4

Embodied Energy of Communication Devices

Modeling Embodied Energy for Communication Devices

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4.1 Introduction

During past few decades, the Information and Communication Technology (ICT) has played a very important role in a modern society. However, the extensively growing numbers of users, new product and service launches as well as the rising service usage times are putting great demand on energy consumption in ICT infrastructure today.

4.1.1 Energy Consumption of ICT in Figures

From the operating point of view, approximately 600 TWh or 3% of total worldwide electrical energy is being consumed by the ICT [1, 2], causing approximately 2% of the world's CO_2 emissions, and this number is even expected to grow to 1,700 TWh by the end of 2030 [3]. Telecommunication equipment (mobile, fixed, and communication devices, excluding consumer entertainment and media) currently contributes 30% to this figure or roughly 1% of the world's total electricity consumption, resulting in 30 TWh per year in United States (US) only. The major branch of this sector is mobile telephony responsible for a half of this energy

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consumption [2, 4]. It is expected to grow[1] further with a still rising demand for ICT services in developing countries and due to their above-mentioned popularity.

Being a large consumer, the ICT community has increasingly recognized the importance of energy-related topics during last years. There are at least two strong motivating factors driving further research and improvements in this field. The first one is definitely to minimize the environmental impact of this sector on the climate change caused by increased CO_2 and other greenhouse gases concentration levels in the atmosphere emitted mostly due to the use of fossil fuels as a primary source for production of electrical energy. As its usage in ICT sector has grown lately, it is estimated to contribute a 2.7% to the global CO_2 emissions in 2020, resulting in 1.43 Gtons per year. Besides their corporate responsibility regarding the environmental protection, the telecommunication operators are becoming increasingly aware of their energy bills, which are estimated to grow to approximately four billion EUR of their operating expenses (OpEx9 in European Union). Thus, the reduction of energy consumption has also a direct economic effect.

4.1.2 The Approaches to Reduce ICT Energy Consumption

From the two above-mentioned reasons and in the perspective of the energy-efficient society, it is desirable that the ICT sector reduces its energy consumption. Consequently, the researchers are suggesting many different approaches to reduce operating costs and effects on the environment.

There are three main basic concepts aiming at energy consumption of ICT [1] and are as follows:

1. Re-engineering – is based on introduction and design of more energy-efficient elements for network device architectures, rearrangement and optimization of the organization of devices as well as at reduction of their intrinsic complexity levels.
2. The dynamic adaptation of network or device resources – modulates the capacities of network interfaces and processing engines to follow actual traffic loads and requirements. It is achieved by two power aware capabilities: dynamic voltage scaling and idle logic – a dynamic trade-off between packet service performance and power consumption.
3. Sleeping/standby approaches – are used to selectively drive unused network/device portions to low standby modes and to wake them up only if necessary.

4.1.3 The Problem of Past Researches

In previous works, the authors suggested different approaches to reduce the energy consumption and improve energy efficiency of ICT for each of the above-mentioned concepts. However, some of the proposed approaches related to the concept of network re-engineering or sleeping/standby strategies suggest adding network elements in order to decrease operating energy of the existing elements.

An example of such approach that is discussed later in more detail is a cellular network. Its general idea is to find a trade-off between a decrease in operating energy based on reduced

[1] The power consumption is growing 16–20% per year [5].

transmission power and a consequently increased operating energy caused by higher number of cells, where sleep-mode strategy can be used for further energy savings. A common suggestion of these research works is to improve the energy efficiency of cellular networks by using base stations (BS) with a reduced transmission power (reduced operating energy) such as micro, pico, or femtocells, but employing a larger number of them to maintain the coverage and capacity.

Another example is the network connectivity proxying scheme [6] which employs external network proxies that virtually maintain presence for network computers, but lets them powered-down and saves energy while idle. In some cases, this approach may require additional hardware that should be further evaluated from the perspective of energy consumption.

Even if we overlook the problem that most of today's widely employed hardware does not necessarily support a sudden total power-off strategy suggested in many of these researches, there is another notable drawback in the proposed approaches. Although all of these researches successfully proved to reduce the operating energy consumption, they paid no attention to the embodied energy[2] which is consumed by the manufacturers to produce the additional high-tech equipment. Some of the analyses avoid the consideration of the embodied energy claiming that there are no publicly available databases to collect the required parameters; others simply ignore it without any remarks. Until recently, it was thought that the embodied energy content of electronic devices is negligibly small compared to the energy used in operating the device over its life; therefore, most previous researches endeavored for energy conservation on this assumption.

In contrast to approaches from previous studies, this chapter shows how important it is to include embodied energy in energy efficiency modeling. The simulation results of such an extended modeling confirm the important trade-off between operating and embodied energy consumption. The results provide some guidelines for manufacturers, operators, and researchers.

4.2 The Extended Energy Model

It is obvious that a lot of energy is needed by the ICT equipment to operate. However, a lot of energy is also needed to manufacture the device. Hence, to analyze the total energy usage, it is not sufficient to only look at the operating energy consumption, the embodied energy of a device must also be included.

4.2.1 The Embodied Energy and Its Meaning in ICT Technology

By the common definition, the embodied energy E_{EM} is the energy consumed by all the processes associated with the production of a device. The initial embodied energy E_{EMinit} comprises the energy used to acquire and process raw materials, transport, manufacture components as well as to assembly and install all products in the initial construction of the device. The maintenance embodied energy E_{EMmaint} includes the energy associated with maintaining, repairing, and replacing materials and components of the device over its lifetime. Some authors prefer an expanded definition associated with a broader field known as life cycle assessment

[2] See Section 4.2.1 for further details on embodied energy.

(LCA) which attempts to characterize all environmental impacts from "cradle-to-grave," extending the above-mentioned components with the energy used for extraction of resources following by the energy for sales, use, demolition, and disposal of equipment.

Even though it seems that the consideration of the embodied energy in the process of total energy evaluation in the field of ICT is a somehow new approach, it has a long tradition in other disciplines, such as building construction [7] and car production [8]. Embodied energy has already been taken into account in some fields of electronics engineering, such as photovoltaic [9] and even with ICT more closely related areas, such as computer industry [10] and mobile phone production [11]. Figure 4.1 shows the relation between the embodied and operating energy for the representative technologies/products of three selected societies (urban, industrial, and information) during their life cycles (a) buildings/house, (b) vehicles/car, and (c) ICT/electronic equipment (a BS[3] which will later be discussed in more detail). Although

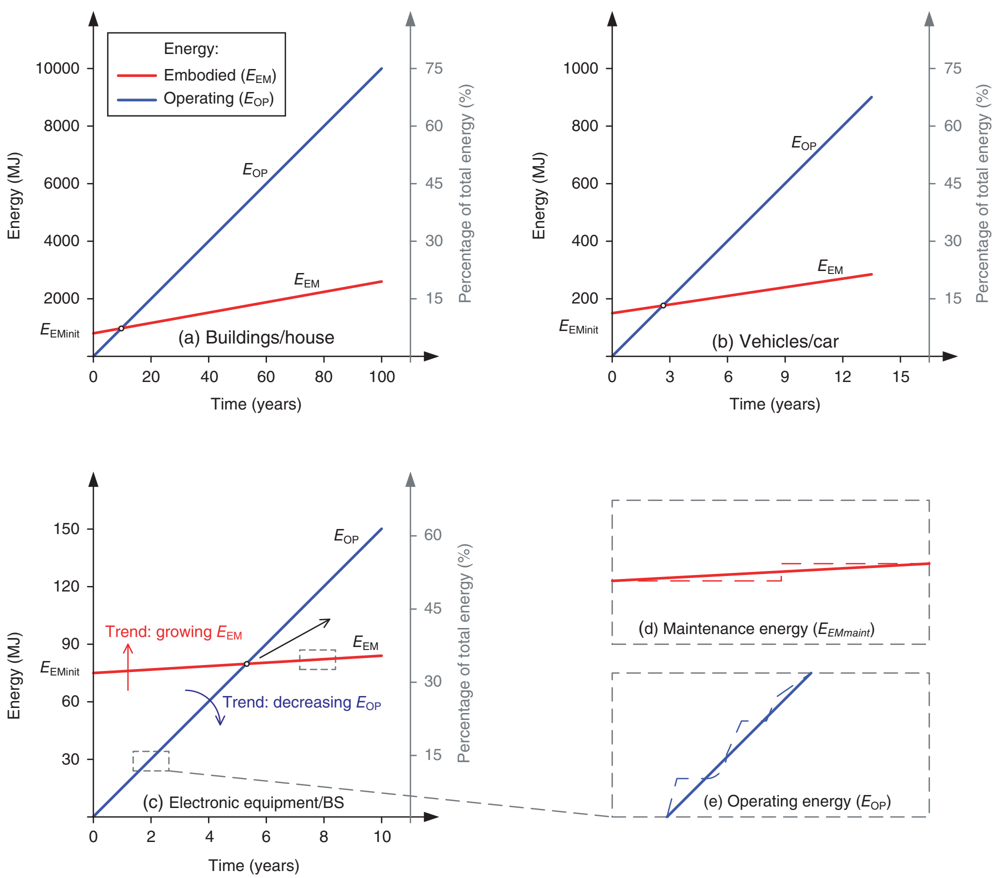

Figure 4.1 Embodied and operating energies of house, car, and electronic/ICT device during their lifetimes

[3] Based on our estimation for a general BS, see Section 4.2: Embodied energy estimation for a general BS.

the numbers used in these figures are rough estimations for averages of greatly varying values[4] given by the literature, an obvious difference among them enables us to draw some important conclusions that directly influence ICT area.

One of the most remarkable facts that should be noted in these graphs is the shift of the intersection point between the curves of embodied and operating energy to the upper-right position, explaining that the ratio between embodied and operating energy during the life cycle of modern (electronic or ICT) equipment is much higher in comparison to the house or car, mainly reasoning in a sophisticated and energy-insensitive production of semiconductors, minimized operating energy consumption of these devices, and their relatively short life cycles due to frequent replacements caused by the upcoming technologies.

The scale on the right explains the share (percentage) of initial embodied energy relative to the total energy used in devices lifetime. While the embodied energy represents a relatively small part of total energy in houses (7–10%) or cars (10–15%) in comparison to electronic or ICT devices (30–40%), it is ironic that the problem of embodied energy is studied in depth in the aforementioned disciplines, while research work in the area of ICT simply neglects it.

4.2.2 Embodied Energy Assessment of an ICT Equipment

Several different methodologies to assess the device's initial embodied energy and its environmental impacts exist and are designed to be conducted by the manufacturing companies and their component suppliers. They range from the well-known LCA [12], employing very extensive studies, requiring data that are not easily available and taking a great deal of time to be completed, to the ecological footprint analysis (EFA) [13] and key environmental performance indicators (KEPI) [14] approach which is more easy to use and requires less time and input data. Although some of manufacturers (i.e., [4, 11, 15]) have already conducted at least some parts of LCA, the collected data is usually kept confidentially or provided with a great delay, sometimes also because of the extensive space of time spent to perform assessment (e.g., a report in year 2004 discusses the equipment from the year 2000 or earlier), which is of little use due to quickly changing component materials and developing processes of manufacturing. The data is often provided merely in an aggregated form – that is, the embodied energy for the entire equipment of an operator's network, including radio access networks, data centers, and office equipment. It is thus not possible to distinguish the embodied energy of a single ICT equipment. It should also be noted that most of the publicly available data is given for commercial purposes, which makes them questionable in reliability.

Since no detailed, trustworthy, and up-to-date data is provided by the manufacturers, it is necessary to employ a different approach enabling the external observer to estimate the initial embodied energy. As an illustration, we provide an example of embodied energy estimation for a BS of a cellular network in the next subsection.

In the past, researchers suggested many different methods, but the work [16] does not offer just a versatile approach for estimation of embodied energy but a suitable tool as well, referring to many studies for the embodied energy parameters of different materials and processes. The basic principle of this methodology is to make assumptions on the most important materials and manufacturing processes of electronic equipment and to then use the data from available high-quality studies for individual parts and extrapolate the results to get representative integrative figures.

[4] The embodied energy of buildings in different counties depends on traditionally used construction materials, whereas the operating energy depends on the climate conditions.

ICT equipment is generally made of several thousands of components made up of a large variety of materials and substances. Mechanical housing and electrical components are usually made up of metals and plastic polymers. The hart is a set of printed wiring boards with active electronic components such as integrated circuits and passive electronic components such as resistors, capacitors, conductors, and connectors. The power supply may include batteries, but for the sake of their diversity they were excluded from our study.

A great majority of a state-of-the-art electronic device's embodied energy is used for semiconductors' processing and manufacturing. This is due to very complex processes of wafer manufacturing that may include up to several hundred distinct process steps. The share of energy used for semiconductor devices in our estimation is in agreement with previous research [17] revealing that in computer industry, almost 95% of the energy content for electronics manufacturing goes into the wafer manufacturing/chip packaging. In Ref. [16], they have also noted that in comparison with this numbers, the energy of other phases of electronic manufacturing (printed board manufacture, board-level assembly, display manufacturing, and final assembly) may be safe to neglect. As ICT equipment consists not only of electronics, but also a large power supply, climate (cooling) equipment, and housing, the share of embodied energy of semiconductors in general telecommunication equipment is not expected to be as high as with computers. The passive electronic components usually account for only 1% of total initial embodied energy [11]. The rest of embodied energy can be summarized in the following groups: bulk and metal materials, conventional manufacturing, components manufacturing and assembly, and cables. The energies of supply chain, transportation, and setup of the equipment also have to be considered.

It should be noted that given approach focuses strictly on materials and manufacturing processes, consequently some parameters, such as research and engineering activities or software developments (that are also energy consuming), are disregarded, since they are hard to relate to specific processes or products. This is also an interesting direction for further research in the field of total LCA that have to be carried out in cooperation with equipment manufacturers.

4.2.3 Maintenance

The maintenance embodied energy is associated with maintaining, repairing, and replacing materials and components of the ICT equipment over its lifetime. The dashed line in Figure 4.1 shows that maintenance activities are performed consecutively at certain time periods, which can be interpreted as a linear function of time illustrated with the solid line on the same picture. The estimations of maintenance embodied energy slightly differs by the sort of ICT equipment, but in general, it can be estimated by 1% of initial embodied energy per year (maintenance power $P_{\mathrm{EMmaint}} = E_{\mathrm{EMinit}}/(100\ \ \mathrm{years})$).

4.2.4 Importance of Lifetime

To be able to compare the manufacturing phase with the operation phase of the ICT equipment within its life cycle, it is essential to consider the time aspect. To do that, the lifetime for the studied products must be reflected. The lifetime of ICT equipment can vary, but it is usually in the interval between 5–15 years. Unfortunately, this corresponds to anticipated commercial lifetime which is in many cases sufficiently shorter than the technical lifetime. Since the new technologies supersede the previous one very expeditiously, the equipment is usually replaced before the end of it technical lifetime, what virtually extends the share of embodied energy in total energy during lifetime. This high-energy intensity of manufacturing combined with rapid turnover in equipment further encourages the need to rethink the suggested energy models. Assumption about lifetime of ICT device has a significant impact on the results of the share of embodied energy in total devices energy.

4.2.5 The Operating Energy

As it has already been noted in the introduction, ICT consumes approximately 600 TWh per year, corresponding to roughly 3% of global electricity consumption [5].

For further analysis, it should be noted that the operating energy E_{OP} can be divided into two parts: a constant part $E_{OPconst}$ representing the fixed energy consumed by ICT equipment that does not depend on the traffic load (i.e., in idle state it is the same as in case of fully loaded system): energy, used to power up a device, battery backup, and so on, and E_{OPlin}, that is linearly scaled with the transmission energy, representing the power needed to process the traffic, perform signal processing, cooling or to cover amplifier and feeder losses in cellular networks. ($E_{OP} = E_{OPlin} + E_{OPconst}$). Consequently, the linear relation of the operating power (P_{OP}) to its transmission power (P_{TX}) can be applied as $P_{OP} = a \cdot P_{TX} + b$.

4.2.6 The Total Energy Consumption Model

With regard to the conclusions of previous chapters, we propose a total energy consumption model of ICT device that includes both the embodied energy and the operating one as follows:

$$E = E_{EM} + E_{OP} = E_{EMinit} + E_{EMmaint} + E_{OPlin} + E_{OPconst} \quad (4.1)$$

The initial embodied energy is expended once in the initial production of the device, whereas maintenance embodied and operation energy accrues over the effective lifetime of the BS and can be expressed as $E_{OP} = P_{OP} \cdot T_{lifetime}$, $E_{EMmaint} = P_{EMmaint} \cdot T_{lifetime}$.

Sleep-mode or power-off strategies, suggested by some of past researches, will further decrease the operating energy in comparison with embodied energy. Similarly, shortening the commercial lifetime of the equipment will additionally alter this relation, strengthening the part of embodied energy.

The ratio between the embodied and operating energy is also given in Figure 4.1. Comparing with total energy, the share of embodied energy of information society devices is much higher (32%) as opposed to the representative products of urban (7%) and industrial (13%) societies.

4.3 Embodied/Operating Energy of a BS in Cellular Network – A Case Study

As we already noted, mobile telephony is the major branch in telecommunications sector, responsible for a half of its energy consumption. A detailed look inside the energy consumption of operating mobile telephony services reveals that only up to 10% is associated with the users equipment, whereas the remaining share of 90% is consumed by the network components [18], more specifically, around two-thirds are used by the BSs.

4.3.1 Overview of Past Studies in BSs Energy Modeling

For this reason, the cellular networks have attracted many researchers with the aim to improve their energy efficiency. We will draw attention to just a few of them that are related to the system-level architectures and features of cellular networks. The main idea of these studies is to save energy with power-off strategy.

The study [19] suggests to power off the underutilized BSs during the period of low traffic. To maintain the coverage with the reduced number of BSs, the transmission operating power of the active BSs has to been increased. The authors search for an optimal energy saving in cellular access network, neglecting the increment of transmission operating power, avoiding the optimization problem of finding the lowest operating energy with different number of BSs and their coverage. Using trapezoidal and real-environment daily traffic patterns, they have proved that the savings of the order of 25–30% in the operating energy can be achieved with an optimal power-off scheme employed.

Similarly, the work [20] strives to find the optimal cell size between large and small cell deployments. The optimization process between increased cell radius (increases transmission operating power) and reduced cell radius (higher number of required cells increases fixed operating power) was upgraded by using sleep-mode strategy, powering off the cells without active users, but maintaining the capacity of the system. Using a simulation, they have shown that the reduction of cell sizes improves the operating energy consumption ratio (the energy, needed to transfer a bit of information), whereas the energy consumption gain (the ratio between the energies of large and small cell deployments) remains constant or increases linearly with the number of cells when using the sleep-mode strategy.

The second main research stream (such as the work provided in Ref. [21]) improves the energy efficiency by employment of two-tier cellular access network. The main idea of two-tier networks is to extend the conventional macro sites with the deployment of femto/pico/microcells covering much smaller area with cell radius between several meters to several hundred meters. They have addressed the optimization problem between the energy consumption by the macrosites (high transmission operating energy) and the additional operating energy required by the employment of femto/pico/microcells. A BS sleep-mode strategy was once more proved to be a promising mechanism to eliminate the energy consumption of underutilized BSs.

The general idea of all the above-mentioned and other similar studies is to find a trade-off between a decrease in operating energy, based on reduced transmission power, and a consequently increased operating energy, caused by higher number of cells, where sleep-mode strategy can be used for further energy savings. A common suggestion of these researches is to improve the energy efficiency of cellular networks by using BSs with a reduced transmission power (reduced operating energy), but employing a larger number of them to maintain the coverage and capacity. On the other hand, the main limitation of the above-mentioned studies is that they neglect the embodied energy of cellular network's equipment.

Due to the continuous efforts of communication systems manufacturers to improve [22, 23] the operating energy efficiency of their systems on one side and the increasingly complex processes of semiconductor manufacturing on the other side, the embodied energy of cellular networks' equipment is obviously far from being neglected. The embodied energy can be as high as half of operating energy in the equipment's lifetime. The previously described suggestions for saving the operating energy can obviously be very boomeranging: to save some operating energy, much additional equipment has to be installed, requiring much more embodied energy. And it is also clearly evident that the embodied energy cannot be avoided by using the power-off strategies.

4.3.2 The Need to Rethink Previous Models

Although none of the previous researches have yet investigated the energy efficiency of cellular network including the embodied energy, many authors have proposed it as an important further research direction. In the introduction of their paper [20], the authors have suggested that "both operating as well as embodied energy need to be considered in the evaluation", but the latter was neglected in the further analysis. The same opinion is shared in Ref. [2], where authors discuss the introduction of femtocells as an enhancement to the architecture of cellular networks. Evaluating the environmental effects of this approach, they noted that the "impact of equipment manufacturing should also be taken into account." It should also not be neglected that this topic has recently attracted some research groups, standardization bodies, as well as research departments of cellular network equipment manufacturers, who have started to work toward the analysis of environmental impacts associated with delivering of their product, which will hopefully result in environmentally friendly outputs and solutions. All these facts urge for a revision of energy-saving models in cellular network [24, 25] – with the consideration of the embodied energy, further investigated in next subsection.

4.3.3 The Embodied Energy of a BS

With the methodology, given in Section 4.2.2 we have made a rough estimation of embodied energy for a general BS. The results are summarized in Table 4.1.

Table 4.1 The constituents of initial embodied energy for materials and processes during the production of a general BS

Material/process	Energy requirement (MJ/kg)	Energy (GJ)
Semiconductor devices (silicon wafers and integrated circuitry)	60,000–120,000	37.2
Printed circuit board manufacturing and assembly	300–500	4.3
Bulk materials (plastic, glass, and rubber)	20–140	5.3
Metals (aluminum, copper, steel, lead, and zinc)	100–400	7.0
Conventional manufacturing (cutting, welding, finish machining, and injection molding)	1–30	1.5
Telecom cables	50	2.3
Supply chain		5.8
Components manufacturing and node assembly		8.1
Transportation, setup		3.5
Total embodied energy of a base station		75.0

To further position these results, we have compared the estimated energy of BS with a powerful state-of-the-art computer server [26]. As expected, the embodied energy of BS precedes the embodied energy of computer server, but the results are in the same order of magnitude. The results are also in concordance with Ref. [4], claiming that approximately 20% of mobile equipment's energy is used by raw materials.

The embodied energy content of BS varies greatly with different construction types. This study is focused on macrocell BS only, albeit the equipment manufacturers provide heterogeneous assortment of micro/femto/picocell BSs varying in their power, dimensions, and the embodied energy. However, lower radiation power usually does not mean lower embodied energy; its share in total lifetime energy is usually even higher with the small cells' BSs comparing with the large ones.

4.3.4 The Operating Energy of a BS

The past analysis [27] has decomposed this energy among power amplifier, idling transceiver, power supply, cooling fans[5], transceiver power conversion, combining/duplexing, central equipment, transmit power, and cabling (see Figure 4.2 for the detail). The authors of previous works have suggested many different approaches to reduce the energy consumption of BSs which have been brought into use by the manufacturers with the aim to improve cellular networks' energy efficiency (the details and estimated reductions of energy consumption are given in brackets): improvements of BS hardware design (improvement of power amplifier and signal processing efficiencies, RF techniques and reduction of feeder losses, and application of free cooling, 40%), usage of several system level architectures (optimal cell sizes, two-tier networks: 30%) and features (resource allocations, sleep-mode strategies: 10–30%), differentiation of BS site solutions (indoor/outdoor solutions, modular solutions: 20%), and the usage of renewable energy sources.

The operating energy of a BS is easier to assess, since we can rely on the previously published data. The values for operating and peak power consumptions provided by BS manufacturers[6] are a good starting point. For a typical macrocell[7] installation, the figures for the net power of a BS can vary from 0.4 to 3.0 kW. In Ref. [18], the authors have estimated the average power consumption of equipment dating before the year 2000 as 1.1 kW. From this time, using the above-mentioned approaches the power consumption of BSs is claimed to be reduced substantially [28], to less than 500 W [22, 31]. Thus, we presume this number as average power consumption of state-of-the-art BS, used for modeling in our study. As the radio access in cellular network is intended to work 24/7, the annual operating energy consumption is roughly 15 GJ, resulting in 150 GJ in the estimated device's lifetime (estimated to 10 years).

The power consumption of every BS depends on traffic load and statistical spread. As it is detailed in Figure 4.1(e) with the dashed line the power consumption is a nonlinear function of time with some high-consumptive busy periods as well as periods with no power consumption

[5] This portion can vary due to different climate conditions.
[6] The data was of Ericsson, Nokia, Motorola, and Huawei were collected on their websites.
[7] For the sake of simplicity, this study evaluates single-tier (macrocell) architecture only. However, the employment of smaller (femto/pico/micro) cells is a subject of an ongoing research.

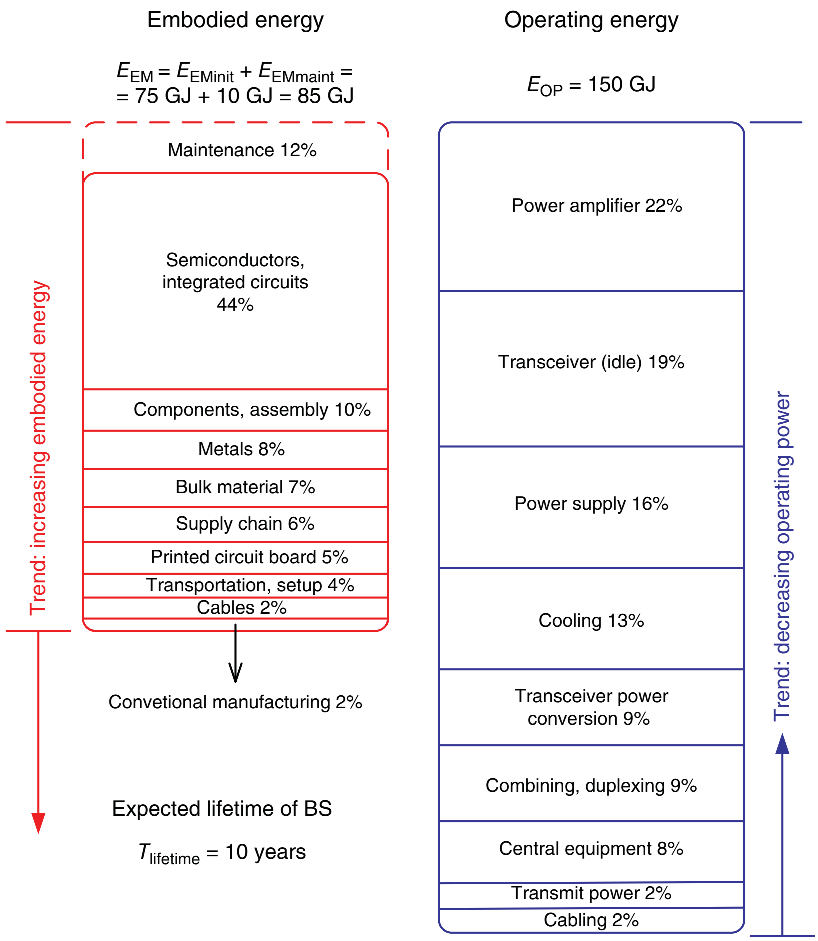

Figure 4.2 The proportion of embodied and operating energy during BS's lifetime, breakdowns, and trends

representing the possible sleep-mode/power-off intervals during low traffic. The average value used in our study can be represented as a linear function of time illustrated with the solid line.

The ratio between embodied and operating energies during the BS's life cycle is evident from Figure 4.2. The results of our estimation can successfully reflect in the aggregated data given by [4] where the authors found that the share of embodied energy in the mobile network's total energy was approximately 15% in 2001, 25% in 2005, and has grown up to 43% by the end of 2006. It also confirms our claim that the operating energy is being reduced on account of embodied energy. However, all these evidences ground an existence of relationship between the embodied and operating energy $E_{OP} = f(E_{EM})$, meaning that the higher embodied energy (such as improvements in BS hardware design) can result in reduced operating energy. This relation was not explored in our study, but it is definitely an interesting question for further research.

4.4 The Cell Number/Coverage Trade-Off

In this section, we apply our energy consumption model to two scenarios, excluding and including the power-off strategy. A simple simulation has been conducted to provide energy consumption optimization with respect to the number of cells and their coverage, considering the trade-off between operating and embodied energy.

4.4.1 The Energy Consumption Model Without Power-Off Strategy

The transmission power of BS antennas is dissipated into the air, and the transmitted signal is deteriorated by path loss, shadowing, and multipath fading effects in wireless propagation channels. The average receiving power decreases with distance r between the receiver and transmitter approximately with $1/(r)^{\gamma}$ [29], mainly accounting for the path losses, where γ is the path loss exponent that typically ranges from 2 to 5, depending on the propagation environment. Besides, all the mobile devices within the cell require a certain level of received signal-to-noise ratio (SNR), asserting at least minimum receiving power $P_{\min}$ for acceptable performance. Therefore, the transmission power of the BS P_{TX} is proportional to $P_{\min}(r)^{\gamma}$, where r represents the cell radius. Considering the link budget for noise, shadowing, and other loss effects (as well as gains), the transmission power can be further scaled with the term $P_{\min}(r)^{\gamma}$. For simplification, suppose a BS with radius $r_0 = 1$ km, the transmission power is $P_0 = 40$ W, then the transmission power for BSs with different cell radius can be expressed as $P_{\mathrm{TX}} = P_0\ (r/r_0)^{\gamma}$. Referring to the previous section, the operating power $P_{\mathrm{OP}} = \mathrm{a} \cdot P_0(r/r_0)^{\gamma} + b$; and the energy model for the whole system consumption E_{system} for the scenario without power-off strategy of a certain area, covered by n BSs can be expressed as:

$$E_{\mathrm{system}} = n\ (E_{\mathrm{EM}} + E_{\mathrm{OP}}) = n\ (E_{\mathrm{EMinit}} + E_{\mathrm{EMmaint}} + P_{\mathrm{OP}} \cdot T_{\mathrm{lifetime}}) \tag{4.2}$$

where the operating power P_{OP} is a function of cell radius as described above.

4.4.2 The Number/Coverage Trade-Off

The deployment of a larger number of BSs with smaller size (cell radius), such as femto/pico/micro BSs [20, 30] will enable decreased transmit power of BSs as well as reduced operating power and electromagnetic radiation. However, the total power consumption of the system is the multiplication of the number of BSs and a single BS power consumption. As the number of BSs becomes large, the power consumption rises, since the embodied energy of a newly deployed BS adds to the total energy. In theory, there exists a trade-off between the number and the coverage of a single BS, translating into a trade-off between the embodied energy and the operating energy. In practical deployments, the position of the BS, the capacity, and the traffic requirements are always taken into account. However, to explore the number/coverage problem on a simple scenario, we assume the total coverage to be the multiplication of the number of active BSs and a single BS coverage. Under this coverage constraint, the optimal energy consumption is explored in simulation by considering the trade-off between operating and embodied energy consumptions.

4.4.3 The Energy Consumption Model with the Power-Off Strategy

The power-off strategy is an important energy-saving technique by adapting BS activities to traffic dynamics. When the traffic of a certain cell remains at low level, the BS can be shut down for operating energy-saving purposes. The other active BSs should increase their transmission range, thus with larger transmission power, to cover the entire area. When the traffic in a cell increases, the shutdown BS will be activated. Thus, when power-off strategy is applied, the operating power varies with the number of shutdown BSs or depends on the number of active BSs. The average traffic intensity in a day or year varies periodically between its peaks, sometimes assumed to have a trapezoidal or sinusoidal pattern [19]. Consider uniform distribution of users in the cells, and the random use of mobile devices, then the traffic patterns among different BSs are the same except that the traffic peaks are uniformly distributed during the period. Each BS in an area has a power-off probability p, proportional to the share of the low traffic period in the day. At a particular time, there may be M sleeping BSs, where M is a random variable satisfying binomial distribution: $\mathsf{Prob}(M = m) = \binom{m}{n} p^m (1-p)^{n-m}/(1-p^n), 0 \leq m \leq n-1$, and n again is the total number of BSs, covering the area. The energy model for the entire system consumption E_{system} for the scenario with sleeping strategy is expressed as follows:

$$E_{\text{system}} = n \cdot (E_{\text{EMinit}} + E_{\text{EMmaint}}) + \sum_{m=0}^{n-1} (n-m) \cdot \mathsf{Prob}(M = m) \cdot P_{\text{OP}}(n-m) \cdot T_{\text{active}} \quad (4.3)$$

where, as distinguished from Eq. (4.2), the operating energy consumption is the probabilistic average over the distribution of random variable M; and the active time T_{active} of BSs can be estimated by $(1-p) \cdot T_{\text{lifetime}}$.

When considering the power-off strategy, the operating power of BSs can be reduced by around 25% [2, 19]. The operating energy savings are significant, especially when more BSs are deployed. However, our study argues that the embodied energy consumption will be in larger proportion of the total energy consumption than in the case without power-off strategy. Reconsidering the number/coverage problem, if a large number of smaller BSs are deployed, the embodied energy consumption increase will be dominant in the total energy consumption. That means, the BS is manufactured with great energy cost while it is powered-off during most of its lifetime. Therefore, the consideration of power-off strategy is most necessary for the number/coverage trade-off problem resolution.

4.4.4 Simulation Results

In this section, the presented energy consumption models are evaluated in simple simulation scenarios in order to optimize the total energy consumption by exploring the trade-off between the operating energy and embodied energy. Consider a typical urban area of radius $R = 5$ km

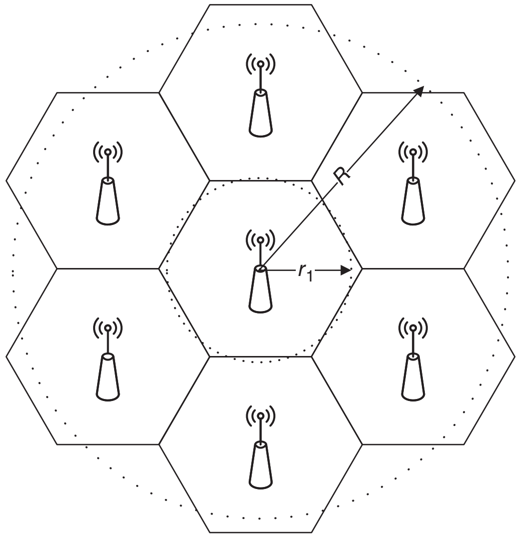

Figure 4.3 The simulation scenario topology

covered by n BSs with the same cell radius r as illustrated in Figure 4.3. During the simulation, the embodied energy is calculated using the estimated data in Section 4.3. The parameters used to evaluate the operating energy are given in Table 4.1 [21].

Parameter	Value
Path loss exponent γ	3.2
Power-off probability p	1/4
Operating power consumption model – parameter a	7.84
Operating power consumption model – parameter b	71.50
Embodied power model parameters	see Section 4.2
Transmission power P_0	40 W

Under this simulation scenario, the energy consumptions with different number of BSs or cell sizes are evaluated in Matlab, both including and excluding power-off strategy, to find the optimal number of BSs or cell size, as depicted in Figure 4.4. It is evident that an optimal number of BSs or cell size with minimal energy consumption exists. When only a small number of BSs with large cell sizes are deployed, the energy consumption is high; this is due to the increased operating energy with cell size. However, when a large number of BSs with small cell sizes are deployed, the embodied energy consumption dominants and leads to the increase in total energy consumption. The optimum is achieved with the trade-off between operating energy and the embodied energy. Compared with past research [32], where the optimal cell size/number of BSs is affected only by the fixed operating energy consumption part,

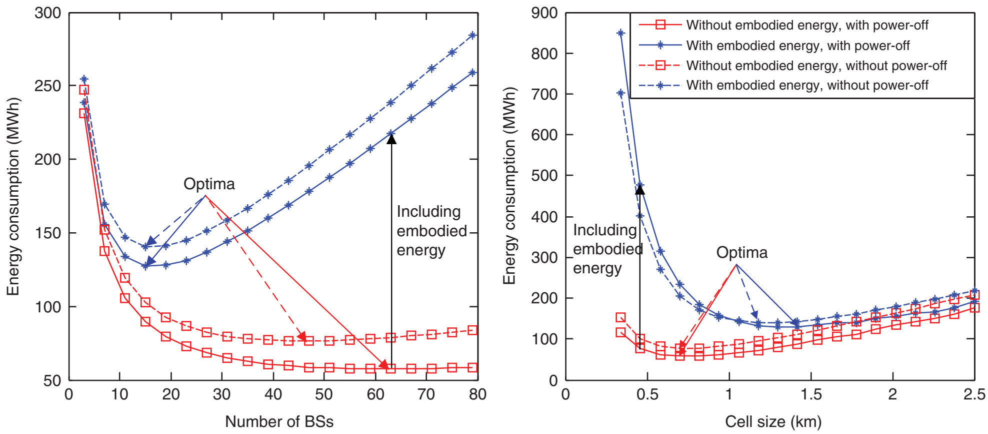

Figure 4.4 The optimal energy consumption of cellular network with respect to number of BSs (a) or cell sizes (b)

the embodied energy in our case has a much stronger effects when the cell size becomes small or the number of BSs becomes large. This finding averts from the suggestions that energy savings can be achieved with a larger number of cells with reduced transmission power. Besides, when sleeping strategy is applied, the operating energy savings will only slightly shift the optimum to higher number of cells due to the decreased operating energy consumption. However, in practical deployments, the power-off strategy is only possible, when the number of BSs is relatively large. This emphasizes the problem of the embodied energy and even raises its share in the total energy, when power-off strategy is applied.

Results on energy efficiency versus the number of BSs are provided in Figure 4.5. Since the system capacity of increases linearly with the number of active BSs [20], the energy consumption ratio (ECR) [33] will decrease with increasing number of BSs. The results ignoring the embodied energy are in accordance with the previous research [20]. However, the energy efficiency of both models, with or without consideration of the embodied energy, is almost the same, when the number of cells is small, but the consideration of the embodied energy reveals that several times more energy is required for the same capacity when the number of cells is large (detailed on the scaled part of Figure 4.5). This again calls for reconsideration of past suggestions in energy saving solutions.

4.5 Discussion and Future Challenges

This chapter extends the energy model of ICT device with the embodied energy constituent. It consists of the energy for production and maintenance of ICT devices, which as shown for the majority of complex electronic ICT devices it is far from being neglected. We have provided and explained a case study of such modeling for a Base station in Cellular network and have shown the important trade-off between operating and embodied energy consumption that provides guidelines for manufacturers, operators, and researchers.

The results given above provide an insight into optimizations considering both operating and embodied energy. It is evident, that the latter plays a very important role and should not simply

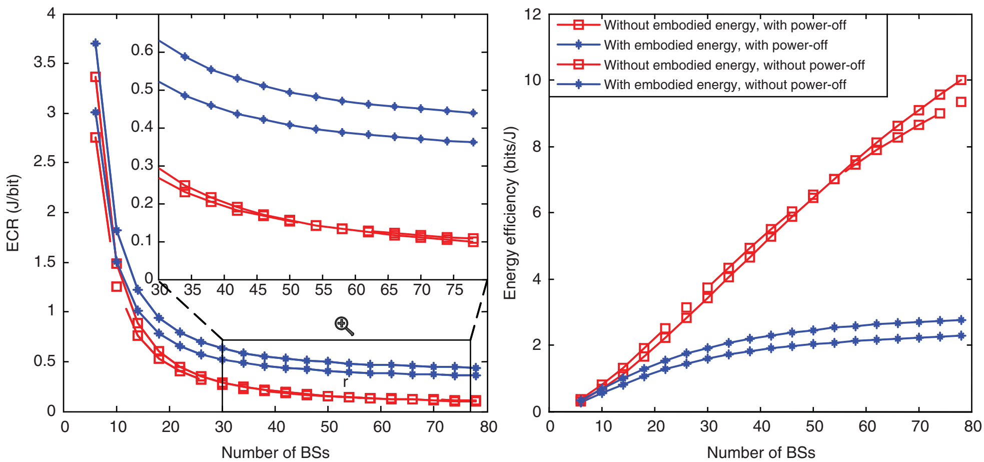

Figure 4.5 The ECR (a) and energy efficiency (b) of cellular network, covering the same area with different number of BSs

be neglected. However, there are still many open questions that manufacturers, operators, and researchers should address in future work.

The ICT equipment manufacturers should advocate total LCA, including the energy consuming activities of research, engineering, and software development. Cooperating closely with component suppliers, they should perform cradle-to-grave assessments of embodied energy for at least a selected set of their radio network product portfolio. This will be of great interest to operators and researchers in relation to network optimization and analysis, respectively. Furthermore, the up-to-date embodied energy estimations should be made publicly available, and simple to interpret and use, even for nonexperts in the field of LCA.

Moreover, the manufacturers should strengthen the awareness of embodied energy and the environmental impacts for the nonmass produced ICT equipment, as they do for mobile phones for example [11]. The manufacturers should inform the customers not only about the improvements in operating energy consumption but also the assessed embodied energy of the equipment should be provided. To ensure this outcome, the standards of embodied energy measurement and estimation should be made a matter of regulation and enforcement by the regulatory authorities.

Operators should perform a cost analysis for building new sites in terms of energy, expenditure, and environmental impacts. Also, the impact of different traffic intensive application on the energy efficiency should also be addressed.

Although there exist some obstacles for public and creditable embodied energy data, this is not an excuse to neglect its influence in energy efficiency modeling and optimizations. We hope this chapter provides further motivation in this perspective, although there remain many open research issues in the embodied energy modeling of ICT equipment.

There is also some evidence that operating energy is being reduced on account of embodied energy. To explore the relationship between the embodied and operating energy is an interesting question for further research.

Although the provided example focuses mainly on cellular networks as they are one of biggest consumers and attract much attention in the recent ongoing research, results of our study are general and can be easily applied to other fields of ICT. For instance, the proposed models are directly applicable to the wireless local area networks. The provided approach of embodied energy consideration may also target other energy efficiency concepts, requiring the deployment of additional hardware to save energy. The network connectivity proxying scheme [6], for example, employs external network proxies that virtually maintain presence for network computers but let them sleep and save energy while idle. This approach may require additional hardware and should be further evaluated by considering the embodied energy limitations. To avoid wasting with the embodied energy of immense proxies employed in thousands of small offices around the world, the implementations using the existing network equipment [6] (either on one of the network servers, implemented within the network interface controller or residing in the already-employed network devices, such as switches) should be greatly encouraged.

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