

# Green ICT Research and Challenges

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**Abstract** Green ICT is a young and pioneering field. Therefore, as often pointed out in the literature, studies evaluating the main research activities and the general direction of this new and continuously evolving research field are scarce and often incomplete. This study presents a quantitative analysis, through a systematic literature review, of the main activities, trends and issues that can be found in the Green ICT literature. The research reports the analysis of various characteristics of the studies gathered for this review, such as addressed type of effect and year of publication. It also led to the identification of the most recurrent issues of the research and development of Green ICT strategies. Finally, this study proposes a new category of effect (*people awareness*) that, even if often addressed by the field, is not included in current Green ICT frameworks.

**Key words:** Green ICT, Systematic Literature Review, Environmental impact of ICT

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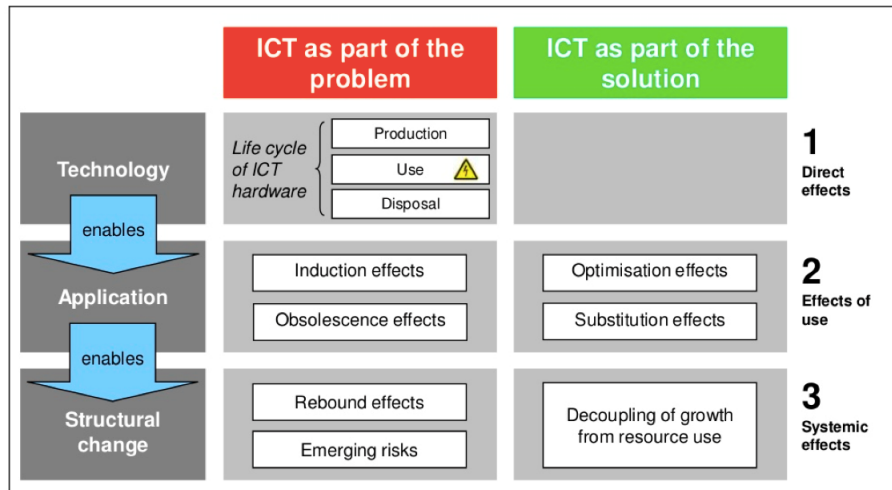
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## 1 Introduction

In academic research, the environmental impact of ICT is an important topic, spanning across multiple disciplines. ICT is seen as both a relevant contributor to CO<sub>2</sub> emissions due to its increasing carbon footprint [10], and as an enabler for reducing the footprint of other sectors through “smart” systems (e.g. smart buildings, smart grids). We define Green ICT as a combination of activities that minimise the negative impact of ICT on the environment and optimise the positive impact ICT can have. Or, in other words, as any activity that considers the direct, indirect and systemic impact of ICT on the environment [1]. We especially want to see how research activities relate to the possible effects ICT can have. For this we use the framework proposed by Hilty [3]. Accordingly, the effects of ICT on the environment can be



**Fig. 1** Conceptual Framework of ICT impacts [3]

classified as follows:

- **First order** or *primary* effects: effects of the physical existence of ICT (environmental impacts of the production, use, recycling and disposal of ICT hardware).
- **Second order** or *secondary* effects: indirect environmental effects of ICT due to its power to change processes (such as production or transport processes), resulting in a modification (decrease or increase) of their environmental impacts.
- **Third order** or *tertiary* effects: environmental effects of the medium- or long-term adaptation of behavior (e.g. consumption patterns) or economic structures due to the stable availability of ICT and the services it provides

What follows is a systematic literature review focused on the effects of ICT on the environment. We look into how research activities relate to these effects, what

common issues are in the papers selected for our study and - given those analyses - the direction of the Green ICT research field and emerging research gaps.

This paper is structured as follows: after this introduction, Section 2 presents our research method and its protocol. Section 3 presents our results and in Section 4 we discuss them providing useful insights. Finally, Section 5 concludes the paper.

## 2 Methodology

Our chosen research method for this study is the Systematic Literature Review (SLR) [6], a secondary study aimed at collecting and analyzing evidence from the existing state-of-the-art. Our goal is to identify current trends and challenges in the Green ICT field, and possibly gaps for further research. In this section we describe the protocol adopted for our SLR, i.e. how we searched for publications, selected our primary studies and classified those studies.

### *Research question*

Green ICT is a relatively young research field that has been explored only in the last two decades. Therefore, as mentioned by Jenkin et al. in [4], an overview of the literature of this thematic has not been fully developed. This research is intended to give a comprehensive overview of the research activities that have been carried out during the short timespan of the topic. The general research question of this study has been therefore defined as follows:

*How do Green ICT research activities relate to the effects of ICT on the environment?*

### *Literature Search*

In order to select the research activities related to the effects of ICT on the environment two distinct groups of keywords were created. At least one of the keywords of each group had to be in the title of a study in order to be included in this literature review. The resulting query, written in pseudocode, follows:

*TITLE: (ICT or "Information technology" or "Information system") AND TITLE: (green or sustainable or sustainability) AND (effect or impact or influence or dematerialization or e-waste or rebound or societal change")*

Expanding the research by taking into account also studies that included the keywords in the abstract could have led to interesting outcomes. Nevertheless it resulted infeasible due to the query syntax of some digital libraries. In fact, some of the online libraries, as *Google Scholar*, limit the query to two search options: the title of the paper or a full text search.

Regarding the digital libraries adopted for this research, as customary *Google Scholar*, *ACM*, *IEEE*, *Web of Science* and *Aisel* were selected to carry out the selection of primary studies. Since the research field of Green ICT can be considered as relatively new, we decided not to insert any time constraints on the publication date of the studies. Zotero<sup>1</sup> reference management tool was utilized to keep track of the papers gathered for this research.

### *Selection of Primary Studies*

Executing the research query in different digital libraries resulted in a preliminary set of 1178 studies. An overview of the distribution of these studies among the different repositories is shown in Table 1. The second column of the table reports the total number of studies that were collected in the various digital libraries, while in the third column the papers that were selected for this study are stated.

Digital Library	Total	Selected
<i>Google Scholar</i>	971	67
<i>IEEE Xplore</i>	62	19
<i>Web of Science</i>	64	13
<i>AISeL</i>	40	14
<i>ACM</i>	41	9

**Table 1** Distribution of studies among digital libraries

As detailed in Table 1, the selection of the literature by means of queries executed on different digital libraries led to a large set of studies. In order to further refine the research by identifying only the papers relevant to answer the research question presented in Section 2, inclusion and exclusion criteria were generated. The papers that were gathered in the first phase of the literature selection were then evaluated against these criteria. A comprehensive list of the utilized inclusion and exclusion criteria can be found as on-line material<sup>2</sup>. The whole process resulted in the selection of 122 primary studies.

### *Classification of Primary Studies*

In order to identify the effects addressed in the primary studies, we adopted a manual evaluation process. This process consisted in analyzing the selected resources and identifying which category of effects they primarily address in their research. Subsequently the studies were mapped on the effects they primarily focus on. Papers that only marginally address an effect, e.g. by only mentioning it in a few sentences, were not mapped to such effect. The focus of this process was to map the papers exclusively to the effects actively researched by the study. Therefore effects that were

<sup>1</sup> <https://www.zotero.org/>

<sup>2</sup> <https://goo.gl/JmwSfp>

merely reported as introductory text, related works etc. were not taken into account during the mapping.

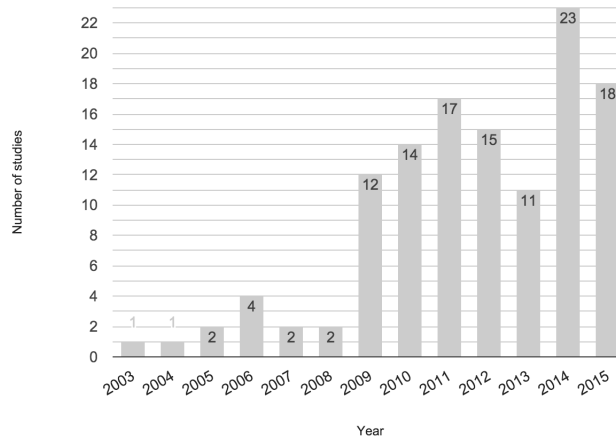
The definitions of the various categories of effects reported in Figure 1 were taken from the description of the framework provided by Hilty [3]. It is important to notice that, in various cases, multiple effects were addressed in the same research. Therefore studies could not be mapped exclusively to a single category of effect. For this research these latter type of researches were associated to all the effects they primarily address.

The process of the identification, selection and classification of the issues throughout the literature review was done as follows. In a first phase, all the issues regarding the application of Green ICT practices that were found in the studies were annotated. Secondly the listed problems that were strictly domain dependent, i.e. specific to the particular case studies, were discarded. After this process the most recurrent issues were merged into macro-classes that uncovered similar problems. Finally, the issues that resulted to be mapped exclusively to a single study were discarded, as this issues were considered as irrelevant to answer the research question.

### 3 Results

#### *Studies per year*

Figure 2 shows on the x-axis the years in which the studies were published and on the y-axis the relative number of studies. As depicted in the Figure, all the studies selected for this research were published from 2003 onwards. Since Green ICT is a relative young research field, this result is not that surprising. However, there is a

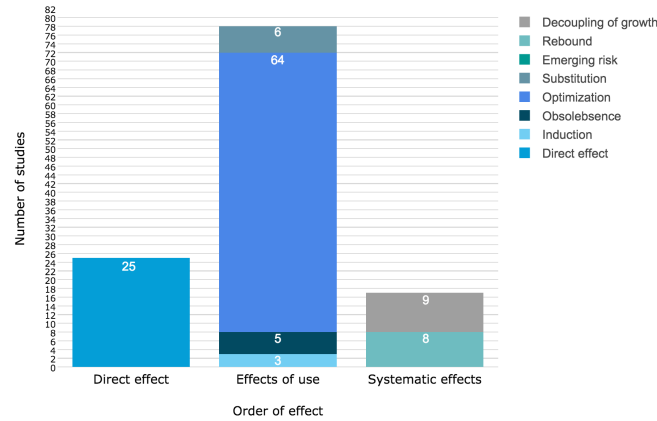


**Fig. 2** Distribution of the studies over time

clear increase of publications from 2009, which is not that surprising either, especially if we consider the increasing attention to sustainability and energy efficiency in global concerns and international agendas, and the recognition of the potential transformational power of ICT in achieving sustainability objectives.

### *Studies per effect*

Figure 3 depicts a representation of the distribution of the primary studies among the different orders of effect and relative subcategories.



**Fig. 3** Number of studies categorized by effect

On the x-axis the three orders of effect are reported, while the y-axis denotes the number of studies that addressed these orders. The colors of the stacked bar chart represent the different effects in which the three orders are divided according to the three orders of effects and relative sub-classes described by Hilty [3].

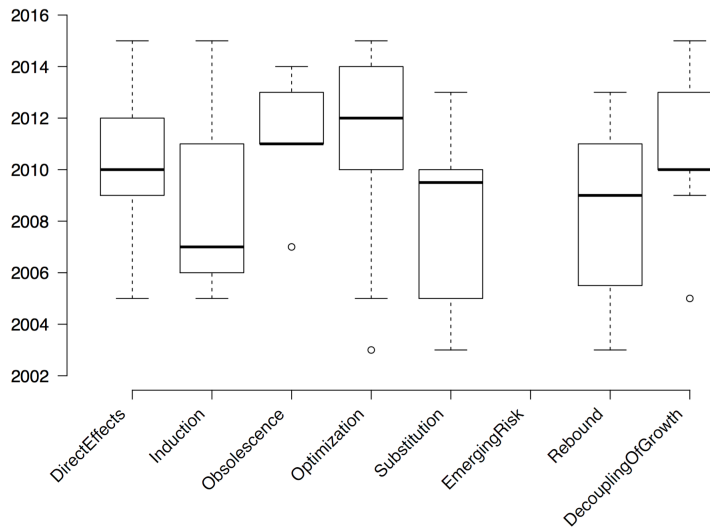
### *Researched effects per year*

A detailed representation of the years in which the distinct effects of the framework were researched is given by Figure 4.

### *Recurrent issues*

Seven distinct general classes of issues were identified: *Green ICT is a complex subject in rapid evolution, Lack of research and documentation, Lack of metrics and standards, Lack of incentives and regulations, Lack of people awareness, High cost or unclear return on investment, Need of complex data.*

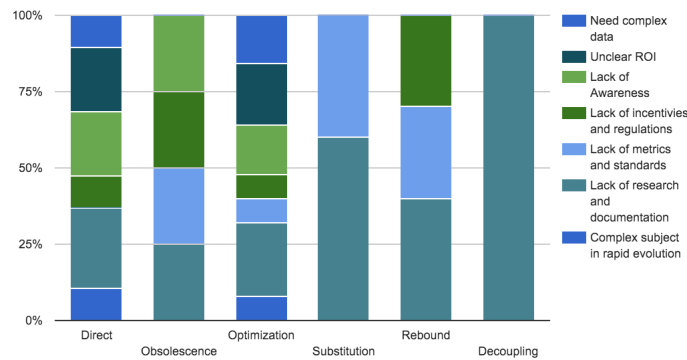
The recurring issues were mapped to the effects described by Hilty [3] according to the study in which the problems appeared and the effect described in the research.



**Fig. 4** Publication year of the studies categorized by effect

This was done in order to identify if a specific category of issues could be traced back to a particular category of effects.

Figure 5 depicts the appearance of the different issues among the effects. Effects that did not report any problem classifiable in one of the above mentioned classes of issues were omitted from the figure.



**Fig. 5** Distribution of the issues among effect

As shown in Figure 5, the *lack in research and documentation* is the most common problem among the different levels and was found in a total of 22 papers among the different effects. *Lack of people awareness* was the second most common issue and was reported by 13 distinct papers. *High cost or unclear return on investment*

was mentioned in several papers, but focused exclusively on two types of effect. On the contrary *lack of incentives and regulations* was reported in the same amount but by studies focusing on different effects. Other problems, such as *lack of metrics/standards* and *Complex subject in rapid evolution* were mentioned only by a minority of the studies.

## 4 Discussion

The analysis presented in Section 3 gives a comprehensive view of the most important characteristics of the data set used as inputs to answer our research question, i.e. “*How do Green ICT research activities relate to the effects of ICT on the environment?*”.

### *Conflicting trends*

Figure 2 shows a general increasing trend in the number of researches carried out per year. The exceptions are for years 2012, 2013 and 2015. Regarding 2015, the lower number of researches found can be attributed to the fact that, when the research was conducted during 2015 and therefore, if the research would be conducted again in the future, this number is likely to be higher. A more extensive evaluation is needed to understand the reasons behind the drop in 2012 and 2013 since we could not find an obvious explanation from our results.

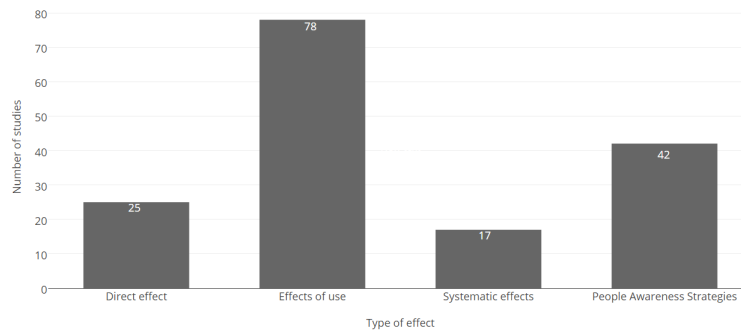
### *People awareness strategy effects*

During the mapping of the ICT environmental effects reported in the primary studies to the ones described by Hilty [3], we discovered an interesting gap. A class of papers could not be classified as they did not report any of the effects described in the framework. These papers focus on something referred to by Lago & Jansen as *people awareness strategies* [7], which can be defined as strategies to use ICT to give people insight in their energy consumption and suggest alternative consumption models (paraphrased from [7]). This latter type of researches could be discarded from this study by including an additional exclusion criteria. Nevertheless, the high number of papers tackling this topic clearly suggests that this new type of effect addresses a need. Therefore, we have decided to include them.

As shown in Figure 6, the research carried out in this field of Green ICT is not negligible, constituting about 34.4% (42 studies) of the total number of primary studies. Notice that, as explained in Section 2, single studies may cover multiple types of effects.

The broad definition of the effects as described by Hilty [3] allows the categorization of a wide range of ICT effects on the environment. Unfortunately, effects resulting from *people awareness strategies* do not fall under any of the specific cat-





**Fig. 6** Number of studies categorized by type of effect

egories of effects in the framework. Of course, this requires a revision of Hilty's framework.

In particular, we suggest to expand the framework by including *People Awareness effects* as new category. This causes the inclusion of a new sub-class of effects that falls under the second order of effects, constituting an additional class of positive impacts of ICT on the environment.

#### *Research direction and research gaps*

As depicted in Figure 3, *optimization* was the most researched effect in the primary studies, by contributing more than half of the total number of studies. This was followed by studies on direct effects. These two effects combined made up 74% of the total primary studies. In contrast, none of the studies focused on *emerging risk* effects. Other complex effects more strictly related to the Green ICT theory, such as *Induction* and third order effects, have been only marginally addressed. As noted in Section 2, the third group of keywords of the research query contained terms specifically focused on including studies on effects of the third order. The scarcity of papers addressing this order of effects can therefore not be attributed to the query formulation, which suggests an important research gap.

Regarding the years of publication, surprisingly maybe, the studies focusing on the third order of effects were spread over a longer period of time, starting relatively early when compared to the others. While studies on the first and second order of effects appeared later in time, all remain actively researched topics (see Figure 4).

Considering the studies that take into account *direct* effects, this subject seemed to be considered only partially and was often used to introduce specific optimization techniques. Of course there are many studies focusing on energy efficiency in ICT that were not included in our literature review as they were addressing only a small part in detail, such as processors in servers. In-depth analyses focusing solely on the direct effects of ICT and relating them to the bigger picture, such as e-waste, were scarce in our primary studies and tend to give an overview rather than analyzing them in depth.

Studies on *optimization* effects often addressed very specific topics, such as ad-hoc motorway wireless networks [2] or RAM optimization techniques [5]. As detailed in Section 3 a recurrent issue of the Green ICT research field is the lack of knowledge. Nevertheless in this case an overview of actual optimization solutions seems to be missing (there are overviews of possible solutions): a comprehensive overview of the optimization techniques of the various optimization sub-fields, such as data center optimization, smart building approaches etc. While the development of standards, metrics and tools is crucial, having an overview of the state-of-the-art research activities of the various optimization fields has to be considered paramount. In this direction, in previous work [9] proposes a tool to estimate the economic impact of Green ICT practices from the state-of-the-art. In the field of software architecture, we are building a catalogue of reusable tactics for energy-aware software solutions [8, 11],

Regarding the *systemic* effects of ICT on the environment, as reported in Section 3, very little related research has been conducted. Only few of the selected papers focused exclusively on these effects, and these often did not report any theoretically or empirically proven data. Therefore it is difficult to identify specific research gaps of the third order of effects, as it seems that the implication of these *systemic* effects requires much more exploration to be understood.

As reported in Section 3, during the literature review process a set of common issues shared among the selected studies was determined. The problems belonging to this set recurred often in the literature and were explicitly reported. Nevertheless none of the selected studies focused primarily on documenting and analyzing these easily standardizable issues. This might be an indicator of a general lack of research and understanding of these problems. A more in-depth study on this topic could potentially lead to a comprehensive documentation of the common issues of Green ICT strategies deployment and research, enabling further analyses of the identified problems.

## 5 Conclusion

This systematic literature review provides an overview of the trends, problems and research gaps (hence open challenges) that are uncovered from the Green ICT literature. To do so, we have used a framework created by Hilty [3] that categorizes positive and negative effects of ICT on the environment. As a co-product, we could provide feedback on how the existing literature relates to this framework.

Green ICT is a relatively new research field and the interest in related topics is constantly growing. Section 3 provides evidence of this growing interest. We could also show that the corpus of literature on this topic is heterogeneous, presenting several research gaps. A major part of the literature is mostly focused on *direct effects* and *optimization effects*, leaving a large number of other effects not well explored, if researched at all, as is the case of *emerging risks* effects. Furthermore,

we found a set of papers did not fit Hilty's framework and classified these as *people awareness effects* [7].

While carrying out this SLR, it became clear that much work is still needed to establish a precise and complete framework aimed to evaluate effectively the wide range of possible impacts of ICT on the environment. The next step is to further investigate and refine our key findings so that we can contribute to attaining a more comprehensive framework. In addition an in-depth description of the studies found in the SLR to carry out a more qualitative review could be of value as well.

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