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# Computing in the Age of Climate Crisis: Dialogues about Concerns, Analyses and Solutions for the Future

Work presented in partial fulfillment of the requirements for the degree of Bachelor in Computer Science

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**ABSTRACT**

The climate crisis is obliging humanity to rethink how it conducts every area of its life. Computing will be one of the main subjects due to its ubiquity in society, alongside its high demand in energy and nonrenewable resources. This work proposes an analysis of the role of computing in the climate crisis, doing a literature review across multiple areas of computing science and how they are tackling issues of sustainability and ecology, interview researchers from multiple areas about how computing sustainability interacts with their subject areas, and a discussion of common patterns and knowledge gaps for future works to broaden the discussions on how computer science can do its part in this crisis.

**Keywords:** Sustainability. climate crisis. computer science. collapse informatics. computing within limits.

**A Computação na Era Climática: Diálogos sobre Preocupações, Análises e Soluções para o Futuro**

## RESUMO

A crise climática está obrigando a humanidade a repensar como ela conduz cada área da sua vida. A computação será um dos principais assuntos devido a sua ubiquidade na sociedade, além da sua alta demanda de energia e de recursos não renováveis. Este trabalho propõe uma análise do papel da computação na crise climática, revisando a literatura de múltiplas áreas da ciência da computação e como estas estão abordando as questões de ecologia e sustentabilidade, além de entrevistar pesquisadores de diversos campos científicos sobre como a sustentabilidade da computação interage com as suas áreas de pesquisa, e também uma discussão de padrões comuns e possíveis trabalhos futuros para ampliar as discussões de como a ciência da computação pode fazer a sua parte nesta crise.

**Palavras-chave:** Sustentabilidade, Crise Climática, Ciência da Computação, Informática do Colapso, Computação com Limites.

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## LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ICT | Information and Communication Technologies |
| IPCC | Intergovernmental Panel on Climate Change |
| GHG | Greenhouse Gases |
| SBC | Brazilian Society of Computation |
| LIMITS | Computing Within Limits |
| ICT4S | ICT for Sustainability |
| IoT | Internet of Things |
| SLR | Systematic Literature Review |
| IC | Inclusion Criteria |
| EC | Exclusion Criteria |
| RQ | Research Question |

## CONTENTS

# 1 INTRODUCTION

“It’s now or never, (..) Without immediate and deep emissions reductions across all sectors, it will be impossible.” said Jim Skea, Co-Chair of the Intergovernmental Panel on Climate Change (IPCC) Working Group III, in the press release for the IPCC’s latest report with updates on what is necessary for climate crisis mitigation.

We have until 2030 to reduce the world’s Greenhouse gas emissions (GHG) by 45%, and until 2050 to reach net zero emissions, if we are to avoid the increase of temperature above 1.5Cº since pre-industrial times. Although this limit was deemed as preferable on the the Paris Agreement as opposed to the hard limit of the 2Cº (United Nations, 2014), this increase would still bring catastrophic changes to Earth, such as increases in climate disaster such as heatwaves and floods, and threats to the extinction of multiple species of fauna and flora. In the latest report (IPCC, 2022) , the IPCC says that avoiding the 1.5ºC increase is "almost inevitable."

Although the IPCC states that it would be possible to bring the temperature increase below 1.5C after the overshoot, this would require carbon removal technology that is still under development. This is an extremely urgent situation that will require an "all hands on deck" approach from all of society, including Computer Science.

Fortunately, Computer Science has shifted a lot its efforts to energy efficiency over the past decades, due to the increasing demand of data centers, and the need for power efficient batteries with the ubiquity of smartphones and the advent of Internet of Things. Unfortunately, this has not stopped from its carbon footprint to keep increasing. Estimates for the emissions of the Information and Communication Technologies (ICT) range between 1.8% to 3.9% of the total global emissions, with the sector’s footprint increasing over the years even as its efficiency improved. (FREITAG et al., 2021)

To understand the extent of computing’s carbon emissions, it’s necessary to look beyond just energy demand, as a computing device does not produce emissions while it is being used. A good example is the "cradle to grave" approach of the Life Cycle Assessment ISO standard (ISO, 2006), where the phases of resource extraction, manufacturing and post-use disposal are considered alongside the use phase.

It is also deceiving to think of an industry’s influence on climate change only by its direct emissions. ICT especially has shown to be influential in shaping society,

Advancements on computing are often centered on optimization and increasing efficiency, as can be seen through the role of Moore’s law in shaping the concept of progress in Computer Science and industry to be about ever increasing growth. Not to mention that ICT has brought innovations that created new niches of resource demand in short periods time. Bitcoin, for example, was launched in 2009, and is now estimated to be demanding as much energy as countries like Poland and Malaysia (CBECI, 2022).

While much of this "eternal progress" brings along with it new developments in energy efficiency, as this urgent need for mitigation increases, questions about whether this progress is actually good start to happen. For example, Jevons' Paradox —- also referred to as the "Rebound Effect" — is often cited as a counterpoint to Moore's law, as it states that an increase in efficiency will bring an increase in overall demand, since the efficiency will be used as justification for increasing the demand (ALCOTT, 2005). Furthermore, new field propositions have appeared to challenge these ideas, like "computing within limits", where computing systems are proposed to "sufficient" instead of efficient, or "collapse informatics", which aims to imagine scenarios where computing could persist after a climate collapse scenario.

These alternative conversations can often be found in recent conferences like Computing Within Limits, the International Conference on ICT for Sustainability (ICT4S), and Sustainable HCI. However, outside these communities these types of work still struggle to get accepted, which is a major problem considering how many factors inside Computer Science need to be improved for this cause. Since the conversations are already insular inside the computing community, it's even harder for them to reach communities outside from computing, which is another concern considering how influential Computer Science can be to other fields, in both positive and negative ways.

These concerns highlight a lack of intersectionality. This work proposes a two-folded approach to tackle this problem. First, a literature review is presented, aiming to map all the different types of propositions and solutions that the computer science field is developing when it comes to climate change and sustainability causes. A concept map will be created from the results, as a way to visualize the possible connections between these works.

Furthermore, a series of interviews with researchers from different fields is presented. These conversations, in semi-structured interview format, aim to identify propositions and concerns from diverse perspectives, to combat the issue of lack of intersectionality through the understanding of what Computer Science is doing, what other fields are doing, and how Computer Science can affect these other fields' works.

Therefore, this project is based around answering the following research questions:

- **RQ1:** What types of work is Computer Science doing to mitigate the Climate Crisis?
- **RQ2:** What Computer Science can learn from other fields of research to improve its efforts to climate crisis mitigation?
- **RQ3:** What Computer Science can do to help other fields of research in their efforts of climate crisis mitigation?
- **RQ4:** What strategies should guide Computer Science's efforts to mitigate the climate crisis?

The remaining parts of this text are organized as follows. Chapter 2 will present the necessary concepts for understanding this study, with concepts related to the subject matter and to the methodology being presented. Chapter 3 encompasses the literature review, discussing the process and analyzing the resulting set of gathered studies. Chapter 4 discusses the interviews conducted for this study, describing the methodology, presenting the participants and highlighting the main ideas from these conversations. Finally, Chapter 5 synthesizes the lessons learned in the previous sections.

# 2 FUNDAMENTALS

This chapter introduces the fundamental theory utilized through this research project. First, we discuss how sustainability and environmental issues have been tackled within computing in Section 2.1. In Section 2.2, we explore the methodology of Systematic Literature Reviews and describe the process to execute one. For the literature review, we will also use Concept Mapping to visualize our findings and synthesize it into a domain, which is explained in Section 2.3. Finally, Section 2.4 will describe the theory behind Semi Structured Interviews, which we will utilize as our method for conducting interviews.

## 2.1 Computing and Sustainability

As Prof. Dr. Sofia Castillo described during one of the interviews conducted for this project, "(...) sustainability has become a wildcard term, in a way, the breadth became so ample that there will be a multiplication of the definition of Sustainability." This is not different within Computer Science, where the term has come to mean multiple things. Possibly one of the more known meanings comes from the term's usage in Software Engineering, often referred to as "the capacity to endure." However, there's no concrete and generally accepted definition for it (PENZENSTADLER, 2013).

Hilty, Lohmann and Huang (2011) defines an overview of Sustainability within ICT, highlighting three major topics: Environmental Informatics, which concerns the processing of environmental data; Green IT/ICT, concerning the the environmental impacts that IT/ICT cause; and Sustainable Human-Computer Interaction, which is concerned with "the relationship between humans and technology in the context of sustainability." Green IT/ICT is often split into two subcategories: Green in IT/ICT, which is concerned with the impacts within the ICT sector itself; and Green by IT/ICT, which concerns how ICT affects other sector's impact, in both positive and negative ways.

In recent years, discourses regarding sustainability appeared in new conferences such as the ICT4S conference. One relevant new space is the Computing Within Limits conference (LIMITS), which aims to challenge the current notions of progress and efficiency in ICT, and urge the communities of ICT and Computer Science to consider the very possible future of planetary and climate limits, and what it may mean computing (NARDI et al., 2018). Another alternative concept used in this work is "Collapse

Informatics", a term proposed in Tomlinson et al. (2013), which argues for the need of imagining post climate collapse scenarios to prepare for the worse, or as the authors write: "Perhaps by thinking now about life after collapse, we may both prepare ourselves for such an outcome, and also make that outcome less likely.

Due to the many possible definitions for sustainability, we do not attempt to define a meaning to the term, preferring instead to either explicitly address which concept we are referring to, or to use it as a synonym to "Environment friendly." when no specification is given.

## 2.2 Systematic Literature Review

Literature reviews are a common approach to recapitulate the current knowledge of a specific scope of research, providing a basis for new research propositions while also finding gaps in the current state of the art that may suggest new ideas for further investigation. However, the review process must be thorough and as unbiased as possible, otherwise it will have little scientific value (KITCHENHAM, 2004).

A Systematic Literature Review (SLR) is a process that aims to structure a literature review that follows these values. The entire review process follows a predefined search strategy that is designed to explore the proposed research questions. According to Kitchenham (2004), a SLR is divided in three phases: planning, conduction and reporting.

The review planning consists of two stages. The first is to identify the need for a review. Prior to conducting the review, the researchers involved must check previous studies to evaluate the role and value of this new proposed review. The second stage is to develop a review protocol, which specifies the methods that will be used throughout the entire review, including the research questions that the study aims to answer, the strategy used for searching for the articles, strategies used for selecting the studies found during the search, the procedures for data extraction, and how this review will be synthesized.

Once a protocol is defined, the review can be conducted. This phase is divided into five stages. First, the search for studies is executed. Then, the relevant studies must be selected within the results from the search, using the inclusion and exclusion criteria elaborated during the planning phase. With a final set of selected articles, the researchers must make a assessment of the quality of the selection, reviewing the threats to validity such as biases from the participants of the process. After the assessment, the data extraction protocol must be followed on all articles selected. Finally, the data extracted is used to synthesize the results of the included studies.

After the conduction phase is finished, the reporting phase is executed. This phase consists of a single stage, that is communicating both process and results found to the scientific community.

## 2.3 Concept Mapping

Concepts maps are defined by Novak and Cañas (2006) as a tool that organizes and represents knowledge. These maps consists of concepts, which can be represented as the nodes in a graph, and relationships, the edges that connect concepts, often accompanied by a description referred to as linking words. When two or more concepts are linked by a relationship, that is called a proposition, which represents a "meaningful statement" between the connected concepts. Figure 2.1 presents an example of a Concept Map.

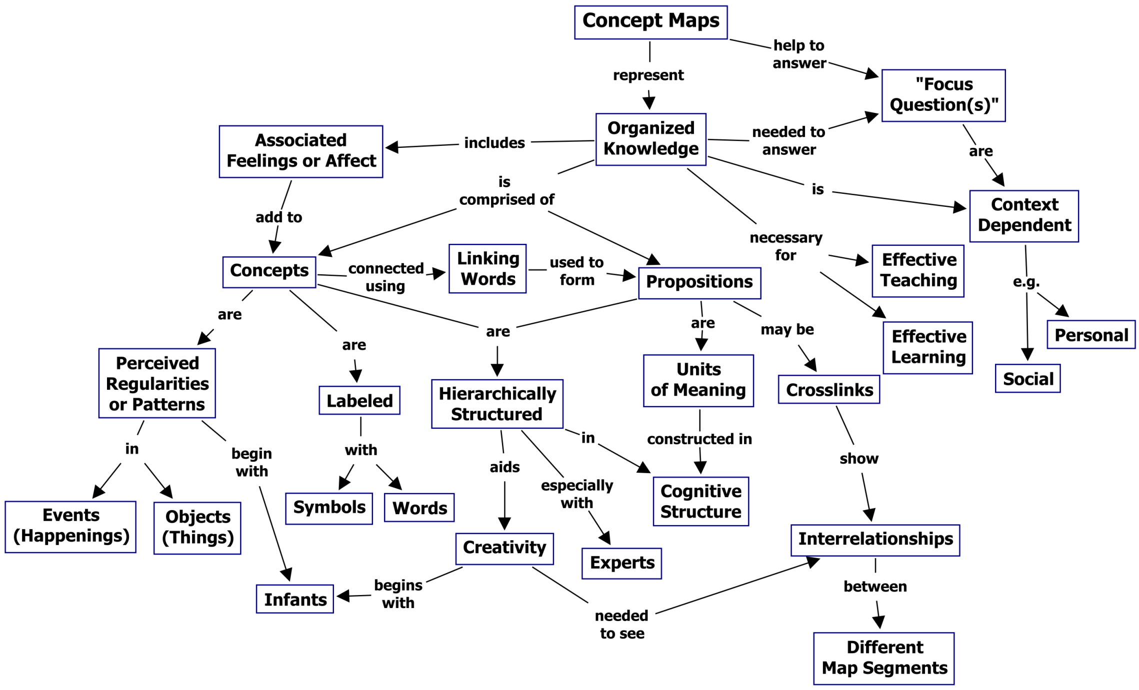


Figure 2.1 – Example of a Concept Map
Source: Novak and Cañas (2006)

The process of creating a Concept Map is similar to the process of Domain Modelling, which is defined as follows by Pressman (2010):

1. Definition of the Domain
2. Categorization of Items extracted from Domain
3. Collection of a representing sample of applications in the domain

4. Analysis of each application in the sample and definition of analysis classes
5. Development of a requirements model for classes

As can be seen, while Concept Maps do not involve the creation of a requirements model, the process of creating them can be analogous to steps 1 to 4 in the Domain Modelling process. Therefore, the resulting concept map in this work could be used as a basis for future work in Domain Modelling.

A helpful tool for creating these maps is the software CmapTools (CAÑAS et al., 2004), which will be used for the creation of our concept maps.

## 2.4 Semi Structured Interviews

In qualitative analysis, there are multiple ways of collecting data, and one of the most prominent forms is through interviews (RECKER, 2013). They provide a flexible method that can be used for a wide range of research problems, allowing rich data to be collected while having a focused target, by way of the established subject of the interview.

While Structured Interviews follow a rigid set of questions, and Unstructured Interviews are conducted without any protocol, Semi-Structured Interviews use a flexible protocol that allows for new questions to be raised during the interview process, according to the participant's answers (RECKER, 2013). The interviews often start with a set general questions about a topic that was planned beforehand. Then the possible answers and reactions to these questions become the basis for new questions. This approach allows for a more dynamic interview, where both interviewer and interviewee can respond to each other's observations, which can lead the interview to paths that would not have been explored with a predefined set of questions. However, it also has its limitations, as these potential new questions might not lead to relevant data.

To collect the data of an interview, there are two main techniques. The answers themselves, which can be recorded through notes or transcribed from an audio recording, and observations, where the interviewer takes notes on certain non-verbal cues from the interviewee, such as sudden movements or facial expressions. We do not consider observations in this project, and will work only with transcriptions.

## 2.5 Chapter Summary

This chapter presented the foundational theory utilize throughout this project. We presented an overview of how Computer Science works have explore Sustainability related topics, how there is a lack of definition and common terminology between research projects, and how new areas like Collapse Informatics and conferences like LIMITS attempt to bring new conversations aiming to improve computing efforts on the issue. The methodology used for our literature review was also presented, with a discussion of the Systematic Literature Review method, and how Concept Mapping will be utilized to map our findings within the review, in an attempt to create a basis for future works. Finally, we explored Semi Structured Interviews, and how we will utilize its protocol to conduct our interviews for qualitative data gathering.

# 3 LITERATURE REVIEW

A literature review was conducted in order to better understand the current state of Computer Science's body of work regarding sustainability and climate crisis mitigation. Section 3.1 discusses the motivation for this review, comparing it to previous secondary studies. Section 3.2 describes the methodology used and presents the selected articles. Section 3.3 discusses the results found and how they relate to our research questions. We finish this chapter presenting a concept map the synthesizes our findings.

## 3.1 The Need for a Review

While we were able to find previous reviews related to our research questions, these reviews were either constrained to Sustainbility in Software Engineering (PENZENSTADLER et al., 2012), (CALERO; BERTOA; MORAGA, 2013), or concerned with the indirect environmental impacts of the ICT sector (BIESER; HILTY, 2018). We did not find any secondary studies that aimed to review sustainability related works across all of computing, nor did we find any that were also aiming to include climate crisis related topics such as Collapse Informatics. Therefore, we believe that this review is relevant. We aim for it to serve as an exploration of the current state of Climate Crisis adjacent research in computing, and that the results may serve not only for the data they contain, but also as a measurement of how our current terminology fares in reaching those interested in the subject.

## 3.2 Methodology

In this section, we present the research protocol followed for the review, using the structure presented in Section 2.2 as a basis.

### 3.2.1 Study Search

For the retrieval of relevant studies to our review, we decided on utilizing the database search engines from relevant databases within the the field of Computer Science. The databases used for gathering the articles were

- ACM Digital Library: <http://dl.acm.org>
- IEEE Digital Library: <http://ieeexplore.ieee.org>

To make the article gathering process reproducible, we developed a search string, iterated and refined to be both comprehensive and accurate, to be used across the chosen databases. The aim of the search string is to capture results across as many types of work as possible. Therefore, a comprehensive search string was elaborated, targeting to find works ranging from software development and hardware optimization to critiques of the current approaches to sustainability and domain-specific applications of sustainable Computer Science.

The search string used was:

```
((sustain* OR ecologic* OR green OR collapse OR climate) AND
(software OR hardware OR comput*))
```

The string was applied for title, abstract and author keywords, with the search restricting publication dates to articles ranging from 2017 to the end of 2021. The search string had to be adapted according to each database's search engine.

### 3.2.2 Article Selection

To selected relevant studies, we define criteria for both inclusion and exclusion, and then apply them to all items gathered in the previous stage. Only the first 100 results for each database were considered, to limit the scope into a feasible one according to the time and resources available for this project.

The inclusion criteria we chose aim to find recent works in the field of Computer Science that are relevant to Climate Crisis mitigation. We limit the range of publications to the past five years as to get the current state of the art, though we exclude 2022 to maintain only full years in our range. The following criteria were chosen to select relevant publications:

1. **IC1:** Publication date between 1/1/2017 and 31/12/2021
2. **IC2:** Published within Computer Science related conferences
3. **IC3:** Explicitly mentions Climate Crisis, Green Computing, or Sustainability concerns

Several exclusion criteria were chosen to define a relevant but also feasible scope.

The terminology of the subject area shares a lot of terms with other areas of Computer Science, so several exclusion criteria were added to make the final set of publications more accurate. The following criteria were chosen:

1. **EC1:** Text is not fully available
2. **EC2:** Work is not in English
3. **EC3:** Duplicated works
4. **EC4:** Secondary Studies, such as literature reviews
5. **EC5:** Non peer-reviewed texts, such as columns and opinion articles
6. **EC6:** Usage of term "Sustainability" in terms of Software Engineering, without directly addressing the Environmental dimension
7. **EC7:** Usage of "Collapse" in terms of Software Stability
8. **EC8:** Usage of "Environment" in the sense of system environment
9. **EC9:** Usage of "Ecosystem" as in a set of interacting systems

Excluding duplicates, texts without full-access availability, non-English texts, proceedings and conferences, this process gathered 87 studies from ACM and 98 studies from IEEE. Then secondary studies and non peer-reviewed items were removed, with 72 articles remaining from ACM, and 79 studies remaining from IEEE. Finally, after reading the abstracts, studies that did not fit the remaining criteria were excluded, leaving this literature review with a total of 78 articles, with 40 articles coming from the ACM search, and 38 articles coming from the IEEE search. Table 3.2 presents the final set of articles originating from the ACM search, and Table 3.3 presents the final set of articles originating from the IEEE search.

| | Search results | EC1, EC2, EC3 | EC4, EC5 | EC6, EC7, EC8, EC9 |
|---|---|---|---|---|
| ACM | 100 | 87 | 72 | 40 |
| IEEE | 100 | 98 | 79 | 38 |
| **Total** | **200** | **185** | **151** | **78** |

Table 3.1 – Summary of the data gathering process

Table 3.2 – List of reviewed articles from the ACM database

| Citation | Title |
|---|---|
| (GONG; GUO; NING, 2017) | Green Virtual Network Embedding for Collaborative Edge Computing in Environment-Friendly Optical-Wireless Networks |
| (JANG et al., 2017) | Unplanned Obsolescence: Hardware and Software After Collapse |
| (LÜNDSTROM; PARGMAN, 2017) | Developing a Framework for Evaluating the Sustainability of Computing Projects |
| (MUNOZ; PINTO; FUENTES, 2017) | Green software development and research with the HADAS toolkit |
| (PARGMAN; WALLSTEN, 2017) | Resource Scarcity and Socially Just Internet Access over Time and Space |
| (PEREIRA et al., 2017) | Energy efficiency across programming languages: how do energy, time, and memory relate? |
| (RAGHAVAN; PARGMAN, 2017) | Means and Ends in Human-Computer Interaction: Sustainability through Disintermediation |
| (TORRE et al., 2017) | On the Presence of Green and Sustainable Software Engineering in Higher Education Curricula |
| (CHENG; ZHAO; WANG, 2018) | User-oriented green computation in small cell networks with mobile edge computing |
| (FATHI; KHANLI, 2018) | Consolidating VMs in Green Cloud Computing Using Harmony Search Algorithm |
| (FRANCESE; BUONINCONTI, 2018) | Sustainable Design and Software Tools by Multimatrix Criteria |
| (GUPTA; ROBINSON; DILKINA, 2018) | Infrastructure Resilience for Climate Adaptation |
| (IYENGAR et al., 2018) | SolarClique: Detecting Anomalies in Residential Solar Arrays |
| (LIU et al., 2018) | Energy-aware task scheduling strategies with QoS constraint for green computing in cloud data centers |

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Table 3.2 – *Continued from previous page*

| Citation | Title |
|---|---|
| (MANCEBO et al., 2018) | EET: a device to support the measurement of software consumption |
| (MANN et al., 2018) | Regenerative computing: de-limiting hope |
| (PENZENSTADLER et al., 2018a) | Everything is INTERRELATED: teaching software engineering for sustainability |
| (WANG; KÖSE, 2018) | Reliable On-Chip Voltage Regulation for Sustainable and Compact IoT and Heterogeneous Computing Systems |
| (BABOU et al., 2019) | Home Edge Computing Architecture for Smart and Sustainable Agriculture and Breeding |
| (KARITA; MOURÃO; MACHADO, 2019) | Software industry awareness on green and sustainable software engineering: a state-of-the-practice survey |
| (NAGY et al., 2019) | Tools supporting green computing in Erlang |
| (PREIST; SCHIEN; SHABAJEE, 2019) | Evaluating Sustainable Interaction Design of Digital Services: The Case of YouTube |
| (STREVELL et al., 2019) | Designing an Energy-Efficient HPC Supercomputing Center |
| (WIDDICKS et al., 2019) | Streaming, Multi-Screens and YouTube: The New (Unsustainable) Ways of Watching in the Home |
| (NORTON et al., 2019) | The SAGE Community Coordinator: A Demonstration |
| (COUTO et al., 2020) | On energy debt: managing consumption on evolving software |
| (KORTBEEK et al., 2020) | BFree: Enabling Battery-free Sensor Prototyping with Python |
| (MAIA et al., 2020) | E-Debitum: managing software energy debt |
| (PARGMAN et al., 2020) | From Moore's Law to the Carbon Law |

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Table 3.2 – *Continued from previous page*

| Citation | Title |
|---|---|
| (RIFAT; TORIQ; AHMED, 2020) | Religion and Sustainability: Lessons of Sustainable Computing from Islamic Religious Communities |
| (RIVERA; ERIKSSON; COMBER, 2020) | Diminishing space - peer-to-peer sharing as a transition practice |
| (WELZ; STUERMER, 2020) | Sustainability of ICT hardware procurement in Switzerland: A status-quo analysis of the public procurement sector |
| (WILLIS et al., 2020) | Low Power Web: Legacy Design and the Path to Sustainable Net Futures |
| (BASHIR et al., 2021) | Enabling Sustainable Clouds: The Case for Virtualizing the Energy System |
| (BHEDA; THAKER; SHAH, 2021) | An Optimized VM Placement Approach to Reduce Energy Consumption in Green Cloud Computing |
| (CHEN; DING, 2021) | Green Clothing Design Based on Computer Aided Design in Ecological Times |
| (COSTALONGA et al., 2021) | The Ragpicking DMI Design: The Case for Green Computer Music |
| (MANZ; MEYER; BAUMGARTNER, 2021) | Life cycle assessment of an Internet of Things product: Environmental impact of an intelligent smoke detector |
| (RAMPRASAD et al., 2021) | Sustainable Computing on the Edge: A System Dynamics Perspective |
| (SARAIVA; ZONG; PEREIRA, 2021) | Bringing Green Software to Computer Science Curriculum: Perspectives from Researchers and Educators |

Table 3.3 – List of reviewed articles from the IEEE database

| Citation | Title |
|---|---|
| (ANTHONY; MAJID; ROMLI, 2017) | A model for adopting sustainable practices in software based organizations |
| (HASAN et al., 2017) | A model for adopting sustainable practices in software based organizations |
| (KLINE et al., 2017) | Sustainable IC design and fabrication |
| (LIGHT, 2017) | Energy usage profiling for green computing |
| (LONDE; MATH, 2017) | Green computing based cost optimization in cloud computing |
| (PA; KARIM; HASSAN, 2017) | Dashboard System for Measuring Green Software Design |
| (VISTER; EVANS, 2017) | Identifying contributing factors to sustainability awareness in the norwegian software industry |
| (ABUGABAH; ABUBAKER, 2018) | Green computing: Awareness and practices |
| (ALNAHDI; BAZARAH, 2018) | Building Quality Metrics for Green Computing Projects: A Model and a Case Study of Engineering a Green Computing Awareness Website |
| (BRUNVAND; KLINE; JONES, 2018) | Dark Silicon Considered Harmful: A Case for Truly Green Computing |
| (CHANG et al., 2018) | From Insight to Impact: Building a Sustainable Edge Computing Platform for Smart Homes |
| (FRATERNALI et al., 2018) | Quantifying the Impact of Variability and Heterogeneity on the Energy Efficiency for a Next-Generation Ultra-Green Supercomputer |
| (HANIEF et al., 2018) | A Proposed Model of Green Computing Adoption In Indonesian Higher Education |
| (HSIEH; CHEN, 2018) | Toward Green Computing: Striking the Trade-Off between Memory Usage and Energy Consumption of Sequential Pattern Mining on GPU |
| (PENZENSTADLER et al., 2018b) | Software Engineering for Sustainability: Find the Leverage Points! |

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Table 3.3 – *Continued from previous page*

| Citation | Title |
|---|---|
| (PONSARD; LANDTSHEER; GERMEAU, 2018) | Building sustainable software for sustainable systems: case study of a shared pick-up and delivery service |
| (TURKIN; VYKHODETS, 2018) | Software engineering master's program and Green IT: The design of the software Engineering Sustainability course |
| (ZANAFI et al., 2018) | Enabling Sustainable Smart Environments Using Fog Computing |
| (CAI et al., 2019) | An energy-efficiency-aware resource allocation strategy in multi-granularity provision for green computing |
| (SHVEDCHYKOVA; SOLOSHYCH; POCHTOVYUK, 2019) | Creating the Educational and Research Software for Integrated Assessment of Energy Consumption and Sustainable Development of Regions |
| (WADHWA et al., 2019) | Green Cloud Computing – A Greener Approach To IT |
| (ALHARBI; ALAHRBI; ALKHAMALI, 2020) | A Proposed Framework for Adoption Green Cloud Computing in Saudi Arabia |
| (GUHA et al., 2020) | Ensuring Green Computing in Reconfigurable Hardware based Cloud Platforms from Hardware Trojan Attacks |
| (LI et al., 2020) | An Algorithm Incarnating Deep Integration of Hardware-Software Energy Regulation Principles for Heterogeneous Green Scheduling |
| (SOJAT; SKALA, 2020) | The Rainbow through the Lens of Dew |
| (YAHAYA et al., 2020) | Software Model for Learning Quarry Industry Impacts on Green Environment |
| (ZHENG; ZHANG; CHEN, 2020) | Research of pervasive ecological monitoring applications based on edge computing technologies |
| (ZONG, 2020) | An Improvement of Task Scheduling Algorithms for Green Cloud Computing |

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Table 3.3 – *Continued from previous page*

| Citation | Title |
|---|---|
| (CHAUDHRY; KUMAR, 2021) | A Multi-objective Meta-heuristic Solution for Green Computing in Software-Defined Wireless Sensor Networks |
| (DAUTOV; SONG; FERRY, 2021) | Towards a Sustainable IoT with Last-Mile Software Deployment |
| (HAMDAN; SALEM; SHAMAYLEH, 2021) | Harmonization between Renewable Energy and Cloud Computing towards Green Computing A Case Study: Data Center at The University Of Jordan |
| (HEWAGAMAGE et al., 2021) | Computer-Vision Enabled Waste Management System for Green Environment |
| (HU et al., 2021) | Deep-Green: A Dispersed Energy-Efficiency Computing Paradigm for Green Industrial IoT |
| (KUMAR et al., 2021) | Green Computing in Software Defined Social Internet of Vehicles |
| (RAISIAN et al., 2021) | The Green Software Measurement Structure Based on Sustainability Perspective |
| (RAJA, 2021) | Green Computing and Carbon Footprint Management in the IT Sectors |
| (ROUQUIER; KARIM; ALMHANA, 2021) | Redundant Transmitter Placement in Rural Areas for User-to-User Communication in Green Computing |
| (SINGH et al., 2021) | Green and Sustainable Software Model for IT Enterprises |
| (ZHANG; LIU, 2021) | Research on the Development of Software for Predicting Ecological Impacts in Coastal Waters |

### 3.2.3 Study Quality Assessment

The following threats to validity were identified during the process:

- Researcher bias: Due to the time and resources available, the entire process was done by a single research. Adding more researchers to the process would be a good measure to reduce bias.
- Search string validity: More than half of the results gathered from the search string did not fit our Inclusion and Exclusion criteria, which may indicate that the search string returned too many irrelevant studies. However, it is important to notice that the lack of a proper terminology for sustainability is a huge factor in false positives, especially since this review aims to have a broad scope.
- Selection scope: This review only includes articles selected from database searches, which is not recommended for Systematic Literature Reviews, which often include other sources such as reference lists or reviewing the proceedings of relevant conferences. As future work, it would be interesting to review the proceedings of Sustainability related conferences such as LIMITS and ICT4S. A future review could also include results from more databases, and also increase the amount of search results analyzed.

## 3.3 Data Extraction and Synthesis

This section is guided by our research questions, and describes the data extraction processes used to answer them. For synthesis, we summarize our finding in both writing and the presentation of the resulting concept map from the extracted data. Since this literature review aims to map the current works regarding Computer Science and the climate crisis, we aim to investigate only RQ1 and RQ3 with it.

### 3.3.1 RQ1: What types of work is Computer Science doing to mitigate the Climate Crisis?

During the process of reading through the selected articles, each text would be assigned two values to help organize and present our findings. "Content Type", which describes, in broad terms, what type of research object was used. The Table 3.4 describes the Content Types used to categorized the selection of works, alongside the count of how many articles fit into that category. Each article was assigned a single Content Type.

The second value is "Domain", which was used to categorize which areas of Computer Science the paper is best fitted in. Each article was assigned up to three different domains, as to better represent articles that explore multiple domains at the same time. Domains outside of Computer Science were grouped into a single value called "Domain Outside CS.", and will be further explored in section 3.3.2, where we investigate RQ3.

| Content Type | Description | Article Count |
|---|---|---|
| Method | Describes a specific technique or model | 27 |
| Strategy | Discussions of best practices, challenges, concerns | 17 |
| Study | Evaluation, Case Studies, Surveys, Metrics | 13 |
| Tool | Design and Implementation of a system | 11 |
| Framework | Description of a reproducible process | 10 |

Table 3.4 – Article count per Content Type

Table 3.5 presents the domains found within the selected articles. Aiming to be concise, the following review will omit citations for every individual article,as they can be found on Table 3.2 and Table 3.3. Instead, we will provide a overview of works found for each domain, with standout articles being summarized and cited directly. Following that, we'll discuss the resulting concept map presented in Section 3.3.3.

| Domain | Frequency Count |
|---|---|
| Energy Efficiency | 27 |
| Software Engineering | 16 |
| Cloud Computing | 12 |
| Domain Outside CS | 10 |
| Internet of Things | 10 |
| Edge Computing | 10 |
| Footprint Evaluation | 7 |
| Hardware Manufacturing | 6 |
| Human-Computer Interaction | 5 |
| Education | 5 |
| Awareness Surveys | 4 |
| Computing within Limits | 4 |
| Hardware Procurement | 3 |
| Collapse Informatics | 2 |

Table 3.5 – Domain type frequency count

As expected, Energy Efficiency related articles were the most common within the selection, with 25 works filed under its category. These works range from algorithm optimizations and architecture design to tool development and procurement strategies. As a broad category, these works were also filed under other domains, and will be discussed below.

The infrastructure of energy sources was a common topic. For renewable sources, we found works concerned with the unpredictable availability of these types of energy sources. Iyengar et al. (2018) propose an algorithm to detect anomalies in Solar Panel systems by correlating their performance to nearby solar power sites. Bashir et al. (2021) explore the virtualization of the energy, so that computing systems would be able to know which power sources are available at a given time. Hasan et al. (2017) propose a energy virtualization system for Cloud Computing, where applications would have full control over their virtual energy system, which would then be allocated across available power sources. Other works related to Cloud Computing explored topics such as task scheduling, virtual machine migration, and virtual machine consolidation.

Concerns about energy and infrastructure were also common within distributed computing. Internet of Things (IoT) papers explored problems such as energy-aware device placements; energy-efficient task scheduling; voltage regulation techniques for devices. Kortbeek et al. (2020) present a beginner-friendly system for prototyping battery-free sensors with a custom verison of Python.

Several works also explored how heterogeneous IoT architectures can benefit from adding new layers of devices systems to make them more sustainable, such as Fog Computing and Dew Computing layers. For example, Dautov, Song and Ferry (2021) propose an Internet of Things architecture where edge devices connected to a service would deploy updates to the IoT devices in a cost effective way, incentivizing device reuse in a situation where deploying new devices can be cheaper than updating them.

Edge Computing works approached subjects like the virtualization of edge device networks and green workload offloading algorithms. Chang et al. (2018) propose a framework for Edge Computing systems for Smart Homes using solar energy, detailing a energy management system that includes weather forecasting, energy scheduling and task scheduling processes. Ramprasad et al. (2021) uses System Dynamic modelling to assess the carbon footprint of a cloud-edge hybrid system for a video analytics service over its long-term use.

Software Engineering was the second most used category, comprised of works ranging from processes and frameworks to tool development and case studies. Frameworks included processes for evaluating the sustainability of a project, sustainable usage of software tools in software companies, plans for increasing green computing adoption in college infrastructures, and measurement processes for sustainability metrics.

Software Engineering tool development spanned several works regarding energy efficiency. Mancebo et al. (2018) present a metering device capable of measuring the energy consumption of the CPU, GPU and storage disk during the execution of a application, through the use of energy and temperature sensors. Maia et al. (2020) propose a tool that identifies energy inefficient code smells in Android applications, using the concept of "energy debt" to represent the energy cost over time if the smells are left unaddressed. Other works include tools for measuring the energy consumption of specific programming languages, a dashboard system for measuring the sustainability of green software development projects, and tools developed for domains outside of Computer Science.

Education papers were concerned with green and/or sustainable software engineering classes, including surveys with educators on best practices and challenges, and the designs for a course. Penzenstadler et al. (2018a) present the design of Software Engineering for Sustainability class, including feedback from students and a reproducible blueprint of the class. Awareness studies were evaluated across many demographics, including works that investigated the sustainability awareness of: clients of cloud computing services, college students and workers in the software industry.

Human-Computer Interaction works explored how design choices can affect a system's sustainability. Preist, Schien and Shabajee (2019) investigates how Sustainable Interaction Design can reduce emissions on digital service providers through a life cycle assessment of Youtube's design. Widdicks et al. (2019) analyze the usage of internet and streaming services across nine households to identify the habits of users and how more sustainable design can reduce the data demand created from those.

Hardware related works were concerned with manufacturing, design and procurement. Strevell et al. (2019) investigates the design questions around building a sustainable supercomputer, using the Los Alamos National Laboratory as a case study. Kline et al. (2017) present a model for evaluating the impacts of integrated manufacturing. Brunvand, Kline and Jones (2018) argues that, despite being more energy-efficient during the use phase, the inclusion of Dark Silicon accelerators on integrated chips is not sustainable when you analyze the manufacturing process and the amount of energy that must be amortized during the use phase. Manz, Meyer and Baumgartner (2021) presents a Life cycle assessment of a Internet of Things device, including impacts that are not related to energy, like mineral resource scarcity and ecotoxicity of water.

Computing within Limits papers discussed strategies for more sustainable and non-growth based computing. Pargman et al. (2020) identifies a need for moving beyond discussion, citing a lack of system and design propositions within the LIMITS community, and proposing Carbon Law as a replacement for Moore's Law going forward. Mann et al. (2018) discusses how pessimistic thinking might create a self-fulfilling prophecy for sustainability not working out, and suggest the approach of Regenerative Computing as an alternative. Collapse Informatics papers imagined challenges and strategies for post climate-collapse scenarios. Jang et al. (2017) details the challenge of maintaining current software and hardware functional in a scenario where resources might be scarce, and how computing would look like in that scenario.

### 3.3.2 RQ3: What Computer Science can do to help other fields of research in their efforts of climate crisis mitigation?

Table 3.6 describes the domains that were grouped into the "Domain Outside CS" value.

Francese and Buoninconti (2018) proposes a model using Proposes a model utilizing Multicriteria matrices to estimate the sustainability of a archtitectural model in a Computer Assisted Design (CAD) software, estimating criterias such as biocompatibiity, mitigation of gases, and land occupation. Also focused on CAD, Chen and Ding (2021) describes how it can be used for creating more sustainable clothes.

Two works proposed works intersecting with Edge Computing. Babou et al. (2019) proposes a three level Edge Computing architecture for smart agriculture, detailing uses cases such as control of soil erosion, pastoral conflict and monitoring of water. Zheng, Zhang and Chen (2020) propose an Edge Computing microservice for data monitoring environments.

Two works works proposed applications to visualize environmental impacts related to other domains.(ZHANG; LIU, 2021) presents a system that predicts the environmental impacts of coastal area developments in the coastal waters, including a time history graph and a 3D visualization of the results. Yahaya et al. (2020) proposes a software model for an application that helps users learn the environmental impacts of the Quarry Industry, having the user go through a simulation of a quarry scenario. Hewagamage et al. (2021) proposes a Computer Vision based system for garbage bin waste management, where the system recognizes the trash being thrown out, segregates it depending on the object, and then informs updated waste and methane levels.

(COSTALONGA et al., 2021) explores how the manufacturing of Digital Music Instruments can be made more sustainable, using strategies such as ragpicking, life cycle analysis and modular design.

Norton et al. (2019) propose a system to help beginners in the field of Sustainable Polyculture, suggesting which plants mesh well with the user's current ones, and best practices to maintain them.

| Citation | Domain |
|---|---|
| (FRANCESE; BUONINCONTI, 2018) | Architecture |
| (BABOU et al., 2019) | Agriculture |
| (NORTON et al., 2019) | Sustainable Polyculture |
| (YAHAYA et al., 2020) | Quarry Industry |
| (ZHENG; ZHANG; CHEN, 2020) | Ecological Monitoring |
| (HEWAGAMAGE et al., 2021) | Waste Disposal |
| (ZHANG; LIU, 2021) | Coastal Water |
| (ROUQUIER; KARIM; ALMHANA, 2021) | Rural Area |
| (COSTALONGA et al., 2021) | Digital Music Instrument Design |
| (CHEN; DING, 2021) | Green Fashion Design |

Table 3.6 – List of Domains from outside of Computer Science

### 3.3.3 Concept Map

The idea for our concept map was to synthesize the process used to analyzed the selected articles. Therefore, the categories follow closely the ones detailed in Section 3.3. We define a Computer Science Sustainability Solution as an object consisting of one Content Type and one or more domains. Figure 3.1 presents the Concept Map.

As we mapped the relationships found during the research process, we found some new groupings to better represent the fields. Hardware Manufacturing and Hardware Procurement were merged into a Hardware category, as they are related. Awareness studies was added under Education, due most of the awareness work being concerned with awareness at colleges, and also due to main purpose being to educate on the current awareness of certain groups. Internet of Things, Edge Computing and Cloud Computing were grouped into a Distributed Computing category, due to the large overlap of works between the three. As for Computing within Limits and Collapse Informatics, they were grouped into the "New Alternatives to Sustainability" category, as they are very similar in concept i.e critiques and designs that break out of the currents beliefs.

Note that the category nodes (in Orange) share child nodes between them, this is to represent the overlap and intersectionality between areas. However, we opted to not to do the same their child nodes, as to avoid readability issues. Instead, we imagined the model to have more than one domain, so that instead of having, for example, Cloud Computing pointing to Algorithm Optimization — a child node of Energy Efficiency — the Cloud Computing object could just have both Cloud Computing and Energy Efficiency as its domain.

## 3.4 Chapter Summary

This chapter presents the conduction of a literature review that aims to map the current state of the art for Climate Crisis and Sustainability related works within Computer Science. The methodology for a Systematic Literature Review is described, sharing the database selection, search string and the inclusion and exclusion criteria utilized. From a total 200 results analyzed, we selected 78 articles relevant to the criteria chosen. During the quality assessment, we discussed the issues of bias and scope that may be threats to validity. Aiming to answer our research questions, we describe our data collection methodology, and present the categories of "Content Type" and "Domain" which were used to map the selected articles. We then discussed our findings, describing what types of work we found, in which domains they were categorized, including domains from Computer Science and Domains outside of it. Finally, we presented the Concept Map created to synthesize our findings.

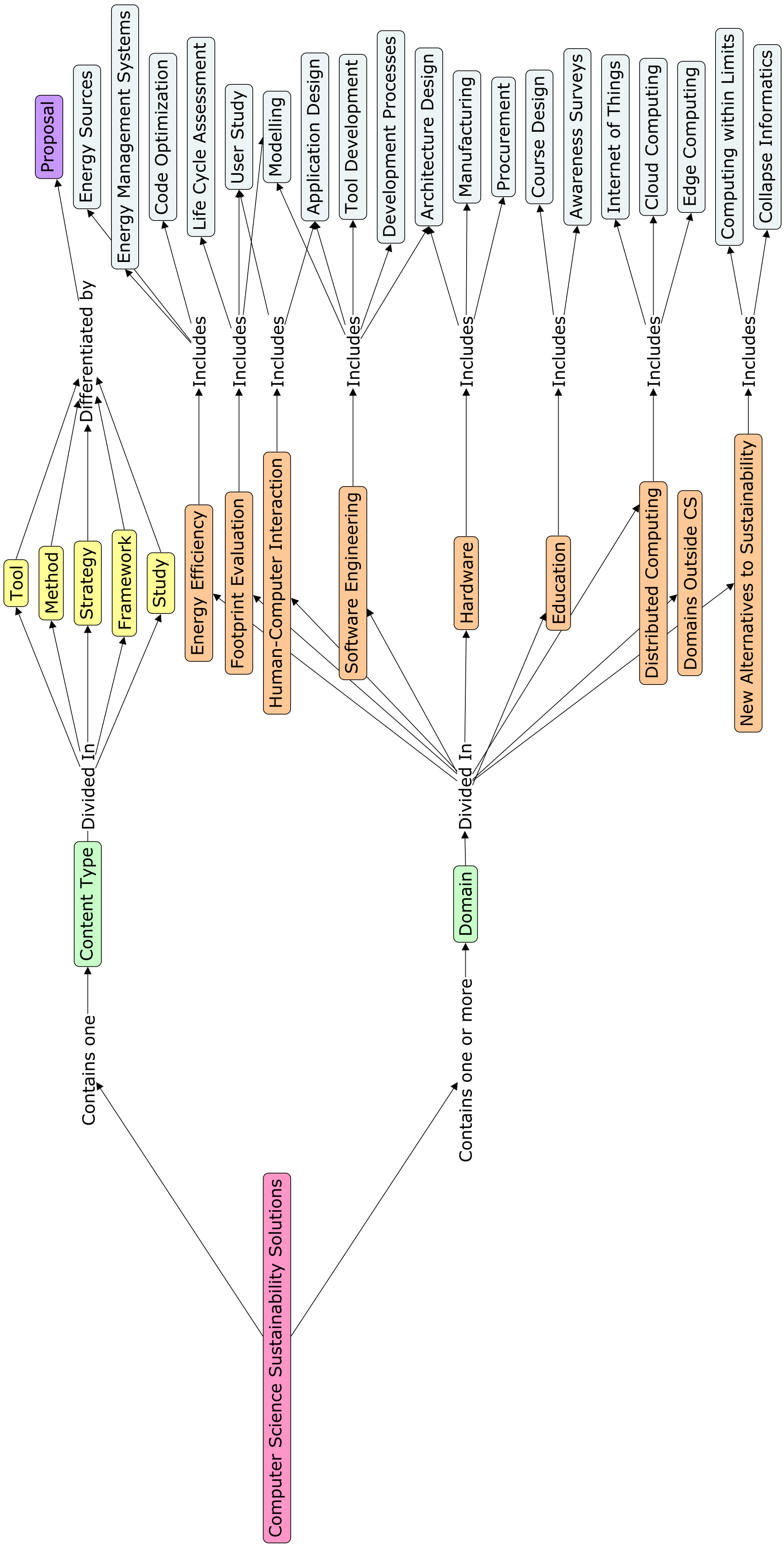


Figure 3.1 – Resulting Concept Map
Source: Authors

# 4 INTERVIEWS

While the literature review was able to provide a broad perspective from within Computer Science, several of our research questions are concerned with how Computer Science intersects with other fields of research, since the Climate Crisis is an intersectional problem. Therefore, a series of interviews were conducted with research from multiple fields, as to better understand what other fields are working on and how Computer Science could help them, and also their perspectives on the current state of Computer Science's efforts to mitigate the climate crisis. Section 4.1 describes the methodology utilized. Section 4.2 introduces the participants that were interviewed. Finally, Section 4.3 presents and analyzes the results.

## 4.1 Methodology

The interviews were conducted through video conference, with only the audio of the call being recorded, with the interview asking consent to start the recording, and also warning the participant when the recording would be stopped. Transcriptions were done manually, the interviews conducted in Portuguese were translated to English. The audio recordings will be deleted after this work is published.

The recorded interviews ranged from 38 to 50 minutes (44 minute mean), although each sessions was scheduled as an one hour meeting, so interviewer and participant could introduce themselves at the beginning, and also so the participant could give feedback after the interview had ended.

Participants were given a term of consent to sign, which granted them full control of what parts of the interview would be published, if any at all. After the transcriptions were finished, an email was sent to each participant including the audio recording of their interview session, alongside the full transcript. Participants then were free to ask for any parts to be removed or edited with full privacy and no explanations needed.

Interview questions focused on learning about the participant's body of work and how it relates to the Climate Crisis, their perspective on what Computer Science is doing for this cause, and what they wish they would see more from Computer Science in this regard. Following the Semi-Structured Interview process, we did not follow a strict script of questions, opting instead to raise questions and observations according to the participant's remarks.

Therefore, a set of five "pillar" questions were use throughout all interviews, with remaining questions varying from interview to interview:

1. Could you describe your work and does it relate to the Climate Crisis? (RQ1, RQ2, RQ3)
2. What were the main challenges you found while conducting your work? (RQ2, RQ3, RQ4)
3. What you believe is Computer Science's main role in fighting the Climate Crisis? (RQ1, RQ2)
4. What is your major concern about how Computer Science is handling the Climate Crisis? (RQ4)
5. What types of research you wish you would see more from Computer Science? (RQ3, RQ4)

## 4.2 Participants

To further understand the intersectionality questions around Computer Science's role in the Climate Crisis, we aimed to interview as diverse of a roster of participants as possible. This meant inviting not only researchers from different fields of Computer Science, but also researchers from outside Computer Science as well. Participants were invited according to their relevance to Climate Crisis adjacent topics. Availability was also a major factor, as over fifty researchers were invited, but several of them were not available. To be as inclusive as possible, we also aimed to have researchers from different countries and origins, as to further increase the diversity of perspectives. Having gender diversity was also a concern during the invitation process.

Find below a brief introduction for each of the participants:

**Prof. Dr. Bill Tomlinson** is a professor at the Computer Science department at the University of Irvine in Irvine, California, USA. He is one of the founders of the Computing Within Limits conference. His work spans multiple proposals at the intersection of Computer Science and sustainability concerns, such as the imagining the future of computing in post climate collapse scenarios under the proposed area of Collapse Informatics.

**Prof. Dr. Andrés Mendiburu** is a Professor at the Department of Mechanical Engineering at the Federal University of Rio Grande do Sul in Porto Alegre, Rio Grande do Sul, Brazil. His work includes investigations on alternative energies, solar energy, and cooling by absorption systems.

**Prof. Dr. Kádna Camboim** is a Professor in the Computer Science Department at the Federal University of Agreste de Pernambuco at Garanhuns, Pernambuco, Brazil. Her work explores how to make more sustainable data center through architectural decisions.

**Prof. Dr. Raimundo Macêdo** is a Professor in the Computer Science Department at Federal University of Bahia in Salvador, Bahia, Brazil. He is the current president of the Brazilian Society of Computation (SBC), and is currently helping to organize a task-force with other SBC members to release a manifesto concerning Computer Science's importance in mitigating climate crisis.

**Prof. Dr. Sofia Castillo** is a Professor at the Department of International Relationships at the University of Vale do Rio dos Sinos in São Leopoldo, Rio Grande do Sul, Brazil. Her work investigates the cultures surrounding energy use, and how social factors can change how people perceive and utilize energy.

**Prof. Dr. Josh Lepawsky** is a professor at the Department of Geography at the Memorial University of Newfoundland in St John's, Newfoundland and Labrador, Canada. His work is concerned with electronic waste, spanning mining, manufacturing and use phases, and chemical emissions created during the manufacturing of electronics.

**Prof. Dr. Kelly Widdicks** is a professor at the Computer Science department at the University of Lancaster in Lancaster, Lancashire, England. Her work includes investigations on how design of systems and human-computer interfaces can be more sustainable, and investigations on the climate impacts of the ICT sector.

**Dr. Jeffrey Anderson** is a computational scientist and head of the Data Assimilation Research section at the National Center for Atmospheric Research in Boulder, Colorado, USA. His work is concerned with predictions of atmospheric and earth systems, including climate change scenarios, such as global temperature increase and the melting of polar ice caps, through techniques of data assimilation.

### 4.3 Analysis

This section is guided by our research questions, with a focus on quotations from the conducted interviews as possible answers to them. We aim to explore RQ2, RQ3 and RQ4 in this section. RQ1 is indirectly explored through the sections below and the participant introductions above, for brevity's sake as the interviews did not explore this questions as much as the literature review.

### 4.3.1 RQ2: What Computer Science can learn from other fields of research to improve its efforts to climate crisis mitigation?

Prof. Dr. Lepawsky questioned what a computer science concept of sufficiency would look like, comparing it to sustainability studies from other fields.

> *I think, you know, in the broader area of let's call it sustainability studies, or sustainability fields, like Geography, instead of thinking about efficiency, people are talking about the importance of sufficiency. But what would that look like in computer science? I don't know. What would sufficient code look like as opposed to each efficient code? No idea. I mean, that's a purely speculative question on my part. You know, I've started thinking — So the desktop that I'm using to have this conversation with you is from 2012. (...) And in the last year or so, I've been asking myself, you know, what if this was the last computer I was able to buy? Like, could I keep it going? It's still perfectly adequate for my purposes.*

Prof. Dr. Mendiburu argued about the importance of acknowledging the social dimension of technology, using an example about the history of solar energy and how it was supposed to bring a different perception to energy use, before it was assimilated into the predominant ideas.

> *Once I heard a professor from Spain at a solar energy conference, and he brought up some interesting things — that solar energy, how it was conceived at the beginning of the century by the first people that studied it, how it was understood, was not only a technological change, but a social change. Where it would bring limitations that would make you think about how to use this energy. It was intermittent, so you couldn't leave all the lights of your house turned since you had energy all the time. You couldn't use that air-conditioning at moment, when it's 25 degrees outside but you're feeling warm so you put it on 18. These situations, that are more social situations, solar energy made think about them. But from the moment that it is inserted into the grid, you return to the previous paradigm: I have energy on the grid, it always works, I spend what I can pay for.*

Prof. Dr. Castillo urged Computer Science to perceive itself also as a social practice.

*I think it's fundamental that computer scientists understand the impact they have on all of society, and the role they have in society. (...) They change values, practices, beliefs, so all of this is reflected on technological products. For example, all the discussion regarding Artificial Intelligence and racism. If Computer Science can understand itself as a social practice, it will be able to see these aspects of how technology is tied into that area.*

Dr. Anderson warned about the dangers of focusing on solvable problems instead of the problems that need to be solved.

*There is a danger when doing this type of data science on producing answers, producing methods that cannot be rigorously verified in a way that is useful. Again, for this sort of out of sample stuff that we really need for informing climate future scenarios. There is a lot of work out there getting into the literature. A lot of scientists who may be very good scientists on machine learning and other stuff, but they are not trained to deal with this issue of "is this really predictive for the physical climate system?" And so there are lots of, there are also lots of people trying to bridge that gap, not enough, I think. And so I think the research that's really useful is building more collaborative communities that span physical science, computational science, and then this sort of middle ground of climate modeling science and things there, to make sure that everyone's solving useful problems as opposed to solvable problems.*

### 4.3.2 RQ3: What Computer Science can do to help other fields of research in their efforts of climate crisis mitigation?

Prof. Dr. Mundiburu stated that other fields of research can often struggle to design and model simulations, which they could use help from people within Computer Science.

*We have several studies with complex numerical simulations. Very complex. It takes a lot of time for us to learn how to utilize it. And a lot of time we say "Here we would need someone that know about this subject, from programming, from computing." (...) [this interaction] is always present because we always need to study complex systems and really complex computational tools. And if we were to study a system — for example, about the life cycle of* *a fuel — I would have to create precisely a tool that would be able to capture all of this life cycle, and with our knowledge we would not be able to do it all, because we would need people with other backgrounds such as informatics.*

Dr. Anderson shared how research teams can benefit from software engineers with a Computer Science background.

*Scientific software engineering is a field that doesn't get the respect it deserves, especially in the computer science side of things. (...) What you end up having is a lot of scientific folks who came into the field through science. They had to write code because they needed that for their science. And then they have transitioned to be scientific software engineers because gee, they liked coding. These people are really smart, but their knowledge doesn't look anything like the knowledge of people who've come from a software engineering in most computational computer science departments.*

Prof. Dr. Lepawsky described how electronic devices are made to operate only in their optimal environmental conditions, and how that shows a narrow vision of Earth's environments.

*One of the things that can continues to interest me is how electronics are — they're kind of assumed to be globalizing or universalizing devices. But when you look at the ideal operating — environmental operating conditions, they're actually built for a relatively narrow range of environmental conditions to operate in. And so, you know, when I've done field work in tropical countries, it can be harder for things to work in very high humidity and all of that kind of stuff. (...) So, in other words, for computer science to understand that the planet is a uniform Euclidean space, right? That environmental conditions are highly variable. That computer scientists are designing for a planet rather than an abstract space of the mind*

Prof. Dr. Tomlinson discussed the importance of Computing's power to support other fields to be more sustainable.

*So, I don't know what the impact of the computing industry is right now. Maybe it's like 5% or 10% maybe, which is important, I mean, that's not nothing, certainly. But that is the most you'll ever got out of it. It's that 5% or 10%. In a way, that greening through IT, looking at the other 95% and*

> *how computing can enact change in that area feels to me like the bigger part of the pie.*

Prof. Dr. Castillo discussed that helping other fields to have a better understanding of Computer Science would be important.

> *A big challenge that they stating, these researchers from the Common and Interdisciplinary Project of Energy Cultures, was for everyone to sit down and establish a common language to all disciplines, so that everyone understood that a concept with values and norms meant the same to everyone. So, I think that if you all participated in this establishment of meanings would be really important for us, because we can say what is technology, what is Artificial Intelligence, Natural Language, but we are not the ones that are in research processes about these objects.*

### 4.3.3 RQ4: What strategies should guide Computer Science's efforts to mitigate the climate crisis?

#### *4.3.3.1 Challenge Energy as Price and Efficiency*

A common subject between interviews was how Energy is perceived. Prof. Dr. Mendiburu asserted how talking about energy in terms of prices and efficiency can hide its actual impact on the environment:

> *If I am doubling the consumption I made a month ago, it's a very deep impact that's been made to operate this equipment, and we don't even perceive it. Well, if it shows up on the bill — but we don't think in terms of energy, only in monetary terms. "Oh, it was 100, now it is 200." But you are spending the double amount of electrical energy. You are not seeing it, but it is there somewhere. (...) So, you can see that when you transform it into money is when you really forget about the environment, about the impact. Because you are only thinking about the economical impact, and not on the environmental impact.*

This was also brought up during the interview with Prof. Dr. Widdicks, which discussed how even renewable sources must be treated as more than just a concept of energy:

*Obviously, renewable energy has lower carbon footprint, but it does have some carbon in its creation and use. It's just significantly lower than fossil fuel energy. And there's also kind of limited resources for some types of renewables. So for example, there's limits on silver. That's required for solar panels. So we can't just kind of continue growth and just say, "Oh, we'll just continue increase in renewable energy" because we've kind of got a finite resource on that.*

Prof. Dr. Castillo, whose work is concerned with energy cultures, described in her interview how presenting Energy only in terms of consumption hampers our perceive climate impact as collective:

*There were some studies in New Zealand and Canada that were about (...) the inclusion of [energy] consumption monitoring and tracking system inside households. And what happens is that a lot of them only covered households that did not have financial problems, and that became something like those data from calorie counting: if you don't feel like doing it, it [the system] will give you a number and you will settle with "Ah, maybe I'll do it next week, I'll consume less." But [the person] doesn't integrate with a social practice of consumption monitoring. But why? Because you are not thinking that this impact is collective, you are thinking about the individual impact on your wallet.*

Prof. Dr. Camboim mentioned how this perspective of energy as money can even drive groups away from projects that would be both sustainable and cheap.

*The planning stage is a bit undermined, due to this cultural rigidness of having to have infrastructure ready fast. While, it turns out, that the return of investment for energy efficiency takes an average of five years. So many businesses undermine these investments in energy efficiency, mainly due to the cost it brings to project. In other words, they don't take in consideration the parts of environmental sustainability and future savings.*

#### *4.3.3.2 To look beyond Energy Efficiency*

Several of the conversations discussed the necessity to question the standard of Energy Efficiency as the most important concern.

Prof. Dr. Lepawsky questioned the limits of efficiency, and how it may generate more demand.

> *(...) as a form of engineering, broadly conceived, there does seem to be a real emphasis on efficiency. And one of the reasons that is — it's not that that focus is bad or wrong, but it is inherently limited in what an efficiency approach can do in terms of sort of matching up the pollution, the waste, the climate issues related to electronics. (...) So, you know, my phone is much more energy efficient than three or four models ago. So you can improve per unit efficiency, but per unit efficiency is usually wiped out by aggregate growth in the adoption of devices. And there's a name for this, the Jevon's paradox. And so to me, it seems like one of the challenges for computer science or engineering fields similar to it is to be very... I guess, mindful or careful of the default to efficiency as a or even the solution. (...) That is not just for electronics. That happens in pretty much any sort of area you can look at. Jevon's paradox is named after a 19th century economist William Stanley Jevons, and he was talking about coal use during the industrial revolution.*

Prof. Dr.Widdicks also questioned energy efficiency as the main tool, describing how ICT's progress in efficiency can bring more demand not just from within the sector, but also affect other sectors.

> *Obviously, if you look back historically, there's lots of talk about how efficiencies in ICT have continued, but if you look at the emissions for ICT, they've also risen alongside efficiency. So, you know, ICT emissions are increasing potentially because of these efficiencies. Because of the fact that if you make something more efficient than you're probably going to use it more. And so there's this rebound effect happening where we end up consuming more technology and the emissions increase. So there's rebound effects within the ICT sector, but also ICT can create rebound effects in other sectors. Because if we're introducing efficiencies elsewhere, then we might be raising the emissions for other sectors. So a classic example is that sometimes ICT can be seen as a way to green the — well, most of the time, ICT is seen as a way to green the economy. It's hailed as this great thing, but if you actually look at the evidence, that's kind of lacking. So an example is quite often people cite things like video conferencing technologies as a way to reduce*

*flights. Which, I say something like the pandemic could potentially be — say that that happened because there was a constraint on flights and we kind of relied more on online video conferencing side. But if you look again at the data... and historically, you know, video streaming has increased. The data used by video online has increased. Flights have increased also, and ICT has made it easier to book flights so you can fly — and sometimes rebound effects happen like us was talking now.*

Prof. Dr. Mendiburu discussed how funding can often only be available for efficiency related projects:

*If you approach sustainability merely from the point of view of efficiency and of the financial return this efficiency can bring, it's likely that you'll get a lot of funding. If you approach it more from the point of view the environment, like a process life cycle, it's harder, because not everyone has their eyes set on the complete process. I'll give you an example: If I say that I'll burn hydrogen in a turbine, and I say that it will produce less pollutants, that it will produce water vapor, it's likely that I'll get funding. Now, if I say from where this hydrogen came from; the process that produces it, how much this process will contaminate and want to study all of it, it will be difficult that someone will give you money for such a broad study.*

*4.3.3.3 The need for spaces and discussions regarding Climate Crisis*

In most interviews, when asked about challenges in doing these types of research, participants discussed the need of new spaces for these conversations.

Prof. Dr. Bill Tomlinson shared how certain areas within Computer Science are more open to these debates than others, but that it's far from enough, and how this was a major factor to the creation of the Computing Within Limits conference.

*In terms of what areas of computing I expect to see change come from, the HCI community is much more open than lots of other pieces of computing to random stuff. And in that respect, I think HCI has the possibility to be a sort of a focal point from which things emerge in a way that like, you know, you're never going to find like, I don't know, the systems conference or whatever, being really fired up about sustainability. It's just not their bag. There's been a little bit of networking but —– have you encountered [name anonymized]?*

*So, he came out of the networking community and like, he managed to wrestle a couple of papers in networking conferences out of this set of topics, but that's part of why he and I and others formed LIMITS, it was hard to publish these papers in other venues.*

Prof. Dr. Widdicks discussed the difficulties of publishing articles due to their intersectionality.

*When we did our climate impacts of ICT paper, we weren't really sure where to publish or where to submit it. Because, you know, it was quite a detailed review. It did do some kind of life cycle analysis, but it was also a understanding of trends in the future and some analysis of European policy, so it didn't really feel like it could go to some of the life cycle assessment conferences.*

Prof. Dr. Castillo shared how proposals of intersectional projects can be hard for funding.

*Brazil's research structure is not oriented for this. If you think about journals, for example if you publish in the field of Social Sciences, it does not count for the Engineering field. (...) Then when you reach a moment of submitting a project and to ask for funding, you have to send it to one field, so there are very few grants that are really interdisciplinary, that will have interdisciplinary reviewers. The engineer that would review my research would say: "Where is the math?"*

Prof. Dr. Widdicks proposed more research that is transparent about the environmental impact of its processes to increase the amount of conversations.

*I think to get people more involved, there's smaller level suggestions we've made over the years — and papers like, for example, in natural language processing. I think they're moving towards a way of getting people to report — when they submit a paper — report the environmental impacts of the algorithm, or the efficiency, or the accuracy or whatever it is. And so that kind of information is transparent to all the researchers reading the papers. So I think there's smaller things that conferences could do like that. But then they need to address, you know, the emissions associated with the conferences themselves as well.*

Prof. Dr. Macêdo shared his hopes that the SBC task-force and its upcoming manifesto will be able to foster more debates.

> *Maybe a good share of the community still doesn't have access to this information, although this is a topic that is in media, everyone talks about and know about global warming, but especially within digital technologies, a broad awareness still doesn't exist. We hope to move more people from the Brazilian Society of Computation to this challenge. [This challenge] is transversal in computation, there's concerns of Internet of Things, of Dynamic Systems, of Computational Modelling, of communication, Embedded Systems, Real Time Systems, Software Engineering, Databases — several different areas that need to articulate themselves. It's also an internal challenge. We will publish this manifesto and certainly we will have debates, like the we're having here. We will make it open to the public in general.*

Dr. Anderson discussed how an organization that is concerned about climate creates a space where team members make the decision to have individual sustainable practices.

> *So obviously at an organization like NCAR, there's a natural tendency for people who are attracted to solving climate problems, to being concerned about the environment, to migrate into these fields. And so my team is extremely environmentally conscientious, unlike many people in the US, we almost all exclusively commute by bicycle. We all have solar panels that we've chosen to get, and all these sort of things. So there's a huge motivation for this. That being said, our team has almost zero impact on the decisions that are made for our users and how they get their supercomputing. NCAR, the organization I'm at, has its own supercomputer and in the recent procurements, there has been a strong emphasis on having those be energy efficient. They're actually located in Wyoming, one state north of us, because there was a lot of wind power available there. So we are working with organizations that try to make green decisions on supercomputing, but we have little influence.*

#### *4.3.3.4 Dispute Influence with Stakeholders*

The main challenged identified by all of the participants is on how to drive change against the market and stakeholders that are not interested in that change.

Prof. Dr. Tomlinson questioned how we can push back against the market's desires, and how Academia is one of the places of resistance.

> *The computing within limits premise that the entirety of the computing industry is reinforcing corporate businesses' usual, I still feel like that is deeply true. And I don't know how to push back on that because — Do you know the saying "it's hard to convince somebody of something when their salary depends on the not being convinced of it?" (...) And so in that respect, I feel like academia is one of the rare places that individuals are given the intellectual freedom to pursue things as they see fit, as opposed to eventually being held accountable to make it profitable.*

Dr. Anderson discussed how market driven innovations, even if designed sustainably, are not necessarily effective for research, since they were not developed with accessibility in mind.

> *We're running into problems like, GPUs are so useful for so many thing, so we have lots of companies out there marketing GPU hardware. It's really super fast. It's cheap. It's energy efficient. It is unbelievably difficult to make it work for the problems we have. We don't really know how to do it effectively right now. The real problem here is you're not going to make a hundred billion dollars selling computing to solve our problems. You either have to have a motivation besides making a huge amount of money to do it, or your motivation has to be that we figured out how the way this can be a 10% add on (...)*

Prof. Dr. Camboim expressed concern that only governmental action can drive change

> *While there are no governmental initiatives to hold them accountable, the corporate culture will not change to how it must be. If there aren't accountability agencies that say how sustainable that product is. Within academia, I notice that there are efforts. There are efforts of research, of literature, of concerns. However, while this remains only on paper, in the format of publication and not of demands for change to the government, I think it won't change our current scenario, which is the lack of initiative of the industrial sector.*

Prof. Dr. Tomlinson mentioned that of his latest project is related to cryptocurrency because he feels like it's a field that has potential to be disputed, even if it isn't his biggest interest.

> *Like the thing that I love, like ecology, I'm so like — there's a whole different world in which I'm a field biologist. (...) Part of me is like, "Ah, I'm writing financial software." (...) But that, that I think is one of the challenges, like what what's important to do versus what feels good to do. And that, that lies at the heart of a lot of these challenges. So yeah, I guess you know, financial tech stuff makes a difference. It's certainly what I'm working on right now.*

Prof. Dr. Macêdo mentioned how the SBC task-force aims to reach policy makers.

> *I hope that the impact will generate national policies that collaborate with the mitigation of climate change. We hope that the people in charge of mid to long term policy making read the manifest and are moved by it. (...) a mobilization campaign alongside federal, state and municipal spheres that results in medium to long term policies that can really help to revert this scenario (...)*

## 4.4 Chapter Summary

This chapter presented a series of interviews with researchers from within and from outside of Computer Science, in an attempt to learn more about the role of Computer Science in Climate Crisis mitigation, and how it intersects with other fields that are also attempting to mitigate it. The methodology for the interviews is described, presenting our protocol for Semi-Structured Interviews, and discussing how the invitations and preparation for the interviews was done. We introduce eight different researchers, describing the backgrounds and why they are relevant to our research. Finally, we synthesize our findings using our research questions as guides.

Regarding what Computer Science can learn from other fields, interviewees mentioned the importance of a concept of sufficiency replacing the current concept of efficiency, comparing it to how other fields like Geography are exploring it. Understanding the social dimensions of both Computer Science and the technology it develops was also highlighted, urging members of the field to recognize the influence the field has to impact society, and that the solutions it comes up to can affect and shape the world. The common pattern of focusing on solvable problems instead of the problems we need to solve was also a concern.

When it came to what Computer Science could do to do help other fields, interviewees brought up a series of areas to work on. A common request was to have more people from Computer Science to help other fields with designing and implementing model simulations, and also that other fields could really use the presence of people with Software Engineering skills in their teams. This further highlighted the need for more intersectionality within Academia. The importance of designing equipment that runs in non optimal environments was also brought up, which underscored the need for Computer Science to understand that when it comes to environmental questions, we cannot pretend that all parts of the planet are the same. Another major concern was that Computer Science should put more effort in helping the mitigation of emissions of other fields, as focusing only on its own emissions will not be enough for our current scenario. The need for our field to share knowledge and help people from outside of Computer Science to better understand what we are creating was also highlighted, with a proposal to create a common language between research fields to work together.

As to what strategies should guide Computer Science's efforts in Climate Crisis mitigation, we found four main patterns within the interviews. Computer Science must develop an understanding of Energy that looks beyond its price and efficiency, recognizing that energy sources have impacts on the environment that cannot be seen through these points of views. Even renewable sources like solar energy have impacts beyond the emissions that go beyond its use phase, and can depend on limited resources like silver. The need to understand that energy efficiency cannot be the only focus of mitigation was also a common concern. Increasing efficiency can still increase the demand, since the higher efficiency can be used to justify an increase in demand that can often be more than costly than the previous scenario. The dangers of not understanding rebound effects was also underscored, as the efficiencies developed within ICT can create increases in demand and emissions in other sectors, going against the common belief that ICT can be a way to make the economy green. This focus on developing efficiency can also be a major challenge to research projects, as funding often only goes to projects that focus only on increasing it, ignoring projects that aim to look beyond it.

Another major point was the urgent need for more spaces and discussions regarding Climate Crisis. Computer Science has communities that are open to these discussions, but they are still far and between when compared to the big picture of our field. This need is further supported by how research projects that use intersectional approaches struggle to find conferences to publish, and how current structures often treat intersectional projects with rules that were made for traditional, single field projects, which makes it harder for researchers to meet their performance goals and to find funding for new projects. As to how to tackle this, approaches such as making the environmental impacts of the research transparent, the usage of manifestos to increase awareness, and creating teams and spaces that value sustainable practices were mentioned.

The final pattern identified was the challenge to dispute influence with stakeholders in this crisis. The interviewees questioned the market's behavior and how we could push back against it. Another main concern was the need for more governmental action, and how difficult it could be to drive government to make more initiatives. However, the efforts within Academia were also brought up as a possible resistance. Not only can we found spaces to dispute influence when it comes to decentralized technology such as Blockchain, but we can can also start generating debates within our space, which will in the future help to mobilize new sustainable policies. While these proposals are not enough to solve this crisis, they show that there is much work to be done, and that Computer Science can and must do much more.

## 5 CONCLUSION

This work presented a study on the role of Computer Science in mitigating the Climate Crisis. To understand what Computer Science is currently doing, a literature review was conducted, constructing a Concept Map with the finds as to have a better understanding of the current areas. To investigate what Computer Science must change and improve, we conducted a series of interview with researchers from multiples backgrounds to learn from their perspectives. It is unquestionable that there are several works being done within Computer Science to make our area and others more sustainable. However, it clearly is not enough, and changes have to happen fast. It is imperative that we detach ourselves from the ever growing progress paradigm, and start grounding ourselves to the reality: the only way to mitigate this crisis is to establish limits to our growth and to efficiency. Energy Efficiency will always be important, but it must be considered alongside all the other factors that may cause an impact. We cannot optimize our way out of this problem, as the Climate Crisis is not a algorithmic or technological problem, it is a transdisciplinary and intersectional problem that requires changes across all fields. However, that can also play to this field's strength. ICT has proven to extremely influential across all areas of life, therefore our responsibility is to under this social importance our field has, and how we can leverage it for good. It is urgent that more spaces open themselves for these discussions. Researchers need more conferences that allow for intersectional works. A common language for interdisciplinary work should be developed. Institutions must change their structures not only to acknowledge and fund these types of work, but also to pass them on to the next generations. The biggest challenge will be to dispute influence with the market. Institutions can and should position themselves, but even they can do so much. Finding dispute points in new technologies might be a way, figuring out how to mobilize might be another. We don't have an answer and may never find it, so we must not only do everything that is possible, but also do everything to keep going in case the worst happens.

# REFERENCES

ABUGABAH, A.; ABUBAKER, A. Green computing: Awareness and practices. In: **2018 4th International Conference on Computer and Technology Applications (ICCTA)**. Istanbul: IEEE, 2018. p. 6–10. ISBN 978-1-5386-6995-2. Available from Internet: <https://ieeexplore.ieee.org/document/8398646/>.

ALCOTT, B. Jevons' paradox. **Ecological Economics**, v. 54, n. 1, p. 9–21, jul. 2005. ISSN 0921-8009. Available from Internet: <https://www.sciencedirect.com/science/article/pii/S0921800905001084>.

ALHARBI, E. H.; ALAHRBI, M. M.; ALKHAMALI, S. S. A Proposed Framework for Adoption Green Cloud Computing in Saudi Arabia. In: **2020 2nd International Conference on Computer and Information Sciences (ICCIS)**. Sakaka, Saudi Arabia: IEEE, 2020. p. 1–6. ISBN 978-1-72815-467-1. Available from Internet: <https://ieeexplore.ieee.org/document/9257690/>.

ALNAHDI, A.; BAZARAH, F. Building Quality Metrics for Green Computing Projects: A Model and a Case Study of Engineering a Green Computing Awareness Website. In: **2018 14th International Conference on Signal-Image Technology & Internet-Based Systems (SITIS)**. Las Palmas de Gran Canaria, Spain: IEEE, 2018. p. 595–600. ISBN 978-1-5386-9385-8. Available from Internet: <https://ieeexplore.ieee.org/document/8705943/>.

ANTHONY, B.; MAJID, M. A.; ROMLI, A. A model for adopting sustainable practices in software based organizations. In: **2017 8th International Conference on Information Technology (ICIT)**. Amman: IEEE, 2017. p. 26–35. ISBN 978-1-5090-6332-1. Available from Internet: <https://ieeexplore.ieee.org/document/8079911/>.

BABOU, C. S. M. et al. Home Edge Computing Architecture for Smart and Sustainable Agriculture and Breeding. In: **Proceedings of the 2nd International Conference on Networking, Information Systems & Security - NISS19**. Rabat, Morocco: ACM Press, 2019. p. 1–7. ISBN 978-1-4503-6645-8. Available from Internet: <http://dl.acm.org/citation.cfm?doid=3320326.3320377>.

BASHIR, N. et al. Enabling Sustainable Clouds: The Case for Virtualizing the Energy System. In: **Proceedings of the ACM Symposium on Cloud Computing**. Seattle WA USA: ACM, 2021. p. 350–358. ISBN 978-1-4503-8638-8. Available from Internet: <https://dl.acm.org/doi/10.1145/3472883.3487009>.

BHEDA, H.; THAKER, C.; SHAH, S. An Optimized VM Placement Approach to Reduce Energy Consumption in Green Cloud Computing. In: **Proceedings of the International Conference on Data Science, Machine Learning and Artificial Intelligence**. Windhoek Namibia: ACM, 2021. p. 130–135. ISBN 978-1-4503-8763-7. Available from Internet: <https://dl.acm.org/doi/10.1145/3484824.3484894>.

BIESER, J. C. T.; HILTY, L. M. Assessing indirect environmental effects of information and communication technology (ict): A systematic literature review. **Sustainability**, v. 10, n. 8, 2018. ISSN 2071-1050. Available from Internet: <https://www.mdpi.com/2071-1050/10/8/2662>.

BRUNVAND, E.; KLINE, D.; JONES, A. K. Dark Silicon Considered Harmful: A Case for Truly Green Computing. In: **2018 Ninth International Green and Sustainable Computing Conference (IGSC)**. Pittsburgh, PA, USA: IEEE, 2018. p. 1–8. ISBN 978-1-5386-7466-6. Available from Internet: <https://ieeexplore.ieee.org/document/8752110/>.

CAI, X. et al. An energy-efficiency-aware resource allocation strategy in multi-granularity provision for green computing. In: **2019 International Conference on Computing, Networking and Communications (ICNC)**. Honolulu, HI, USA: IEEE, 2019. p. 782–786. ISBN 978-1-5386-9223-3. Available from Internet: <https://ieeexplore.ieee.org/document/8685591/>.

CALERO, C.; BERTOA, M. F.; MORAGA, M. A. A systematic literature review for software sustainability measures. In: **Proceedings of the 2nd International Workshop on Green and Sustainable Software**. [S.l.]: IEEE Press, 2013. (GREENS '13), p. 46–53. ISBN 9781467362672.

CAÑAS, A. J. et al. Cmaptools: A knowledge modeling and sharing environment. In: **Concept maps: Theory, methodology, technology. Proceedings of the first international conference on concept mapping**. Pamplona, Spain: Universidad P{ùblica de Navarra, 2004. I, p. 125–133.

CBECI. **Cambridge Bitcoin Electricity Consumption Index: Comparisons**. 2022. Available from Internet: <https://ccaf.io/cbeci/index/comparisons>. Accessed in: 2022-04-27.

CHANG, X. et al. From Insight to Impact: Building a Sustainable Edge Computing Platform for Smart Homes. In: **2018 IEEE 24th International Conference on Parallel and Distributed Systems (ICPADS)**. Singapore, Singapore: IEEE, 2018. p. 928–936. ISBN 978-1-5386-7308-9. Available from Internet: <https://ieeexplore.ieee.org/document/8644647/>.

CHAUDHRY, R.; KUMAR, N. A Multi-objective Meta-heuristic Solution for Green Computing in Software-Defined Wireless Sensor Networks. **IEEE Transactions on Green Communications and Networking**, p. 1–1, 2021. ISSN 2473-2400. Available from Internet: <https://ieeexplore.ieee.org/document/9583604/>.

CHEN, L.; DING, W. Green Clothing Design Based on Computer Aided Design in Ecological Times. In: **2021 4th International Conference on Information Systems and Computer Aided Education**. Dalian China: ACM, 2021. p. 302–306. ISBN 978-1-4503-9025-5. Available from Internet: <https://dl.acm.org/doi/10.1145/3482632.3482695>.

CHENG, Y.; ZHAO, P.; WANG, L. User-oriented green computation in small cell networks with mobile edge computing. In: **Proceedings of the 4th International Conference on Communication and Information Processing - ICCIP '18**. Qingdao, China: ACM Press, 2018. p. 246–250. ISBN 978-1-4503-6534-5. Available from Internet: <http://dl.acm.org/citation.cfm?doid=3290420.3290456>.

COSTALONGA, L. et al. The Ragpicking DMI Design: The Case for Green Computer Music. In: **10th International Conference on Digital and Interactive Arts**. Aveiro, Portugal Portugal: ACM, 2021. p. 1–10. ISBN 978-1-4503-8420-9. Available from Internet: <https://dl.acm.org/doi/10.1145/3483529.3483711>.

COUTO, M. et al. On energy debt: managing consumption on evolving software. In: **Proceedings of the 3rd International Conference on Technical Debt**. Seoul Republic of Korea: ACM, 2020. p. 62–66. ISBN 978-1-4503-7960-1. Available from Internet: <https://dl.acm.org/doi/10.1145/3387906.3388628>.

DAUTOV, R.; SONG, H.; FERRY, N. Towards a Sustainable IoT with Last-Mile Software Deployment. In: **2021 IEEE Symposium on Computers and Communications (ISCC)**. Athens, Greece: IEEE, 2021. p. 1–6. ISBN 978-1-66542-744-9. Available from Internet: <https://ieeexplore.ieee.org/document/9631250/>.

FATHI, M. H.; KHANLI, L. M. Consolidating VMs in Green Cloud Computing Using Harmony Search Algorithm. In: **Proceedings of the 2018 International Conference on Internet and e-Business - ICIEB '18**. Singapore, Singapore: ACM Press, 2018. p. 146–151. ISBN 978-1-4503-6375-4. Available from Internet: <http://dl.acm.org/citation.cfm?doid=3230348.3230369>.

FRANCESE, D.; BUONINCONTI, L. Sustainable Design and Software Tools by Multimatrix Criteria. In: **Proceedings of the 2nd International Symposium on Computer Science and Intelligent Control**. Stockholm Sweden: ACM, 2018. p. 1–6. ISBN 978-1-4503-6628-1. Available from Internet: <https://dl.acm.org/doi/10.1145/3284557.3284695>.

FRATERNALI, F. et al. Quantifying the Impact of Variability and Heterogeneity on the Energy Efficiency for a Next-Generation Ultra-Green Supercomputer. **IEEE Transactions on Parallel and Distributed Systems**, v. 29, n. 7, p. 1575–1588, jul. 2018. ISSN 1045-9219. Available from Internet: <https://ieeexplore.ieee.org/document/8081827/>.

FREITAG, C. et al. The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations. **Patterns**, v. 2, n. 9, p. 100340, sep. 2021. ISSN 26663899.

GONG, X.; GUO, L.; NING, Z. Green Virtual Network Embedding for Collaborative Edge Computing in Environment-Friendly Optical-Wireless Networks. In: **Proceedings of the 26th International Conference on World Wide Web Companion - WWW '17 Companion**. Perth, Australia: ACM Press, 2017. p. 1531–1536. ISBN 978-1-4503-4914-7. Available from Internet: <http://dl.acm.org/citation.cfm?doid=3041021.3054768>.

GUHA, K. et al. Ensuring Green Computing in Reconfigurable Hardware based Cloud Platforms from Hardware Trojan Attacks. In: **2020 IEEE REGION 10 CONFERENCE (TENCON)**. Osaka, Japan: IEEE, 2020. p. 1380–1385. ISBN 978-1-72818-455-5. Available from Internet: <https://ieeexplore.ieee.org/document/9293796/>.

GUPTA, A.; ROBINSON, C.; DILKINA, B. Infrastructure Resilience for Climate Adaptation. In: **Proceedings of the 1st ACM SIGCAS Conference on Computing and Sustainable Societies**. Menlo Park and San Jose CA USA: ACM, 2018. p. 1–8. ISBN 978-1-4503-5816-3. Available from Internet: <https://dl.acm.org/doi/10.1145/3209811.3209859>.

HAMDAN, M.; SALEM, A.; SHAMAYLEH, Y. Harmonization between Renewable Energy and Cloud Computing towards Green Computing A Case Study: Data Center at The University Of Jordan. In: **2021 12th International Renewable Engineering Conference (IREC)**. Amman, Jordan: IEEE, 2021. p. 1–5. ISBN 978-1-66542-548-3. Available from Internet: <https://ieeexplore.ieee.org/document/9427865/>.

HANIEF, S. et al. A Proposed Model of Green Computing Adoption In Indonesian Higher Education. In: **2018 6th International Conference on Cyber and IT Service Management (CITSM)**. Parapat, Indonesia: IEEE, 2018. p. 1–6. ISBN 978-1-5386-5434-7. Available from Internet: <https://ieeexplore.ieee.org/document/8674275/>.

HASAN, M. S. et al. Exploiting Renewable Sources: When Green SLA Becomes a Possible Reality in Cloud Computing. **IEEE Transactions on Cloud Computing**, v. 5, n. 2, p. 249–262, abr. 2017. ISSN 2168-7161. Available from Internet: <http://ieeexplore.ieee.org/document/7164298/>.

HEWAGAMAGE, P. et al. Computer-Vision Enabled Waste Management System for Green Environment. In: **2021 3rd International Conference on Advancements in Computing (ICAC)**. Colombo, Sri Lanka: IEEE, 2021. p. 276–281. ISBN 978-1-66540-862-2. Available from Internet: <https://ieeexplore.ieee.org/document/9671222/>.

HILTY, L.; LOHMANN, W.; HUANG, E. M. Sustainability and ICT - An overview of the field. 2011. Publisher: Tipolito Subalpina. Available from Internet: <https://www.zora.uzh.ch/id/eprint/55640>.

HSIEH, Y.-H.; CHEN, M.-S. Toward Green Computing: Striking the Trade-Off between Memory Usage and Energy Consumption of Sequential Pattern Mining on GPU. In: **2018 IEEE First International Conference on Artificial Intelligence and Knowledge Engineering (AIKE)**. Laguna Hills, CA: IEEE, 2018. p. 152–155. ISBN 978-1-5386-9555-5. Available from Internet: <https://ieeexplore.ieee.org/document/8527465/>.

HU, N. et al. Deep-Green: A Dispersed Energy-Efficiency Computing Paradigm for Green Industrial IoT. **IEEE Transactions on Green Communications and Networking**, v. 5, n. 2, p. 750–764, jun. 2021. ISSN 2473-2400. Available from Internet: <https://ieeexplore.ieee.org/document/9372936/>.

IPCC. **Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change**. Cambridge, UK and New York, NY, USA: Cambridge University Press, 2022.

ISO, I. O. for S. **ISO 14040:2006: Environmental management —- Life cycle assessment -— Principles and framework**. [S.l.], 2006.

IYENGAR, S. et al. SolarClique: Detecting Anomalies in Residential Solar Arrays. In: **Proceedings of the 1st ACM SIGCAS Conference on Computing and Sustainable Societies**. Menlo Park and San Jose CA USA: ACM, 2018. p. 1–10. ISBN 978-1-4503-5816-3. Available from Internet: <https://dl.acm.org/doi/10.1145/3209811.3209860>.

JANG, E. et al. Unplanned Obsolescence: Hardware and Software After Collapse. In: **Proceedings of the 2017 Workshop on Computing Within Limits**. Santa Barbara California USA: ACM, 2017. p. 93–101. ISBN 978-1-4503-4950-5. Available from Internet: <https://dl.acm.org/doi/10.1145/3080556.3080566>.

KARITA, L.; MOURÃO, B. C.; MACHADO, I. Software industry awareness on green and sustainable software engineering: a state-of-the-practice survey. In: **Proceedings of the XXXIII Brazilian Symposium on Software Engineering**. Salvador Brazil: ACM,

2019. p. 501–510. ISBN 978-1-4503-7651-8. Available from Internet: <https://dl.acm.org/doi/10.1145/3350768.3350770>.

KITCHENHAM, B. **Procedures for Performing Systematic Reviews**. Department of Computer Science, Keele University, UK, 2004.

KLINE, D. et al. Sustainable IC design and fabrication. In: **2017 Eighth International Green and Sustainable Computing Conference (IGSC)**. Orlando, FL: IEEE, 2017. p. 1–8. ISBN 978-1-5386-3470-7. Available from Internet: <http://ieeexplore.ieee.org/document/8323572/>.

KORTBEEK, V. et al. BFree: Enabling Battery-free Sensor Prototyping with Python. **Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies**, v. 4, n. 4, p. 1–39, dec. 2020. ISSN 2474-9567. Available from Internet: <https://dl.acm.org/doi/10.1145/3432191>.

KUMAR, N. et al. Green Computing in Software Defined Social Internet of Vehicles. **IEEE Transactions on Intelligent Transportation Systems**, v. 22, n. 6, p. 3644–3653, jun. 2021. ISSN 1524-9050, 1558-0016. Available from Internet: <https://ieeexplore.ieee.org/document/9234040/>.

LI, S. et al. An Algorithm Incarnating Deep Integration of Hardware-Software Energy Regulation Principles for Heterogeneous Green Scheduling. **IEEE Access**, v. 8, p. 111494–111503, 2020. ISSN 2169-3536. Available from Internet: <https://ieeexplore.ieee.org/document/9120000/>.

LIGHT, J. Energy usage profiling for green computing. In: **2017 International Conference on Computing, Communication and Automation (ICCCA)**. Greater Noida: IEEE, 2017. p. 1287–1291. ISBN 978-1-5090-6471-7. Available from Internet: <http://ieeexplore.ieee.org/document/8230017/>.

LIU, X. et al. Energy-aware task scheduling strategies with QoS constraint for green computing in cloud data centers. In: **Proceedings of the 2018 Conference on Research in Adaptive and Convergent Systems**. Honolulu Hawaii: ACM, 2018. p. 260–267. ISBN 978-1-4503-5885-9. Available from Internet: <https://dl.acm.org/doi/10.1145/3264746.3264792>.

LONDE, V.; MATH, M. M. Green computing based cost optimization in cloud computing. In: **2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)**. Chennai: IEEE, 2017. p. 37–41. ISBN 978-1-5386-1887-5. Available from Internet: <https://ieeexplore.ieee.org/document/8390205/>.

LÜNDSTROM, A.; PARGMAN, D. Developing a Framework for Evaluating the Sustainability of Computing Projects. In: **Proceedings of the 2017 Workshop on Computing Within Limits**. Santa Barbara California USA: ACM, 2017. p. 111–117. ISBN 978-1-4503-4950-5. Available from Internet: <https://dl.acm.org/doi/10.1145/3080556.3080562>.

MAIA, D. et al. E-Debitum: managing software energy debt. In: **Proceedings of the 35th IEEE/ACM International Conference on Automated Software Engineering Workshops**. Virtual Event Australia: ACM, 2020. p. 170–177. ISBN 978-1-4503-8128-4. Available from Internet: <https://dl.acm.org/doi/10.1145/3417113.3422999>.

MANCEBO, J. et al. EET: a device to support the measurement of software consumption. In: **Proceedings of the 6th International Workshop on Green and Sustainable Software - GREENS '18**. Gothenburg, Sweden: ACM Press, 2018. p. 16–22. ISBN 978-1-4503-5732-6. Available from Internet: <http://dl.acm.org/citation.cfm?doid=3194078.3194081>.

MANN, S. et al. Regenerative computing: de-limiting hope. In: **Proceedings of the 2018 Workshop on Computing within Limits**. Toronto Ontario Canada: ACM, 2018. p. 1–10. ISBN 978-1-4503-6575-8. Available from Internet: <https://dl.acm.org/doi/10.1145/3232617.3232618>.

MANZ, O.; MEYER, S.; BAUMGARTNER, C. Life cycle assessment of an Internet of Things product: Environmental impact of an intelligent smoke detector. In: **11th International Conference on the Internet of Things**. St.Gallen Switzerland: ACM, 2021. p. 72–79. ISBN 978-1-4503-8566-4. Available from Internet: <https://dl.acm.org/doi/10.1145/3494322.3494332>.

MUNOZ, D.-J.; PINTO, M.; FUENTES, L. Green software development and research with the HADAS toolkit. In: **Proceedings of the 11th European Conference on Software Architecture: Companion Proceedings**. Canterbury United Kingdom: ACM, 2017. p. 205–211. ISBN 978-1-4503-5217-8. Available from Internet: <https://dl.acm.org/doi/10.1145/3129790.3129818>.

NAGY, G. et al. Tools supporting green computing in Erlang. In: **Proceedings of the 18th ACM SIGPLAN International Workshop on Erlang - Erlang 2019**. Berlin, Germany: ACM Press, 2019. p. 30–35. ISBN 978-1-4503-6810-0. Available from Internet: <http://dl.acm.org/citation.cfm?doid=3331542.3342570>.

NARDI, B. et al. Computing within limits. **Communications of the ACM**, v. 61, n. 10, p. 86–93, sep. 2018. ISSN 0001-0782, 1557-7317. Available from Internet: <https://dl.acm.org/doi/10.1145/3183582>.

NORTON, J. et al. The SAGE Community Coordinator: A Demonstration. In: **Proceedings of the Fifth Workshop on Computing within Limits**. Lappeenranta Finland: ACM, 2019. p. 1–10. ISBN 978-1-4503-7281-7. Available from Internet: <https://dl.acm.org/doi/10.1145/3338103.3338108>.

NOVAK, J. D.; CAÑAS, A. J. **The Theory Underlying Concept Maps and How to Construct Them**. [S.l.], 2006. Available from Internet: <http://cmap.ihmc.us/Publications/ResearchPapers/TheoryCmaps/TheoryUnderlyingConceptMaps.htm>. Accessed in: 2022-04-28.

PA, N. C.; KARIM, F.; HASSAN, S. Dashboard System for Measuring Green Software Design. p. 5, 2017.

PARGMAN, D. et al. From Moore's Law to the Carbon Law. In: **Proceedings of the 7th International Conference on ICT for Sustainability**. Bristol United Kingdom: ACM, 2020. p. 285–293. ISBN 978-1-4503-7595-5. Available from Internet: <https://dl.acm.org/doi/10.1145/3401335.3401825>.

PARGMAN, D.; WALLSTEN, B. Resource Scarcity and Socially Just Internet Access over Time and Space. In: **Proceedings of the 2017 Workshop on Computing Within Limits**. Santa Barbara California USA: ACM, 2017. p. 29–36. ISBN 978-1-4503-4950-5. Available from Internet: <https://dl.acm.org/doi/10.1145/3080556.3084083>.

PENZENSTADLER, B. Towards a definition of sustainability in and for software engineering. In: **Proceedings of the 28th Annual ACM Symposium on Applied Computing - SAC '13**. Coimbra, Portugal: ACM Press, 2013. p. 1183. ISBN 978-1-4503-1656-9. Available from Internet: <http://dl.acm.org/citation.cfm?doid=2480362.2480585>.

PENZENSTADLER, B. et al. Sustainability in software engineering: A systematic literature review. In: **16th International Conference on Evaluation Assessment in Software Engineering (EASE 2012)**. [S.l.: s.n.], 2012. p. 32–41.

PENZENSTADLER, B. et al. Everything is INTERRELATED: teaching software engineering for sustainability. In: **Proceedings of the 40th International Conference on Software Engineering: Software Engineering Education and Training**. Gothenburg Sweden: ACM, 2018. p. 153–162. ISBN 978-1-4503-5660-2. Available from Internet: <https://dl.acm.org/doi/10.1145/3183377.3183382>.

PENZENSTADLER, B. et al. Software Engineering for Sustainability: Find the Leverage Points! **IEEE Software**, v. 35, n. 4, p. 22–33, jul. 2018. ISSN 0740-7459, 1937-4194. Available from Internet: <https://ieeexplore.ieee.org/document/8254307/>.

PEREIRA, R. et al. Energy efficiency across programming languages: how do energy, time, and memory relate? In: **Proceedings of the 10th ACM SIGPLAN International Conference on Software Language Engineering**. Vancouver BC Canada: ACM, 2017. p. 256–267. ISBN 978-1-4503-5525-4. Available from Internet: <https://dl.acm.org/doi/10.1145/3136014.3136031>.

PONSARD, C.; LANDTSHEER, R. D.; GERMEAU, F. Building sustainable software for sustainable systems: case study of a shared pick-up and delivery service. In: **Proceedings of the 6th International Workshop on Green and Sustainable Software - GREENS '18**. Gothenburg, Sweden: ACM Press, 2018. p. 31–34. ISBN 978-1-4503-5732-6. Available from Internet: <http://dl.acm.org/citation.cfm?doid=3194078.3194083>.

PREIST, C.; SCHIEN, D.; SHABAJEE, P. Evaluating Sustainable Interaction Design of Digital Services: The Case of YouTube. In: **Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems**. Glasgow Scotland Uk: ACM, 2019. p. 1–12. ISBN 978-1-4503-5970-2. Available from Internet: <https://dl.acm.org/doi/10.1145/3290605.3300627>.

PRESSMAN, R. S. **Software Engineering: A Practitioner's Approach. Fifth Edition**. European. [S.l.]: McGraw-Hill, 2010.

RAGHAVAN, B.; PARGMAN, D. Means and Ends in Human-Computer Interaction: Sustainability through Disintermediation. In: **Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems**. Denver Colorado USA: ACM, 2017. p. 786–796. ISBN 978-1-4503-4655-9. Available from Internet: <https://dl.acm.org/doi/10.1145/3025453.3025542>.

RAISIAN, K. et al. The Green Software Measurement Structure Based on Sustainability Perspective. In: **2021 International Conference on Electrical Engineering and Informatics (ICEEI)**. Kuala Terengganu, Malaysia: IEEE, 2021. p. 1–6. ISBN 978-1-66540-555-3. Available from Internet: <https://ieeexplore.ieee.org/document/9611108/>.

RAJA, S. P. Green Computing and Carbon Footprint Management in the IT Sectors. **IEEE Transactions on Computational Social Systems**, v. 8, n. 5, p. 1172–1177, oct. 2021. ISSN 2329-924X, 2373-7476. Available from Internet: <https://ieeexplore.ieee.org/document/9432394/>.

RAMPRASAD, B. et al. Sustainable Computing on the Edge: A System Dynamics Perspective. In: **Proceedings of the 22nd International Workshop on Mobile Computing Systems and Applications**. Virtual United Kingdom: ACM, 2021. p. 64–70. ISBN 978-1-4503-8323-3. Available from Internet: <https://dl.acm.org/doi/10.1145/3446382.3448607>.

RECKER, J. **Scientific Research in Information Systems**. Berlin, Heidelberg: Springer, 2013. ISBN 978-3-642-30047-9 978-3-642-30048-6. Available from Internet: <http://link.springer.com/10.1007/978-3-642-30048-6>.

RIFAT, M. R.; TORIQ, T.; AHMED, S. I. Religion and Sustainability: Lessons of Sustainable Computing from Islamic Religious Communities. **Proceedings of the ACM on Human-Computer Interaction**, v. 4, n. CSCW2, p. 1–32, oct. 2020. ISSN 2573-0142. Available from Internet: <https://dl.acm.org/doi/10.1145/3415199>.

RIVERA, M. B.; ERIKSSON, E.; COMBER, R. Diminishing space - peer-to-peer sharing as a transition practice. In: **Proceedings of the 7th International Conference on ICT for Sustainability**. New York, NY, USA: Association for Computing Machinery, 2020. (ICT4S2020), p. 220–226. ISBN 978-1-4503-7595-5. Available from Internet: <https://doi.org/10.1145/3401335.3401672>.

ROUQUIER, L.; KARIM, L.; ALMHANA, J. Redundant Transmitter Placement in Rural Areas for User-to-User Communication in Green Computing. In: **2021 International Wireless Communications and Mobile Computing (IWCMC)**. Harbin City, China: IEEE, 2021. p. 1460–1464. ISBN 978-1-72818-616-0. Available from Internet: <https://ieeexplore.ieee.org/document/9498926/>.

SARAIVA, J.; ZONG, Z.; PEREIRA, R. Bringing Green Software to Computer Science Curriculum: Perspectives from Researchers and Educators. In: **Proceedings of the 26th ACM Conference on Innovation and Technology in Computer Science Education V. 1**. Virtual Event Germany: ACM, 2021. p. 498–504. ISBN 978-1-4503-8214-4. Available from Internet: <https://dl.acm.org/doi/10.1145/3430665.3456386>.

SHVEDCHYKOVA, I.; SOLOSHYCH, I.; POCHTOVYUK, S. Creating the Educational and Research Software for Integrated Assessment of Energy Consumption and Sustainable Development of Regions. In: **2019 IEEE International Conference on Modern Electrical and Energy Systems (MEES)**. Kremenchuk, Ukraine: IEEE, 2019. p. 458–461. ISBN 978-1-72812-569-5. Available from Internet: <https://ieeexplore.ieee.org/document/8896654/>.

SINGH, S. et al. Green and Sustainable Software Model for IT Enterprises. In: **2021 5th International Conference on Electronics, Communication and Aerospace Technology (ICECA)**. Coimbatore, India: IEEE, 2021. p. 1157–1161. ISBN 978-1-66543-524-6. Available from Internet: <https://ieeexplore.ieee.org/document/9675938/>.

SOJAT, Z.; SKALA, K. The Rainbow through the Lens of Dew. In: **2020 43rd International Convention on Information, Communication and Electronic Technology (MIPRO)**. Opatija, Croatia: IEEE, 2020. p. 1916–1921. ISBN 978-953-233-099-1. Available from Internet: <https://ieeexplore.ieee.org/document/9245361/>.

STREVELL, M. et al. Designing an Energy-Efficient HPC Supercomputing Center. In: **Proceedings of the 48th International Conference on Parallel Processing: Workshops**. Kyoto Japan: ACM, 2019. p. 1–8. ISBN 978-1-4503-7196-4. Available from Internet: <https://dl.acm.org/doi/10.1145/3339186.3339212>.

TOMLINSON, B. et al. Collapse informatics and practice: Theory, method, and design. **ACM Transactions on Computer-Human Interaction**, v. 20, n. 4, p. 24:1–24:26, sep. 2013. ISSN 1073-0516. Available from Internet: <https://doi.org/10.1145/2493431>.

TORRE, D. et al. On the Presence of Green and Sustainable Software Engineering in Higher Education Curricula. In: **2017 IEEE/ACM 1st International Workshop on Software Engineering Curricula for Millennials (SECM)**. Buenos Aires, Argentina: IEEE, 2017. p. 54–60. ISBN 978-1-5386-2795-2. Available from Internet: <http://ieeexplore.ieee.org/document/7964623/>.

TURKIN, I.; VYKHODETS, Y. Software engineering master's program and Green IT: The design of the software Engineering Sustainability course. In: **2018 IEEE 9th International Conference on Dependable Systems, Services and Technologies (DESSERT)**. Kyiv, Ukraine: IEEE, 2018. p. 662–666. ISBN 978-1-5386-5903-8. Available from Internet: <https://ieeexplore.ieee.org/document/8409215/>.

United Nations. **Paris Agreement**. 2014. Available from Internet: <https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf>. Accessed in: 2022-04-14.

VISTER, K. K.; EVANS, R. D. Identifying contributing factors to sustainability awareness in the norwegian software industry. In: **2017 IEEE 4th International Conference on Knowledge-Based Engineering and Innovation (KBEI)**. Tehran: IEEE, 2017. p. 0700–0705. ISBN 978-1-5386-2640-5. Available from Internet: <http://ieeexplore.ieee.org/document/8324888/>.

WADHWA, M. et al. Green Cloud Computing - A Greener Approach To IT. In: **2019 International Conference on Computational Intelligence and Knowledge Economy (ICCIKE)**. Dubai, United Arab Emirates: IEEE, 2019. p. 760–764. ISBN 978-1-72813-778-0. Available from Internet: <https://ieeexplore.ieee.org/document/9004283/>.

WANG, L.; KÖSE, S. Reliable On-Chip Voltage Regulation for Sustainable and Compact IoT and Heterogeneous Computing Systems. In: **Proceedings of the 2018 on Great Lakes Symposium on VLSI**. Chicago IL USA: ACM, 2018. p. 285–290. ISBN 978-1-4503-5724-1. Available from Internet: <https://dl.acm.org/doi/10.1145/3194554.3194602>.

WELZ, T.; STUERMER, M. Sustainability of ICT hardware procurement in Switzerland: A status-quo analysis of the public procurement sector. In: **Proceedings of the 7th International Conference on ICT for Sustainability**. Bristol United Kingdom: ACM, 2020. p. 158–169. ISBN 978-1-4503-7595-5. Available from Internet: <https://dl.acm.org/doi/10.1145/3401335.3401352>.

WIDDICKS, K. et al. Streaming, Multi-Screens and YouTube: The New (Unsustainable) Ways of Watching in the Home. In: **Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems**. Glasgow Scotland Uk: ACM, 2019. p. 1–13. ISBN 978-1-4503-5970-2. Available from Internet: <https://dl.acm.org/doi/10.1145/3290605.3300696>.

WILLIS, M. et al. Low Power Web: Legacy Design and the Path to Sustainable Net Futures. In: **Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems**. Honolulu HI USA: ACM, 2020. p. 1–14. ISBN 978-1-4503-6819-3. Available from Internet: <https://dl.acm.org/doi/10.1145/3334480.3381829>.

YAHAYA, J. et al. Software Model for Learning Quarry Industry Impacts on Green Environment. In: **2020 10th International Conference on Cloud Computing, Data Science & Engineering (Confluence)**. Noida, India: IEEE, 2020. p. 82–87. ISBN 978-1-72812-791-0. Available from Internet: <https://ieeexplore.ieee.org/document/9057916/>.

ZANAFI, S. et al. Enabling Sustainable Smart Environments Using Fog Computing. In: **2018 International Conference on Electronics, Control, Optimization and Computer Science (ICECOCS)**. Kenitra: IEEE, 2018. p. 1–6. ISBN 978-1-5386-7868-8. Available from Internet: <https://ieeexplore.ieee.org/document/8610509/>.

ZHANG, C.; LIU, X. Research on the Development of Software for Predicting Ecological Impacts in Coastal Waters. In: **2021 4th International Symposium on Traffic Transportation and Civil Architecture (ISTTCA)**. Suzhou, China: IEEE, 2021. p. 190–193. ISBN 978-1-66542-592-6. Available from Internet: <https://ieeexplore.ieee.org/document/9654714/>.

ZHENG, D.; ZHANG, X.; CHEN, L. Research of pervasive ecological monitoring applications based on edge computing technologies. In: **2020 IEEE 18th International Conference on Embedded and Ubiquitous Computing (EUC)**. Guangzhou, China: IEEE, 2020. p. 49–55. ISBN 978-1-66540-400-6. Available from Internet: <https://ieeexplore.ieee.org/document/9343403/>.

ZONG, Z. An Improvement of Task Scheduling Algorithms for Green Cloud Computing. In: **2020 15th International Conference on Computer Science & Education (ICCSE)**. Delft, Netherlands: IEEE, 2020. p. 654–657. ISBN 978-1-72817-267-5. Available from Internet: <https://ieeexplore.ieee.org/document/9201785/>.