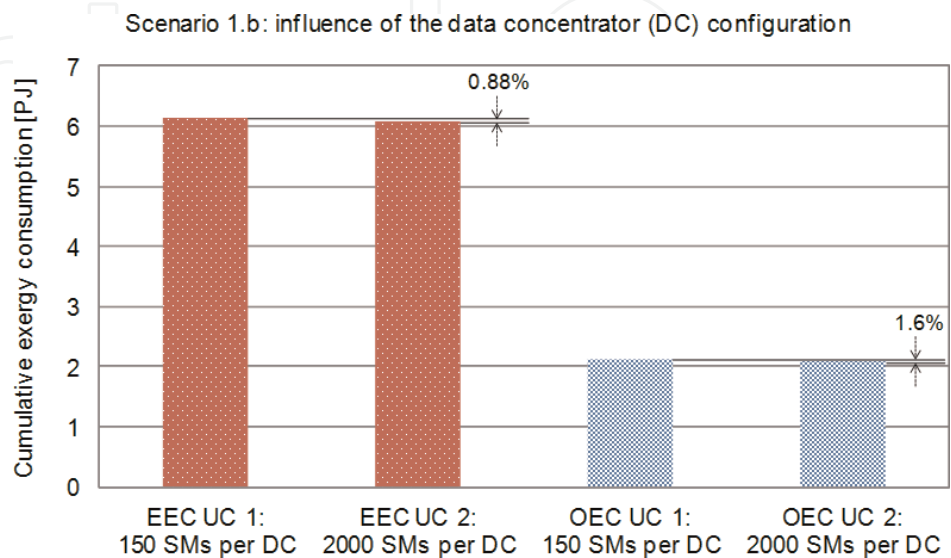


number of DCC equipment is much less than that of UE. The cumulative EEC of the DCC equipment was ascertained to be around 1% and is for that reason almost negligible. The contribution of radio access network (RAN) and core network (CN) equipment to the total cumulative EEC and OEC turned out to be very low compared to that of the UE and DCC equipment (i.e., lower than 1%). Such a low contribution of RAN and CN equipment to the total cumulative exergy consumption of the overall system arises from the fact that it is used relatively shortly for AMI throughout the day, i.e., for only a few minutes daily.

**Figures 9 and 10** depict the share of the embodied exergy consumption (EEC) and operational exergy consumption (OEC) to the total cumulative exergy consumption of the overall system for the Scenarios 1.a and 1.b, respectively, at the end



**Figure 9.** Distribution of the cumulative embodied exergy consumption (EEC) and operational exergy consumption (OEC) of Scenario 1.a for the three defined use cases (UCs) with different utility equipment (UE) lifetimes, after an operational duration of 20 years.



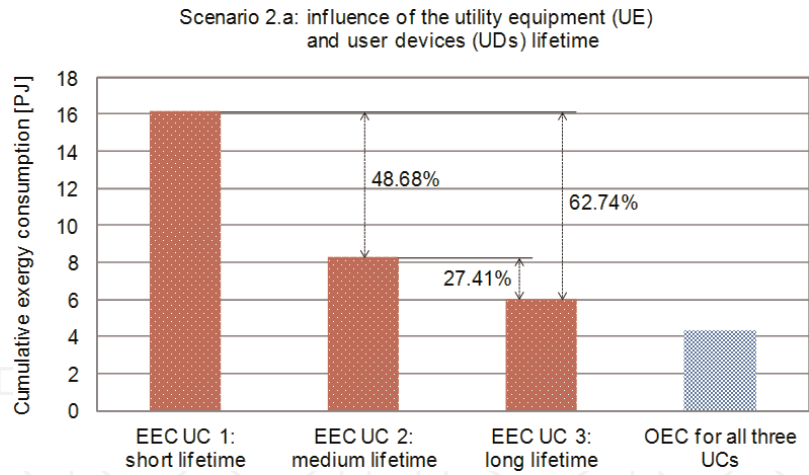
**Figure 10.** Distribution of the cumulative embodied exergy consumption (EEC) and operational exergy consumption (OEC) of Scenario 1.b for the two defined use cases (UCs) with different numbers of smart meters (SMs) per data concentrator (DC), after an operational duration of 20 years.

of the operational duration of 20 years. As can be seen from **Figure 9**, the cumulative EEC differs significantly for different utility equipment (UE) lifetimes. The cumulative OEC is the same for all the three use cases (UCs) and is, moreover, lower than their cumulative EEC. A longer UE lifetime decreases considerably the cumulative EEC (see the provided percentages in **Figure 9**). A reduction of up to about 61.77% at the end of the operational duration of 20 years is possible, if the lifetime of smart meters, power line communication (PLC) modems, and data concentrators is extended to 20, 15, and 10 years (i.e., UC 3), respectively, in contrast to 5, 5, and 3 years (i.e., UC 1). Extending the lifetime of smart meters, PLC modems, and data concentrators to 15, 10, and 7 years (i.e., UC 2), respectively, reduces the cumulative EEC by about 49.53% compared to UC 1. Moreover, the difference between the cumulative EEC of UC 2 and UC 3 at the end of the operational duration of 20 years corresponds to approximately 24.25%.

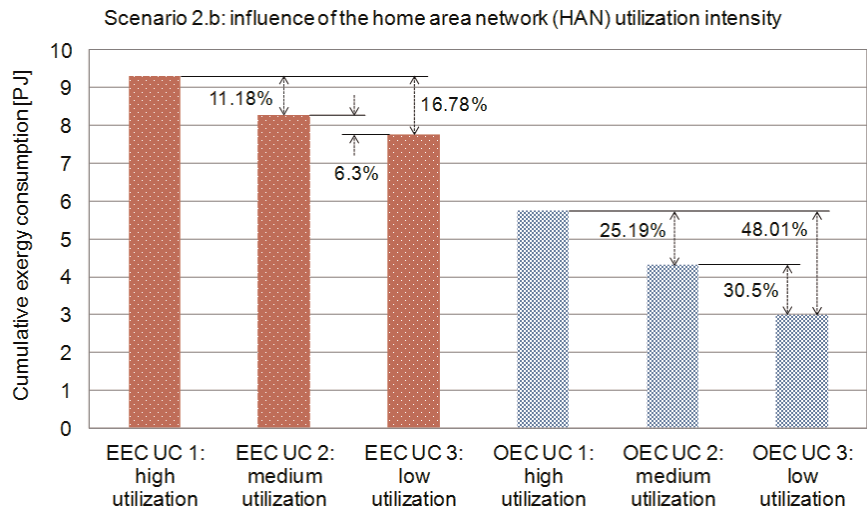
From **Figure 10** it is evident that the number of smart meters (SMs) that can be served by a single data concentrator (DC) does not have a strong impact on the cumulative EEC as well as OEC. The difference between the cumulative EEC of UC 1 (which assumes that 150 smart meters are linked to a data concentrator) and UC 2 (which assumes 2000 smart meters per data concentrator) corresponds to approximately 0.88%, which is not that high. The difference between the cumulative OEC of these two UCs is not that large as well and equals to about 1.6%. It can be concluded that the number of smart meters connected to a data concentrator does not have a large influence on the cumulative EEC and OEC of the overall system. The impact of the UE lifetime has a much stronger impact on the total cumulative exergy consumption of the overall system (see the percentages provided in **Figure 9**).

In the case of the advanced metering infrastructure (AMI) and home area network (HAN) scenarios (i.e., Scenarios 2.a–2.c), the utility equipment (UE) was determined to be the ICT equipment category group with the highest share to the cumulative embodied exergy consumption (EEC). The user devices (UDs) were ascertained to be the next largest contributor to the overall cumulative EEC. The assessment of the cumulative operational exergy consumption (OEC), however, revealed a large dependence on the utilization intensity of HANs. That is, for a high and medium utilization intensity of HANs, it was shown that the UE represents the most dominant ICT equipment category group until a certain time point, from where on the UD becomes the ICT equipment category group with the highest exergy expenditure and with that the category group closely linked to environmental sustainability issues. For a low utilization intensity of HANs, however, the UE turned out to be the ICT equipment category group with the highest contribution to the cumulative OEC over the entire operational duration of 20 years. In this case, it is the UE that is closely associated with increased environmental sustainability issues. The share of radio access network (RAN) and core network (CN) equipment to the total cumulative exergy consumption of the overall system was determined to be less dominant for all the three considered scenarios, as this equipment is utilized for AMI for only a few minutes daily. Therefore, it can be argued that the RAN and CN equipment is associated with lower environmental sustainability issues. The contribution of the data and control center (DCC) equipment to the total cumulative exergy consumption of the overall system turned out to be larger than that of the RAN and CN equipment, but lower than that of the UE and UD.

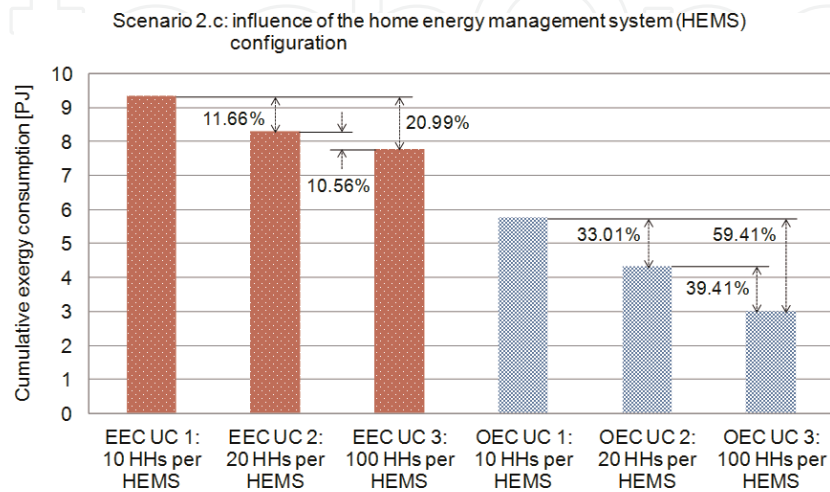
**Figures 11–13** provide the distribution of the cumulative embodied exergy consumption (EEC) and operational exergy consumption (OEC) to the total cumulative exergy consumption of the overall system for Scenarios 2.a–2.c, respectively, after the operational duration of 20 years.



**Figure 11.** Distribution of the cumulative embodied exergy consumption (EEC) and operational exergy consumption (OEC) of Scenario 2.a for the three defined use cases (UCs) with different utility equipment (UE) and user device (UD) lifetimes, after an operational duration of 20 years.



**Figure 12.** Distribution of the cumulative embodied exergy consumption (EEC) and operational exergy consumption (OEC) of Scenario 2.b for the three defined use cases (UCs) with different home area network (HAN) utilization intensities, after an operational duration of 20 years.



**Figure 13.** Distribution of the cumulative embodied exergy consumption (EEC) and operational exergy consumption (OEC) of Scenario 2.c for the three defined use cases (UCs) with different numbers of households (HHs) per home energy management system (HEMS), after an operational duration of 20 years.

From **Figure 11** it is clear that an increased lifetime of user devices (UDs) and utility equipment (UE) leads to a significant reduction of the cumulative EEC of the overall system, at the end of the operational duration of 20 years. Moreover, the cumulative OEC is the same for all three use cases (UCs) and turns out to be lower than the cumulative EEC for all the three considered UCs. A decrease of about 48.68% can be achieved if the short lifetime of UD and UE (i.e., UC 1) is extended to a medium lifetime (i.e., UC 2). Extending the lifetime of UD and UE further (i.e., UC 3), an even larger cumulative EEC reduction of about 62.74% becomes possible. Furthermore, the cumulative EEC difference between UC 2 and UC 3 corresponds to approximately 27.41%.

As can be seen from **Figure 12**, an increased utilization intensity of home area networks (HANs) leads to a significant increase of the cumulative EEC but even more notably the cumulative OEC. Nevertheless, the cumulative OEC is lower than the cumulative EEC in the case of all the three considered use cases (UCs). The cumulative EEC difference between the high and medium utilization intensities of HANs (i.e., UC 1 and UC 2) equals to about 11.18%. Comparing UC 1 and UC 3 (i.e., low utilization of HANs) provides a cumulative EEC difference of approximately 16.78%. Moreover, the cumulative EEC difference between UC 2 and UC 3 equals to about 6.3%. From **Figure 12** it is also obvious that the usage pattern of HANs has a much higher impact on the cumulative OEC than on the cumulative EEC. The difference between the high and medium utilization of HANs (i.e., UC 1 and UC 2) shows an approximately 25.19% difference of the cumulative OEC, at the end of the operational duration of 20 years. The difference of the cumulative OEC between UC 1 and UC 3 (which assumes a low utilization of HANs) is even more pronounced and corresponds to about 48.01%. Furthermore, a comparison of the cumulative OEC between UC 2 and UC 3 exhibits a difference of approximately 30.5%. Such a large cumulative OEC difference between the three considered UCs is mainly associated with the different average home energy management system (HEMS) loads assumed for each of these UCs (see also **Table 11**). That is, an increased HAN usage pattern is related to higher average HEMS loads and leads therefore to an increase of the cumulative OEC. The contributions of the daily charging durations as well as the respective home energy management usage factors (HEMUFs) of smartphones, tablets, and notebooks have a minor impact on the total cumulative OEC of the overall system compared to that of the average HEMS load.

From **Figure 13** it is obvious that the number of households (HHs) that can be served by a single home energy management system (HEMS), i.e., its configuration, has a large impact on the cumulative EEC as well as OEC of the overall system. Moreover, the cumulative OEC is ascertained to be lower than the cumulative EEC for all the three considered use cases (UCs). A cumulative EEC reduction of about 11.66% can be achieved if 20 households are linked to a single HEMS (i.e., UC 2) instead of 10 households (i.e., UC 1). Increasing the number of households from 10 (i.e., UC 1) to 100 (i.e., UC 3) leads to an even larger cumulative EEC reduction of approximately 20.99%. Furthermore, the difference between the cumulative EEC of UC 2 and UC 3 equals to about 10.56%. Taking a look at **Figure 13**, it can be seen that the HEMS configuration has also a considerable, and an even larger, impact on the cumulative OEC of the overall system. The difference between the cumulative OEC of UC 1 and UC 2 (i.e., for 10 and 20 households per HEMS, respectively) amounts approximately to 33.01%. If the number of households that can be managed by a single HEMS is increased from 10 to 100, the cumulative OEC difference becomes even larger and amounts about 59.41%. Moreover, a cumulative OEC reduction of approximately 39.41% can be attained if 100 households are managed by a single HEMS instead of 20.



## 5. Conclusions

The exergy-based life cycle assessment (E-LCA) of utility equipment (UE), i.e., smart meters, power line communication (PLC) modems, and data concentrators, revealed that the lifetime embodied exergy consumption (EEC) represents the most exergy consumption-related category. Based on that, it can be argued that the lifetime EEC is the exergy consumption category closely associated with environmental sustainability issues. The lifetime operational exergy consumption (OEC) was ascertained to have a much lower impact on the environment. Furthermore, the manufacturing and assembly stage turned out to be the most dominant life cycle stage in the case of the considered UE. The processor was additionally ascertained to be the most exergy consumption-related UE component.

Similar to the results for the utility equipment, the analysis has shown that also for user devices such as smartphones, tablets, and notebooks the most exergy-consumption related category is the embodied exergy consumption (EEC). In particular, the manufacturing and assembly stages turned out to be the most dominant life cycle stage in the case of these user devices (UDs). The processor was also here ascertained to be the most exergy consumption-related component. Just as in the case of the UE, the lifetime operational exergy consumption (OEC) of the smartphone, tablet, and notebook was determined to be the exergy consumption category associated with lower (i.e., almost negligible) environmental sustainability issues, when compared to the lifetime EEC of these devices. However, the E-LCA of the home energy management system (HEMS) revealed that the lifetime OEC represents the most exergy consumption-related category, i.e., the category closely associated with environmental sustainability issues.

The exergy-based life cycle assessment (E-LCA) of the overall model developed for the city of Vienna revealed that the customer and distribution domains are the most exergy consumption-related domains, i.e., these domains are closely linked to environmental sustainability issues. Scenarios considering only the advanced metering infrastructure (AMI) ascertained the utility equipment (UE) as the ICT equipment category group leading to the highest cumulative embodied exergy consumption (EEC) as well as operational exergy consumption (OEC). The share of the data and control center (DCC) equipment to the total cumulative OEC was determined to be relatively high (i.e., about 20%), considering the much lower number of DCC equipment compared to that of the UE. The share of radio access network (RAN) and core network (CN) equipment to the total cumulative exergy consumption of the overall system was ascertained to have a much lower impact on the environment than the UE and DCC equipment. The reason for such a low contribution of RAN and CN equipment to the overall cumulative exergy consumption arises from the fact that it is used relatively shortly for the AMI application throughout the day. Moreover, the cumulative EEC was ascertained to be the most exergy consumption-related category over the entire operational duration of 20 years. For that reason, it is associated with increased environmental sustainability issues. It was shown that an increase of the UE lifetime has a strong impact on the cumulative EEC. Increasing the lifetime of smart meters, power line communication (PLC) modems, and data concentrators from 5, 5, and 3 years, respectively, to 15, 10, and 7 years, in that order, results at the end of the operational duration of 20 years in a cumulative EEC reduction of about 49.53%. A cumulative EEC decrease of approximately 61.77% is possible if the smart meter, PLC modem, and data concentrator are replaced every 20, 15, and 10 years, respectively, instead of every 5, 5, and 3 years. Moreover, it was shown that the number of smart meters that can be served by a single data concentrator does not have a strong impact on the total cumulative exergy consumption of the overall system. A reduction of the

cumulative EEC of approximately 0.88% after the operational duration of 20 years can be attained if 2000 smart meters are linked to a data concentrator instead of 150. The reduction of the cumulative OEC for these two different data concentrator configurations is not that large as well and corresponds to about 1.6%.

The exergy-based life cycle assessment (E-LCA) of the advanced metering infrastructure (AMI) and home area network (HAN) scenarios ascertained the utility equipment (UE) as the ICT equipment category group with the largest contribution to the cumulative embodied exergy consumption (EEC). The user devices (UDs) were determined to be the next largest contributor to the total cumulative EEC of the overall system. However, the analysis and evaluation of the cumulative operational exergy consumption (OEC) showed that the HAN utilization intensity determines which ICT equipment category group is the most dominant one. It turned out that for a high and medium HAN utilization intensity, the UE contributes the most to the cumulative OEC until a specific time point, from where on the UD becomes the most dominant ICT equipment category group, i.e., the category group closely associated with increased environmental sustainability issues. For a low utilization intensity of HANs, the UE was ascertained to be the ICT equipment category group with the highest contribution to the cumulative OEC over the entire operational duration of 20 years, i.e., the category group closely related to environmental sustainability issues. The contribution of radio access network (RAN) and core network (CN) equipment to the overall cumulative exergy consumption was determined to be less dominant. This result is based on the fact that this equipment is utilized for AMI for merely a few minutes daily. For that reason, this equipment is associated with lower environmental sustainability issues. The share of the data and control center (DCC) equipment to the total exergy consumption of the overall system was ascertained to be larger than that of the RAN and CN equipment, but lower when compared to that of the UD and UE. Moreover, the contribution of the DCC equipment to the cumulative OEC is more pronounced than its share to the cumulative EEC. As in the case of the AMI scenarios, an increase of the UD's as well as UE lifetime leads to a considerable decrease of the cumulative EEC. Further, the cumulative EEC turned out to be the most exergy consumption-related category over the entire operational duration of 20 years, i.e., the category group closely linked to environmental sustainability issues, just as in the case of the scenarios considering only AMI. It was determined that an increase of the lifetime of UD and UE results in a significant reduction of the cumulative EEC. A decrease of the cumulative EEC of about 48.68% at the end of the operational duration of 20 years is possible, if the UD's and UE lifetime is extended from a short lifetime to a medium lifetime. A further extension of the UD's and UE lifetime resulted in an even larger cumulative EEC reduction of approximately 62.74%. The assessment of the utilization intensity of home energy management applications, i.e., HANs, revealed a large influence on the cumulative EEC and, even more, the cumulative OEC. It was shown that an increase from a low utilization intensity of HANs (i.e., average HEMS load equals to 20%) to a medium utilization intensity of HANs (i.e., average HEMS load equals to 50%) leads to an approximately 11.18% cumulative EEC increase as well as an approximately 25.19% cumulative OEC increase at the end of the operational duration of 20 years. A further increase of the utilization intensity to a high utilization of HANs (i.e., the average HEMS load corresponds to 80%) showed an even larger cumulative EEC and OEC increase of about 16.78% and 48.01%, respectively, compared to a low utilization intensity of HANs. Furthermore, it was ascertained that the number of households that can be managed by a single home energy management system (HEMS), i.e., its configuration, has a considerable impact on the cumulative EEC as well as OEC of the overall system. That is, an increase of households that can be

served by a single HEMS from 10 to 20 households showed, after the operational duration of 20 years, a cumulative EEC and OEC decrease of about 11.66 and 33.01%, respectively. A further increase of households linked to a single HEMS from 10 to 100 revealed an even larger cumulative EEC and OEC reduction of approximately 20.99% and 59.41%, respectively.

Finally, it can be concluded that the lifetime of utility equipment (UE) as well as user devices (UDs) has a strong influence on the cumulative embodied exergy consumption (EEC). An increase of the UE's and UD's lifetime results in a considerable decrease of the cumulative EEC. Moreover, the utilization intensity of home energy management applications, i.e., home area networks (HANs), defined especially by the average home energy management system (HEMS) load, revealed a large impact on the cumulative operational exergy consumption (OEC). The daily charging durations as well as home energy management usage factors (HEMUFs) of smartphones, tablets, and notebooks have a minor influence on the cumulative OEC when compared to the average HEMS load. Nevertheless, the cumulative EEC turned out to be related to the largest exergy consumption for all of the studied scenarios and over the entire considered operational duration of 20 years. For that reason, it can be concluded that the most dominant life cycle stages of the considered overall system relate to those involved in the raw material extraction and processing, manufacturing and assembly, recycling and disposal, as well as the transportation. The operation phase of the overall system turned out to be the less dominant one. Therefore, it can be concluded that the EEC is closely associated with environmental effects, i.e., increased environmental sustainability issues.

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