Environmental Sustainability of Information and Communication Technologies for Advanced Metering and Home Area Networks

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Abstract - The challenges imposed on the current electric power grid have led to the need of an improved and smarter electric power grid, i.e., the smart grid. The smart grid will enable not only a bidirectional transfer of electricity, but also a two-way data exchange between various systems essential for a correct operation of the advanced metering infrastructure (AMI) and home area network (HAN) applications. The realization of the smart grid will require the deployment of additional information and communication technology (ICT) equipment in various domains. This will unavoidably lead to an increase in electricity consumption. In order to obtain a meaningful environmental sustainability analysis, additional 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. In this paper, we present an exergy-based life cycle assessment (E-LCA) of ICT equipment for smart grids involved in AMI and HAN applications. Based on a model developed for the city of Vienna, it is shown that the cumulative embodied and operational exergy consumption distribution and their development significantly differ for the AMI and the AMI/HAN scenario.

I. INTRODUCTION

The current electric power grid does not fulfill the requirements of the 21st century [1]. An improved and smarter electric power grid, i.e., the smart grid, promises a reduction of greenhouse gas (GHG) emissions, introduction of huge amounts of renewable energy sources, and improvement of methods associated with current electric power production, delivery, and consumption [2]. Such benefits and features of the smart grid will heavily rely on a bidirectional information exchange between various systems, accompanied by a massive deployment of information and communication technologies (ICTs) in its different domains. The overall smart grid can be divided into seven domains according to the National Institute of Standards and Technology (NIST) smart grid conceptual reference model, namely into: 1. bulk power generation, 2. transmission, 3. distribution, 4. customer, 5. operations, 6. markets, and 7. service provider [2]. The customer and distribution domains of the smart grid are those that are expected to be equipped with the largest number of additional ICT equipment [3], such as smart meters, power line communication (PLC) modems, and data concentrators. This ICT equipment is required for various smart grid applications, making the customer and distribution domain more pronounced than the others. Additionally, user devices (UDs) like smartphones, tablets, notebooks, digital subscriber line (DSL) modems, and home energy management systems (HEMSs) are seen as an important part of the customer domain [2,4]. These devices will provide users with real-time information on their actual electricity consumption, and are essential for various management and control applications. Based on these considerations, we focus our research on the advanced metering infrastructure (AMI) and home area network (HAN) applications for smart grids. AMI includes the entire network infrastructure as well as the ICT equipment between customer smart meters and the meter data management system (MDMS) located in the data and control center (DCC) [4]. Some examples of AMI equipment are smart meters, PLC modems, data concentrators, base stations, switches, and routers. The HAN defines the network required to link various consumer appliances and systems with the HEMS, in order to achieve efficient management and control functions [4].

In this paper, we apply a holistic modeling method to assess the environmental sustainability of ICT equipment required for the AMI and HAN smart grid applications. While many studies analyze only the energy consumption of ICT equipment during its use (i.e., operational energy consumption), many other life cycle stages are not considered, such as raw material extraction and processing, manufacturing and assembly, recycling and disposal, as well as the transportation of various materials and components. To obtain a more meaningful environmental sustainability analysis of ICT equipment, the evaluation of these other life cycle stages has to be included in the assessment as well [5]. The *exergy-based life cycle assessment* (E-LCA) provides means for such an analysis, and takes the entire lifetime of ICT equipment into consideration, i.e., from cradle to grave. It represents a sound approach for the environmental sustainability analysis of ICT equipment, based on its life cycle exergy consumption. The obtained total exergy consumption of a component or a system serves as a measure for the attained environmental sustainability. The main benefit of an exergy analysis in comparison to an energy analysis is the fact that different forms of energy can be directly compared with each other, which is related to its utilization of the second law of thermodynamics, not considered in an energy analysis. Moreover, the application of E-LCA for the environmental sustainability analysis of ICT equipment does not take as much time as a LCA, and leads to more meaningful and unambiguous results [6]. The E-LCA is therefore used here as the environmental sustainability indicator of choice for the assessment and evaluation of ICT equipment required for a proper operation of the AMI and HAN applications. The assessment based on the E-LCA framework confirms the assumption that the customer and distribution domains are indeed the most exergy consuming ones (considering the AMI and HAN smart grid applications), i.e., those domains are closely linked to environmental sustainability issues.

The paper is structured as follows. Section II provides basic insights into exergy and the E-LCA approach for ICTs. In Section III, the description of the overall model developed for the environmental sustainability analysis of the AMI and HAN applications is outlined. Moreover, basic assumptions are provided. Section IV presents and discusses the obtained results. Finally, a summary and conclusions are provided in Section V.

II. Exergy-based Life Cycle Assessment (E-LCA) of ICT Equipment

E-LCA provides a very useful framework for the environmental sustainability assessment of ICTs. This has been recognized by many researchers, and there are already a few studies which utilize the exergy concept for the evaluation of the environmental sustainability of ICTs [5-9]. The quantity *exergy* itself relies on the first and second law of thermodynamics. It 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 [10,11]. Put more simply, it can be understood as the quantity of energy that can be converted into useful work, i.e., the portion of energy available to be consumed [12]. The major difference which distinguishes exergy from energy is the fact that it is never conserved due to irreversibilities (i.e., internal inefficiencies) attributed to most real processes [13]. The energy balance of a process states that the difference between input and output energy equals zero, i.e., $En_{in} - En_{out} = 0$ [13]. This means that the total amount of energy is conserved. According to the exergy balance, on the other hand, the difference between input and output exergy is greater than zero, i.e., $Ex_{in} - Ex_{out} > 0$, indicating a decrease in the quality of energy (i.e., exergy) of a process [11,13]. Based on that, more insights into the efficiency of diverse processes are provided. The exergy balance is, moreover, proportional to entropy generation ΔS, weighted by the temperature T_0 of the exergy reference environment:

$$Ex_{loss} = Ex_{in} - Ex_{out} = \Delta S T_0. \tag{1}$$

Relation (1) is also known as the law of exergy loss [13], and states that the difference between the exergy at the input and the output of a system corresponds to entropy creation, i.e., irreversibilities. The total exergy loss of a system is obtained by estimating and summing up the exergy losses of its subsystems or components, i.e., $Ex_{loss,system} = \sum Ex_{loss,component}$. The E-LCA considers the same life cycle phases just like a life cycle assessment (LCA) framework, but leads to a simple and unambiguous outcome (i.e., an exergy consumption value) that can be used for easy and more meaningful ICT equipment environmental sustainability assessment purposes. Moreover, it is not that time consuming and difficult to derive in contrast to a LCA [6]. Figure 1 depicts graphically the different exergy consumption life cycle stages of ICT equipment that are considered [5]. The exergy consumption of ICT equipment in each of these life cycle stages are estimated and analyzed using the E-LCA framework. As exergy cannot be conserved, it is assumed that the overall exergy losses accumulated during the ICT equipment lifetime correspond to their cumulative exergy consumption [13]. Therefore, the evaluation of various ICT equipment involved in AMI and HAN applications is based on their exergy consumption, which, on the other hand, serves as a measure for the attained environmental sustainability. Additionally, a distinction is made between *embodied exergy consumption* (EEC), i.e., the exergy consumed during raw material extraction and processing, manufacturing and assembly, recycling and disposal, as well as transportation, and *operational exergy consumption* (OEC), i.e., the exergy consumed during operation (including cooling if present). This will allow us to compare these two different exergy consumption categories with each other, and to indicate the most exergy consumption related one. Based on that, more information about category groups of ICT equipment with significant improvement potential is provided, i.e., the ICT equipment most strongly related to environmental sustainability issues.

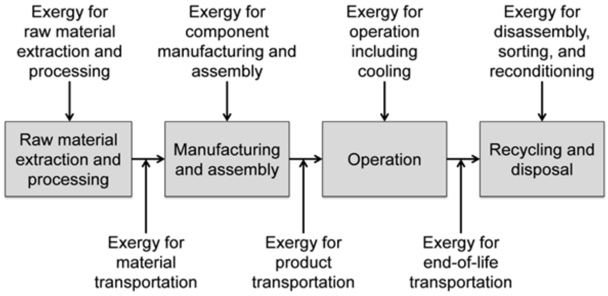
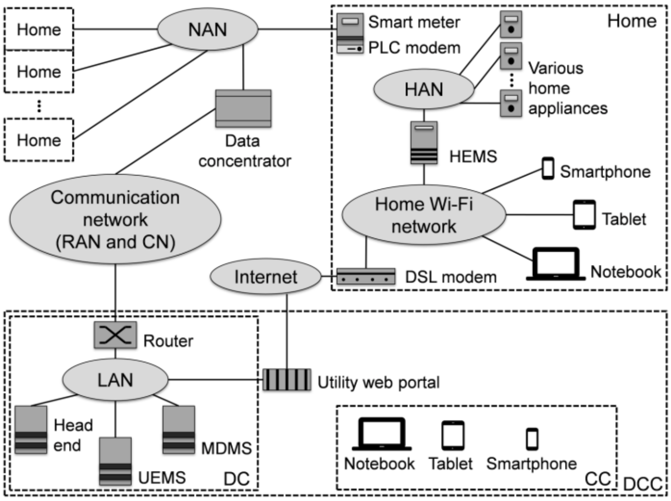


Figure 1. Life cycle exergy consumption stages of ICT equipment

III. Description of the Model

In this section, we present the overall smart grid model developed for the assessment of the AMI and HAN applications. Additionally, main assumptions required for the E-LCA of ICT equipment are provided. The considered overall smart grid model is composed of submodels for the home area network/building area network (HAN/BAN), neighborhood area network (NAN), radio access network (RAN), core network (CN), and the data and control center (DCC). A case study for the city of Vienna has been developed, with the aim to assess the EEC and OEC over a time period from 2020 to 2040 (i.e., operational duration of 20 years). Our assumption is that by the year 2020, the city of Vienna



PLC:	power line communication
HAN:	home area network
HEMS:	home energy management system
DSL:	digital subscriber line
NAN:	neighborhood area network
RAN:	radio access network
CN:	core network
LAN:	local area network
MDMS:	meter data management system
DC:	data center
CC:	control center
DCC:	data and control center

Figure 2. Overall smart grid model for the advanced metering infrastructure (AMI) and home area network (HAN) applications

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 [14]. The equipment needed for an appropriate functioning of the HAN application (e.g., smartphones, tablets, notebooks, 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 HEMS. For that purpose, adequate software programs would be required. 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. The approach of dividing the overall smart grid model in different submodels will give us the opportunity to point out the most exergy consumption related ICT equipment, and with that the most dominant smart grid domains. Based on that, the domains that are closely related to environmental sustainability issues can be indicated.

A. Overall Model

The overall smart grid model is schematically depicted in Figure 2. The HAN/BAN equipment includes smart meters and PLC modems, as well as user devices (UDs) like smartphones, tablets, notebooks, DSL modems, and HEMSs required for a proper utilization of the HAN application. 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 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 model as well. Such a holistic approach allows us to obtain more meaningful conclusions on the environmental sustainability of ICTs associated with the AMI and HAN applications.

B. Model for AMI and HANs

The AMI represents the basic infrastructure of the future smart grid. It includes, e.g., smart meters, PLC modems, data concentrators, communication network equipment, and DCC equipment (see Figure 2). It is assumed that the data measured by smart meters are delivered to the data concentrator by means of the PLC technology. Moreover, the average number of smart meters (i.e., households) that can be supported by a data concentrator is assumed to be equal to 150. The forwarding of data for further evaluation and processing purposes from the data concentrator to the DCC is accomplished by means of cellular mobile communication systems, i.e., GSM and UMTS,. 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 [4].

The HAN considered here can be seen as an enhancement of the AMI. It extends the smart grid idea into the home, and enables important home energy management functions. It is used to link various consumer appliances with the HEMS by means of PLC or, e.g., the low-rate wireless personal area network (LR-WPAN) communication technology ZigBee. User devices such as smartphones, tablets, notebooks, DSL modems, and HEMSs are interconnected by means of the home Wi-Fi network and provide users with real-time electricity consumption information. This enables the users 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 [4], as depicted in Figure 2).

C. Assumptions and Scenarios

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. An operational duration of 20 years is assumed, i.e., a time period from 2020 to 2040, with the aim to gain more insight into the development of the lifetime exergy consumption of ICTs associated with the AMI and HAN smart grid applications. Based on that, the number of households in Vienna is expected to increase from 927,905 in 2020 to 1,027,846 in 2040 [15]. This corresponds to a yearly average household increase of 4,997.05 households. The average number of persons per household during this time period is assumed to be equal to 2. 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 5,000 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 damaged or used up 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. Table I provides additionally some further ICT equipment assumptions required for the E-LCA case study, e.g., lifetime assumptions, EEC, and OEC of various devices. The OEC values listed in Table I were calculated based on the respective lifetime of the considered device. Material/component composition of smart meters, PLC modems, data concentrators, and HEMSs, required for the E-LCA, was in part based on analytical analyses, as well as information obtained from [16], [17], [18], and [5], respectively. 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 [7-9]. The lifetime of BTS and BSC racks is assumed to be equal to 7 and 8 years, respectively; 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 routers, switches, and DSL modems is assumed to be 3 years. Data on technology and ICT equipment penetration was based on the information obtained from Statistics Austria and on the forecasts provided in [9].

It should be mentioned that the EEC of ICT equipment is, moreover, weighted by a usage factor (UF), accounting for the time it is used for the AMI and HAN applications. Smartphones, tablets, and notebooks will be used for other purposes most of the time (e.g., telephony, various internet services, mobile and video games). They will be used for home energy management applications for only about one hour daily (i.e., uptime of 4.17%). For that reason, their EEC is much smaller than that of smart meters, PLC modems, and data concentrators (see Table I). The same holds for the RAN and CN equipment, i.e., this equipment will be used for only a few minutes daily for the AMI application. The uptime of HEMSs and DSL modems, on the other hand, is assumed to be equal to 95% (i.e., 22.8 hours), however, with an average load of 50%. Based on these assumptions, the cumulative EEC and OEC of ICT equipment is investigated over the defined time period of 20 years for the AMI application alone (AMI scenario), and then in combination with the HAN application (AMI/HAN scenario). Moreover, the most exergy consuming ICT equipment in the case of these two scenarios is indicated. Based on that, the most dominant exergy consumption related (i.e., environmentally pronounced) smart grid domains are provided.

TABLE I. MAIN ASSUMPTIONS FOR THE E-LCA CASE STUDY

Device	*Lifetime [years]*	*EEC [MJ]*	*OEC [MJ]*
Smart meter	15	1,511.31	709.56
PLC modem	10	1,528.21	378.43
Data concentrator	7	2,849.66	529.80
HEMS	4	6,664.83	15,878.37
Smartphone	2	59.9	0.54
Tablet	2	62.13	1.17
Notebook	3	85.53	9.89

IV. RESULTS AND DISCUSSION

This section presents the results obtained from the E-LCA applied to ICTs involved in AMI and HAN applications. In the AMI scenario, only ICT equipment required for a correct operation of the AMI application is included in the assessment of the exergy consumption (i.e., environmental sustainability). The AMI/HAN scenario considers additionally UDs, i.e., smartphones, tablets, notebooks, DSL modems, and HEMSs, required for various home energy management applications. These devices are essential for a proper utilization of the HAN application.

Figure 3 depicts the distribution and the development of the cumulative EEC and OEC of ICTs for the AMI scenario over the defined period of 20 years. It is evident that the cumulative EEC dominates over the entire operational duration. The cumulative EEC and OEC values at the end of the operational duration of 20 years were estimated to be equal to 6.14 petajoules (PJ) and 2.127 PJ, respectively. This corresponds to 74.27% and 25.73% of the overall cumulative exergy consumption. Smart meters, PLC modems, and data concentrators, termed advanced metering, processing, and forwarding (AMPF) equipment in the scope of this paper, represent the ICT equipment category with the strongest contribution to the depicted cumulative EEC development. The large increase of the cumulative EEC between 2030

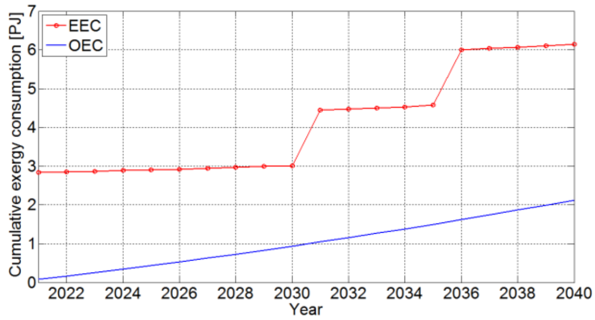


Figure 3. AMI scenario: distribution and development of the cumulative embodied exergy consumption (EEC) and the cumulative operational exergy consumption (OEC) of the overall smart grid model considering the AMI smart grid application

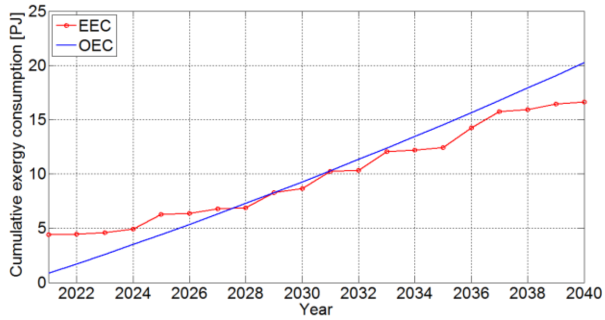


Figure 4. AMI/HAN scenario: distribution and development of the cumulative embodied exergy consumption (EEC) and the cumulative operational exergy consumption (OEC) of the overall smart grid model considering the AMI and HAN smart grid applications

TABLE II. AMI SCENARIO: CUMULATIVE EEC AND OEC DISTRIBUTION AMONG ICT EQUIPMENT CATEGORIES

ICT equipment category	*Cumulative EEC [%]*	*Cumulative OEC [%]*
AMPF	99.10	78.54
RAN	0.04	0.87
CN	0.01	0.41
DCC	0.86	20.19

and 2031, as well as between 2035 and 2036 arises due to the replacement of a huge number of PLC modems and smart meters, respectively, i.e., those that have been installed at customer locations in the year 2020. Table II provides additionally the breakdown of the cumulative EEC and OEC among the different ICT equipment categories of the overall smart grid model for the AMI scenario, obtained at the end of the operational duration of 20 years. As can be seen, the AMPF equipment contributes the most to the overall cumulative exergy consumption (i.e., EEC and OEC). Even though the number of ICT equipment deployed in the DCC is very much less than that of the AMPF equipment, their contribution to the cumulative OEC of about 20% is comparatively high. This is because the power consumption of the AMPF equipment is much lower than that of the ICT equipment utilized at the DCC. The share of the DCC equipment to the cumulative EEC is less than 1%, and therefore almost negligible. The share of the other ICT equipment categories (i.e., RAN and CN) to the cumulative EEC and OEC is very low compared to the AMPF and DCC equipment. Such a low contribution of RAN and CN equipment to the overall cumulative exergy consumption comes from the fact that it is utilized for the AMI application for only few minutes daily. These results clearly indicate the large importance of the customer and distribution domains of the smart grid (i.e., domains encompassing a large number of smart meters, PLC modems, and data concentrators), as well as the DCC because of their relatively high OEC. The cumulative EEC of ICT equipment was determined to be the largest contributor to the overall cumulative exergy consumption, during the entire operational duration, in the case of the AMI application. The AMPF equipment was ascertained to be the most dominant ICT equipment. The cumulative OEC is comparatively low, considering the large amount of AMPF equipment deployed in the customer and distribution domains, whereas the cumulative OEC of the DCC equipment contributes considerably to the overall cumulative OEC.

Figure 4 visualizes the distribution and the development of the cumulative EEC and OEC of ICTs for the AMI/HAN scenario. All assumptions made for the AMI scenario were left equal. However, the AMI/HAN scenario includes in the assessment of the cumulative exergy consumption besides the ICT equipment of the AMI scenario also UDs, namely smartphones, tablets, notebooks, DSL modems, and HEMSs. The quite different cumulative EEC and OEC distribution and development for the AMI/HAN scenario compared to the AMI scenario is clearly evident from Figure 4. It can be seen that the cumulative OEC becomes the most dominant exergy consumption category after approximately 7.5 years (i.e., between the year 2027 and 2028). The cumulative EEC and OEC for the AMI/HAN scenario were estimated to be equal to 16.628 PJ and 20.249 PJ at the end of the operational duration of 20 years, respectively. This corresponds to 45.09% and 54.91% of the overall cumulative exergy consumption. In Table III, the distribution of the cumulative EEC and OEC consumption among the different ICT equipment categories of the overall smart grid model for the AMI/HAN scenario, obtained at the end of the operational duration of 20 years, is provided. It is evident that the cumulative OEC becomes the major contributor to the overall exergy consumption, with the UDs being the most exergy consumption related ICT equipment category. The most dominant (i.e., exergy consumption related) component of the UDs was determined to be the HEMS. This is because the uptime of most other UDs (i.e., smartphones, tablets,

TABLE III. AMI/HAN SCENARIO: CUMULATIVE EEC AND OEC DISTRIBUTION AMONG ICT EQUIPMENT CATEGORIES

ICT equipment category	*Cumulative EEC [%]*	*Cumulative OEC [%]*
UDs	63.07	89.49
AMPF	36.59	8.25
RAN	0.01	0.09
CN	0.00	0.04
DCC	0.32	2.12

and notebooks) was assumed to be only about one hour daily. The uptime of the HEMS, however, was assumed to be equal to 95% (i.e., 22.8 hours). This fact makes the HEMS the most important (i.e., environmentally relevant) UD. Furthermore, it represents with 95.86% the strongest contributor to the cumulative OEC of all other UDs.

V. Summary and Conclusions

In this paper, we analyzed the environmental sustainability of ICT equipment involved in advanced metering (AMI) and home area network (HAN) smart grid applications. For that purpose, we applied an exergy-based life cycle assessment (E-LCA) framework. The assessment was based on a smart grid model developed for the city of Vienna. The cumulative embodied exergy consumption (EEC) and operational exergy consumption (OEC) of ICT equipment deployed in the various submodels of the overall smart grid model have been estimated and analyzed. The obtained exergy consumption of ICT equipment served as a measure for the attained environmental sustainability. We defined two scenarios, namely the AMI and the AMI/HAN scenario, and estimated the cumulative EEC and OEC for both of them. We proved that the customer and distribution domains are indeed the most exergy consumption related domains of the smart grid, and consequently, the most environmentally important domains considering the AMI and HAN smart grid applications.

The cumulative EEC was determined to be the most dominant exergy consumption related category over the entire operational duration of 20 years in the case of the AMI scenario. This result justifies and clarifies the importance of a holistic assessment approach, as it takes the entire ICT equipment life cycle exergy consumption into account and not just the exergy consumption during operation. The advanced metering, processing, and forwarding (AMPF) equipment, namely smart meters, PLC modems, and data concentrators was, moreover, ascertained to be the ICT equipment category with the strongest contribution to the overall cumulative exergy consumption (i.e., EEC and OEC). The cumulative OEC was determined to be the less exergy consumption related category over the defined operational duration in the case of the AMI scenario, and with that the category associated with lower environmental effects. The cumulative OEC of the DCC equipment was estimated to contribute by about 20% to the overall cumulative OEC, which is a comparatively high percentage considering the moderate number of ICT equipment deployed in the DCC. It can be concluded that in the case of the AMI scenario, the cumulative EEC of AMPF equipment strongly relates to environmental sustainability issues, i.e., it has the strongest potential to negatively impact the environment.

In the case of the AMI/HAN scenario, the cumulative OEC was determined to be the leading exergy consumption related category after about 7.5 years of operation. The strongest contribution to the overall exergy consumption is attributed to home energy management systems (HEMSs). Such a result arises due to a large number of deployed HEMSs and their respective high uptime of 95%, leading to a cumulative OEC share of 95.86% compared with all other UDs. The fact that HEMSs contribute the most to the overall cumulative OEC is, however, relaxed by the fact that their main purpose is the energy efficient management of consumers' electricity consumption. The energy consumption savings related to the use of HEMSs are believed to be larger than their own power consumption, leading to an indirect improvement of the environmental sustainability.

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