School of Industrial and Information Engineering

Master of Science in Computer Science and Engineering

Energy Efficiency on Sustainable ICT: A Systematic Literature Review

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Abstract

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Keywords: *Sustainable ICT, ICT for Sustainability (ICT4S), Green IT, Green ICT,.*

Chapter I: Introduction

1-1 The Concept of sustainability

In this section, we first define the basic definitions of sustainability and then reconstruct the concept of "sustainable development" based on its original definition by the World Commission on Environment and Development (WCED).

Definition 1: *Sustainable use*. Sustainable use of the S system with respect to F performance and a time horizon of L means using S in a way that does not jeopardize its ability to achieve F for a period of L. In other words, a system has sustainable use, if the user can maintain this use "long enough".

S may also be called the broadest term for "resource" and the process of achieving F can also be called "services". We may think of S as a man-made or a natural system or a combination of the two: a human environment system. This definition may seem quite formal at first glance. However, this is only an attempt to clarify what is logically derived from the idea of using something for a purpose, and the everyday meaning of the adjective is "stable," that is, "able to maintain a certain rate or level." [1] For example, if we want to make sustainable use of a climbing rope, we simply avoid overloading it to the point that it breaks. When H.C. Von Carlovitz wrote his principles of sustainable forestry in 1713. [2] The world was less complex than it is today. The function of a forest was to produce wood. His basic premise was simple: Don't cut wood more than it grows in the same amount of time. Today, we know that forests have other functions, such as air and water filtering, keeping soil in place and maintaining biodiversity, as well as conservation and recreational functions. So there are different ideas on how to use the forest sustainably. Depending on the F that governs our view and interest, we may have different opinions about how to sustainably use a forest. Worse, it may not be clear exactly where S begins and ends: where do we draw the boundary of the system? Can S be significantly separated from the rest of the world? Much of the controversy over sustainability stems from the fact that people are concerned about the sustainability of different systems and functions, as well as different time horizons, and do not explicitly state when designing a discourse, when designing a technological artifact, or creating a business model. Therefore, any theory or practice related to sustainability must answer the main question of Dabson's [3] organization, namely: What should be sustained?

Sustainable use, as we defined above, can be called a relative concept of sustainability. The reason for this is that its meaning depends on how the S system is defined, the function F and the time horizon L in the text. It is a burden to the sustainability discourse that an increasing number of terms use "sustainable x" (such as "sustainable management" or "sustainable software") without providing a clear context in which S, F and L are defined. However, there is at least one term "sustainable x " that can be considered as an absolute concept of sustainability, as the context was set in 1987 by WCED [4]: Sustainable Development. Below, we explicitly point to this original definition of sustainable development, not the later ones.

Definition 2: *Sustainable Development*. “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” [4] This definition, also known as the “Brundtland definition,” can be reformulated as “making sustainable use of our planet to maintain its function of fulfilling human needs.” As a first glance, it therefore seems that sustainable development is just a special case of sustainable use, whereby *S = planet*, *F = fulfilling human needs*, and *L = several generations* (Table 1-1).

Table 1-1: Examples used in the text

Description	System S (resource)	Function F (service provided)	Time horizon L
Using a climbing rope	A rope	rope Securing a person	A decade
Sustainable forestry 1	A forest	Producing wood	Generations
Sustainable forestry 1	A forest	Preserving biodiversity	Generations
Sustainable forestry 1	A forest	Other functions	Generations
Sustainable development	The planet	Meeting human needs	Generations

However, there is a second element in the Brundtland definition that cannot be reduced to sustainable use: distributive justice. The WCED highlighted “the essential needs of the world’s poor, to which overriding priority should be given” [5]. M. Christen points out that sustainable development “might best be conceptualized as an attempt to grant the right to a decent life to all living human beings without jeopardizing the opportunity to live decently in future.” Christen therefore revises Dobson’s “principal organizing question” in the following manner:

What has to be guaranteed or safeguarded for every person, no matter whether she lives at present or in the future? [5]

It should be clear that no single product, process, policy, region, or technology can be “sustainable” in the sense of “sustainable development”, as the latter concept has a global scope by definition.

Definition 3: *Sustainability Indicator*. A sustainability indicator is a measure that is used in a process of governance to identify actions that are more beneficial to sustainability than others. In this definition, “sustainability” can be understood either as sustainable use (Definition 1) or as sustainable development (Definition 2). In the second case, there are two types of sustainability indicators:

Resource-oriented indicators: They cover the “sustainable use of the planet” aspect of sustainable development. The term “footprint” has become a generic metaphor for resource-oriented sustainability indicators. Carbon footprint indicators estimate to what extent an activity uses the atmosphere’s limited capacity to absorb greenhouse gases. The ecological footprint is an indicator trying to map any human impact onto a share of the carrying capacity of the planet. [6]

Well-being-oriented indicators: They cover the “fulfill human needs” aspect of sustainable development. As a basic indicator, Gross Domestic Product (GDP) is used. However, because “economic indicators such as GDP were never designed to be comprehensive measures of prosperity and well-being”, additional indicators, known as “beyond-GDP indicators,” are under discussion. [7]

It is important to understand that sustainable development (Definition 2) can only be quantified using indicators of both types; the idea is to fulfill human needs and make sustainable use of global resources.

Resource-oriented indicators reduce the complexity of deeply nested resource systems S to simple metrics. This is why any resource-oriented indicator—at least implicitly—relies on a model of the service-providing system. This model is used to estimate the impact of an action in terms of sustainability of use: The greater an unwanted impact on the resource, the less sustainable the action.

Established indicators are linked to specific impact assessment methods that prescribe how the data are collected and the models used to calculate the indicator for a specific case. Examples include the environmental impact assessment categories used in Life-Cycle Assessment (LCA).

In engineering contexts, there is a tendency to focus on energy use or CO2 emissions as central resource-oriented indicators. The terms “energy-efficient,” “carbon-neutral,” and “sustainable” are often used interchangeably. However, this is an oversimplification, for three reasons. First, the diffusion of energy efficient technologies does not necessarily lead to an overall reduction of energy use: Efficient technologies can also stimulate the demand for the resource they use efficiently. This is known as Jevon’s paradox or the “rebound effect.” Second, the production, use, and disposal of these technologies needs resources as well: When assessed from a life-cycle perspective, energy efficiency may look somewhat different. Third, although energy is crucial, the impact on other natural resources should also be included.

1-2 Classification of Resources and the Question of Substitutability

Resources can be classified in natural and human-made resources and in material and immaterial resources [8]. These two dimensions are orthogonal, in other words, all combinations are possible. Furthermore, material natural resources can be renewable or non-renewable. A renewable resource can replenish if the rate at which it is used does not exceed its renewal rate. A non-renewable resource does not renew itself in meaningful human timeframes.

We will not introduce formal definitions of these resource categories here as they are defined more or less consistently in the literature. However, the distinction between ‘‘material’’ and ‘‘immaterial’’ resources deserves some clarification. UNEP’s International Resource Panel introduced this useful distinction: A resource is called material if using it affects other uses of the resource. For example, a stone used to build a wall will no longer serve for other functions. By contrast, resources ‘‘whose use has no effect on the qualities that make them useful’’ are called immaterial. In this sense, ‘‘the shine of a star used by a captain to find his way’’ is an immaterial resource [8].

Technological innovation leads to the diffusion of new technologies, which are then partially or fully substituted for older technologies or natural resources. Cars have replaced horse-drawn carriages, the computer has replaced the abacus, and LCD screens have recently replaced CRT screens. To express substitution in the terms we defined above, we can regard each technological product as a resource S’ that may fulfill the same function F as a resource S. If this is the case, S’ is obviously a potential substitute for S. Many controversies around sustainability are based on different beliefs about the future substitutability of resources. Below, we first define substitutability and then discuss an extended example.

Definition 4: *Substitutability*. If a function F provided by a system S can also be provided by S’, we say that S’ is substitutable for S. Note that substitutability is a ternary relationship: S’ is substitutable for S with regard to F.

Substitution is crucial with regard to non-renewable resources. Unless we assume, for example, that fossil energy sources are substitutable by renewables, transition to a sustainable use of energy must appear impossible.

Substitutability has implications for the actions to be taken to promote sustainability. If S can be substituted by an S’ fulfilling F as well, there is no need to sustain S. What makes this concept hard to grapple with in political discourse is the fact that substitutability depends on future technological developments and discoveries, so it is impossible to know who is right today. An extreme technological optimist may believe that any limited material resource will become substitutable by some unlimited resource in due time, while a person thinking in an extremely precautionary way would not cut down a single tree as it might have some irreplaceable properties. Most people’s beliefs are located somewhere between these two poles.

In fact, substitution is more complex as it can occur at different levels. An example will illustrate this idea. Bob wants to meet up with Jill, who lives on another continent. He may use an airline to travel to Jill’s country. The airline needs planes, airport infrastructure, personnel, fuel, the atmosphere, stable weather conditions, and many other resources. For the aircraft to be built, materials must be extracted from the Earth’s crust, people trained to build planes, power plants must generate electricity, and so on. The power plants, in turn, need fuel, they must be built, maintained, and so on. If Bob were to decide to have a virtual meeting with Jill instead, we would, of course, discover a similar structure of nested resource use.

This example shows that there is usually a hierarchy (formally, a tree) of resources that provides a service. From an economic perspective, each node of the tree is a production process, whose input is resources provided by other processes. Thus, the airline produces the service of transporting Bob from A to B, the aircraft industry produces aircraft, and a refinery produces fuel. The overall system that produces the final service delivered to Bob is inconceivably complex, and we would probably never understand it in all detail if we tried.

Given this hierarchy of resources that emerges when one asks how a specific service is produced, it is essential to understand that substitution can in principle occur at any level, as shown in Fig. 1-1:

- Bob could replace physical transport with an immersive telepresence technology that makes a virtual meeting with Jill sufficiently similar to a face-to-face meeting.
- He could replace air travel with a new means of transport, such as a vactrain traveling through evacuated tubes at five times the speed of sound with almost zero resistance.
- The airline could use a new type of aircraft that is extremely energy-efficient.
- The aircraft could use a new type of fuel, e.g., based on solar energy.
- CO2 emissions to the atmosphere could be reversed by a new carbon sequestration technology.

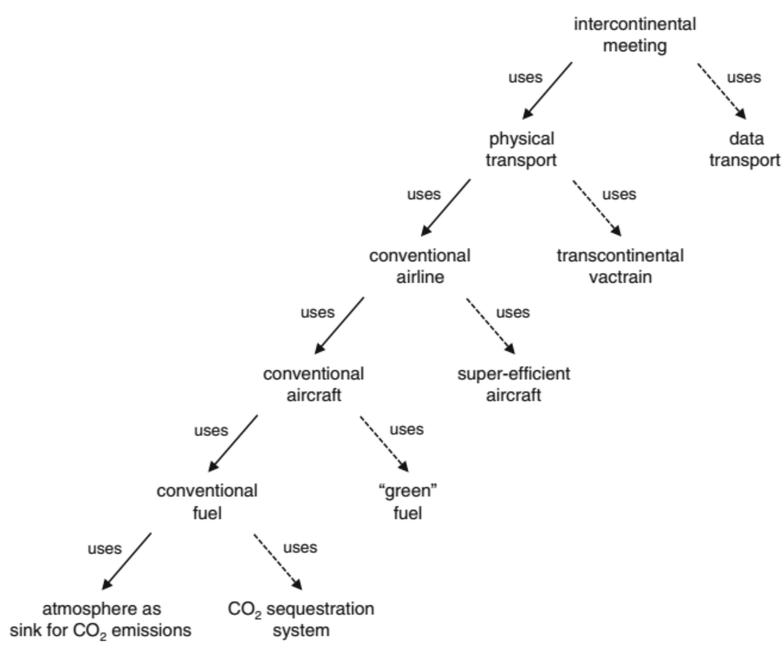

Figure 1-1: A single branch of a resource-use hierarchy with potential substitutes at each level

People have different beliefs in substitutability depending on the level of the resource hierarchy. Some people tend to believe that we will still use planes 100 years from now, but with some substitutions at the lower levels. Others think that it is easier to change social practices—adopt new forms of virtual meetings— than to replace fossil fuels or solve the problem of greenhouse gas emissions.

An interesting question is what type of resource is at the bottom of the resource hierarchy. All human-made material resources are made from natural resources, abiotic or biotic, and even long-lasting human-made material resources need energy from the environment to be operated and maintained. No house can be built or repaired without using some form of energy; no food has ever been created without biomass as its raw material. Immaterial resources can be substituted for material ones only to a certain extent. All information needs a physical substrate; there is a theoretical minimum to the amount of energy used for information processing, known as Feynman's limit.

We depend on the resources that we take from the environment. Humankind has learned to transform this environment, which makes it debatable to which extent it should still be called the ''natural environment.'' There is, however, no reason to assume that we could or should replace the basic ecosystem services provided by nature, which include the production of food and many raw materials, water and some forms of energy, as well as regulation services such as the purification of water and air, carbon sequestration, and climate regulation. These services, in turn, rely on supporting ecosystem services such as nutrient dispersal and cycling, seed dispersal and many others. The complexity of the global ecosystem is much greater than that of any human-made structure, and it can be regarded an ethical imperative that we should ''sustain ecosystem services for all countries and generations to come.'' [9]

1-3 ICT for sustainability

Perhaps the clearest statement of what ICT for Sustainability (ICT4S) means, or should mean, is the preamble of the recommendations endorsed by the 200 participants of the first ICT4S conference held in Zurich in 2013. These recommendations are published under the title ''How to Improve the Contribution of ICT to Sustainability'' in the appendix of the proceedings [25]. The preamble reads:

> *"The transformational power of ICT can be used to make our patterns of production and consumption more sustainable. However, the history of technology has shown that increased energy efficiency does not automatically contribute to sustainable development. Only with targeted efforts on the part of politics, industry and consumers will it be possible to unleash the true potential of ICT to create a more sustainable society." [25]*

ICT4S was not originally intended as a research field. It began as a conference attended by experts from academia, industry and politics with a common aim: Harnessing this technology for sustainable development. For this reason, there are many overlaps between ICT4S and pre-existing fields. ICT4S can be subdivided into [26]:

- Sustainability in ICT: Making ICT goods and services more sustainable over their whole life cycle, mainly by reducing the energy and material flows they invoke
- Sustainability by ICT: Creating, enabling, and encouraging sustainable patterns of production and consumption by means of ICT

Parts of the first aspect are covered by Green ICT, parts of the second by Sustainable HCI and EI. If there is something specific to ICT4S as a field, it is the critical perspective that challenges every technological solution by assessing its impact at the societal level: What is the effect of the solution on society at large – does it have a potential to contribute to sustainable development? In other words, sustainable development is seen a societal transformation, and technological impacts are interesting mainly for their transformational aspect.

The methods used in ICT4S are as varied as the disciplines contributing to it. Due to the critical perspective mentioned above, assessment methods such as LCA, approaches from Technology Assessment, and others are in use. Empirical methods from the social sciences are used to study the interactions between technology design and human behavior. Scenario methods and interdisciplinary approaches to modeling and simulation are employed to deal with complex dynamic systems. ICT4S refers to sustainable development in the sense used by Brundtland, as defined in Sect. 2 (Definition 2) [26].

1-4 Thesis Structure

In the second chapter of this thesis, we will define research questions, describe search strategy and study selection in our systematic literature review. In the third chapter of the research, the obtained results are reviewed and in the fourth chapter the thesis, we will analyze the results. Finally, we will make conclusions about findings in Chapter 5 of the research and provide some suggestions for future works.

Chapter II: Research Method

2-1 Introduction

Software and hardware technologies as the main ingredients of ICT plays an essential role in defining the level of energy efficiency of ICT.To improve energy efficiency both software and hardware technologies [2, 6, 7], can be targeted. However, software technologies determine the way hardware is exploited , and as such can have a more dominant influence on reaching efficiency goals compared to hardware technologies. [1].

Nowadays, thanks to the rapid proliferation of mobile phones, tablets, and unwired devices in general, energy efficiency is becoming a key software design consideration where the energy consumption is closely related to battery lifetime.It is also of increasing interest in the non-mobile arena, such as data centers and desktop environments. Energy-efficient solutions are highly sought after across the compute stack,with more established results through innovations in hardware/architecture, operating systems [8, 9, 10] ,and runtime systems [11,12,13]. In recent years, there is a growing interest in studying energy consumption from higher layers of the compute stack and most of these studies focus on application software.These approaches complement prior hardware/OS-centric solutions, so that improvements at the hardware/OS level are not cancelled out at the application level, e.g., due to misuses of language/library/application features. [2]

The growing energy consumption of IT systems is quickly becoming a major concern for users, ranging from corporation trying to keep the total cost of ownership low, to end-users who expect their mobile devices not to run out of battery while on the run.Choices that developers make in their software architecture and software algorithms have a significant effect on the energy usage of a system. All hardware has a baseline which the hardware consumes regardless of the activity of the system; on top of this, current hardware has a large dynamic energy component caused by the specific interactions of software with hardware components. Aside from improving hardware to reduce its energy consumption, the system energy consumption can be reduced by optimizing the interaction of software with hardware.When trying to write energy-efficient software, developers currently have to rely on their intuition, because few tools and methods exist which give insight into the energy consumption of software. [3]

Although hardware design and utilization are undoubtedly key factors affecting energy consumption, there is solid evidence that software design can also significantly alter the energy consumption of it products. To this end, dedicated conference tracks (e.g., greens,1 Energy 2) have identified energy efficiency as an emerging research area for reducing software energy consumption through software development practices.

Existing research works in the area have tried to address some of the challenges for reducing energy consumption in software development by defining appropriate metrics, employing energy measuring tools, and proposing best practices. For example, Bozzelli et al. [3] presented some energy consumption metrics and classified them under various environments and purposes. In the context of energy monitoring tools, Noureddine et al. [20] performed a study to point out the current state-of-the-art by contextualizing existing approaches regarding energy measuring tools for workstations/servers and smart-phones. An initial study by Procaccianti et al. (2016) shows 34 best practices that can improve the energy efficiency of software.

In this chapter, we have followed an SLR with the Kitchenham and Charter instructions [27]. The first step involved defining a set of research questions (Section 2-2) that led to this study. Also, based on these research questions, we defined the search fields for the various digital libraries used in this work (Section 2-3). We also defined a set of exclusion and inclusion criteria for selecting elementary studies (Section 2-4). Finally, we describe the data extraction method used in this study (Section 2-5).

2-2 RESEARCH METHOD

"Systematic literature review (also referred to as a systematic review) is a form of secondary study that uses a well-defined methodology to identify, analyse and interpret all available evidence related to a specific research question in a way that is unbiased and (to a degree) repeatable".In this section, we describe in detail the research method used for this systematic review. We firstly define the research questions, which define the aim of our research, and then we describe which protocol has been performed to search and collect studies about reducing energy consumption in the context of software.

We apply the systematic literature review methodology and target peer-reviewed papers focusing on energy consumption. Furthermore, in all primary studies software is event triggered and performed in a best-effort manner, without a strict guarantee on the duration of the software process. Most of the approaches are not specific to any application domain, with a lack of case study evaluation.it was very difficult to distinguish the all primary studies we found in energy consumption either related to software engineer's or the end user's.

The main contributions of this study are an up-to-date systematic review of the literature on energy consumption in the context of Software.The target audience of this paper includes: researchers working in the field of software developer and software engineers that want to have better insight of the literature when specifically dealing with energy consuming in software application, researchers and mobile application developers looking to implement less consuming energy Application in their system but do not have prior experience in the field and need a guide to understand what has been done so far.

2-3 Defining Research Questions

The main objective of this systematic literature review is to investigate the state of the art of research on the sustainable ICT. However, this statement is very broad, so we divide the goal into different questions to pay attention to each aspect, separately. Our research questions are listed on the Table 2-1.

Table 2-1: Research Questions

RQ No.	Question
RQ1	What researches have been done during the last 10 years?
RQ2	What research topics have been considered?
RQ3	What are the limitations of these researches?
RQ4	How is ICT sustainability supported?
RQ5	What is the used method?
RQ5.1	How is the method validated?
RQ5.2	How is the method evaluated?
RQ6	Is there any case-study available?
RQ7	Which domain has already been considered?

In Table 2-1, RQ1 refers to the evolution of ICT sustainability methods and the attention of researchers to this field during years. RQ2 focuses on main concepts of research topic. In the next step, we focus on the limitation of researches in RQ3. The next question, RQ4, deals with how the method supports sustainability in ICT. RQ5, assess used methods and how these approaches are evaluated and validated, respectively. In RQ6, we will check whether the approach has studies a specific case? Finally, we search for domains in RQ7 and classify approaches into a general or specific domain, in which case we also register the domain.

2-4 Search Strategy

Based on the defined research questions, we determined the appropriate keywords for searching primary studies on the basis of research strategies presented in [27] and conducted the research phase. These words and their associated synonyms in our search are listed in Table 2-2.

Table 2-2: Used keywords for constructing search strings

Term	Keywords	Synonyms
A	Sustainability	“Sustainability” , “Sustainable ?(development)”
B	ICT	“ICT”, “IT”, “Information ?((and|&) communication) technolog*”
C	Energy Efficiency	“Energy efficiency”, “Renewable energy”, “Energy (Saving|consumption reduction)”
D	Green ICT	“Green ?(by) ICT” , “Green IT”

Preliminary studies search was conducted on the following digital libraries:

- ACM Digital Library[1],
- IEEE Xplore Digital Library[2],
- ScienceDirect[3],
- Scopus[4],
- Springer Link[5], and
- Wiley[6].

Because these digital libraries have their own search APIs, we now explain the search process used for each library:

- ACM: We used advanced search to generate a basic set of articles. ACM now allows users to export multiple articles. So we used this option and exported results as a .bib file.
- IEEEEXplore: In this library, searching was restricted to abstract and title of each article. The only format available for exporting results in IEEEXplore was csv.
- Science Direct: We first used advanced search to generate a collection of articles, and then did an expert search for these results. It was a complete text search, where we chose computer science as the knowledge area. Results were saved in a .bib file.
- Scopus: By adding the words "TITLE-ABS" before the search terms, we restricted the search to abstracts and titles of articles. We also restricted computer science search by adding “AND SUBJAREA (“COMP”)” at the end of the search. Results were saved in a .bib file.

1 http://dl.acm.org
2 http://ieee.org/ieeexplore
3 http://www.sciencedirect.com
4 http://www.scopus.com
5 http://link.springer.com
6 http://onlinelibrary.wiley.com

- Springer: We did an advanced search limited to computer science. This search type, uses abstracts and titles, where the results are stored as a .csv file. The amount of articles originally obtained from Springer was very large (about 14,000), so we searched some of them. We have limited the places of publication related to the subject of our study.
- Wiley: Searched for abstracts and titles. We used the .bib format to export each 20 cases at a time (limited to this digital library).

The specific search fields used in each digital library has been listed in the Table 2-3, as well as the number of studies obtained in each case. Note that Science Direct does not use the quotation mark in the search string.

Table 2-3: Search strings in various digital libraries

Library name	Search string	Results
ACM	(“Sustainability” OR “Sustainable” OR “Sustainable development”) AND (“ICT” OR “IT” OR “Information technolog*” OR “Information and communication technolog*” OR “Information & communication technolog*”) AND (“Energy efficiency” OR “Renewable energy” OR “Energy saving” OR “Energy consumption reduction”) AND (“Green by ICT” OR “Green ICT” OR “Green IT”)	77
IEEExplore	(“Sustainability” OR “Sustainable” OR “Sustainable development”) AND (“ICT” OR “IT” OR “Information technology” OR “Information and communication technology” OR “Information & communication technology” OR “Information and communication technologies”) AND (“Energy efficiency” OR “Renewable energy” OR “Energy saving” OR “Energy consumption reduction”) AND (“Green by ICT” OR “Green ICT” OR “Green IT”)	131
Science Direct	({Sustainability} OR {Sustainable} OR {Sustainable development}) AND ({ICT} OR {IT} OR {Information technology} OR {Information and communication technology} OR {Information & communication technology} OR {Information and communication technologies}) AND ({Energy efficiency} OR {Renewable energy} OR {Energy saving} OR {Energy consumption reduction}) AND ({Green by ICT} OR {Green ICT} OR {Green IT})	298
Scopus	TITLE-ABS((“Sustainability” OR “Sustainable” OR “Sustainable development”) AND (“ICT” OR “IT” OR “Information technology” OR “Information and communication technology” OR “Information & communication technology” OR “Information and communication technologies”) AND (“Energy efficiency” OR “Renewable energy” OR “Energy saving” OR “Energy consumption reduction”) AND (“Green by ICT” OR “Green ICT” OR “Green IT”)) AND SUBJAREA(“COMP”)	96
Springer	((Title: “Sustainability” OR Title: “Sustainable” OR Title: “Sustainable development”) AND (Title: “ICT” OR Title: “IT” OR Title: “Information technology” OR Title: “Information and communication technology” OR Title: “Information & communication technology” OR Title: “Information and communication technologies”) AND (Title: “Energy efficiency” OR Title: “Renewable energy” OR Title: “Energy saving” OR Title: “Energy consumption reduction”) AND (Title: “Green by ICT” OR Title: “Green ICT” OR Title: “Green IT”)) OR ((Abstract: “Sustainability” OR Abstract: “Sustainable” OR Abstract: “Sustainable development”) AND (Abstract: “ICT” OR Abstract: “IT” OR Abstract: “Information technology” OR Abstract: “Information and communication technology” OR Abstract: “Information & communication technology” OR Abstract: “Information and communication technologies”) AND (Abstract: “Energy efficiency” OR Abstract: “Renewable energy” OR Abstract: “Energy saving” OR Abstract: “Energy consumption reduction”) AND (Abstract: “Green by ICT” OR Abstract: “Green ICT” OR Abstract: “Green IT”))	102

Library name	Search string	Results
Wiley	(“Sustainability” OR “Sustainable” OR “Sustainable development” OR “ICT” OR “IT” OR “Information technology” OR “Information and communication technology” OR “Information & communication technology” OR “Information and communication technologies” OR “Energy efficiency” OR “Renewable energy” OR “Energy saving” OR “Energy consumption reduction” OR “Green by ICT” OR “Green ICT” OR “Green IT”) in Article Titles OR (“Sustainability” OR “Sustainable” OR “Sustainable development” OR “ICT” OR “IT” OR “Information technology” OR “Information and communication technology” OR “Information & communication technology” OR “Information and communication technologies” OR “Energy efficiency” OR “Renewable energy” OR “Energy saving” OR “Energy consumption reduction” OR “Green by ICT” OR “Green ICT” OR “Green IT”) in Abstract	83
Total:		787

2-5 Inclusion and Exclusion Criteria

We only selected items that met all of the following inclusion criteria, and discarded items that met each of the exclusion criteria.

- Inclusion criteria:
    - The article is available online and its language is English,
    - The article has been published in a journal between 2010 and 2020
    - The article focuses on ICT sustainability.
    - The article discusses on some aspects of energy efficiency in ICT sustainability,
    - It is reasonable in description of the method and validated.
- Exclusion criteria:
    - ICT sustainability is a small part of the study
    - The article is a survey, SMS or SLR,
    - The article is not scientific (workshop, meeting, …).

2-6 Data Extraction Procedure

In this section, we will describe our followed procedure of data extraction, which consists of four selection stages and one final data collection stage.

1. Initial searching and filtering: We used the search strings described in the previous section and saved the resulting articles in a dataset. Table 2-3 shows the number of articles in each digital library. The initial search resulted a total of 787 articles shown on the table. At the first step, 381 duplicate copies were deleted and a total of 406 articles were obtained at the end of the first phase.

2. Selection based on abstracts and titles: In this step, we have read the titles and abstracts of articles and checked them according to inclusion and exclusion

criteria. Table 2-4, shows the result of this step. Thus, a total of 94 articles remain after this stage.

3. Full reading and selection: In this step, each one of remaining papers was read by two reviewers and their answers to the research questions were recorded. After reviewing all primary studies, the extracted data were compared and the differences were discussed. In this process, inclusion and exclusion criteria are also used. There was 74 articles on the agreement: 41 have been removed and 33 have been retained. The remaining 20 articles were approved by the expert in the next step.

4. Validating by expert: The author of this SLR reviewed the remaining 20 articles and decided to accept 14 of them.

Table 2-4: Details of data extraction procedure

Stage	Stage name	Papers at start	Excluded papers	Selected papers
#1	Initial searching and filtering	787	381	406
#2	Selection based on abstracts and titles	406	312	94
#3	Full reading and selection	94	41	**33**+{20}
#4	Validating by expert	20	6	**14**

Four stages of selection were performed for a total of 47 primary studies (33 from the third stage and 14 from the last stage 4). These 47 studies are the result of data collection stage.

Chapter III: Results

In this chapter we show the results of our systematic literature review. We proceed step by step, following the protocol defined in the previous chapter. We will add some figures and tables in order to make it easier to understand the workflow and how we obtained these results.
This work is divided in three parts; initially we discuss the results of the selection of the papers, then those of sentences and finally we will organize the sentences grouping them by topic.

3-1 Introduction

In the previous chapters, the research topic and its scope were explained, and research questions were proposed. Then the strategy of searching and selecting articles was described. According to the process described in the previous chapter, we found 47 related articles that can be useful for answering the research questions. In this chapter of the research, we intend to describe the findings and search results and examine the characteristics of the selected papers.

3-2 Selected articles

According to the process described in the previous chapter, the article search process was performed, and 47 papers were selected based on the inclusion and exclusion criteria. Table 3-1 describes the specifications of selected articles.
In this table, the details of the title, year of publication of the article, scientific database which the article has been accessed by, and study type (CP: Conference Paper or AJ: Article of Journal) are given.

Table 3-1: Included results in this study

Authors	Title	Year	Source	Pub. Type
Loeser, F. et al [28]	Information and Communication Technologies for Sustainable Manufacturing: Evaluating the Capabilities of ICT with a Sustainability Balanced Scorecard	2012	IEEE	CP
Ahmed, F. et al [29]	ICT and renewable energy: a way forward to the next generation telecom base stations	2017	Springer	AJ
Ziemba, E.[30]	The contribution of ICT adoption to the sustainable information society	2019	Scopus	AJ
Sissa, G.[31]	An Agent Based approach for sustainable ICT services toward environmental sustainability: The use of Agent Based Models to explain the ICT-driven (societal) behavioral changes and their effects on environmental sustainability	2013	IEEE	AJ

Authors	Title	Year	Source	Pub. Type
Dawadi, B. R. et al [32]	Towards energy efficiency and green network infrastructure deployment in Nepal using software defined IPv6 network paradigm	2020	Wiley	AJ
Gorbenko, A. et al [33]	Green economics: A roadmap to sustainable ICT development	2018	IEEE	CP
Suryawanshi, K., & Narkhede, S. [34]	Green ICT for sustainable development: A higher education perspective	2015	ScienceDirect	CP
Anthony, B. J., & Majid, M. A. [35]	Development of a Green ICT model for sustainable enterprise strategy	2016	Scopus	AJ
Bull, R. [36]	ICT as an enabler for sustainable development: reflections on opportunities and barriers	2015	ACM	AJ
Masud, M. H., & Malik, N. A. [37]	A strategic model for evaluating energy efficient ICT infrastructures for sustainable environment	2012	ACM	AJ
Madan, S. et al [38]	Identification, Selection and Prioritization of Sustainable and Green Software Factors Using Fuzzy Set theory	2019	ScienceDirect	CP
Porras, J. et al [39]	PERCCOM: A Master Program in Pervasive Computing and Communications for sustainable development	2016	IEEE	CP
Suryawanshi, K., & Narkhede, S. [40]	Green ICT at higher education institution: Solution for sustenance of ICT in future	2014	ACM	AJ
Curry, E. et al [41]	Measuring energy efficiency practices in mature data center: A maturity model approach	2013	Springer	AJ
Rahim, R. A., & Rahman, A. [42]	Green IT capability and sustainable development	2013	IEEE	CP
Radu, L.[43]	Determinants of green ICT adoption in organizations: a theoretical perspective	2016	Scopus	AJ
Yao, M. et al [44]	Sustainable green networking: exploiting degrees of freedom towards energy-efficient 5G systems	2019	Springer	AJ
Dao, V. et al [45]	From green to sustainability: Information Technology and an integrated sustainability framework	2011	ScienceDirect	AJ
Büyüközkan, G., & Çifçi, G. [46]	A novel fuzzy multi-criteria decision framework for sustainable supplier selection with incomplete information	2011	ScienceDirect	AJ

Authors	Title	Year	Source	Pub. Type
Donnellan, B. et al [47]	A capability maturity framework for sustainable information and communication technology	2011	IEEE	AJ
Kostoska, O., & Kocarev, L. [48]	A novel ICT framework for sustainable development goals	2019	Scopus	AJ
Ng, W., & Nicholas, H. [49]	A framework for sustainable mobile learning in schools	2013	ACM	AJ
Kramers, A. et al [50]	Smart sustainable cities–Exploring ICT solutions for reduced energy use in cities	2014	ScienceDirect	AJ
Bibri, S. E. [51]	The IoT for smart sustainable cities of the future: An analytical framework for sensor-based big data applications for environmental sustainability	2018	ScienceDirect	AJ
Zhang, J., & Liang, X. J. [52]	Promoting green ICT in China: A framework based on innovation system approaches	2012	ScienceDirect	AJ
Dahunsi, F. M. [53]	Conceptual framework for sustainable energy development in Africa.	2013	IEEE	CP
Aleksic, S. [54]	Green ICT for sustainability: A holistic approach	2014	IEEE	CP
Vidas-Bubanja, M. [55]	Implementation of green ICT for sustainable economic development	2014	IEEE	CP
Uddin, M., et al [56]	Green Information Technology (IT) framework for energy efficient data centers using virtualization	2012	Wiley	AJ
Garg, S. K., & Buyya, R. [57]	Green cloud computing and environmental sustainability	2012	ACM	CP
Uddin, M., & Rahman, A. [58]	Validation of green IT framework for implementing energy efficient green data centers: A case study	2012	ACM	AJ
Uddin, M., & Rahman, A. [59]	Energy efficiency and low carbon enabler green IT framework for data centers considering green metrics	2012	ScienceDirect	AJ
Garg, S. et al [60]	Green cloud framework for improving carbon efficiency of clouds	2011	Springer	AJ

Each of the articles in Table 3-1, is an attempt to develop sustainable ICT with main goal of energy efficiency. Details of the techniques used in these researches will be studied in the next chapter. But before that, we need to review these articles in terms of research questions. In the continuation of this chapter, we will analyze the characteristics of articles based on research questions.

3-3 Results for the research questions

In this section, we will review the selected studies for energy efficiency in sustainable ICT. For this purpose, we will examine the characteristics of the selected studies in terms of the questions raised in the research. These results are shown in Table 3-2.

Table 3-2: Characteristics of selected articles in this research

Authors	RQ2	RQ3	RQ4	RQ5	RQ6	RQ7
Loeser, F. et al [28]	ICT for Sustainable Manufacturing	High Complexity	Evaluation	Analyze PMS	No	domain-specific
Ahmed, F. et al [29]	renewable energy	high domain-specificity	Analysis	Resource management	Yes	domain-specific
Ziemba, E.[30]	ICT for Sustainable Information Society	high domain-specificity	Model	theoretical model for the SIS	Yes	domain-specific
Sissa, G.[31]	Agent Based model for sustainable ICT services	High Complexity	framework	Agent based Models	No	domain-specific
Dawadi, B. R. et al [32]	green network infrastructure	high domain-specificity	method	Software Defined Networking	Yes	domain-specific
Gorbenko, A. et al [33]	analysing energy efficiency and sustainability of a ICT products	High Cost	Prototype	Product Analysis	No	general-purpose
Suryawanshi, K., & Narkhede, S. [34]	implementation of Green ICT at education system	high domain-specificity	Evaluation	framing polices and strategies for ICT sustainable	No	domain-specific
Anthony, B. J., & Majid, M. A. [35]	Sustainable Enterprise Strategy implementation		model	IT Professionals-assisted monitoring enterprise strategy	No	general-purpose
Bull, R. [36]	Slow Tech	limited studies involved	Study	studying latest developments in EE and sustainability	Yes	general-purpose
Masud, M. H., & Malik, N. A. [37]	Evaluating Energy Efficient ICT sustainability	High Cost	model	Energy consumption thresholding	Yes	general-purpose

Authors	RQ2	RQ3	RQ4	RQ5	RQ6	RQ7
Madan, S. et al [38]	prioritization of sustainable and green software factors	High Complexity	method	Fuzzy Sets	yes	domain-specific
Porras, J. et al [39]	ICT in Sustainable Development for education		model	PERCCOM programme	Yes	domain-specific
Suryawanshi, K., & Narkhede, S. [40]	Green ICT at higher education institution		Analisys	identification of critical success factors for Green ICT	Yes	domain-specific
Curry, E. et al [41]	Energy Efficiency in mature data centers	High Complexity	model	Maturity Model	No	domain-specific
Rahim, R. A., & Rahman, A. [42]	pollution prevention and product stewardship in ICT		Study	association of NRBV with Green IT	No	general-purpose
Radu, L.[43]	Green ICT Adoption in Organizations		perspective	determining positively influence green ICT adoption in organizations	No	general-purpose
Yao, M. et al [44]	energy-efficient 5G systems	High Complexity	method	joint OFDMA/SDMA communications system	Yes	domain-specific
Dao, V. et al [45]	Human resources management	High Complexity	framework	Supply chain management and sustainability	No	general-purpose
Büyüközkan, G., & Çifçi, G. [46]	sustainable supplier selection	High Complexity	framework	fuzzy multi-criteria decision making	Yes	general-purpose
Donnellan, B. et al [47]	SICT Capability Maturity	High Cost	framework	capability maturity evaluation	No	general-purpose
Kostoska, O., & Kocarev, L. [48]	addressing sustainable development goals	limited sustainability goals	framework	evidence-based design	No	general-purpose
Ng, W., & Nicholas, H. [49]	sustainable mobile learning in Education	High Cost	framework	energy efficiency has not been fully investigated	No	domain-specific

Authors	RQ2	RQ3	RQ4	RQ5	RQ6	RQ7
Kramers, A. et al [50]	Smart sustainable cities	High Complexity	framework	estimating energy efficiency by lifecycle of household function	No	domain-specific
Bibri, S. E. [51]	Smart sustainable cities	High Cost	framework	Sensor-Based Big Data analysis	No	domain-specific
Zhang, J., & Liang, X. J. [52]	Smart sustainable cities	High Complexity	framework	analytical framework for ICT sustainability	Yes	domain-specific
Dahunsi, F. M. [53]	Renewable/Alternative energy	limited to energy efficiency	framework	conceptual framework for ICT sustainability	Yes	domain-specific
Aleksic, S. [54]	Holistic Approach for ICT sustainability		Model		No	general-purpose
Vidas-Bubanja, M. [55]	ICT in energy production and distribution		Prototype	ICT based Green Economy	Yes	general-purpose
Uddin, M., et al [56]	energy efficiency in data centers	High Complexity	framework	Virtualization	No	domain-specific
Garg, S. K., & Buyya, R. [57]	cloud and environmental sustainability	high cost	Study	energy efficient cloud	No	domain-specific
Uddin, M., & Rahman, A. [58]	energy efficiency in data centers	High Complexity	framework	energy efficient data centers	Yes	domain-specific
Uddin, M., & Rahman, A. [59]	energy efficiency in data centers	High Complexity	framework	energy efficient by CO2 measurement	No	domain-specific
Garg, S. et al [60]	user-oriented Cloud architectural framework	High Cost	framework	Resource management	Yes	domain-specific

The first research question deals with the number of researches on the subject during the last 10 years. Figure 3-1 shows the time distribution diagram of the articles searched and selected in this thesis.

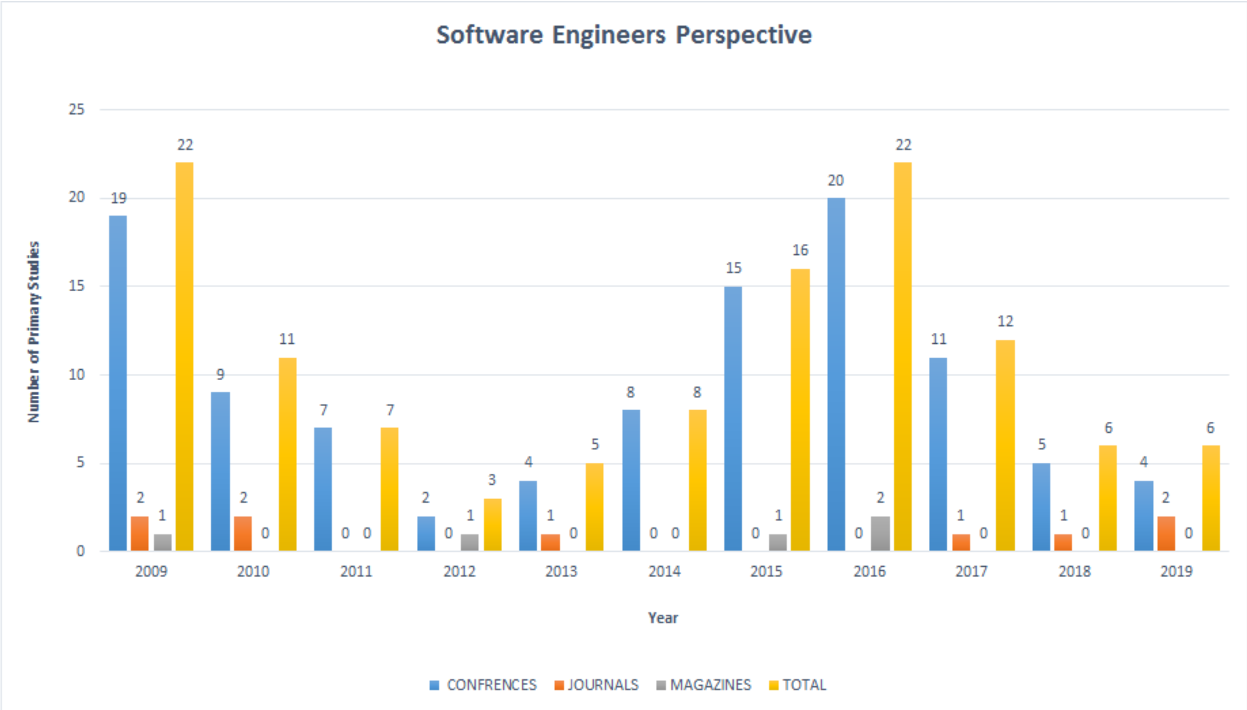

Figure 3-1: Chart of searched and selected articles by year of publication

According to Figure 3-1, the subject studied in this research has received a lot of attention in recent years and with the prevalence of information and communication technology, sustainability and energy efficiency has been the subject of many studies. Accordingly, the largest number of downloaded and selected articles belong to recent years and it is expected that the study and research on energy efficiency in sustainable ICT will continue to grow. Also in Figure 3-2, we found which concept of software elements are most used.

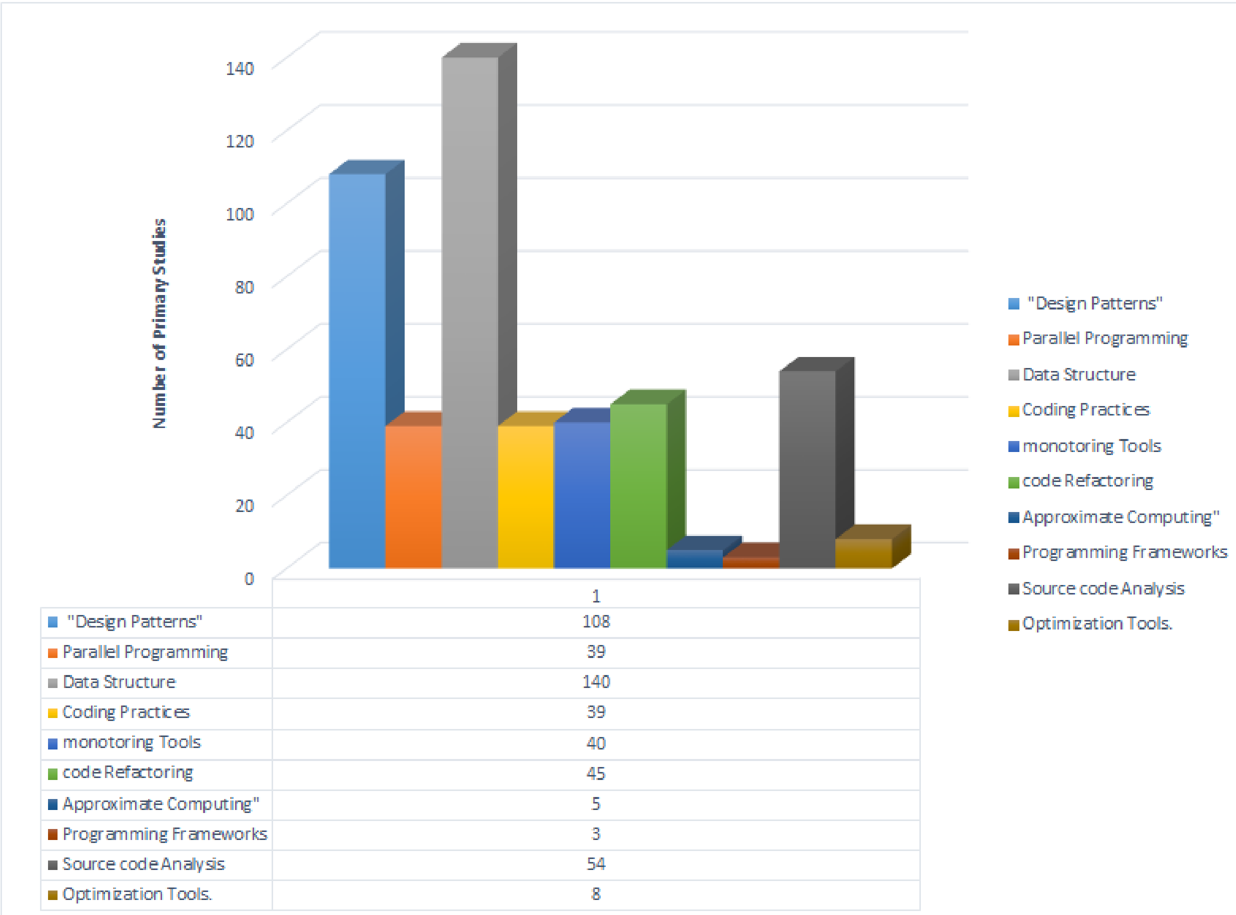

Figure 3-2: **Distribution of the types of the software approaches in different application**

- **Design Patterns**
  Design patterns are general and reusable solutions to commonly appearing software design problems. In the context of design patterns, Sahin et al. (2012) and Bunse et al. (2013) performed empirical studies where they compared the energy consumption of selected patterns. Both works evaluated design patterns from the creational, structural,and behavioral categories introduced by Gamma et al . (1995).in the Figure 5 we have found 108 Primary studies related to design patterns .
- **Parallel Programming**
  Parallel programming is the process of breaking a large problem into smaller ones to solve them simultaneously.As it has shown in Figure 5 we have found 30 Primary studies related to Parallel Programming.
- **Approximate Computing**
  Approximate computing is an approach for sacrificing computation accuracy—when an application tolerates it—to increase runtime performance or energy savings [16]. In Figure 5 we can see we have found only 5 Primary studies during 2009 and 2019.
- **Programming Frameworks**

For their research, both Misailovic et al. [17] and Baek andChilimbi [18] introduced energy-conscious programming frameworks to achieve energy savings through approximate computations. Specifically, Misailovic et al. proposedChisel, an optimization framework that acts in an automated manner by selecting approximate kernel operations that result in energy, reliability, and accuracy optimizations. As shown in Figure 5 we have found only 3 primary studies related to Programming frameworks.

- **Source Code Analysis**
  Source code analysis is a testing process that focuses on revealing defects and vulnerabilities in a computer program before its deployment phase. As can be seen we have found 54 primary studies had work on the subject of Source Code Analysis which shows that in order to have appropriate energy consumption in software Application this part of working is very important and has a massive influence.
- **Data Structures**
  A data structure is a way to organize, manage, and store data for further process or analysis. This section consists of Empirical Studies and Tooling Support for data structures. We have found 140 Primary studies related to Data structure which is the most studies in this part of SDLC.
- **Coding Practices**
  Best coding practices are sets of rules, formally or informally, established from various coding communities that help software practitioners to improve software quality. In this section, we discuss work on empirical evaluation that examines the energy consumption of coding practices. results identified from the related works as “Good” and “Bad” coding practices. By the terms “Good” and “Bad,” we refer to coding practices that may impact a program’s readability,maintainability, efficiency, and usability positively or negatively, respectively. As Figure 5 shows there has been 39 primary studies related to coding practices.
- **Monitoring Tools**
  To derive the energy consumption of a computer system, two approaches currently exist: (1) indirect energy measurements through estimation models or performance counters or (2) direct measurements, through hardware energy analyzers and sensors. As shown in Figure 5 we have found 40 primary studies related to Monitoring Tools.
- **Code Refactoring**
  Code refactoring is part of maintenance . maintenance is the process of enhancing or fixing errors in a software after its deployment. In the context of SDLC for energy efficiency, refactoring is the practice that aims to optimize energy consumption of applications through code-level modifications without altering the underlying code structure. As can be seen we have found 45 primary studies had work on the subject of Code Refactoring.

The third research question addresses the limitations of the models presented in the selected articles. These results have been shown in Table 3-2. The limitations of these researches will be discussed in detail in Chapter Four. We performed a pragmatic and informal gap analysis that resulted in three major limitations:

- High complexity
- High cost
- High domain-specificity

According to these studies, the main limitation of the studied researches is the high complexity of the models, which often results from the complexity of ICT infrastructure. This complexity makes it difficult to implement the structure in different scenarios. The fourth research question deals with the support of ICT sustainability in the research. Constructive support for sustainability is performed by frameworks, models, methods, and metrics . Thereby, most approaches are specific to a special application domain, as visible in Table 3-2.

The fifth question of the research examines the methods used in the research. These methods are studied in detail in Chapter 4, but a summary of the methods used, has been given in Table 3-2.

In the sixth question of the research, the availability of a case studies in the researches has been considered. Many of the present researches have been satisfied with evaluating through simulated environments, empirical studies or logical models. At the same time, some studies have used case studies to evaluate the effectiveness of their method.

In the last research question, the domains of the studies has been examined. We have derived a taxonomy for the domains that were used and described in the publications in Figure 3-4. The dimensions of the taxonomy are the degree of domain specificity, from general purpose to domain-specific research and the indexing between analytical approaches (frameworks and assessment) and constructive approaches (methods and Prototypes). The taxonomy shows a tendency towards domain-specific, constructive approaches. There are not many publications rated as general purpose, and there is little methodical guidance for supporting sustainability.

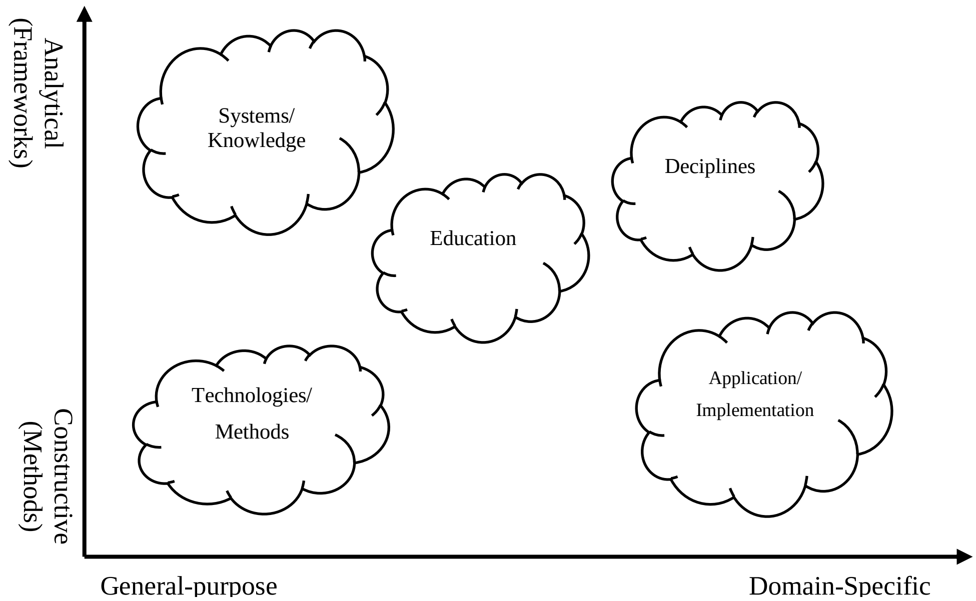

Figure 3-4: Application domains in selected studies

Chapter IV: Findings

4.1 Introduction.

Now, we are going to analyse final sentences with our considerations. We obtained 9 discussion topics about energy consumption's aspects. We defined this structure to use it as a sort of guideline, whereas chapter 5 will contain last evaluations of the work.

4.2 Considerations on the energy consumption topics.

4.2.1 Smart Sustainable Cities

The way cities are developed and managed is of fundamental importance for sustainable development. Several initiatives have highlighted how ICT can be used to achieve cities' climate targets by lowering energy use and greenhouse gas (GHG) emissions from other sectors. When discussing ICT solutions for cities, reference is often made to the concept of a "smart city". This concept has been used for the last 20 years and has been seen as a strategic concept combining modern urban production factors within a common framework [28]. Today, cities with strong environmental ambitions and telecommunication industries are seeking to understand how best to utilise ICT as an enabler for reducing energy use. For cities, it is a matter of having a better understanding of what types of ICT investments provide the best benefits for environment and society. There are many initiatives for the use of ICT solutions in cities, but without an overarching guiding framework there is a risk that efforts are being directed in the wrong areas. To minimise this risk, the aim is to demonstrate clearly where the 'hot spots' are for ICT investments to reduce energy use. A 'hot spot' is defined here as an activity with high energy use where there are one or more ICT solutions available for decreasing this energy use. The hot spots are thus identified by combining an assessment of the most energy consuming household activities with an assessment of what types of ICT solutions exist that could have an impact on these activities. In order to relate ICT solutions to activities in the city, the concept of household functions elaborated by Höjer et al. (2011) was used. The six household functions are personal, housing, food, care, common and support and these are defined so that together they provide a comprehensive account of all the energy used by a city's residents, calculated from a full lifecycle perspective. The energy data taken from Höjer et al. (2011) was used to identify the activities or "activity areas" resulting in the most energy use. These activity areas were tentatively seen as the areas with the greatest potential for ICT solutions to reduce energy use

ICT opportunities to decrease energy use in different household activities. Energy use data from Höjer et al. (2011).

Energy use per household function	Dematerialisation	Demobilisation	Mass customisation	Intelligent operation	Soft transformation
Personal (35%)	x	x	x	x	x
Housing (32%)	–	–	x	x	x
Food (13%)	–	–	x	x	x
Care (11%)	–	x	x	x	x
Common (5%)	–	x	x	x	x
Support (4%)	–	x	x	x	x

Table 4-1: Type of different household activities

To be able to judge whether the ICT opportunities were applicable for the different household functions, a review of each activity included in the household functions was undertaken. The result is presented in Table 4-1.

Many of the durable goods included in personal have already been dematerialised. Money and keys have been digitalised and films, music and books have been converted to media files. Indeed, the benefits of this type of dematerialisation depend on a number of factors, such as frequency of use and the lifetime of the devices [29]. Moreover, other goods such as phones, cameras, CD-players and navigation devices have been miniaturised by being integrated into one and the same device. Cloud computing allows computer-processing resources to reside in the cloud and thus means that only display devices need to be physically present. The energy used for cloud computing services would still be allocated to the household but, depending on the energy performance of the cloud computing service, could be lower than if all households have their own computing devices. Cloud computing is envisioned to achieve both minimised energy con- Sumption and the efficient processing and utilisation of a computing infrastructure [30]

The purchase of services and goods via e-shopping could lead to more streamlined logistics of goods. To estimate energy savings from e-shopping, it is important however to include both the processes of browsing for and purchasing a product, as well as including both business-to-consumer (B2C) and freight transport. This is required if it is to be understood whether the activity really does lead to lower energy usage [31] Moreover, it must be acknowledged that ICT alone cannot stabilise freight transport; other factors such as energy prices have a greater influence [32].

Public transport, car-sharing services and city bike systems are all examples of shared resources that benefit from the use of ICT to offer information about availability, facilitate payment or provide access. There is however great potential for ICT to be used to integrate these systems further, e.g. by providing a common booking system, interface and payment system. Heating is by far the largest portion of energy use within the housing category. Energy use in the housing category consists of the residential service and parts of its equipment, heating and lighting, furnishings such as furniture, carpets and textiles, and domestic services such as cleaning, maintenance and repair.

Residential service comprises energy use for the operation and management of the residence, as well as electricity for common areas in multi- family buildings [29]. Energy trading between buildings will establish requirements relating to how to arrange the buildings for a more optimised use of the energy system. If office buildings were located close to residential buildings, excess waste heat could be used to heat residential buildings [29]
Indoor space could to some extent be reduced by sharing spaces. The use of virtual worlds for certain activities could lead to a transformation in the physical infrastructure.
Food includes energy use related to food items and the equipment required for the storage, purchase and preparation of food, as well as parts of visits to restaurants and cafés. Food production uses the largest amount of energy in this category e what people eat is important for energy use [30]. The second largest portion comes in the storage and cooking of food. Travel for the purchase of food is included in this category but is much smaller than the other two activities.

The care category represents an eighth of households' energy use. The category is divided into three major parts: education, social security and healthcare. Only 10% of energy use in the care category is related to private households according to Höjer et al. (2011). The rest is mainly energy use in public buildings.
Being a service, it may be hard to see how care could be dematerialised. It is possible to demobilise certain care services. Examples of this are remote healthcare via sensors and mobile phones, distance education and security systems via surveillance equipment. An opportunity for mass customisation is to make use of ICT for a more personalised service for people requiring care according to their needs.
Intelligent operation can be used to manage and operate energy use in premises used by the care function and soft transformation can take place by reducing the number of premises for healthcare, education and social security by providing elements of the service remotely.

4.2.2 From green to sustainability

The idea that businesses and organizations in general have more than mere financial responsibilities is not a new idea. Research as early as the post-World War II era focused on businesses' role within society [33].[34].
model of sustainability, managers, corporations, and employers in general have four levels of responsibility: capital, legal, ethical, and philanthropic. Carroll also suggests that organizations owe these duties to a broad group of ‘‘stakeholders’’ that includes anyone with a ‘‘stake, claim or interest in the operations or decisions of the firm’’. Likewise, Mintzberg et al. (2002) suggest that too many corporations operate on a

series of ‘‘half-truths’’ that result in a sole focus on profits. Over the last decades, sustainability has increasingly become mainstream within management studies and practices.

More recently, a triple bottom line (TBL) perspective of sustainability, as illustrated in Fig. 4-1, has been adopted which considers organizational sustainability to include three components: The natural environment, society, and economic performance. By considering people and planet in addition to profit, effects on the environment and stakeholders will be incorporated when contemplating alternatives, leading (presumably) to a more sustainable outcome (Elkington, 1994).

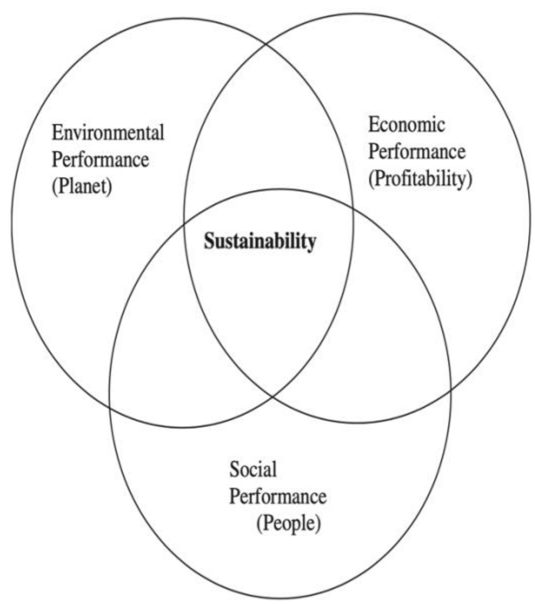

Fig 4-1. The triple bottom line of sustainability.

Besides focusing on economic profits of business activities, firms also need to take into account the social and environmental impacts of their business activities. Doing so could actually help firms reduce cost, increase profitability, sustain their business market, gain competitive advantage, and become viable contributors to the society and business market in the long-term.

Using the resource-based-view of the firm as the theoretical foundation, and literature in HRM, SCM, MIS, and sustain- ability, we synthesize an integrated sustainability framework and introduce a research model which suggests that the integration of HR, SCM, and IT resources are critical for firms to develop sustainability capabilities that enable firms deliver sustainability value to stakeholders and concurrently create value and gain sustained competitive advantage for themselves. More specifically, our propositions argue for the distinct contributions of different types of IT resources – automate, informate, transform, infrastructure – in helping firms develop sustainability capabilities for different sustainability objectives across the four quadrants of the integrated sustainability framework. Our research makes several contributions to our collective knowledge about sustainability.

While sustainability has gained increasing attention in management and supply chain management research, our literature review finds limited research in MIS examining the contribution of IT resources in helping firms develop sustainability capabilities. While limited academic research has examined IT and sustainability, practitioners' literature has been increasingly paying more attention to the role of IT in sustainability. However, the role of IT in sustainability is not clearly defined. Recent conceptualization of ‘‘green IT’’ has primarily aimed at reducing carbon footprints via reductions in energy consumption of companies' technical IT infrastructure. While IT resources have been found to have significant impacts on organizational changes, it has become well understood that such resources are not interchangeable. Different types of IT investments induce distinctive performance effects through their differential impacts on organizational capabilities, structures, processes and product-markets.

4.2.3 Green ICT

Green ICT provides an opportunity for a synthesis of policies of different fields. It addresses multiple objectives of economic growth, environmental sustainability, technological innovation, and ICT development simultaneously. Policy makers should have a systematic and cross-sector perspective in formulating green ICT policies. The growing awareness of ICT's environmental impacts triggered the rise of green ICT. Similar concepts include sustainable ICT, green/sustainable information technology (IT) and green/sustainable information system (IS).

The two words green and sustainable are sometimes used interchangeably in the literature. Furthermore, green ICT means different things to different people. For the firms that provide ICT products, it means developing new technologies for greening their own businesses and, in a broad sense, developing greener products for their customers to help them achieve goals of environmental sustainability.

What we have found out is that the analytical framework, as shown in Fig. 4-2 begins by defining an innovation system for green ICT, for which the scope and structural components of the system should be determined. Then, an assessment of the structural components is conducted to identify the system failures. Considering the constraints of limited resources, policy makers should not expect to solve all of the problems in one attempt. In fact, it typically takes a long time to improve the overall performance of an innovation system. Therefore, priorities should be assigned to the most stringent obstacles for green innovation when formulating policies. The process of policy formulation and implementation is a cyclic process that may last for years.

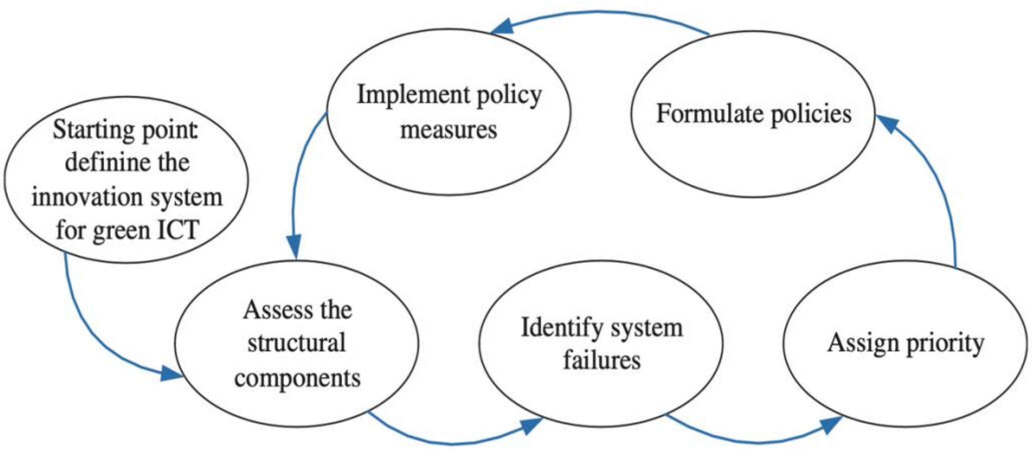

Fig. 4-2 An analytical framework for formulating green ICT policies based on innovation system approaches.

The framework can also be used as a tool for evaluating policies and strategies. that have been implemented. By checking whether the policies have addressed the identified system failures, policy makers can examine the effectiveness of strategies such that improper policies can be terminated or adjusted.

4.2.4 ICT and renewable energy

First of all, we have to know that the demand for energy is exponentially increasing as technology is infused into every aspect of our lives. Global demand for energy is expected to rise by 37 % from 2013 to 2035, or by an average of 1.4 % per year [34]. Like other technology sectors ICT sector also has a significant contribution towards global warming through CO_2 emissions [35]. There is direct contribution from ICT sector itself and indirect contribution through other sectors where ICT is employed to support their businesses [38]. In ICT, the energy consumption mainly occurs at the data centres and the wireless base stations (BS). According to Gartner report of 2007, ICTs are contributing two percent towards global warming, which seems quite less as compared to some other sectors such as construction and transportation [38]. Distribution of renewable energy generated through various sources is as important as its generation and utilization and requires equal attention. That is why research is being directed towards infrastructures and policies of distribution networks. Smart grids are the key to energy distribution and thus focus of special interest by the researchers. There is study to integrate the present grids with right communication infrastructure to make them smart or to develop new grid designs that have communication technology fused into them [39]. A concept closely associated with energy generation and smart grid is the concept of distributed generation (DG) but lot of terminologies and definitions exist in the industry, which have been amply explored in [40]. A smart grid can be defined as ICT-enabled distributed generation of electricity. ICT can provide the required intelligence and computing power to the distribution system to make it efficient and controllable. An overview of the essentials of the progressive smart grid paradigm and integration of different communication technologies for legacy power system has been presented in [41]. A study of communication infrastructures and network architecture for the smart grid has been undertaken by the researchers in [42], and [43] respectively, while the objective of [44] is to design decentralized controls and communications for autonomous distribution networks in Smart Grid. In [44], an overview of demand management with a particular focus on the necessary enabling wireless technologies is presented.

4.2.5 Sustainable information and communication technology

Researchers estimated that information and communication technology (ICT) is responsible for at least 2 percent of global greenhouse gas (GHG) emissions.[45]. Furthermore, in any individual
business, ICT is responsible for a much higher percentage of that business's GHG footprint. Yet researchers also estimate that ICT can provide business solutions to reduce its GHG footprint fivefold. It thus seems imperative that IT departments and

professionals get their house in order to deliver on this potential.[46]. Sustainability is an important business issue, affecting new products and services, compliance, cost reduction opportunities, the organization's reputation, and revenue generation. Many organizations think it requires a significant transformational change program, yet the ultimate goal is to embed sustainability into business as usual activities.
Once the scope and goals of SICT are clear, the organization must identify its current capability maturity level by examining, across business functions, its broader attitude toward SICT and its view of SICT's contribution to sustainability. The framework defines a five-level maturity curve for identifying and developing SICT capabilities:
1. Initial: SICT is ad hoc; there's little understanding of the subject and few or no related policies. Accountabilities for SICT aren't defined, and SICT isn't considered in the systems life cycle.
2. Basics: There's a limited SICT strategy with associated execution plans. It's largely reactive and lacks consistency. There's an increasing awareness of the subject, but accountability isn't clearly established. Some policies might exist but are adopted inconsistently.
3. Intermediate: A SICT strategy exists with associated plans and priorities. The organization has developed capabilities and skills and encourages individuals to contribute to sustainability programs. The organization includes SICT across the full systems life cycle, and it tracks targets and metrics on an individual project basis.
4. Advanced: Sustainability is a core component of the IT and business planning life cycles. IT and business jointly drive programs and progress. The organization recognizes SICT as a significant contributor to its sustainability strategy. It aligns business and SICT metrics to achieve success across the enterprise. It also designs policies to enable the achievement of best practices.
5. Optimizing: The organization employs SICT practices across the extended enterprise to include customers, suppliers, and partners. The industry recognizes the organization as a sustainability leader and uses its SICT practices to drive industry standards. The organization recognizes SICT as a key factor in driving sustainability as a competitive differentiator.

4.2.6 A framework for sustainable mobile learning

Mobile technologies are one of the fastest growing areas of technology. For educators, they offer an appealing opportunity for learners to transcend teacher defined knowledge or approaches by accessing multiple, alternative sources of information. Most studies of mobile learning are short-term, funded projects where access to technical support and pedagogy are often predetermined through sponsorship. The longevity of these projects beyond the funding period is usually unclear. There are few studies that conceptualise sustainable learning with mobile devices. Reflecting its variable, context-dependent and context-making capacities, many researchers (Frohberg, Göth & Schwabe, 2009; Koszalka & Ntloedibe-Kuswani, 2010; Traxler, 2007) have highlighted the lack of a definitive conceptual framework for mobile learning. Definitions of mobile learning focus on access (Parsons & Ryu, 2006) and support for learning in multiple locations without physical network connections (Geogiev, Georgieva & Smrikorov, 2004). The key players studied in this research were the principal, the programme coordinator, the teachers and the students. We found out that effective integration of ICT into teaching and learning is complex. It is dependent on the successful interactions between the leadership team, the community, the technical support personnel and the key users' teachers and students. A less explicitly person-centred aspect of the model is the interactions between people and devices and management's decisions to provide the financial support to support the interactions. Nevertheless, the personal dimensions of trust and confidence in the potential of the devices to enable formal learning and in other stakeholders to play their part in supporting the exploration of new practices mean that the pedagogic uses of mobile devices are clear elements of a person-centred model of sustainable innovation in learning with mobile devices. The complexity of sustainable mobile learning programmes is further exacerbated by the fast pace of change of digital technologies, where with every change, new possibilities are opened up. There is no single or simple solution to the effective integration of m-Learn (or ICT) programmes in teaching and learning and it takes time to develop effective working relationships between management, teachers and students. As the school rolls back the PDA programme and changes over to the netbook programme, unless the fundamental issues that are human-related are addressed, its longevity could be affected in similar ways to the PDA programme.

4.2.7 Evaluating Energy Efficient

The trend of increasing energy cost and rapid growth in voice and data communications usage makes orthodoxy to develop a more energy efficient and feasible "green" communications in future. The number of users of ICT is increasing rapidly over time because of better and enhanced services as estimated, there are around 6 billion users in 2007 (The World Telecommunication, 2007). Moreover, new services with several benefits being offered and increasing trend of data volume follows Moore's law that shows users doubling every 18 months. Besides in telecommunications sectors, Information Technology (IT) industry also consume huge amount of energy. IT infrastructures create several environmental pollutions both during its production and disposal. Furthermore, IT infrastructures along with computers having some toxic like lead, cadmium, mercury and chromium; those are dangerous for the environment. Hence, research study explores that, 'If computers are buried in landfills, toxic materials can leak harmful chemicals into waterways and the environment whereas if burned, they release toxic gases into the air'. Therefore, it is very important to discard the electronic waste (e- waste) in proper ways for the wellness of human health. Besides the telecommunication networks, there are many sectors of ICT where energy is being consumed greatly. The energy consumption of ICT is divided into six significant sectors such as PCs and monitors (40%), datacentres (23%), fixed-line telecoms (15%), mobile telecoms (9%), LAN (7%) and printers (6%).All stakeholders have been trying to design and implement more energy saving devices to reduce power consumptions and manufacturing cost. It is well-known to the industry that reduction of power consumption makes products cheap and eco-friendly.

4.2.8 Conceptual Framework for Sustainable Energy

There are many important factors considered in the proposed conceptual framework, it includes: enlightenment, present state of energy provision and usage; monitoring energy provided; energy management and efficiency; alternative energy; research and development and government policies. These are necessary prerequisite sub-systems required for the implementation of the proposed framework. "Knowledge is power" is a well-known adage which over the years had been found to be true. Making the users of energy (customers) aware of the challenges faced in generating adequate and enough energy to meet their needs is definitely a step in the right direction. When users know, they will use their knowledge to make informed decision on energy use which is critical to making sustainable energy available to all. Everyone is connected directly or indirectly when energy use, availability and sustainability are considered. Realizing cost-effective energy efficiency potentials will be beneficial not only for individual energy consumers, but also for the economy as a whole. For example, saved energy costs can be used to produce energy saving domestic goods and services. And as cost-effective energy improvements are realized, additional profitable opportunities for improvement will continue to open up as a result of research [48]. Energy saving in developing countries has not been well researched into unlike research carried out on the same topic in developed countries. Some researchers have indicated that energy efficiency might not be feasible in developing countries as successful as it is in developed countries until there is a well-established energy supply expansion. This might be because energy when available is used to suit any and all purpose because the consumers are not sure of when they will enjoy such privileges again [49, 50].

4.2.9 Green ICT in Organizations

Green ICT refers to communication with customers, suppliers, public institutions and communication and interaction among employees or members of an organization. The implementation of some collaborative green business processes, based on green web services, is conditioned by the adoption of green ICT and constitutes the base of the corporate environmental strategy. The situation is similar for modelling and implementation of new green processes which is impossible to achieve without adoption of green ICT, and, at a broader level, without implementing a green information system. Green ICT can be used for measuring, monitoring and performance-checking of the various emissions generated by the devices employed in the organization's activities. However, green ICT is not limited to the information system of a single organization. It provides the necessary tools for comparing the performance in reducing carbon emissions across organizations and multiple industry sectors and facilitates the understanding of the economic advantage of green initiatives among competing organizations [51].

4.2.10 The IoT for smart sustainable cities of the future

The IoT technology and related big data applications are clearly on a penetrative path across the systems and domains of smart sustainable cities [50]. Despite the recent increase of research on the IoT and related big data applications in the domain of urban development, the bulk of work tends to deal largely with economic growth and the quality of life in the realm of smart cities [51,52,53,54].In these studies we saw that the term 'cloud computing' has been defined in multiple ways by ICT experts and researchers and a wide range of organizations (e.g. government agencies) and institutions (e.g. educational institutions). Common threads running through most definitions are that cloud computing describes a computing model in which standardized, scalable, and flexible ICT-enabled capabilities delivered in real-time via the Internet. In recent years, cloud computing has attracted great attention and gained popularity worldwide, proliferating as part of the infrastructure of smart cities (see[56] and [57]) as an extension of distributed and grid computing due to the advance and prevalence of sensing devices, storage facilities, data/information pro- cessing platforms, pervasive computing infrastructures, and wireless communication networks. Additionally, cloud computing offer solutions to many challenges facing smart sustainable cities by facilitating big data storage and providing the capabilities needed for data information processing, analysis, and management for extracting useful knowledge from large masses of urban data. Therefore, cloud computing is the basic backbone for distributed urban computing involving the various functionalities of big data applications in the realm of smart sustainable cities. As a combination of infrastructure, platform, and software, it entails a set of powerful machines in large data centres across distributed environments, which are used to deliver a variety of services and thus meet the needs of different urban constituents in terms of the use of big data analytics tools, methods, techniques, models, and technologies in the context of urban sustainability.

Chapter V: Conclusions

Analysing the findings of the systematic literature review, we can assert that there is a strong impact of Green ICT on energy consumption and on all of the differences involved in this assessment. Green ICT provides an opportunity for a synthesis of policies of different fields. It addresses multiple objectives of economic growth, environmental sustainability, technological innovation, and ICT development simultaneously. Another assert we found in our studies is the important of sustainability framework we understood Sustainability has recently gained increasing widespread attention among business practitioners and scholars. Besides focusing on economic profits of business activities, firms also need to take into account the social and environmental impacts of their business activities. Regarding sustainability our research shows that the development of sustainability capabilities requires a holistic approach by integrating different firm resources. Particularly, in our study, IT resources need to be integrated for the effective development of sustainability capabilities. While sustainability research has recently gained greater attention within different business disciplines, our literature review finds little research that takes an inter-disciplinary approach to study sustainability. Our research represents an early effort in approaching sustainability research from an inter-disciplinary approach. Additionally, our research lays theoretical foundation for future research on the sustainability value of IT in several ways. First, our research has shown that the contributions of IT to the sustainability go beyond reducing IT's energy consumption through green IT initiatives.
In addition, we found another crucial aspect in our studies which is energy efficiency. we found out in recent years, energy efficiency has emerged as one of the most important design requirements for modern computing systems, such as data centres, as they continue to consume enormous amounts of electrical power. In this research we understood that Green IT Frame- work using virtualization technology and green metrics to achieve power and energy efficiency in data centres. It is an implementation framework for data centre managers to properly implement green IT technologies in their data centres. The last level we analysed, we found out Cloud computing has attracted great attention and thus gained popularity worldwide, proliferating as part of the infrastructure of smart sustainable cities. This is justified by the numerous advantages it provides as a computing model. Among the key advantages provided by cloud computing technology include cost reduction, location and device independence, virtualization (sharing of servers and storage devices), multitenancy (sharing of costs across a large pool of cloud provider's clients), scalability, performance, reliability, and maintenance. Furthermore, the findings from the case study indicate that most of the green concepts are quite new for most of data centre managers who participated, and they were quite unaware about the latest techniques and technologies that were being studied and implemented in greening data centres.

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