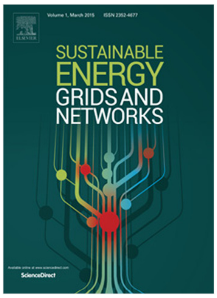

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Exergy Cost of Information and Communication Equipment for Smart Metering and Smart Grids

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***Abstract*—Future smart grids are expected to offer numerous advantages over the current electricity grid due to an improved efficiency of electricity production, distribution, consumption as well as sophisticated grid management and integration of distributed renewable energy sources. In order to enable these functionalities, however, additional equipment has to be installed, which, on the other hand, will lead to increased electricity consumption and more e-waste. This paper provides, for the first time, to the best of our knowledge, insights into the overall exergy cost related to the introduction of additional information and communication technology (ICT) equipment such as smart meters and other ICT devices required for future smart grids. We present results obtained using a model for the city of Vienna and considering all life cycle phases. Additionally, the impact of the components' lifetime and various implementation options is shown. Since the environmental impact of the additional ICT equipment for smart grids is presented in a simple and transparent manner using a holistic approach referred as to as the exergy-based life cycle assessment (E-LCA) method, the results presented in this paper can easily be integrated in a more complete model of smart grids with the aim of assessing the exergy efficiency of various concepts and applications for future smart energy generation, distribution, and consumption systems.**

***Index Terms* — Advanced Metering Infrastructure (AMI); Home Area Network (HAN); Information and Communication Technology (ICT); Smart Grids; Exergy-based Life Cycle Assessment (E-LCA); Environmental Sustainability.**

I. INTRODUCTION

THE realization of the smart grid will only be possible by a pervasive deployment and use of information and communication technologies (ICTs) on top of the electricity grid [1]. It is the ICT in the smart grid, which will enable an improvement of the efficiency of current electricity production, distribution, and consumption systems as well as support an efficient 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 [2]. The future electricity grid will be augmented by a magnitude of additional 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. Additional to exploiting the potentials for optimizing the generation, distribution, and consumption of electricity in future smart grids, these components and devices also need electricity to proper function, so they will unavoidably contribute to increased electricity consumption. Moreover, production, transport, and disposal of the additional ICT equipment for smart grids also require energy and cause e-waste, thereby causing a pollution of the environment. These facts have also to be carefully taken into consideration when assessing the impact of future smart grids.

In this paper, we apply a holistic framework to assess the environmental impact of smart meters and additional ICT equipment, which is required for implementing the advanced metering infrastructure and home area network applications as essential parts of the future smart grid. The holistic framework has been briefly explained in a recent conference paper [3], which also presents a few preliminary results on environmental sustainability of advanced metering infrastructure (AMI). In this correspondence, we provide a more exhaustive description of the framework and show results of an extended study by considering additional to advanced metering infrastructure also a part of the customer domain such as the home are network (HAN), which on the one hand, opens new possibilities for increasing the energy efficiency in the customer domain but, on the other, leads to a higher overall energy consumption of the ICT equipment. The key question that we address in this study is how large is the environmental cost of an implementation of AMI and HAN and what are possible ways to mitigate the environmental impact of the additional ICT components.

The paper is structured as follows. The next section introduces the exergy-based life cycle assessment (E-LCA), which is used here to assess the sustainability of the advanced metering infrastructure (AMI) and home area networks (HANs). The application of the E-LCA method is presented on a case study of smart grid deployment for the city of Vienna. Section III describes the considered scenario. In Section IV, results at the component level are presented, while in Sections V and VI, we show and discuss results on the sustainability of the entire system with varying equipment lifetimes and configurations. Section VII summarizes and concludes the paper. Finally, Section VIII discusses future work.

II. EXERGY-BASED LIFE CYCLE ASSESSMENT (E-LCA)

An objective and accurate estimation of environmental effects is possible by applying the fundamental laws of thermodynamics, which allow assessing mass and energy transfers attributed to various processes. The second law of thermodynamics enables further the estimation of the exploited energy and provides information on how efficiently the supplied energy is being exploited by a process [4]. Environmental sustainability indicators based on thermodynamics include, among others [5]:

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

Life cycle assessment (LCA) represents a framework that can be used to assess various products or processes by means of their impact on the environment. For that purpose, all inputs and outputs of a product or process are analyzed during its considered lifetime, i.e., the evaluation takes the entire product's or system's life cycle under consideration. There are a lot of variants of a LCA, but most of them concentrate on emissions. 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 an easy and meaningful comparison between various potential approaches. The other drawback is its time exposure and cost. In contrast to a LCA approach, an exergy-based life cycle assessment (E-LCA) tracks lifetime exergy consumption and implies the second law of thermodynamics [5]. It provides a single outcome, which makes this approach suitable for a fast comparison of different systems. A decrease in exergy consumption, i.e., an increase in exergy efficiency of a system, leads to a reduction of resource depletion, which means that environmental impacts can often be minimized by minimizing exergy consumption. However, the single output value of the E-LCA can also turn out to be a drawback in some cases because it makes impossible a differentiated and in-depth assessment of various environmental impacts.

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 [6,7]. It 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 that distinguishes exergy from energy [8]. Any exergy loss indicates possible process improvements. The exergy of a macroscopic system is given by:

$$E_{ex} = U + P_r V - T_r S - \sum_i \mu_{ri} n_i \,, \tag{1}$$

where extensive system parameters are the internal energy (*U*), the volume (*V*), and the number of moles of different chemical components *i*, i.e., n_i, while intensive parameters of the reference environment are the pressure (P_r), the temperature (T_r), and the chemical potential of component *i*, i.e., $\mu_{r,i}$. A useful formula for practical determination of exergy is [9]:

$$E_{ex} = U - U_0 + P_r(V - V_0) - T_r(S - S_0) - \sum_i \mu_{r,i}(n_i - n_{0,i}), \tag{2}$$

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

$$E_{ex,mat} = \sum_i (\mu_i^0 - \mu_{o,i}^0) n_i + RT_r \sum_i n_i \ln \frac{c_i}{c_{o,i}}. \tag{3}$$

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

$$E_{ex,loss} = E_{x,in} - E_{x,out} = T_r \Delta S, \tag{4}$$

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

Exergy analysis has been performed in industrial ecology to indicate the potentials for improving the use of resources and minimizing environmental impact. The higher the exergy efficiency is, i.e., the lower exergy losses, the better the sustainability of the considered system or approach. An exergy analysis eliminates the most of the drawbacks of an energy analysis and LCA. In contrast to an energy analysis, an 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 [5]. E-LCA is also quicker and less costly to accomplish than LCA. All these benefits make E-LCA the environmental sustainability indicator of choice for evaluating the sustainability of ICTs for smart grids.

III. CONSIDERED SCENARIO

The advanced metering infrastructure (AMI) represents the basic infrastructure for future smart grids. It includes utility equipment (UE) such as smart meters, power line communication (PLC) modems, data concentrators, data and control center (DCC) equipment, as well as communication network equipment such as access network (AN) and core network (CN) elements.

AMI is expected to offer a huge number of advantages regarding reliability and energy efficiency, as well as a thorough insight into the state of the entire smart grid. This will open the possibility to use advanced management and monitoring as well as to enable important remote control functions essential in the course of unusual or unexpected events [10]. Here, we assume that smart meter measurements are delivered to the data concentrator by means of PLC links. The data forwarding from the data concentrator towards the DCC is accomplished by means of cellular radio (GSM and UMTS) and the core network. Additionally, user devices (UDs) and systems like smartphones, tablets, notebooks, and home energy management systems (HEMSs) are considered as an important part of the customer domain, which will allow consumers to visualize and minimize their own energy consumption. These devices and systems are essential for establishing and properly utilizing the home area networks (HANs). Other forms of power management techniques that can be performed without direct involvement and action of the user will become possible as well, such as, e.g., various demand response (DR) methods [1].

A. Description of the Scenario

We define a scenario for a possible deployment and use of the advanced metering infrastructure and home area networks in order to analyze the impact of different system parameters on the environmental sustainability. The presented scenario is based on a model developed for the city of Vienna. The main results obtained by the model are the overall embodied exergy consumption (EEC) and the operational exergy consumption (OEC) over a time period between 2020 and 2040, i.e., assuming an operation time of 20 years. The EEC is the exergy consumed during the raw material extraction and processing, production, transportation, and disposal phases of the product's or system's life cycle, while the OEC is related to the use phase of the equipment, i.e. the operational phase. We assume that that by the year 2020, appropriate smart metering, data processing, and forwarding equipment required for a correct operation of the AMI application will be deployed in the city of Vienna. Moreover, home energy management system (HEMS) services are assumed to be present in a large number of households. Consumer devices such as smartphones, tablets, and notebooks are further assumed to be used in a combination with the home area network, i.e., users will be able to visualize, monitor, and manage their home energy consumption via a wireless connection.

The information on the number of households in Vienna, their expected development, as well as the average number of persons per household is obtained from the Statistics Austria. According to these data, the number of households in Vienna is expected to increase from 927,905 in 2020 to 1,027,846 in 2040 [11]. This corresponds to a yearly average increase by 4,997.05 households. The average number of persons per household during this time period is assumed to be equal to 2. We assume that the equipment required to implement AMI and HAN applications is mainly manufactured in China. 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 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 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 675 km. The distances between the different ICT equipment life cycle stages were estimated by using the Google Maps route planner. Moreover, various transportation modes between these different locations are considered, i.e., truck, rail, and ship.

IV. COMPONENTS' EXERGY CONSUMPTION

The exergy consumption of the utility equipment (UE) and the user devices (UDs) is estimated by defining generic structures and determining typical material compositions for each component type and taking into account the specific exergy content of the used materials. Then, the exergy consumption related to various manufacturing and assembly processes is considered. Finally, the exergy consumed during the end-of-life phase is calculated. The material compositions and the values for the mass-specific exergy consumptions related to different extraction, manufacturing, and recycling processes as well as transportation modes are summarized in the Appendix.

The data on exergy consumption of the communication network equipment including network terminals, edge, aggregation, and core switches as well as copper and optical fiber cables is obtained from [12-14]. The exergy consumption of servers and home energy management systems (HEMSs) deployed in the DCC and the customer/distribution domains, respectively, is taken from [4,15]. The model used to dimension and evaluate the core and access networks takes into account all relevant parameters for the city of Vienna such as coverage, technology penetration, number of subscribers, population density, and current network design practices. The required data is mainly obtained from the Statistics Austria [11], the Forum Mobilkommunikation (FMK) [16] and the Austrian Regulatory Authority for Broadcasting and Telecommunications (RTR) [17]. Additionally, future trends in data traffic growth and technology development as well as the information provided by network operators are considered. For more detailed description regarding the model of the communication network and assumed parameters the reader is referred to [12,18-20]. The main results of this model are (i) estimated number of required network elements and (ii) estimated total electricity consumption of the network, which are used to calculate the contributions of the communication network infrastructure to the total EEC and OEC. Here, we assume that data concentrators are connected to the data and control center (DCC) via the existing core and access network infrastructure. The network related contributions to the overall EEC and OEC are calculated as a portion of the total network exergy consumption and according to the expected amount of AMI traffic, which will most likely be only a small portion of the total network traffic.

TABLE I.

LIFETIME ASSUMPTIONS FOR DIVERSE EQUIPMENT AS INDICATED IN FIG. 1

ICT equipment	ICT equipment category	Lifetime [years]
Data concentrator	UE	7
PLC modem	UE	10
Smart meter	UE	15
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
Edge switch	DCC	3
Server	DCC	4
Notebook (15- and 13-inch)	DCC, UD	3
Tablet	DCC, UD	2
Smartphone	DCC, UD	2
Router	DCC	3
DSL modem	DCC, UD	3
Cat5e cable	RAN,CN,DCC	> 20
Optical fiber cable	RAN,CN,DCC	> 20
HEMS	UD,Others	4

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. For both SGSN and GGSN racks we assume a service time of 10 years. The lifetime of DCC routers, CN/DCC switches, and DCC/UD DSL modems is assumed to be 3 years. Notebooks are replaced after 3 years while both tablets and smartphones after 2 years of use. Data on technology penetration is based on the information obtained from Statistics Austria and on forecasts provided in [12]. The assumptions regarding the ICT equipment lifetime are summarized in Table I, while the model for evaluating the environmental sustainability of the advanced metering infrastructure (AMI) and home area networks (HANs) is graphically depicted in Fig. 1.

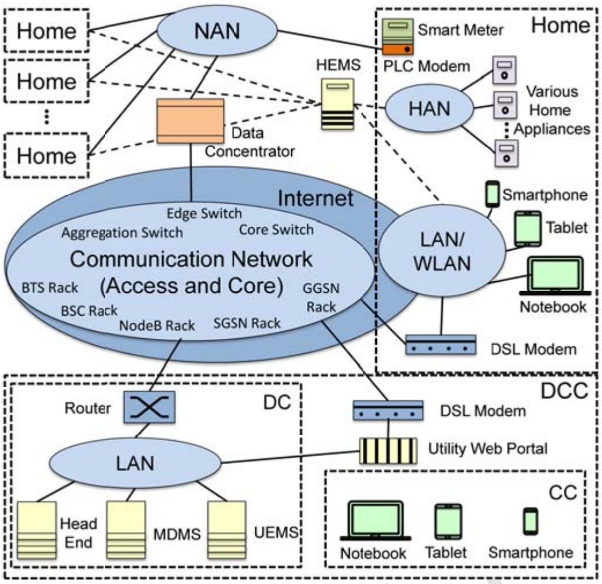


Fig. 1. Model used in the study to assess the environmental sustainability of ICT equipment involved in the advanced metering infrastructure (AMI) and home area network (HAN) applications. NAN: Neighborhood Area Network, PLC: Power Line Communication, HEMS: Home Energy Management System, DSL: Digital Subscriber Line, BTS: Base Transceiver Station, BSC: Base Station Controller, SGSN: Serving GPRS Support Node, GGSN: Gateway GPRS Support Node, LAN: Local Area Network, WLAN: Wireless Local Area Network, MDMS: Meter Data Management System, UEMS: Utility Energy Management System, DC: Data Center, DCC: Data and Control Center, CC: Control Center, HAN: Home Area Network.

Note that the operational power consumption is estimated by taking into consideration the electric power only, i.e., the electricity demanded by the system. Thus, the operational exergy consumption of a system, expressed in joules (J), is calculated according to the following formula:

$$E_{ex,op} = P_{sys,peak} \cdot \bar{L}_{sys} \cdot t_{up} \cdot t_{op} \cdot UF \cdot C\,, \qquad (5)$$

where $P_{sys,peak}$ is given in watts (W) and denotes the system's peak electricity consumption, i.e., the peak exergy consumption, while $\bar{L}_{sys}$ is the average load of the system during its use [15]. $\bar{L}_{sys}$ is expressed as the portion of the peak system load, $\bar{L}_{sys,peak}$. t_{up} denotes the system's daily operation time, while t_{op} denotes the system's total usage time, expressed in years. The usage factor (UF) determines how extensively the component or system is used for smart grid applications. It is defined as $\mathrm{UF}_a = X_a/24\mathrm{h}$, where X_a denotes the time period in hours during which a smart grid application is running on the component a. Finally, C represents a constant required for a correct unit conversion.

Equation (5) allows accounting for the part of the total exergy consumption of shared infrastructure that is related to smart grid applications. For example, the communication network infrastructure (core and access networks) exists without smart grids, but it may need to be slightly extended or adapted to optimally support smart grid applications. Anyway, the data traffic originating from smart grid applications will most probably be just a small portion of the total internet traffic. Similarly, user devices such as smartphones, tablets, and notebooks are assumed to be partly used for HAN applications, while most of the time they are used for other purposes like telephony, work, entertainment, internet surfing, etc. Note that the same reasoning applies to the embodied exergy consumption.

A. Utility Equipment

The cumulative embodied (EEC) and operational (OEC) exergy consumptions obtained for the utility equipment (UE) are summarized in Table II. These values are calculated while considering all life cycle phases and the whole components' service time, i.e. the entire UE lifetime. It is evident that the total exergy consumption of the data concentrator is highest among the utility equipment, which is mainly due to the high embodied exergy consumption (EEC). Note that the high operational exergy consumption (OEC) of the smart meter is due to the assumed long lifetime of 15 years. However, the embodied exergy consumption (EEC) of the smart meter is for about 1.34 GJ lower than that of the data concentrator. In general, the operational exergy is two to five times lower than the embodied exergy consumption as indicated in Fig. 2, which shows the relative contributions of EEC and OEC to the total exergy consumption over the entire UE lifetime. The assumptions regarding the material composition of the utility equipment are listed in Appendix A.

TABLE II.

ESTIMATED EMBODIED EXERGY CONSUMPTION (EEC) AND OPERATIONAL EXERGY CONSUMPTION (OEC) OF VARIOUS UTILITY EQUIPMENT (UE)

Equipment	Exergy Consumption		
	EEC [GJ]	OEC [GJ]	Total [GJ]
Smart meter	1.511	0.709	2.221
PLC modem	1.528	0.378	1.906
Data concentrator	2.850	0.530	3.379

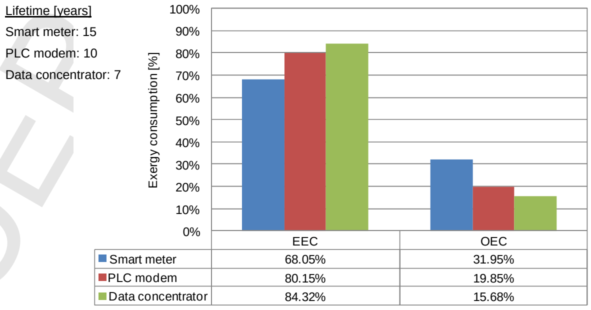


Fig. 2. Relative contributions of embodied (EEC) and operational (OEC) exergy consumptions to the total cumulative consumption over the whole lifetime of the smart meter, PLC modem, and data concentrator.

B. *User Devices*

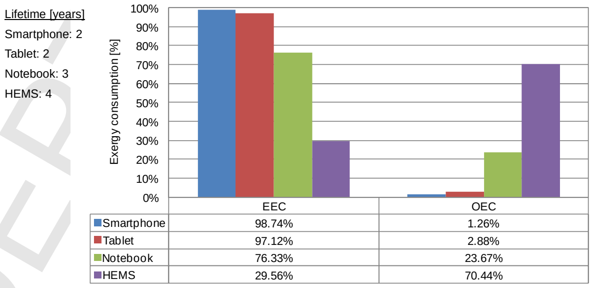
The obtained exergy consumption of user devices (UDs) is listed in Table III. By comparing Table III to Table II one can notice that the exergy values obtained for smartphones, tablet PCs, and notebooks are much smaller than that for the utility equipment (UE). The main reason for this difference is the much smaller usage factor (UF) assumed for the user devices than for the utility equipment. While a factor of 1 (i.e., 100%) is taken for the utility equipment, UF ~ 0.083 (i.e., 2 hours of usage per day) is assumed for smartphones, tablets, and notebooks. Therefore, the contribution of the OEC to the total exergy consumption is negligible for smartphones and tablets as graphically depicted in Fig. 3. However, for a notebook, the operational exergy is higher and accounts for about 24%.

TABLE III.

ESTIMATED EMBODIED EXERGY CONSUMPTION (EEC) AND OPERATIONAL EXERGY CONSUMPTION (OEC) OF DIFFERENT USER DEVICES (UDS)

Equipment	Exergy Consumption		
	EEC [GJ]	OEC [GJ]	Total [GJ]
Smarthone	0.120	0.0015	0.121
Tablet PC	0.124	0.0037	0.128
Notebook	0.171	0.0530	0.224
HEMS (Server)	7.016	16.7140	23.730

The HEMS is related to significantly higher exergy consumption when compared to the other user devices. This is because we assumed that HEMS applications are running on an enterprise-class server, which remains in the active state all the time, i.e., its UF = 1. For this reason, the operational exergy consumption (OEC) of the HEMS is more than twice as high as the embodied exergy consumption (EEC), as can be seen in Fig. 3.



	EEC	OEC
🟦 Smartphone	98.74%	1.26%
🟥 Tablet	97.12%	2.88%
🟩 Notebook	76.33%	23.67%
🟪 HEMS	29.56%	70.44%

Fig. 3. Relative contributions of embodied (EEC) and operational (OEC) exergy consumptions to the total cumulative consumption over the whole lifetime of the smartphone, tablet PC, notebook, and HEMS.

V. SUSTAINABILITY ANALYSIS OF THE ADVANCED METERING INFRASTRUCTURE (AMI)

Based on the assumptions provided in Section III and exergy consumption values for various equipment presented in Section IV, we analyze now the environmental sustainability of ICT equipment involved in the advanced metering infrastructure for the city of Vienna. We defined different assumptions and parameter variations 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 ICT equipment can be provided.

A. Impact of the Utility Equipment (UE) Lifetime

As both the customer and the distribution domain will be equipped with a huge number of utility equipment (UE), namely smart meters, power line communication (PLC) modems, and data concentrators, means to gain insights into the exergy consumption of this equipment regarding different lifetime assumptions would prove beneficial. For that purpose, we defined three different use cases (UCs) assuming different lifetimes of the considered UE as listed in Table IV.

TABLE IV.

DEFINITION OF USE CASES (UCS) FOR THE UTILITY EQUIPMENT (UE) LIFETIME

Use Case (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

Use case 1 (UC 1) assumes a short lifetime of the UE, i.e., smart meters and PLC modems are replaced every 5 years, the data concentrator even every 3 years. UC 2 and UC 3, on the other hand, envisage a longer lifetime of the UE. In particular, UC 2 is assumed to be the baseline that is taken as a basis for the scenario presented in Subsection V.B, which analyzes how the number of smart meters connected to a single data concentrator influences the cumulative embodied and operational exergy consumptions. It should be noted that the assumed number of smart meters connected to a data concentrator for the present scenario equals to 150, which corresponds to the number provided by UC 2 of the scenario treated in the next subsection. The information on the amount of data traffic per data concentrator, which is required for the assessment of AMI, was obtained from [21].

The cumulative embodied (EEC) and operational (OEC) exergy consumptions of AMI for the three defined use cases (UCs) are shown in Fig. 4. As can be seen from the figure, UC 1 is related to the highest cumulative EEC. Thus, it is associated with increased environmental sustainability issues. Such high exergy expenditure arises due to the short lifetime assumed for the UE in UC 1 (see Table IV). An increase of the UE lifetime reduces considerably the cumulative EEC. A medium lifetime of the UE as assumed in UC 2 leads to a reduction of the cumulative EEC by about 6 PJ at the end of 20 years of operation with regard to UC 1. This corresponds to a reduction by almost 50%. When assuming an even longer UE lifetime, this difference increases. An exergy saving of 7.5 PJ compared to UC 1 is possible if the smart meter, PLC modem, and data concentrator are replaced every 20, 15, and 10 years, respectively. This equals to a relative reduction of the cumulative EEC by about 62%. Note that the cumulative OEC is significantly lower than the cumulative EEC for all three considered UCs.

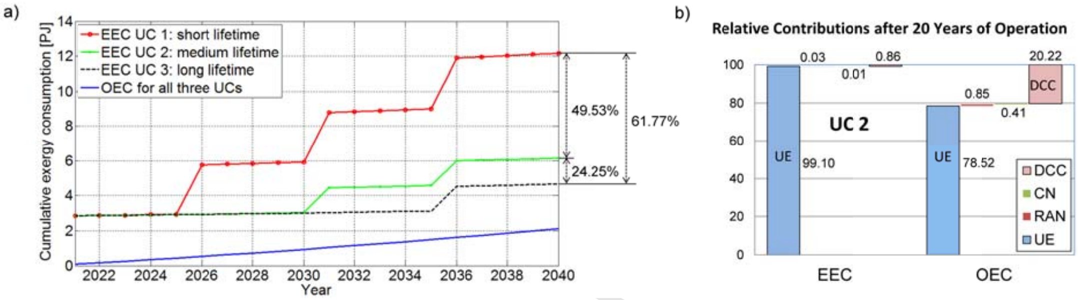


Fig. 4. Cumulative embodied (EEC) and operational (OEC) exergy consumptions for different utility equipment (UE) lifetimes: a) development of the exergy consumption for the three considered use cases (see Table IV) and b) relative contributions of different equipment groups to the total EEC and OEC after 20 years of operation assuming use case 2 (UC 2).

B. *Impact of the Data Concentrator Configuration*

The number of smart meters that can be served by a data concentrator is limited by the distance, transmission effects, and the maximum data volume that can be transmitted over PLC lines. Up to 2,000 smart meters can be connected to a single data concentrator according to manufacturers' data sheets [22]. The present scenario analyzes how the number of smart meters served by a single data concentrator relates to the distribution and development of the cumulative exergy consumption of the overall system. We consider here three use cases with different numbers of smart meters per data concentrator, which are shown in Table V. This scenario is based on the UC 2 of the scenario presented in Subsection V.A, according to which the lifetime of smart meters, PLC modems, and data concentrators equals to 15, 10, and 7 years, respectively.

TABLE V.

DEFINITION OF USE CASES (UCS) FOR THREE DATA CONCENTRATOR (DC) CONFIGURATIONS

Use Case (UC)	Number of smart meters per DC
UC1: 50 smart meters per DC	50
UC 2: 150 smart meters per DC	150
UC 3: 2,000 smart meters per DC	2,000

Use case 1 (UC 1) assumes that 50 smart meters are connected to a data concentrator, whereas UC 2 envisages an average number of 150 smart meters. UC 3 with 2,000 smart meters per data concentrator represents the upper limit, which could eventually be possible under optimal conditions and assuming longer reading intervals.

Fig. 5 shows the cumulative exergy consumption for 50 and 2,000 smart meters per DC. It is evident that a reduction of the cumulative EEC by 0.17 PJ can be achieved after 20 years of operation when connecting 2,000 smart meters to a single DC instead of 50. This value corresponds to a relative saving of 2.69%. This is a relatively small improvement of EEC. The cumulative OEC reduction that can be achieved by choosing the maximum configuration of a DC is also not that strong pronounced. The difference between the cumulative OEC of the two considered UCs equals to 0.06 PJ, which corresponds to a relative saving of 2.92%.

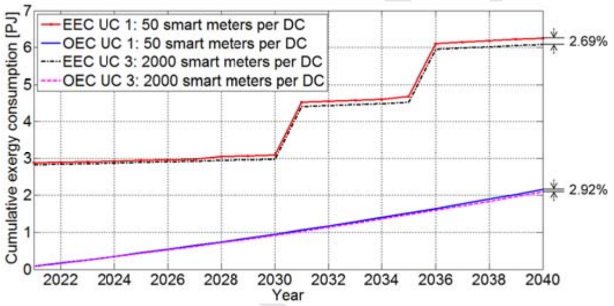


Fig. 5. Cumulative embodied (EEC) and operational (OEC) exergy consumptions for different data concentrator (DC) configurations (see Table V).

It can be concluded that the number of smart meters connected to a data concentrator does not have a strong influence on the cumulative exergy consumption of the overall system. As shown in Fig. 4, an increase of the utility equipment (UE) lifetime leads to a more significant reduction of the cumulative embodied exergy consumption (EEC), and consequently, to reduced environmental effects. The cumulative operational exergy consumption (OEC) turned out to be less dominant category over the entire operating time of 20 years. For that reason, it is associated with a lower environmental burden.

VI. Sustainability Analysis of the Advanced Metering Infrastructure (AMI) and Home Area Networks (HANs)

Now, we consider the entire system as depicted in Fig. 1, which includes additionally to AMI also the devices needed to implement the home area network (HAN). These are mainly user devices (UDs) such as the smartphone, tablet PC, and notebook as well as the home energy management system (HEMS). Additional communication equipment such as wireless routers and DSL modems might be needed to implement local area networks within the customer domain. We assume here that the HEMS is implemented in form of a server, on which suitable programs are running, in order to enable an efficient energy management and control of lights, heaters, air conditioners, dishwashers, refrigerators, washing machines, consumer electronics, and so on. In general, it is assumed that a single HEMS can provide energy management services for more than one household.

A. *Impact of the Equipment Lifetime*

Similar to the AMI case presented in Section V, we first concentrate on the influence of the equipment lifetime. We consider the combined AMI/HAN scenario and assumed three use cases for both utility equipment and user devices as presented in Table VI. Note that the lifetime of the user devices is assumed to be significantly shorter than that of the utility equipment.

TABLE VI.

DEFINITION OF USE CASES (UCS) FOR DIFFERENT USER DEVICES (UDS) AND UTILITY EQUIPMENT (UE) LIFETIMES IN THE COMBINED AMI/HAN SCENARIO

Use Case (UC)	UDs lifetime [years]					UE lifetime [years]		
	Smartphone	Tablet	Notebook	HEMS	DSL modem	Smart meter	PLC modem	Data concentrator
UC 1: short lifetime	1	1	2	2	3	5	5	3
UC 2: medium lifetime	2	2	3	4	5	15	10	7
UC 3: long lifetime	4	4	6	6	10	20	15	10

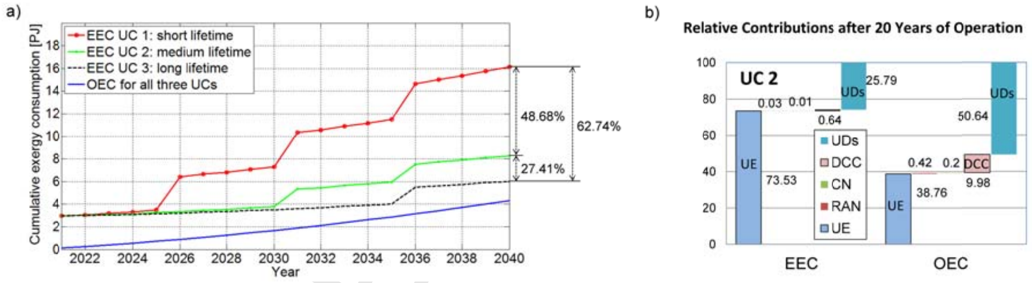


Fig. 6. Cumulative embodied (EEC) and operational (OEC) exergy consumptions for different utility equipment (UE) and user devices (UDs) lifetimes: a) development of the exergy consumption for the three considered use cases (see Table VI) and b) relative contributions of different equipment groups to the total EEC and OEC after 20 years of operation assuming use case 2 (UC 2).

Extending the equipment lifetime can lead to a significant reduction of the cumulative embodied exergy consumption (EEC) as indicated by the results presented in Fig. 6-a). This result is similar to the result obtained for the AMI case (see Section V). The potential reduction of the cumulative EEC after 20 years of operation turned out to be almost 63%, which corresponds to a huge exergy saving of 10 PJ. User devices contribute by about 26% to the total embodied exergy consumption and by almost 51% to the total operational exergy consumption as it becomes evident when observing Fig. 6-b). Note that this result suggests a relatively moderate impact of user devices on the total EEC, even though their lifetime is assumed to be much shorter than that of the utility equipment. This is mainly due to the relatively low utilization factor of UF = 0.083 that we assume here for user devices. The high share of UDs to the total cumulative OEC arises mainly due to the high power consumption of HEMSs, for which an uptime of 100% and an average load of 50% are assumed.

B. *Impact of User Devices Uptime*

In order to elaborate the impact of the utilization of user devices (UDs), which are used for home energy management applications, we define three use cases as shown in Table VII. In particular, we assume that smartphones, tablets, and notebooks are used 1, 2, or 4 hours per day, which corresponds to the usage factors of 0.042, 0.083 or 0.167, respectively. HEMS and DSL modems are assumed to remain active during the whole day, so the usage factor is set to 1 for these components.

TABLE VII.

DEFINITION OF USE CASES (UCS) FOR DIFFERENT USER DEVICES (UDS) UPTIMES

Use Case (UC)	Utilization factor (UF)				
	Smart phone	Tablet	Note book	HEMS	DSL modem
UC 1: high utilization	0.167	0.167	0.167	1	1
UC 2: medium utilization	0.083	0.083	0.083	1	1
UC 3: low utilization	0.042	0.042	0.042	1	1

As becomes evident from Fig. 7, the more intensive the use of the HAN equipment, the higher cumulative exergy consumption can be expected after 20 years of operation. Note that user devices are typically not exclusively used for smart grid applications. In fact, they can also be used for many other applications such as entertainment, communication, gaming, and home office. Therefore, both overall EEC and overall OEC of user devices are divided into of two parts according to their usage, namely into the smart grid related consumption and the consumption that occurs while using the device for all other applications. In this work, we consider the smart grid related consumption characterized by the utilization factor (UF). For this reason, an increase of UF leads to a higher smart grid related part of both EEC and OEC, assumed that the overall uptime of devices remains unchanged. As can be seen in Fig. 7, an increase in the usage of smartphones, tablets and notebooks from 1 hour (UC3) to 4 hours (UC1) per day leads to an increase of the total EEC and OEC by about 17% and 48%, respectively, which corresponds to an absolute increase of approximately 4 PJ in total. The relative contribution of user devices to the total embodied exergy consumption grows thereby from 21% to 34% (see Fig. 8).

The contribution of user devices to the total operational exergy consumption becomes even more significant, as it increases from 29% to 63%. Among other equipment categories, the equipment located in the data and control center (DCC) accounts for 14.5% of the total OEC in case of low utilization (UC3 with UF = 0.042), which can be reduced to about 7.5% when the usage of user devices increases to UF = 0.167 (UC1). The contribution of the network equipment within the access (RAN) and core (CN) areas is negligible since they contribute with less than 1 % in total.

Finally, note that to achieve a sustainable operation one has to ensure that energy savings enabled by home energy management applications are higher than the ICT related exergy consumption of the additional equipment required to introduce and run these applications. For example, assuming a relatively high usage factor (UC1), home energy management applications must achieve an exergy gain above 14 PJ over 20 years of operation in order to be able to compensate for the exergy loss due to the additional ICT equipment (see Fig. 7, EEC UC1 + OEC UC1 after 20 years of operation).

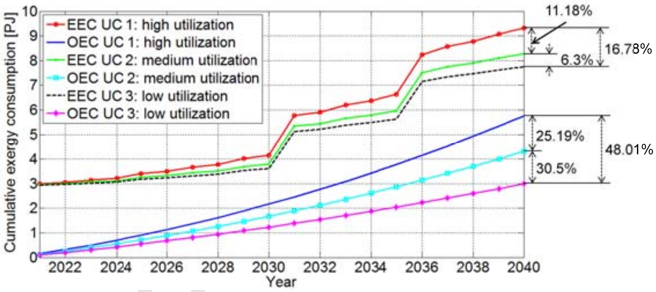


Fig. 7. Influence of the usage intensity of user devices (UDs): cumulative embodied (EEC) and operational (OEC) exergy consumption for the three considered use cases UC1 – UC3 (see Table VII).

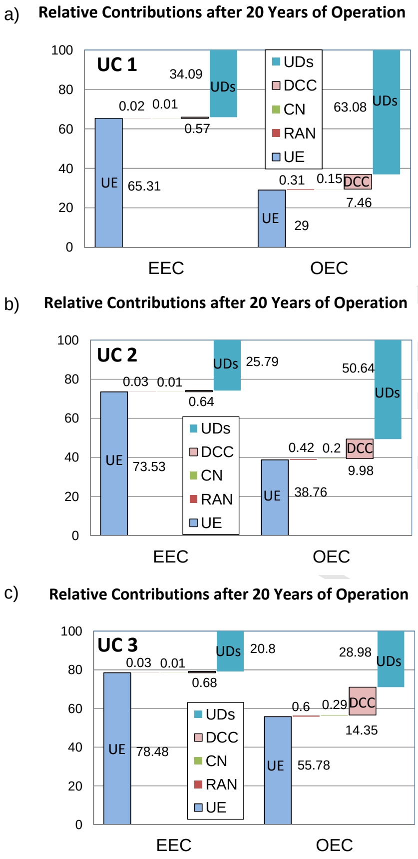


Fig. 8. Influence of the usage intensity of user devices (UDs): breakdown of the cumulative embodied (EEC) and operational (OEC) exergy consumption over different equipment groups and for the three considered use cases UC 1 – UC 3 (see Table VII).

C. Impact of the HEMS Configuration

Even though the HEMS can run on an ordinary personal computer (PC) and serve only one household, we assume here a HEMS implementation using dedicated servers that are able to serve many households (HHs). Such an implementation can lead to a more efficient installation, operation, and maintenance of the system.

The question that arises when a single HEMS device can serve a number of households (HHs) is: What is the influence of the number of HHs served by a HEMS on the cumulative exergy consumption? To answer this question, we assume three different HEMS configurations that enable 10, 20, and 100 HHs to be connected to and served by a single HEMS (see Table VIII).

TABLE VIII.

DEFINITION OF USE CASES (UCS) FOR THREE HOME ENERGY MANAGEMENT SYSTEM (HEMS) CONFIGURATIONS

Use Case (UC)	Number of HHs per HEMS
UC1: 10 households (HHs) per HEMS	10
UC 2: 20 households (HHs) per HEMS	20
UC 3: 100 households (HHs) per HEMS	100

The results presented in Fig. 9 indicate that the HEMS configuration has a significant influence on both cumulative embodied and operational exergy consumptions In particular, when the number of HHs served by a single HEMS is set to 100 instead of 10, a reduction of the cumulative embodied exergy consumption (EEC) of 21% can be achieved. The cumulative operational exergy consumtion (OEC) can even be reduced by almost 60% when assuming the same increase of the number of HHs per HEMS, i.e., from 10 to 100. This result emphasizes the importance of considering the HEMS configuration and resource sharing in the processes of design, implementation, and maintaining both home area networks and applications for home energy management.

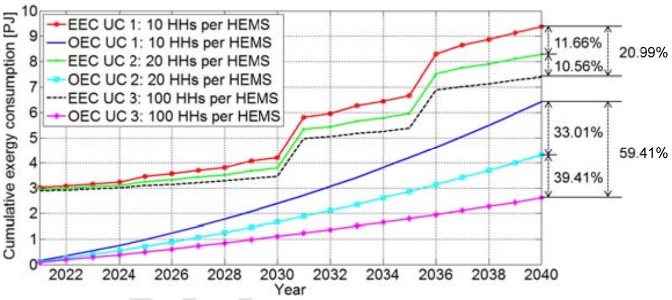


Fig. 9. Influence of the number of served households (HHs) by a single home energy management system (HEMS): cumulative embodied (EEC) and operational (OEC) exergy consumption for the three considered use cases UC1 – UC3 (see Table VIII).

VII. SUMMARY AND CONCLUSIONS

The introduction of smart grids promises a more efficient and reliable management of the electricity distribution network, an improved energy efficiency as well as integration and optimal use of renewable energy sources. However, to let this vision become true, additional equipment needs to be deployed, which will unavoidably contribute to an increase of both operational energy consumption and the environmental impact related to an increased resource depletion and electronic waste.

In this paper, we estimated the environmental sustainability of the information and communication technology (ICT) infrastructure needed for implementing advanced metering infrastructure (AMI) and home area networks (HANs). For this purpose, we carried out a thermodynamic sustainability analysis that utilizes the exergy-based life cycle assessment (E-LCA) method.

Considering the implementation of AMI, the results have shown that the deployment of smart meters and other required communication and data processing equipment can lead to an increase in total exergy consumption between 6.8 and 14.3 PJ over 20 years of operation and considering all life cycle phases. The contribution of the operational phase to the total exergy consumption is about 2.1 PJ, which corresponds to less than 33% of the total. The lifetime of the equipment has a very high impact on the cumulative embodied exergy consumption. The cumulative embodied exergy consumption can be reduced by about 62% by increasing the equipment lifetime by a factor of three. In contrary, the number of smart meters connected to a single data concentrator shows negligible influence on the cumulative exergy consumption. Connecting 2,000 instead of 50 smart meters to a single data concentrator leads to savings of 2.69% and 2.92% in the cumulative embodied and operational exergy, respectively.

Implementation and an extensive use of home area networks and home energy management applications promise an increase in energy efficiency in the customer domain. However, to optimally support the home energy management applications, one has to install additional equipment such as communication equipment and home energy management systems (HEMSs). Additionally, the usage intensity of user devices such as smartphones, tablets, and notebooks might increase. Similar to the AMI case, the additional ICT equipment required for implementing both the AMI and HAN systems would lead after 20 years of operation to an increase of the ICT related embodied exergy consumption by about 63%. The introduction of HEMSs and a more intensive use of user devices will contribute to an increase of the operational exergy consumption by a factor of 2 compared to the AMI case, which is mainly due to the high energy consumption of HEMS servers. The impact of the HEMS can be mitigated if many households are served by a single HEMS server. For example, sharing HEMS resources among 100 households instead of 10 can lead to a reduction of the operational exergy consumption by almost 60% and of the embodied exergy consumption by 21%.

In conclusion, our results have shown that the environmental impact of the additional ICT equipment needed for implementing smart grid applications cannot be neglected and has to be taken into account when assessing the environmental sustainability of smart grids. It is necessary to consider both the possible exergy gains, which can be achieved through introducing new concepts and applications for smart grids, and the exergy cost of the additional equipment needed to run these applications. Possible ways to reduce the exergy consumption of additional ICT components, i.e., to mitigate their environmental impact, are to increase the components' and systems' lifetime, to improve the manufacturing processes, to use existing communication and data processing infrastructure where possible, and to improve the energy efficiency of servers and data centers.

VIII. FUTURE WORK

The work presented in this communication is only a first attempt to assess the environmental impact of communication equipment for smart grids. A more broad study of various technological options for implementing smart grids is needed to obtain a more complete and exact picture of the ICT-related exergy cost as well as to identify realization options having the highest potential to reduce the exergy consumption. Future developments in both communication network and data center areas can be considered such as advanced technologies providing improved flexibility, adaptability, and energy efficiency. In order to fully understand the environmental impact of ICT equipment for smart grids, possible exergy gains through developing advanced smart grid systems and applications should be estimated and compared to the obtained ICT-related exergy consumptions. The final goal is to achieve the highest possible exergy gain while keeping the exergy consumption of the additional ICT equipment as low as possible.

APPENDICES: ASSUMPTIONS FOR THE EXERGY CALCULATION

A. Material Composition of Utility Equipment (UE)

1) Smart Meter

The material/component composition of the Elster REX2 smart meter shown in Table IX is based on analytical conclusions and the information provided in [23]. The material breakdown of the printed circuit board (PCB), the current transformer (CT), and the power transformer (PT) was estimated based on analytical thinking and the data provided in [24-29], with the aim to increase the data accuracy.

TABLE IX.

MATERIAL/COMPONENT COMPOSITION OF THE SMART METER.

Material/Component	Weight [g]	Portion of the total weight [%]
Steel	161	7
Copper	414	18
Plastic	460	20
Printed circuit board (PCB)	184	8
Current transformer (CT)	345	15
Power transformer (PT)	391	17
Liquid crystal display (LCD)	23	1
Other	322	14
Total	**2,300**	**100**

2) *Power Line Communication (PLC) Modem*

The material/component composition of the Texas Instruments (TI)-based power line communication (PLC) modem shown in Table X is based on analytical conclusions and the information provided in [30,31]. The material breakdown of the printed circuit board (PCB) and the PLC transformer (PLCT) was estimated based on analytical thinking and the data provided in [24,32-34].

TABLE X.

MATERIAL/COMPONENT COMPOSITION OF THE PLC MODEM.

Material/Component	Weight [g]	Portion of the total weight [%]
Steel	12.5	5
Plastic	80.0	32
Printed circuit board (PCB)	62.5	25
PLC transformer (PLCT)	57.5	23
Other	37.5	15
Total	**250.0**	**100**

3) *Data Concentrator*

The material/component composition of the Texas Instruments (TI)-based data concentrator shown in Table XI is based on analytical conclusions and the information provided in [35-37], with the aim to increase the data accuracy.

TABLE XI.

MATERIAL/COMPONENT COMPOSITION OF THE DATA CONCENTRATOR.

Material/Component	Weight [g]	Portion of the total weight [%]
Steel	53.2	19
Plastic	72.8	26
Printed circuit board (PCB)	95.2	34
Other	58.8	21
Total	**280.0**	**100**

The material breakdown of the printed circuit board (PCB) was estimated based on data provided in [24]. To the weight of 200 g provided in [36], additional 80 g of plastic, steel, and other materials for the casing were added, resulting in a total weight of 280 g for the data concentrator.

B. Material Composition of User Devices (UDs)

1) Smartphone

The material/component composition of the Apple iPhone 5C smartphone shown in Table XII is based on the data provided in [38]. The material breakdown of the printed circuit board (PCB) and the battery was estimated based on analytical thinking and the data provided in [24,39-53], with the aim to increase the data accuracy.

TABLE XII.

MATERIAL/COMPONENT COMPOSITION OF THE SMARTPHONE.

Material/Component	Weight [g]	Portion of the total weight [%]
Steel	41	31.06
Plastic	7	5.30
Glass	18	13.64
Display	11	8.33
Polycarbonate	14	10.61
Printed circuit board (PCB)	13	9.85
Battery	25	18.94
Other	3	2.27
Total	**132**	**100.00**

2) Tablet

The material/component composition of the Apple iPad mini tablet (see Table XIII) is based on the data provided in [41]. The material breakdown of the printed circuit board (PCB) and the of battery was estimated analytically and based on the data provided in [24,39-53].

TABLE XIII.

MATERIAL/COMPONENT COMPOSITION OF THE TABLET.

Material/Component	Weight [g]	Portion of the total weight [%]
Aluminum	62	20.06
Plastic	10	3.24
Glass	42	13.59
Display	81	26.21
PCB	24	7.77
Battery	78	25.24
Other metals	12	3.88
Total	**309**	**100.00**

4) *Notebook*

The material/component composition of the 13-inch MacBook Pro with Retina Display (w/RD) (see Table XIV) is based on the data provided in [42]. The material breakdown of the printed circuit board (PCB) and the battery was estimated based on analytical thinking and the data provided in [24,39-53], with the aim to increase the data accuracy.

TABLE XIV.

MATERIAL/COMPONENT COMPOSITION OF THE NOTEBOOK.

Material/Component	Weight [g]	Portion of the total weight [%]
Aluminum	614	39.13
Plastics	49	3.12
Glass	150	9.56
Keyboard and trackpad	90	5.74
Display panel	92	5.86
Printed circuit board (PCB)	155	9.88
Battery	334	21.29
Solid-state drive (SSD)	13	0.83
Other metals	72	4.59
Total	**1,569**	**100.00**

3) *Home Energy Management System (HEMS)*

The material composition of the home energy management system (HEMS) provided in Table XV is based on the data provided in [4,15].

TABLE XV.

MATERIAL COMPOSITION OF THE HEMS.

Material/Component	Weight [g]	Amount of total weight [%]
Aluminum	3,250	15.55
Steel	12,380	59.23
Plastic	1,410	7.46
Copper	1,560	4.07
Iron	850	6.75
Glass	110	0.53
Epoxy	70	0.33
Ceramics	40	0.19
Other	1,230	5.89
Total	**20,900**	**100.00**

C. Raw Material Extraction and Processing

The estimation of the raw material extraction and processing exergy consumption of the ICT equipment is achieved by using mass-specific exergy consumption values for different materials obtained from [4] and [15]. 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 summarized in Table XVI.

TABLE XVI.

MASS-SPECIFIC EXERGY CONSUMPTION VALUES FOR RAW MATERIAL EXTRACTION AND PROCESSING.

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, Other	20,000

D. *Manufacturing and Assembly*

The manufacturing and assembly exergy consumption is composed of the exergy needed 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 [4,15]. The exergy consumption values we used for different manufacturing and assembly processes are summarized in Table XVII.

TABLE XVII.

EXERGY CONSUMPTION VALUES FOR MANUFACTURING AND ASSEMBLY.

Material [unit]	Specific exergy
Metals [kJ/kg]	0.28
Plastics [kJ/kg]	14.90
PCBs [kJ/m^2]	238,400.00
ICs [kJ/IC]	12,500.00
Processors [kJ/processor]	1,242,000.00

E. *Transportation*

The transportation exergy consumption does not depend merely on the mass of materials, but also on the distance between process stages, and the transportation mode [4,15]. Table XVIII shows the mass (and distance)-specific exergy consumption values for different transportation modes.

TABLE XVIII.

MASS (AND DISTANCE)-SPECIFIC EXERGY CONSUMPTION VALUES FOR DIFFERENT TRANSPORTATION MODES.

Mode of transportation	Specific exergy [kJ/kg-km]
Air	22.41
Truck	2.096
Rail	0.253
Ship	0.296

F. Recycling and Disposal

The estimation of the exergy consumption expended on the recycling and disposal of the considered ICT equipment is based on the data provided in [14] and equals to approximately 520 kilo joules per kilogram (kJ/kg).

REFERENCES

[1] International Telecommunication Union (ITU), “Boosting energy efficiency through Smart Grids,” 2012, available online: http://www.itu.int/dms_pub/itu-t/oth/4B/01/T4B010000050001PDFE.pdf (accessed on 27 March 2015).

[2] European Commission, Information Society, ICT for Sustainable Growth, “Smart Grids,” available online: http://ec.europa.eu/information_society/activities/sustainable_growth/grids/index_en.htm (accessed on 27 March 2015).

[3] Aleksic S., Mujan V., “Life cycle based analysis of ICT equipment for advanced metering infrastructure,” 13th International Conference on Telecommunications (ConTEL), Graz, Austria, July 2015, pp. 1-7.

[4] Lettieri D. J., "Expeditious Data Center Sustainability, Flow, and Temperature Modeling: Life-Cycle Exergy Consumption Combined with a Potential Flow Based, Rankine Vortex Superposed, Predictive Method," Doctoral Thesis, University of California, Berkeley, Spring 2012.

[5] Lettieri D. J., Hannemann C. R., Carey V. P., Shah A. J., “Lifetime Exergy Consumption as a Sustainability Metric for Information Technologies,” Proceedings of the 2009 IEEE International Symposium on Sustainable Systems and Technology, vol. 00, IEEE Computer Society, 2009, pp. 1–6.

[6] Tsatsaronis G., Cziesla F., “Basic Exergy Concepts,” Exergy, Energy System Analysis and Optimization, vol. 1, UNESCO, EOLSS, 2009, pp. 292.

[7] Rosen M. A., Dincer I., Kanoglu M., “Role of exergy in increasing efficiency and sustainability and reducing environmental impact,” Energy policy, vol. 36, no. 1, January 2008, pp. 128–137.

[8] Aleksic S., “Energy, Entropy and Exergy in Communication Networks,” Entropy, vol. 15, no. 10, 2013, pp. 4484–4503.

[9] Socolow R. H., Rochli G. I., “Efficient Use of Energy, a Physics Perspective,” American Institute of Physics (AIP), Spring Branch, TX, USA, 1975, pp. 305.

[10] Budka K. C., Deshpande J. G., Thottan M., “Communication Networks for Smart Grids - Making Smart Grid Real,” Computer Communications and Networks, Springer, 2014.

[11] Statistics Austria, private households forecastes, Privathaushalte 2011-2060 nach Bundesländern, Dezember 2014, available online: http://www.statistik.at/web_de/statistiken/bevoelkerung/demographische_prognosen/haushalts_und_familienprognosen/023529.html (accessed on 27 March 2015).

[12] Safaei M., “Exergy-based life cycle assessment (E-LCA) of cloud computing,” Master Thesis, Vienna University of Technology, Institute of Telecommunications, Vienna, Austria, September 2013.

[13] Aleksic S., Safaei M., "Exergy consumption of cloud computing: a case study," Invited Paper, NOC 2014, Milan, Italy, June 4–6, 2014, pp. 1–6.

[14] Aleksic S., Safaei M., "Exergy based analysis of radio access networks," Invited Paper, Proceedings of ICEAA - IEEE APWC – EMS 2013, 2013, pp. 1–8.

[15] Hannemann C. R., Carey V. P., Shah A. J., Patel C., "Lifetime Exergy Consumption as a Sustainability Metric for Enterprise Servers," Proceedings of ASME 2nd International Conference on Energy Sustainability, Jacksonville, Florida USA, August 10–14, 2008, pp. 1–8.

[16] Forum Mobilkommunikation (FMK), http://www.fmk.at/en.

[17] Austrian Regulatory Authority for Broadcasting and Telecommunications (RTR), https://www.rtr.at/en/rtr/RTRGmbH.

[18] Scharnhorst W., "Life Cycle Assessment of Mobile Telephone Networks, with Focus on the End-of-Life Phase," Dissertation, Lausanne, EPFL, 2006.

[19] Aleksic S., Deruyck M., Joseph W., "Energy efficiency of optically backhauled LTE: a case study," (invited), Proceedings of ICEAA - IEEE APWC – EMS, Torino, Italy, September, 2013, pp. 39–393.

[20] Aleksic S., Franzl G., Bogner Th., Mair am Tinkhof O., "Framework for Evaluating Energy Efficiency of Access Networks," Proceedings of the IEEE International Conference on Communications (IEEE ICC13) - Workshop on Green Broadband Access: energy efficient wireless and wired network solutions, Budapest, Hungary, June, 2013, pp. 558–563.

[21] Luan W., Sharp D., LaRoy S., "Data Traffic Analysis of Utility Smart Metering Network," Power and Energy Society General Meeting (PES), 2013 IEEE, IEEE, 2013, pp. 1–4.

[22] Prakash P., Texas Instruments, White Paper, "Data concentrators: The core of energy and data management," available online: http://www.ti.com/lit/wp/spry248/spry248.pdf (accessed on 29 March 2015).

[23] EDN Network, "What's inside a smart meter? iFixit tears it down," available online: http://www.edn.com/design/power-management/4368353/What-s-inside-a-smart-meter-iFixit-tears-it-down (accessed on 30 March 2015).

[24] Sunil Mohite, "Disassembly Analysis, Material Composition Analysis and Environmental Impact Assessment of Computer Disk Drives," Dissertation, Texas Tech University, May 2005.

[25] AC Current Transformers for Instrumentation, available online: http://www.omega.com/Heaters/pdf/ctr_series.pdf (accessed on 30 March 2015).

[26] Blue Sea Systems, AC Current Transformer Coil – 150A AC/50mA AC, available online: https://www.bluesea.com/products/8256/AC_Current_Transformer_Coil_-_150A_AC_50mA_AC (accessed on 30 March 2015).

[27] Line Transformers – E-I 30 x 12.5 (1.5 VA Series), Power Magnetic, Falco electronics, available online: http://www.falco.com/products/1frame/pdf/EI-30x12.pdf (accessed on 30 March 2015).

[28] Element 14, Technical portal and online community for Design Engineers, Transformers, available online: http://pdf.datasheetarchive.com/indexerfiles/gl/Datasheets-RS/f35.pdf (accessed on 30 March 2015).

[29] Power Magnetics, Current Transformers for Electronic Watt-Hour Meters, AC, Toroidal Series, Falco electronics, available online: http://www.falco.com/products/1frame/pdf/CTWH_AC.pdf (accessed on 30 March 2015).

[30] Larimore B., Texas Instruments, "PLC With the AC LED Lighting and Communications Developer's Kit," Application Report, SPRABS0–January 2013, available online: http://www.ti.com/lit/an/sprabs0/sprabs0.pdf (accessed on 30 March 2015).

[31] Element 14, Texas Instruments TMDSPLCKIT-V3 C2000, Power Line Modem, Dev Kit, available online: http://in.element14.com/texas-instruments/tmdsplckit-v3/c2000-power-line-modem-dev-kit/dp/2113701 (accessed on 30 March 2015).

[32] Würth Elektronik, PLC Transformer for Texas Instruments AFE030/AFE031/AFE032, available online: http://www.we-online.com/web/en/passive_components_custom_magnetics/products_pbcm/product_spotlight/texasinstruments_750510476.php (accessed on 30 March 2015).

[33] Würth Elektronik, Smart Metering, available online: http://www.we-online.de/web/en/index.php/show/media/06_passive_components_-_custom_magnetics/pdf_doc_files_1/9999043_Metering_Catalog.pdf (accessed on 30 March 2015).

[34] Vacuumschmelze, Current Transformers and Power Line Transformers for Smart Metering, available online: http://www.vacuumschmelze.com/fileadmin/Medienbiliothek_2010/Downloads/KB/PB-CT.pdf (accessed on 30 March 2015).

[35] Texas Instruments, Data Concentrator System Solution, available online: http://www.ti.com/lit/ml/slyt431c/slyt431c.pdf (accessed on 30 March 2015).

[36] Farnell, Element 14, Texas Instruments TMDSDC3359 Eval Kit, Data Concentrator Module, available online: http://uk.farnell.com/texas-instruments/tmdsdc3359/evalkit-data-concentrator-module/dp/2364730 (accessed on 30 March 2015).

[37] Texas Instruments, Data Concentrator Evaluation Module, (ACTIVE) TMDSDC3359, available online: http://www.ti.com/tool/TMDSDC3359 (accessed on 30 March 2015).

[38] iPhone 5C, Environmental Report, available online: https://www.apple.com/environment/reports/docs/iPhone5c_product_environmental_report_sept2013.pdf (accessed on 29 March 2015).

[39] Material Safety Data Sheet, MSDS of Lithium Polymer battery (total 3 pages), available online: http://www.nrel.gov/education/pdfs/lithium-ion_battery_materials_safety_data_sheet.pdf (accessed on 30 March 2015).

[40] Yoku Energy (Zhangzhou) Co., Ltd, Material Safety Data Sheet, available online: http://www.farnell.com/datasheets/1798075.pdf (accessed on 30 March 2015).

[41] iPad mini, Environmental Report, available online: https://www.apple.com/environment/reports/docs/iPadmini_PER_Oct2013.pdf (accessed on 29 March 2015).

[42] 13-inch MacBook Pro with Retina Display, Environmental Report, available online: https://www.apple.com/environment/pdf/products/archive/2014/13inch_MacBookPro_wRetina_PER_July2014.pdf (accessed on 29 March 2015).

[43] bcm/product_spotlight/texasinstruments_750510476.php (accessed on 30 March 2015).

[44] Würth Elektronik, Smart Metering, available online: http://www.we-online.de/web/en/index.php/show/media/06_passive_components_-_custom_magnetics/pdf_doc_files_1/9999043_Metering_Catalog.pdf (accessed on 30 March 2015).

[45] Vacuumschmelze, Current Transformers and Power Line Transformers for Smart Metering, available online: http://www.vacuumschmelze.com/fileadmin/Medienbiliothek_2010/Downloads/KB/PB-CT.pdf (accessed on 30 March 2015).

[46] Texas Instruments, Data Concentrator System Solution, available online: http://www.ti.com/lit/ml/slyt431c/slyt431c.pdf (accessed on 30 March 2015).

[47] Farnell, Element 14, Texas Instruments TMDSDC3359 Eval Kit, Data Concentrator Module, available online: http://uk.farnell.com/texas-instruments/tmdsdc3359/evalkit-data-concentrator-module/dp/2364730 (accessed on 30 March 2015).

[48] Texas Instruments, Data Concentrator Evaluation Module, (ACTIVE) TMDSDC3359, available online: http://www.ti.com/tool/TMDSDC3359 (accessed on 30 March 2015).

[49] iPhone 5C, Environmental Report, available online: https://www.apple.com/environment/reports/docs/iPhone5c_product_environmental_report_sept2013.pdf (accessed on 29 March 2015)

[50] Material Safety Data Sheet, MSDS of Lithium Polymer battery (total 3 pages), available online: http://www.nrel.gov/education/pdfs/lithium-ion_battery_materials_safety_data_sheet.pdf (accessed on 30 March 2015).

[51] Yoku Energy (Zhangzhou) Co., Ltd, Material Safety Data Sheet, available online: http://www.farnell.com/datasheets/1798075.pdf (accessed on 30 March 2015).

[52] iPad mini, Environmental Report, available online: https://www.apple.com/environment/reports/docs/iPadmini_PER_Oct2013.pdf (accessed on 29 March 2015).

[53] 13-inch MacBook Pro with Retina Display, Environmental Report, available online: https://www.apple.com/environment/pdf/products/archive/2014/13inch_MacBookPro_wRetina_PER_July2014.pdf (accessed on 29 March 2015).