Exploring the Role of Digital Interventions in Realising Energy Savings

Christina Bremer, BSc (Hons), MSSc
School of Computing and Communications
Lancaster University

A thesis submitted for the degree of
Doctor of Philosophy

May, 2024

I dedicate this thesis to future generations, in the sincere hope that you won't inherit a burning planet. May the miracle of successful climate change mitigation allow you to build sustainable, prosperous and peaceful lives.

Declaration

I declare that the work presented in this thesis is, to the best of my knowledge and belief, original and my own work. The material has not been submitted, either in whole or in part, for a degree at this, or any other university. This thesis does not exceed the maximum permitted word length of 80,000 words including appendices and footnotes, but excluding the bibliography.

Christina Bremer

Exploring the Role of Digital Interventions in Realising Energy Savings

Christina Bremer, BSc (Hons), MSSc.
School of Computing and Communications, Lancaster University

A thesis submitted for the degree of *Doctor of Philosophy.* May, 2024

Abstract

A strategy for mitigating the ongoing climate crisis is to reduce global energy consumption; as part of this strategy, digital technologies have been used for building automation and behaviour change interventions. However, while these technologies get invested in and relied upon, there remain questions about their overall effectiveness. Focusing on buildings, as their operation is responsible for around 30% of global energy consumption, this thesis explores the role of digital interventions in realising energy savings through both empirical and literature work. Using the Lancaster University campus as a case study, the thesis presents the results from expert interviews and a longitudinal analysis of energy data from 2016 until 2021, including during the global COVID-19 pandemic. The interviews reveal a tendency among experts to problematise occupant behaviour and to trust data-based automation of energy systems as a key to lowering energy consumption. In contrast, the longitudinal analysis shows relatively few energy savings during COVID-19 lockdown periods, suggesting high building baseload and limited potential of digital interventions. Constituting a well-established set of mechanisms that counteract efficiency savings, the thesis then addresses rebound effects: based on a literature mapping showing that rebound effects have received little attention in energy efficiency research, systems thinking and the combination of efficiency with sufficiency strategies are encouraged. The limitations of digital energy-saving interventions, in particular behaviour change technology, have also been discussed in the sustainable HCI (SHCI) community. A literature review of SHCI critique papers and recent publications uncovers that to overcome these limitations, the community has been called to contribute beyond its HCI skillset. Here, I propose "green policy informatics" as an alternative contribution pathway that is characterised by ambitious climate policies. The thesis concludes with a discussion of prevalent narratives around digital energy-saving interventions, policy considerations and future work.

Publications

Contributing Publications

The following publications have resulted from the thesis research and form the basis of Chapters 5, 6 and 7.

Bremer, Christina, Bran Knowles, and Adrian Friday (2022). "Have We Taken On Too Much?: A Critical Review of the Sustainable HCI Landscape". In: *CHI Conference on Human Factors in Computing Systems*, pp. 1–11.

Bremer, Christina, Oliver Bates, Christian Remy, Alexandra Gormally-Sutton, Bran Knowles, and Adrian Friday (2023). "COVID-19 as an Energy Intervention: Lockdown Insights for HCI". In: *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–7.

Bremer, Christina, Harshit Gujral, Michelle Lin, Lily Hinkers, Christoph Becker, and Vlad C Coroamă (2023). "How Viable are Energy Savings in Smart Homes? A Call to Embrace Rebound Effects in Sustainable HCI". In: *ACM Journal on Computing and Sustainable Societies* 1.1, pp. 1–24.

Additional Publications

The following publications have contributed to the thinking process while developing the thesis and to an extent have guided the thesis into what it has become.

Bremer, Christina (2020a). "Not (B)interested? Using Persuasive Technology to Promote Sustainable Household Recycling Behavior". In: *Persuasive Technology. Designing for Future Change: 15th International Conference on Persuasive Technology.* Springer, pp. 195–207.

Bremer, Christina (2020b). "When Mental Models Grow (C)old: A Cognitive Perspective on Home Heating Automation". In: *IEEE Pervasive Computing* 19.4, pp. 48–52.

Bremer, Christina (2021). "A Smart Approach?: Raising Uncomfortable Questions about Building Automation in the Workplace". In: *Automation Experience at the Workplace, workshop at CHI 2021.*

Bremer, Christina (2022). "Efficiency Technology as a Political Act". In: *Towards a Material Ethics of Computing: Addressing the Uneven Environmental Stakes of Digital Infrastructures, workshop at CHI 2022.*

Bremer, Christina, George Kamiya, Pernilla Bergmark, Vlad C Coroamă, Eric Masanet, and Reid Lifset (2023). “Assessing Energy and Climate Effects of Digitalization: Methodological Challenges and Key Recommendations”. In: *nDEE Framing Paper Series.*

Mencarini, Eleonora, **Christina Bremer**, Chiara Leonardi, Jen Liu, Valentina Nisi, Nuno Jardim Nunes, and Robert Soden (2023). “HCI for Climate Change: Imagining Sustainable Futures”. In: *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–6.

Acknowledgements

As a woman with plenty of scientific curiosity, I would first like to acknowledge the fierce, courageous people who fought for my right to legally obtain a PhD. These people raised their voices—in the streets, court rooms and universities—to challenge the notion that women do not belong in labs and lecture theatres; some of them paid a high price. We need to protect this right, not just for women but for everyone outside of the most privileged group. School bans for girls, like those that were recently implemented in Afghanistan, can seem far away, but they highlight the fragility of hard-won progress. While scientific findings should hold independently of the person who conducted the research, it remains subjective which topics deserve funding and attention—the more diverse scientific communities become, the more problems we will be able to solve.

As my research would not have happened without funding either, I would like to thank the Leverhulme Trust Material Social Futures Scholarship programme and everyone who contributed to it for the support. Similarly, it would not have happened without my participants, and so I am grateful for all the experts who were willing to take part in my studies and share their knowledge with me.

On a personal level, I also have a long list of people I would like to thank. I will start with my brilliant supervisors, Bran Knowles and Adrian Friday, whose support and guidance were paramount for me successfully completing my PhD. Bran, thank you for being a role model, for always making time for me, even when you had a long list of other tasks, and for opening the door to so many opportunities. Adrian, thank you for sharing your expertise, for tapping into your large network for me (on more than one occasion) and for lifting me back up when things were not going according to plan. I am also grateful for Mike Hazas' and Richard Harper's supervisory contributions during the first year of my PhD, which shaped the research I conducted in subsequent years.

Alongside my supervision, I was exceptionally well mentored by several experienced colleagues, including Emily Winter, Oliver Bates, Christian Remy and Vlad C. Coroamă; without their continuous advice and encouragement I would not be where I am today. Emily, thank you for your encouraging and helpful advice when I felt stuck and for celebrating my progress and victories with me; I am so glad that our paths have crossed. Oliver, thank you for generously giving your time and resources to help me succeed in my research, career and beyond. Christian, thank you for helping me make good decisions, being a sounding board and answering all of my questions. Vlad, thank you for your helpful advice and feedback and for your unwavering belief in my abilities as a researcher.

I would also like to thank my examiners, Lynne Blair and Maria Håkansson, for their thoughtful and helpful feedback, which has been incorporated into this final

version of the thesis, as well as for creating an enjoyable viva experience.

Throughout my PhD, I could not have asked for more supportive group of people in SDS, C20 and InfoLab: Oliver Bates, Christian Remy, Kelly Widdicks, Helena Tendedez, Kathy New, Adam Tyler, James Devine, Ally Gormally-Sutton, Elisa Rubegni, Carolynne Lord, Ludwig Trotter, Alex Wild and all of the other great people I worked with, many of whom became my close friends outside of work too—thank you for making my PhD journey easier and more fun! Outside of Lancaster I also found fantastic collaborators, including Vlad C. Coroamă, Christoph Becker, Harshit Gujral, Michelle Lin, Lily Hinkers, George Kamiya, Pernilla Bergmark, Eric Masanet, Reid Lifset, Eleonora Mencarini, Chiara Leonardi, Jen Liu, Valentina Nisi, Nuno Jardim Nunes and Robert Soden. Thank you for our fruitful collaborations and for broadening my scientific horizons.

I have been very lucky in that across Europe (with hotspots in Germany and the UK) family members and friends have been cheering me on and have made time for me in line with my travel plans and paper deadlines. These people include Mama, Papa, Elisabeth Zinser, Sophie Burns, Justine Julienne, Simon Smalley, my sister Theresa and my brother Vincent, Opa Dieter and Oma Gilda, Tante Helma, Paula Rühe, Harman Singh, Anne Seeboth, Dom Savage, Melissa van der Sar and Amy Stanning. Thank you, danke & merci!

Contents

List of Figures

List of Tables

List of Abbreviations

AHS Augmented Humans International Conference.

AI Artificial Intelligence.

AM International Audio Mostly Conference.

AutomotiveUI International Conference on Automotive User Interfaces and Interactive Vehicular Applications.

AVI International Conference on Advanced Visual Interfaces.

BAS Building Automation System.

BMS Building Management System.

BREEAM Building Research Establishment Environmental Assessment Method.

C&C Conference on Creativity and Cognition.

CHI Conference on Human Factors in Computing Systems.

CHIIR Conference on Human Information Interaction and Retrieval.

CHP Combined Heat and Power.

CI Collective Intelligence Conference.

CSCW Conference on Computer Supported Cooperative Work.

CUI International Conference on Conversational User Interfaces.

DIS Conference on Designing Interactive Systems.

DOT Development Oriented Triangulation.

EICS Symposium on Engineering Interactive Computing.

EIS Energy Information System.

EMS Energy Monitoring System.

EU European Union.

GHG Greenhouse Gas.

GI Graphics Interface Conference.

GUI Graphical User Interface.

GWh Gigawatt hours.

HBI Human-Building Interaction.

HCI Human-Computer Interaction.

HUCAPP International Conference on Human Computer Interaction Theory and Applications.

HVAC Heating, Ventilation and Air Conditioning.

ICMI International Conference on Multimodal Interaction.

ICT Information and Communication Technology.

IHM International Conference on Association Francophone d'Interaction Homme-Machine.

IMX International Conference on Interactive Media Experiences.

IoT International Conference on the Internet of Things.

IT Information Technology.

iWOAR International Workshop on Sensor-based Activity Recognition and Artificial Intelligence.

kW Kilowatts.

kWh Kilowatt hours.

LAK International Learning Analytics and Knowledge Conference.

LEED Leadership in Energy and Environmental Design.

MobileHCI Conference on Mobile Human-Computer Interaction.

MuC Mensch und Computer.

MVA Megavolt Amperes.

MW Megawatts.

MWh Megawatt hours.

NordiCHI Nordic Conference on Human-Computer Interaction.

PACMHCI Proceedings of the ACM on Human-Computer Interaction.

RecSys Recommender Systems Conference.

SDGs Sustainable Development Goals.

SHCI Sustainable Human-Computer Interaction.

SHT Smart Home Technology.

SIGCHI Special Interest Group on Computer–Human Interaction.

TEI International Conference on Tangible, Embedded and Embodied Interaction.

UK United Kingdom.

UN United Nations.

W4A International Web for All Conference.

Chapter 1

Introduction

Mitigating the climate crisis remains one of the existential challenges of our time, becoming more urgent with each year that passes: compared to pre-industrial levels, the temperature on our planet has has already increased by 1.15°C (World Meteorological Organization, 2022), and current country commitments and policies are estimated to lead to a total warming of 2.5°C by 2100 (International Energy Agency, 2021)—with devastating effects for ecosystems, societies and individuals. Avoiding the most severe consequences of the climate crisis requires global Greenhouse Gas (GHG) emissions to halve each decade, down to net-zero emissions by mid-century (International Energy Agency, 2021). The reason for climate change is an excess of GHGs in the atmosphere, which stem largely from energy conversions, i.e., burning fossil fuels to produce energy; a process that most societies fundamentally rely on. This explains why the energy sector is a key contributor to climate change, accounting for more than two-thirds of global GHG emissions (International Energy Agency, 2022b). It also means that in order to achieve net-zero emissions, global energy consumption needs to drastically change. A key strategy to realise this change is to reduce the GHG emissions that get released per unit of energy: a fundamental shift from fossil fuels to nuclear energy or renewables, including solar and wind energy, could halt global warming. While this realisation is not new, progress is slow: according to the latest status report, fossil fuels still account for almost 82% of global energy consumption (Energy Institute, 2023).

In this context, and especially with the slow increase in the use of clean energy, energy efficiency, i.e., the process of reducing the amount of energy required to provide products and services (Pérez-Lombard, Ortiz, and Velázquez, 2013), is considered critical. According to the International Energy Agency, 2019a, *"[e]nergy efficiency has a central role in tackling climate change, a task made all the more urgent by the recent rise in emissions and the limited time to achieve mitigation targets [...]. Energy efficiency is one of the key ways the world can meet energy service demand with lower* *energy use [...].”* In fact, it is estimated that energy efficiency could deliver more than 40% of the reduction in energy-related GHG emissions by 2040 (International Energy Agency, 2020). To enable these efficiency savings, digital technologies[1] are regarded as essential tools, which can be applied in a variety of ways and across sectors. For energy savings on the end-user side, they are frequently used to encourage behavioural changes, which is sometimes referred to as behavioural energy efficiency (de Leon Barido et al., 2018; Barbu, Griffiths, and Morton, 2013), and to automate energy systems and devices; these are the types of digital energy-saving interventions I focus on in the thesis.

For behavioural changes, a common approach is the design and deployment of behaviour change technology (DiSalvo, Sengers, and Brynjarsdóttir, 2010; Midden et al., 2008; Froehlich, 2009), which covers ambient systems (Gustafsson and Gyllenswärd, 2005) as well as openly persuasive systems that use rewards and/or visualisations of the negative impacts associated with the users’ behaviour (Spagnolli et al., 2011; Bang, Torstensson, and Katzeff, 2006). Many of these systems use feedback as a key mechanism, which is referred to as eco-feedback when provided in a sustainability context (Froehlich, Findlater, and Landay, 2010)[2]. As part of the automation approach, digital technologies are designed to be “smart” so that they can automatically identify patterns and insights in data, learn from experience and improve system performance over time (Romero et al., 2020; International Energy Agency, 2019b). For this, the technologies utilise e.g., Artificial Intelligence (AI) and internet connectivity to enhance and automate tasks. What should be noted is that the interventions have effects beyond reducing the energy consumption of the digital technologies themselves, which is captured as the distinction between direct and indirect effects in the following categorisation (F. Berkhout and Hertin, 2001)[3]:

- First-order effects: direct GHG emissions from the raw materials acquisition, production, use and end-of-life treatment of digital technologies, which are also referred to as their footprint or lifecycle impacts (Hilty and Aebischer, 2015);

---

[1] While both Information and Communication Technology (ICT) and digital technologies refer to electronic devices, systems and resources that store and process data, ICT tends to refer to a narrower set as well to the underlying industrial sector (International Telecommunication Union, 2018). This term is also defined from the perspective of assessment standards, while boundaries of the other terms are more open for interpretation. In this thesis, I use the broader term “digital technologies” and describe interventions that use digital technologies as “digital interventions”.

[2] For this introductory chapter, the references belonging to the literature on behaviour change technology have intentionally been selected to represent well-known and well-cited studies.

[3] The described classification of effects stands in contrast to some of the economic and engineering literature where direct energy use describes operational use, that is, the energy used for running a device or system, whereas device production and disposal fall under indirect effects (Horner, Shehabi, and Azevedo, 2016).

- Second-order effects: indirect effects on GHG emissions resulting from the use of digital technologies and services, which can increase or decrease emissions beyond their footprint;
- Third-order effects: additional indirect effects on GHG emissions originating from the first-order or second-order effects of digitalisation, such as rebound effects, changes in consumption patterns, lifestyles and value systems, which can result in higher or lower emissions (Hilty, Arnfalk, et al., 2006).

A particularly relevant application area for digital energy-saving interventions are buildings as their operation accounts for around 30% of global final energy consumption and 26% of global energy-related emissions (International Energy Agency, 2022a). In addition, recent figures show that the energy consumption in buildings continues to rise: during the past decade, it has grown by just over 1% each year; in 2022 it increased by nearly 1% compared with 2021. What makes this a particularly difficult problem to solve is that buildings cannot be easily changed once built. According to the International Energy Agency, 2022a, *"[b]ecause of the long lifetime of structures, heating and cooling systems, and other appliances, design and purchasing decisions made today will shape energy use for many years to come."* For this reason, digital technologies are a popular tool to make the existing building stock more energy efficient. When buildings are equipped with systems and devices that are Internet-enabled and interconnected and that can be automatically and remotely controlled, they are then referred to as "smart buildings" (Buckman, Mayfield, and Beck, 2014); for residential buildings—which are frequently selected for research studies—the term "smart homes" is used (Jiang, D. Liu, and B. Yang, 2004).

Estimates regarding the energy savings that digital interventions can achieve in buildings range from 0% to up to 50%, depending on the intervention and type of building (Williams and Matthews, 2007; Ford et al., 2017; King and Perry, 2017). However, these numbers do not consistently account for the digital technologies' footprint (Knowles, Widdicks, et al., 2022; Koomey, Matthews, and Williams, 2013) and are often based on evaluations that are rooted in modelling approaches rather than empirical studies, which do not reliably capture e.g., contextual factors, operational practices and occupant behaviour (Van Thillo, Verbeke, and Audenaert, 2022). What these limitations mean for energy consumption predictions can be seen from the well-documented performance gap between energy-saving predictions and real-world assessments of energy use in buildings (Gram-Hanssen and Georg, 2018). A review of 62 non-domestic buildings in the United Kingdom (UK), for example, found an average discrepancy of 34% (Van Dronkelaar et al., 2016). Among the key factors that have been identified as contributors to the energy performance gap are modelling uncertainty, complexity of design, inefficient operational practices, malfunctioning equipment and unexpected occupant behaviour (Zou et al., 2018; Van Dronkelaar et al., 2016). These factors highlight the complexity of real-world environments in which digital technologies are introduced in order to save energy, while also affecting the energy-saving potential of the interventions themselves. What adds to the challenge is that rebound effects can counteract any savings that *have been* achieved through energy efficiency interventions (Sorrell, 2009). Well-established in the energy literature, these effects describe an array of mechanisms that reduce the expected gains from the introduction of technologies which increase the efficiency of resource use, due to behavioural or other systemic responses (Greening, Greene, and Difiglio, 2000; P. H. G. Berkhout, Muskens, and Velthuijsen, 2000; Khazzoom, 1980).

Evidently, the use of digital technologies for energy savings in buildings does not happen in a vacuum but within a real-world context, i.e., it happens in an environment in which people make "non-rational" decisions based on their priorities and backgrounds, in which devices break and savings get re-invested. Both building occupants and decision-makers are shaped by social, cultural and political factors and can respond to digital interventions and their outcomes in unexpected ways. A research field that has had a long-standing interest in the nuanced ways in which digital technologies impact the behaviour of their users in a sustainability context is Sustainable Human-Computer Interaction (SHCI). When the field emerged as a subfield of Human-Computer Interaction (HCI) around 2007, the focus was on behaviour change interventions for resource savings, such as those described above (DiSalvo, Sengers, and Brynjarsdóttir, 2010). Since then, the community has reflected on the limitations of that approach, including unrealistic expectations regarding rational user behaviour, and has had active discussions about the pathways in which the design of digital technologies can effectively contribute to sustainability, e.g., Knowles, L. Blair, Coulton, et al., 2014; Hazas, Brush, and Scott, 2012; Joshi and T. C. Pargman, 2015; Mankoff, 2012. For energy use in buildings specifically, the SHCI community has produced a substantial body of research on how smart systems can undermine energy savings by e.g., introducing new lifestyle expectations and changing behaviours (R. H. Jensen, Strengers, Raptis, et al., 2018; Strengers, Hazas, et al., 2020; Jakobi et al., 2017); this includes SHCI research in smart homes (R. H. Jensen, Strengers, Kjeldskov, et al., 2018; Strengers, Hazas, et al., 2020; Tirado Herrero, Nicholls, and Strengers, 2018).

Given the urgent need for energy savings but also the complex situation in which factors that can undermine the outcomes of digital efficiency interventions are not consistently acknowledged, it is important to understand holistically how these interventions can(not) contribute. For this reason, my thesis explores the role of digital interventions in realising energy savings from an HCI perspective. More specifically, I am interested in the potential tension between the narratives driving these interventions, estimates of their energy-saving potential and complexity of real-world environments. Due to their high energy consumption, I will use buildings as a relevant application domain. My exploration is guided by the following research questions:

- Q1. What are the narratives of digital interventions for energy savings in buildings among experts in the energy domain?
- Q2. What is the theoretical saving potential of digital interventions in buildings?
- Q3. How can contextual factors impact the realisation of this potential?
- Q4. To what extent does energy efficiency research in and beyond smart homes consider rebound effects?
- Q5. Which strategies has the SHCI community employed to overcome the limitations of digital behaviour change interventions?

To answer these questions, my thesis combines empirical research with systematic literature reviews: the first two content chapters present campus-based research, including expert interviews and an analysis and contextualisation of energy data (addressing Q1, Q2 and Q3), while the latter two content chapters present the literature reviews (targeting Q4 and Q5). Both parts of the thesis and the underlying research questions have been informed by the potential tension described above and by the aim to better understand in which situations digital interventions can(not) realise energy savings.

1.1 Thesis Outline

This thesis contains a total of eight chapters, including the introduction, which are outlined below.

1. **Chapter 2** situates the thesis research in terms of its historical background and study context. This covers the strategies behind digital energy-saving interventions, the development of HCI as a subfield of computing and its link to sustainability, SHCI research in (smart) buildings and the identified tensions around digital energy-saving interventions.
2. **Chapter 3** explains the research methodology and describes the buildings and energy systems on Lancaster University's Bailrigg campus where the empirical research was conducted.

3. **Chapter 4**. Using the campus as a case study environment, this chapter uncovers the narratives of digital energy-saving interventions among campus-based experts with energy-related expertise. This includes the role of energy data, energy systems automation and building occupants, as well as the relevance of buildings as an intervention space.
4. **Chapter 5** uses energy data to estimate the theoretical saving potential of digital interventions in buildings. More specifically, it provides an estimate of the baseload of campus buildings as a factor that limits the energy-saving potential of digital interventions. For these calculations, the COVID-19 pandemic presented a unique research opportunity as building were largely unoccupied during lockdown periods. To contextualise my estimates, I report the results from a focus group interview and Jamboard (annotation) study with experts—which also provide insights into the role of energy data itself.
5. **Chapter 6** analyses to what extent rebound effects have been considered in the computing, HCI and general literature on energy efficiency. As a well-established set of mechanisms that counteract efficiency savings, rebound effects can fundamentally undermine the success of digital energy efficiency interventions and must not be ignored. To continue the emphasis on buildings, the chosen application area for this study are smart homes.
6. **Chapter 7**. With a focus on digital behaviour change interventions, this chapter analyses SHCI critique papers and recent publications in the field to understand what SHCI researchers have been to called to do in order to overcome the limitations of digital behaviour change interventions and also whether these suggestions were implemented in subsequent research. Based on the outcome of this review, the chapter proposes “green policy informatics” as a pathway that allows SHCI researchers to leverage their traditional skills more effectively.
7. **Chapter 8**. I conclude the thesis with a review of contributions, discussion of overarching themes and outline of future work that can complement and advance the presented research.

Chapter 2

Background

Given the slow shift towards the use of clean energy sources, digital technologies are a popular tool to reduce Greenhouse Gas (GHG) emissions through energy efficiency measures. This includes both behavioural efficiency, i.e., using behaviour change technology to convince users to consume less energy, and efficiency through the automation of energy systems, including the installation of "smart" devices and algorithmic data analysis. While efficiency interventions can appear promising in theory, it has been shown that the expectations regarding their energy-saving potential do not reliably translate into in the real world, e.g., Hazas, Brush, and Scott, 2012; Peffer et al., 2011; Hargreaves, Wilson, and Hauxwell-Baldwin, 2018a; Tirado Herrero, Nicholls, and Strengers, 2018. Among the reasons for this misalignment are the unexpected impact of contextual factors, operational practices and behavioural responses. In this thesis, I will use an Human-Computer Interaction (HCI) lens to further explore the expectations and narratives of digital energy efficiency interventions as well as the factors that shape their outcomes in the real world. Implemented as a combination of empirical studies and systematic literature reviews, the aim of my research is to better understand the role of digital interventions in realising energy savings. Due to their high energy consumption, I will focus on buildings as a relevant application domain.

2.1 Energy consumption of buildings

Buildings are responsible for a large share of the globally consumed energy: in 2021, the buildings and construction sector accounted for over 34% of energy demand and around 37% of energy and process-related CO_2 emissions (United Nations Environment Programme, 2022). This is largely linked to the operation of buildings, which is responsible for around 30% of global final energy consumption and 26% of global energy-related emissions of which 8% are direct emissions in buildings and 18% are indirect emissions from the production of electricity and heat used in buildings (International Energy Agency, 2022a). This is representative for Europe as well, where the buildings sector represents 40% of the current energy demand, 80% of it from fossil fuels (United Nations Environment Programme, 2022). While both the sector's emissions intensity in kilogrammes of CO_2 per square metre and the energy intensity in Kilowatts (kW) per hour per square metre decreased at least slightly between 2015 and 2021, investments in building infrastructure have reached unprecedented levels. This means that growth is outpacing efforts on energy efficiency and reducing energy intensity (International Energy Agency, 2022a): in 2021, operational energy demand for heating, cooling, lighting and equipment in buildings increased by around 4% from 2020 and 3% from 2019. Currently, the gap between the climate performance of the sector and the 2050 decarbonisation goals is widening (United Nations Environment Programme, 2022).

For the electricity consumption of buildings, a distinction can be made between baseload and peakload (H. Li et al., 2021). Baseload, which is also referred to as continuous load, is defined as the minimum level of electricity demand required over a set period of time; it is needed to provide energy to components, systems and devices that keep running at all times (U.S. Energy Information Administration, 2023). While inefficiencies can increase the baseload of a building (Zhan and Chong, 2021), baseload can also constitute a boundary for possible energy savings from digital interventions as it cannot be lowered through changes in occupant behaviour or to devices that are turned off at night (U.S. Department of Energy, 2017). Incorrect baseload assumptions, as described in Van Dronkelaar et al., 2016, can thus lead to an overestimation of the interventions' energy-saving potential. Peakload on the other hand describes the maximum amount of electricity that a building draws from the grid in a set period of time. Managing the peakload in buildings through e.g., demand-side management is useful to balance energy supply and demand and ensure reliable power supply; it can also help to effectively integrate renewable energy sources into the electricity grid (Uddin et al., 2018; Darwazeh et al., 2022).

In order to reduce buildings' high energy demand—including their electricity demand—work has been carried out across academic disciplines and industries, e.g., in civil engineering (Zavadskas et al., 2017), architecture (B. Bielek and M. Bielek, 2012) and building informatics (Lim and Tee, 2018). This includes the rising use of green or sustainable building technologies, which can be defined as a collection of advanced technologies and products that are applied to building design and construction to allow for the reduction of their energy use and GHG emissions (Zhao et al., 2017); this includes but is not limited to improved building materials (Reddy, 2004) and construction practices (Gunhan, 2019). While this work is important and relevant, it is beyond the scope of this thesis, which focuses on the use of digital technologies and research in the field of HCI.

2.2 Digital energy-saving interventions

Frequently revolving around the provision of data and smart technologies, digital energy-saving interventions use digital technologies in order to optimise energy consumption, reduce waste and mitigate environmental impact. With a focus on the use of digital technologies for energy efficiency, researchers and organisations have claimed that *"[e]nergy efficiency in existing and new buildings is a fast-track solution for limiting the environmental, economic, social, and other impacts in this sector (X. Chen, H. Yang, and L. Lu, 2015)"* (Hafez et al., 2023) and that *"[d]igitalisation offers the potential to increase energy efficiency through technologies that gather and analyse data before using it to make changes to the physical environment (either automatically, or through human intervention)"* (International Energy Agency, 2019b). Responding to such claims, my thesis mainly targets the following two strategies, which use digital technologies in order to increase energy efficiency: behaviour change technology, including energy feedback, with an active user at its core, and automation, which tends to take the user "out of the loop".

While not the focus of the thesis, it should be noted that, on the side of the grid, digital technologies are also used to facilitate the integration of clean energy sources, such as solar and wind power; real-time monitoring is used to manage fluctuations in supply to avoid supply shortages and reduce dependence on fossil fuels (Dileep, 2020). This can extend to the creation of smart grids, which employ real-time data analytics to monitor energy flow, predict demand patterns and adjust energy distribution accordingly. By dynamically managing energy consumption, smart grids aim to prevent wastage and enable the integration of clean energy sources (Melo et al., 2021). Through micro-generation, energy "prosumers" (based on the words "producer" and "consumer", the term describes an individual who both consumes and produces a resource, in this case energy) can also feed renewable energy into the grid, assuming that they have a grid-connected set-up (Kotilainen, 2019). Dynamic pricing can create additional incentives to use energy when it stems from renewable sources (Jia and Tong, 2016).

2.2.1 Behaviour change technology

According to the International Energy Agency, 2023, *"[b]ehavioural changes play an important role in the Net Zero Emissions by 2050 (NZE) Scenario, cutting CO_2 emissions and reducing growth in energy demand."* Aiming to support these changes with the help of digital technologies, the design of behaviour change technology became a well-established approach in Sustainable Human-Computer Interaction (SHCI) and adjacent research communities. By leveraging psychological principles and data analytics on digital platforms, such as mobile apps and stand-alone displays, behaviour change technology is intended to encourage its often individual users to adopt different behaviours, e.g., more sustainable energy consumption behaviours (Pinder et al., 2018; Brynjarsdóttir et al., 2012). In HCI, the underlying design strategies have been divided into strong persuasion and passive persuasion: while the former includes information regarding the extent to which a user's behaviour is or is not sustainable, the latter presents the user with information about their consumption, waste or other impacts that tends to be implicitly contextualised within the theme of sustainability (DiSalvo, Sengers, and Brynjarsdóttir, 2010). Some persuasive systems provide their information ambiently. These ambient awareness systems *"draw upon the histories of calm computing and ambient displays to construct systems intended to make users aware of some aspect of the sustainability of their behavior, or qualities of the environment associated with issues of sustainability"* (DiSalvo, Sengers, and Brynjarsdóttir, 2010, p. 1977). An example for this is the *Power Aware Cord* that glows in response to energy consumption (Gustafsson and Gyllenswärd, 2005).

Behaviour change technology is traditionally based on the theory of persuasive technology by Fogg, 2002 and uses a range of mechanisms of which eco-feedback is arguably the most established one. The term eco-feedback technology describes a type of behaviour change technology that is used to give feedback on individual or group behaviours in order to reduce their environmental impact. The concept of eco-feedback does thereby stem from environmental psychology, where researchers had used it for over forty years before HCI and computing researchers started to focus on its digital implementation (Froehlich, Findlater, and Landay, 2010; Kohlenberg, Phillips, and Proctor, 1976). This includes real-time feedback on users' energy consumption patterns (Pierce, Fan, et al., 2010) as well as interactive consumption visualisations (Costanza, Ramchurn, and Jennings, 2012). In some cases, eco-feedback technology is combined with gamification elements, such as rewards, challenges and competitions, which can be integrated into apps and platforms to engage users in energy-saving activities. Users earn e.g., points or badges for reducing energy consumption or adopting energy-efficient practices (Martin and Kwaku, 2019; Mylonas et al., 2021). By employing social comparison techniques, users might also be able to see how their energy use compares to that of e.g., their peers or neighbours (Geelen et al., 2012; Foster, Lawson, Blythe, et al., 2010); in other cases, a collaborative approach is encouraged (Fraternali et al., 2017). Less frequently, fully fledged serious games are developed (Johnson et al., 2017; Hedin et al., 2017). Behaviour change technology can also include educational elements, such as interactive lessons, quizzes or informative content, to help users understand the impact of their choices (J. C. Yang, Chien, and T. C. Liu, 2012; Janakiraman, S. L. Watson, and W. R. Watson, 2018; Katzeff, Nyblom, et al., 2012), personalised recommendations based on individual energy usage patterns (Sardianos et al., 2019; Eirinaki et al., 2022) and reminder systems that use e.g., nudging to help users develop energy-conscious habits (Stieglitz et al., 2023).

Usually focused on behavioural efficiency, energy-related behaviour change technologies can also be integrated with smart grids to align energy consumption with periods of lower demand or higher availability of renewable energy. Users receive notifications when energy prices are lower or when renewable sources are at their peak, encouraging them to shift energy-intensive activities to these times (Pierce and Paulos, 2012; Costanza, J. E. Fischer, et al., 2014).

2.2.2 Automation in buildings

A variety of automated functions can be found in many modern buildings. These range from simple automatic lighting controls, such as those outdoors that are connected to motion detectors, to complex smart systems (Merz, Hansemann, and Hübner, 2009; Al Dakheel et al., 2020). When a building is described as an "intelligent building", a "smart building" or, if it is a domestic building, a "smart home" (Jiang, D. Liu, and B. Yang, 2004), it typically contains a Building Automation System (BAS), which is used to control and monitor building services responsible for Heating, Ventilation and Air Conditioning (HVAC), lighting, shading, life safety, alarm security systems and other interrelated systems (Domingues et al., 2016). More specifically, a BAS is designed to e.g., keep a building's indoor temperatures within a specified range, light rooms based on occupancy, monitor system performance and device failures, and provide malfunction alarms to building maintenance staff. This can reduce the buildings' energy consumption and maintenance costs (Domingues et al., 2016). In smart homes specifically, Smart Home Technology (SHT), such as smart thermostats and lighting systems, can be used to automate energy-saving actions. Based on sensor data and data analytics, these systems learn user preferences and adjust settings to minimise energy waste, such as turning off lights when a room is empty or optimising indoor temperatures based on occupancy (Alam, Reaz, and Ali, 2012; Jahn et al., 2010). According to a smart home literature review, *"[t]he primary objectives of a smart home are to increase home automation, facilitate energy management, and reduce environmental emissions"* (Saad Al-Sumaiti, M. H. Ahmed, and Salama, 2014).

Due to their energy-saving potential, smart homes are one of the European Union (EU)'s ten priority action areas in its Strategic Energy Technology Plan (European Commission, 2015) and have been an active area of energy research for over three decades (Lutolf, 1992). In line with this prioritisation, numerous sources identify quite substantial energy-saving potential for smart homes: deploying in-home displays to continuously communicate the overall electricity consumption of a smart home to its occupants has been the focus of several studies, and was found to yield electricity savings of between 0% and 18% (Ford et al., 2017). Looking beyond electricity and considering the more substantial energy consumption of space heating, the average energy-saving potential was found to be over 9% in a smart heating simulation based on occupancy detection and prediction from real-world data of more than 3000 Irish households (Becker et al., 2018). Considering all sources of energy consumption in a household, Williams and Matthews suggest that monitoring and control systems can help occupants lower their energy consumption by 3–26%. While the lower end of this estimate applies to the use of programmable thermostats, the upper end refers to *"an integrated system including monitoring and control of appliances, plus zone heating/cooling"* (Williams and Matthews, 2007, p. 239). This is consistent with the claim that the energy-saving potential of smart energy systems tends to be positively linked to the overall level of complexity, with the cost of greater computational requirements (Naylor, Gillott, and Lau, 2018). A representative national survey of over 1000 homeowners in the United Kingdom (UK) found that prospective users have positive perceptions of the multiple functionality of SHTs, including energy management (Wilson, Hargreaves, and Hauxwell-Baldwin, 2017).

While outside the scope of the thesis, it should be noted that the use of digital technologies in buildings often leads to the creation of vast amounts of digital data. Alongside questions around data security, storage and privacy (Tabassum, Kosinski, and Lipford, 2019), this data can also be monetised. An example of this is PropTech, which describes the deployment of digital technologies in the real estate industry, where digital data is used to optimise the acquisition, operation and management of real estate, leading to a highly competitive digitalised global market (Braesemann and Baum, 2020; Siniak et al., 2020).

2.3 HCI and sustainability

As a multidisciplinary field of study specialised in the design of digital technologies and the interactions between humans (the users) and computers, HCI did not actively focus on sustainability during most of its still young history. In this section, I will summarise the development of HCI as a research field, introduce Sustainable Human-Computer Interaction (SHCI) as a subfield that focuses on environmental sustainability and present relevant SHCI research on energy and resource consumption.

2.3.1 The history of HCI

HCI is a relatively young scientific discipline whose roots can be traced back to human factors engineering and information processing. After the Second World War, computers were still relying on vacuum tubes for logic circuitry, and programs were loaded from tapes rather than by pressing buttons and switches; processes which needed to be optimised for efficiency (Grudin, 2017). As transistors replaced vacuum tubes, prototype building gathered pace and Shackel, 1959 published the first HCI paper *Ergonomics for a Computer*; offering a practical design perspective, the paper focuses on the redesign of the control panel of ENIAC II, an early analogue computer. Although the computer was analogue rather than digital, many of the principles of practical usability engineering can already be found in this first HCI paper, e.g., prototyping, empirical testing and visual grouping (Dix, 2017). After a number of key inventions, such as the Graphical User Interface (GUI), desktop interface and mouse, HCI emerged as a research discipline in the 1980s (Dix, 2017). What came to follow was the first of three waves that describe key paradigm shifts in the field (Duarte and Baranauskas, 2016; Harrison, Tatar, and Sengers, 2007).

During the first wave, researchers aimed to achieve an optimal “fit” between humans and machines to reduce errors and disruptions. Their research was founded in empiricism and quantitative methodologies; within an objective rhetoric, users were regarded as “human factors” or calculable elements of human-machine systems. This meant that most of the research was conducted in a closed scientific lab setting. Key technological innovations during the first wave were the advent of mainframe computers and the launch of large-scale data processing projects, which gave rise to methodological innovations, such as style guides, usability labs and task analysis.

The second wave emerged when the arrival of powerful minicomputers and the GUIs enabled interactive and discretionary use of computers by non-specialists, typically in a work setting. HCI researchers who were tasked to optimise the new interfaces, started to require an understanding of both the machine and the mind. Drawing from psychology and cognitive science, their focus shifted from the body to the mind, from human factors to human actors (Bannon, 1991). While the research rhetoric remained emotionally neutral, true experimental methods of inquiry were complemented with more qualitative ones. The importance of context was discovered during this time, and more proactive methods, such as participatory design, prototyping and contextual inquiries, started to emerge (Bødker, 2006).

With the growth of communication networks and the full emergence of the web, the third wave began. In response to the spread of mobile phones, web-based tools like blogs and wikis, and social networking, HCI researchers became interested in digitally-mediated communication. Drawing from disciplines like anthropology and sociology, they started to reflect on the social and emotional aspects of these interactions (Bødker, 2006). The rise of ubiquitous computing brought with it another layer of complexity and fundamentally changed the role of computers, which became far more than the cognition aids they used to be. Digital technologies spread from the workplace to people’s homes and everyday lives (Bødker, 2015). In response, researchers began to stress previously marginalised matters like culture and values, to study a multitude of contexts outside of the workplace and to add wicked problems, including inequalities and climate change, to the research agenda. The objectivist standpoints of the first and second waves gave way to social-constructivist and phenomenological approaches, which acknowledge the existence of multiple subjective realities, biases and the researchers' influence over participants.

2.3.2 Sustainable HCI (SHCI)

Since two foundational publications, i.e., E. Blevis, 2007; Mankoff et al., 2007, were presented at CHI 2007, SHCI has grown into an important subfield of HCI. Driven by the aim to limit environmental consequences related to computing technology and to use computing to help effect pro-environmental behaviours, its research is situated at the intersection of technology, its users and topics like energy, resource consumption and recycling. A widely adopted distinction between two key orientations in the field comes from Mankoff et al., 2007: while the goal of sustainability *in* design is to mitigate the material effects of software and/or hardware, sustainability *through* design targets unsustainable user behaviour and decision-making. From the outset, SHCI has mainly focused on environmental sustainability, as opposed to social and economic sustainability, with climate change, pollution and resource depletion as key motivators (Goodman, 2009). This can also be seen in a 2021 review paper, which mapped SHCI research to the United Nations (UN) Sustainable Development Goals (SDGs): out of the 51 SHCI papers mapped onto the SDGs, more than 80% were linked to SDG 12 "Responsible consumption and production" (Hansson, Cerratto Pargman, and D. Pargman, 2021).

In 2010, three years after the emergence of SHCI, DiSalvo, Sengers, and Brynjarsdóttir, 2010 published a seminal paper that mapped the SHCI literature. They found that persuasive technology accounted for about 45% of their SHCI corpus, making it the most prominent genre. The included papers commonly present behaviour change systems that aim to convince their users to behave more sustainably through a number of mechanisms, ranging from implicitly contextualised to prescriptively enforced persuasion, including eco-feedback. The remaining genres were ambient awareness (about 25% of the corpus), sustainable interaction design (about 10%), formative user studies (about 15%) and pervasive and participatory sensing (about 22%); papers could fall into more than one genre. As described above, ambient awareness is closely linked to persuasive technology as it is intended to raise awareness through ambiently provided information. Sustainable interaction design encourages its audience to rethink design (outcomes) from a sustainability perspective, while formative user studies aim to uncover relevant attitudes of its users. Lastly, pervasive and participatory sensing uses sensors to capture and potentially change (problematic) environmental conditions. The mapping study shows that many of these early SHCI projects deployed digital technologies in order to challenge and change the behaviour of individual users, often with the goal of behavioural efficiency (Soden, Pathak, and Doggett, 2021; S. Liu, S. Bardzell, and J. Bardzell, 2018). The framings and definitions of sustainability within these projects still varied and, in some cases, even led to disagreements (Knowles, Bates, and M. Håkansson, 2018; Silberman, Nathan, et al., 2014). Since the publication of the review by DiSalvo, Sengers, and Brynjarsdóttir, 2010, SHCI scholars have engaged critically with these early understandings in the field and identified their limitations, which I will cover in more detail below.

2.3.3 Energy research in SHCI

Since the field's emergence around 2007, energy consumption has been an important focus in SHCI (Brynjarsdóttir et al., 2012; Froehlich, Findlater, and Landay, 2010). In 2012, Brynjarsdóttir et al., 2012 reviewed the published behaviour change research in the field and found that half of the identified papers had targeted energy consumption; of the remaining papers, half had addressed other forms of resource consumption, including water and gasoline use and printing on paper, and the other half had been concerned with e.g., sustainable transportation choices, improving indoor air quality and reducing CO_2 emissions. For eco-feedback technology the findings were similar: in 2010, 41% of eco-feedback research in HCI had targeted residential electricity consumption (Froehlich, Findlater, and Landay, 2010). Often, this involved the design of energy monitoring systems from a user perspective (Schwartz et al., 2015), which are intended to make the consumption of the abstract resource "energy" visible and understandable as feedback to the user. More recently, there has been a broadening of SHCI's design space to consider energy use in its social and economic context, and as part of social practices (Strengers, 2014; Strengers, 2011b). There have also been projects on energy justice (V. V. Jensen and R. H. Jensen, 2023), renewable energy futures (Hasselqvist et al., 2022) and one-time actions (Kvist Svangren et al., 2020). A large number of these SCHI research projects on energy consumption have focused on domestic settings, e.g., Ishihara et al., 2015; Katzeff, Nyblom, et al., 2012; Pierce and Paulos, 2012; Rasmussen et al., 2017; Costanza, Ramchurn, and Jennings, 2012; studies in non-domestic contexts, such as commercial organisations, have been much less common (Mitchell Finnigan, 2020; Foster, Lawson, Wardman, et al., 2012).

Energy savings also sometimes represent a driver for SHCI research on the interactions of occupants with automation systems, including those in buildings and smart homes, which can be characterised by limited occupant agency (R. H. Jensen, Strengers, Kjeldskov, et al., 2018). Rau et al., 2015, for example, were interested to promote energy conservation in automatic environment control; from a comfort-energy trade-off perspective, they found that occupants preferred less automation (but not manual) in energy conservation systems when they cared about comfort and more automation (but not full automation) when they cared about energy saving. The focus on occupant needs is also present in the call by Mitchell Finnigan, 2020, p. 10 *"to shift the rhetoric of smartness away from automation back towards the human, so that smart buildings can be smart for occupants, too, not just building managers."* In this context, the Human-Building Interaction (HBI) community focuses more broadly on the interactions that take place between people and the built environment, and their design implications, e.g., Alavi et al., 2019; Nembrini and Lalanne, 2017; Dalton et al., 2020.

2.4 Tensions around digital energy interventions

In fields that use empirical research methods to study (digital) energy efficiency interventions, such as SHCI, researchers have uncovered tensions regarding the use of digital energy-saving technologies. These tensions tend to exist between expectations regarding the technologies' energy-saving potential—which motivate their design and implementation—and the complexity of the real-world environments in which they are introduced that can limit their effectiveness. The following subsections describe key tensions that have been identified for digital energy efficiency interventions, which I argue deserve more attention; I explore these tensions in my thesis research.

2.4.1 Limitations of behaviour change technology

A key limitation of behaviour change technology is that it does not reliably lead to lasting behaviour change. This is likely due to the nature of the interventions rather than their digital delivery, as a review of psychology intervention studies aimed at household energy conservation succinctly summarised the same difficulties that SHCI researchers encountered a few years later: *"Interestingly, most studies focus on voluntary behavior change, by changing individual knowledge and/or perceptions rather than changing contextual factors (i.e. pay-off structure) which may determine households' behavioral decisions. [...] Information tends to result in higher knowledge levels, but not necessarily in behavioral changes or energy savings. Rewards have effectively encouraged energy conservation, but with rather short-lived effects"* (Abrahamse et al., 2005, p. 273). In the SHCI community, it was also the absence of significant and lasting behavioural changes in response to the introduction of behaviour change technology for sustainability that led to critical reflections. Hazas, Brush, and Scott, 2012, for example, describe how empirical evaluations show very limited resource savings, which are not proven to be long-lasting. Notably, the critiques extend beyond households, as getting people to change to more pro-environmental behaviour and practices in workplace environments has also been described as *"very difficult"* (Katzeff, Broms, et al., 2013).

What has been identified as an underlying problem is that in many research studies on digital interventions for energy savings, the pressures and dynamics of everyday life that inform the users' behaviour are not consistently taken into account (Strengers, 2014; Brynjarsdóttir et al., 2012). This includes both domestic and non-domestic contexts, where occupants' aims and practices include those related to e.g., work and family life—which can stand in conflict to the rational, energy-efficient behaviour expected of them. A particular obstacle is the "nonnegotiability" of such energy-consuming interactions and practices; a term used by Strengers, 2008 in the context of in-home feedback systems, which links to the work on "inconspicuous consumption" by Shove, 2003 (Pierce, Fan, et al., 2010). This means that e.g., residential energy feedback systems can *"[...] actually work against intended goals such as reducing consumption, as well as against other goals of sustainability"*, which should be considered by designers and researchers (Pierce, Fan, et al., 2010, p. 247). But even when behaviour change technology is able to change practices on an individual level, researchers have argued that this will not lead to sustainability on a societal and structural level (Joshi and T. C. Pargman, 2015; Brynjarsdóttir et al., 2012).

Another limitation regarding the use of behaviour change technology in buildings is that even its theoretical saving potential appears limited. An analysis of over 1600 households' electricity consumption led the authors to conclude that weather and physical characteristics of the building influence residential electricity consumption much more strongly than other categories such as occupant behaviour (Kavousian, Rajagopal, and M. Fischer, 2013). This aligns with previous research that shows that building characteristics determine around 42% of the variability in residential electricity consumption, while occupant behaviour explains around 4% (Santin, Itard, and Visscher, 2009). A more recent literature review produced higher estimates of the energy-saving potential of occupant behaviour—10%–25% for residential buildings and 5%–30% for commercial buildings—while acknowledging that *"[a] significant shortcoming of occupant behavior research is that there are few data on behavior profiles and energy use in real-world buildings"* (Y. Zhang et al., 2018, p. 290). Those estimates would thus need to be empirically validated, which given the influence of real-world factors might lead to different results. In fact, the so-called energy performance gap between energy-saving predictions and real-world assessments in buildings is well-established (Gram-Hanssen and Georg, 2018).

2.4.2 Simplistic efficiency visions of automation

Due to a number of issues, the automation approach to energy efficiency is not always effective either. In workplaces, such issues that confound attempts to save energy include *"the scattered knowledge of context of consumption; the ever-evolving nature of workplace architecture, layouts, occupancy and infrastructure; political tensions* *around hierarchy and organisational change; and the difficulty of communication across organisations"* (Bedwell, Costanza, and Jewell, 2016, p. 1338). In the study by Bedwell, Costanza, and Jewell, 2016 of energy consumption and management in the workplace of a district council, the participants also raised a lack of control, and the authors noted numerous adjustments to circumvent systems and policies by participants to regain control over their environments. A similar pattern could be observed in a study on users' experiences of living with an advanced thermostat, the Nest, which makes use of machine learning, sensing and networking technology, as well as eco-feedback features. In particular the intelligent features of the Nest were not perceived to be as useful or intuitive as expected, and a number of participants developed workarounds for the shortcomings they encountered (R. Yang and Newman, 2013). This can help explain why in a large-scale study of 1628 households' electricity consumption *"[s]ome otherwise energy-efficient features such as energy-efficient appliances, programmable thermostats, and insulation were correlated with slight increase in electricity consumption"* (Kavousian, Rajagopal, and M. Fischer, 2013, p. 184).

Realising the energy-saving potential of smart homes can be particularly challenging: Darby, 2018 points out the scarce number of evaluations under real-world settings in favour of simulations and evaluations under controlled laboratory conditions. This imbalance can be problematic and contribute to the well-documented energy performance gap between energy saving predictions and real-world assessments (Gram-Hanssen and Georg, 2018) due to e.g., contextual factors, building and installation design parameters, and occupant behaviour not being taken into account (Van Thillo, Verbeke, and Audenaert, 2022). This is supported by findings from a 2018 study of SHT in the real world: based on a 9-month field project with ten UK households, it was found that the technology can lead to an overall *energy intensification* through, e.g., increased comfort expectations and pre-warming of domestic spaces (Hargreaves, Wilson, and Hauxwell-Baldwin, 2018b). Tirado Herrero, Nicholls, and Strengers, 2018, p. 65 argue that *"[i]n contrast to aspirational claims for a 'smart utopia' of greener, less energy intensive, and more comfortable homes [...] SHTs [smart home technologies] may reinforce unsustainable energy consumption patterns in the residential sector [...]."*

The HCI community specifically has a longstanding record of work that talks in nuanced ways about how smart homes can undermine energy savings by introducing new lifestyle expectations and changing behaviours. This includes the identification of socio-technical challenges around the integration of new technologies into everyday routines and practices (Costanza, J. E. Fischer, et al., 2014; Jakobi et al., 2017) and the often energy-intensive visions for smart homes. Commonly associated with concepts such as desirability, convenience (including effortless energy savings) and control, these factors can undermine the sustainability promises of smart homes (R. H. Jensen, Strengers, Raptis, et al., 2018; Strengers, Hazas, et al., 2020; R. H. Jensen, Strengers, Kjeldskov, et al., 2018). Gendered and cultural expectations (Strengers, Kennedy, et al., 2019; Dankwa, 2020) and individual preferences (R. H. Jensen, Strengers, Kjeldskov, et al., 2018) add another layer of complexity but are not consistently acknowledged. As Strengers, 2014 points out, many studies on smart energy and technology have focused on design for "resource man", a simplistic persona of a male technology-savvy energy consumer who makes rational decisions about energy use. These studies tend to overlook many of the social activities, domestic dynamics and routines which entail the consumption of energy, but which are still predominantly performed by women. They also tend to neglect the implications, such as new household expectations, that arise from the introduction of smart systems and devices.

2.4.3 Rebound effects

Even when digital energy-saving interventions are initially successful, they can trigger "rebound effects", which can reduce the savings and even lead to a consumption *increase*. Rebound effects are a class of mechanisms that occur when products or services become easier to access or more attractive, leading to their increased demand, therefore their increased consumption and production, and ultimately increased energy consumption, material consumption and GHG emissions. This can explain why, e.g., in developed countries, energy efficiency leads to an increase in per capita emissions (Nishant, Teo, and Goh, 2014). The first mechanism that led to rebound effects was described in 1865 by British economist William S. Jevons. In his book *The Coal Question*, Jevons, 1865 observed that although coal extraction was becoming increasingly more energy efficient overall more, not less, energy was used in coal extraction. The efficiency gains of coal extraction were having unintended consequences: by making coal more affordable, they were making it attractive for a growing number of applications and customers, while also making the process of coal extraction more scalable. It should be noted that such scalability and increasing affordability of resources can be a desirable outcome from e.g., a social perspective, as it allows less economically privileged groups access to these resources (Galvin, 2015). However, in line with the energy consumption focus in my thesis, I will discuss rebound effects solely from an environmental perspective.

Direct rebound and backfire

The rebound effect that increases the attractiveness of the specific good that has been more efficiently produced is today often referred to as "direct rebound effect" (Coroamă and Mattern, 2019). While it did not receive much attention in the century after Jevons' publication, Khazzoom, 1980 brought back to scientific scrutiny.

Neither Jevons nor Khazzoom coined the term “rebound effect”, which started to be widely used around the year 2000, e.g., Greening, Greene, and Difiglio, 2000; Saunders, 2000; P. H. G. Berkhout, Muskens, and Velthuijsen, 2000. Rebound effects are generally expressed in relation to the direct savings that initially triggered them: when smaller than 100%, rebound effects reduce these savings, but there is still an overall resource reduction; when they reach 100%, they fully compensate the initial savings; and when they are larger than 100%, they outweigh them. In many instances, rebound effects do indeed reach 100% or more. For electric lighting, for example, a large-scale study came to the conclusion that *“global energy use for lighting has experienced 100% rebound over 300 years, six continents, and five technologies”* (Saunders, Tsao, et al., 2012, p. 477), (Tsao et al., 2010).

According to their empirical observations, both Jevons, 1865 and Khazzoom, 1980 postulated the size of rebound effects to always be larger than the original savings, which means that they do not only reduce but outweigh these savings. As noted by Alcott, 2005 and Sorrell, 2009, “postulate” is the correct term in this context, as there is not enough evidence to support the claim that rebound effects consistently exceed 100%; increasing evidence points to examples where they do not (Gillingham et al., 2013). The particular case in which efficiency gains paradoxically lead to an overall consumption increase is thus known in the literature as the “Jevons paradox” (Alcott, 2005) or “backfire” (Khazzoom, 1980). To reflect another economist’s (Len Brookes) contributions to the topic, backfire has also been referred to as the “Khazzoom-Brookes postulate” (Saunders, 1992).

Indirect and structural rebound

Efficiency gains and associated price reductions can have consequences beyond the increase in demand for the specific good that is being more efficiently produced. Monetary savings from the more efficient production of a product or service can for example be spent on other energy-consuming and resource-consuming activities; this is known as “income effect” (P. H. G. Berkhout, Muskens, and Velthuijsen, 2000). In addition, a lower price makes a product relatively more affordable than other, similar products, which it might then partly substitute—a phenomenon known as “substitution effect”. The increased consumption can thus propagate to other goods and sectors (P. H. G. Berkhout, Muskens, and Velthuijsen, 2000), making income and substitution effects examples of what are often called “indirect rebound effects” (Coroamă and Mattern, 2019).

Energy efficiency in particular can have a stimulant effect on productivity and lead to cascading rebound effects throughout the economy. More specifically, higher productivity can lead to higher economic output, which in turn requires more (energy) inputs (Sorrell, 2009), and to various readjustments within the entire economic system.

These macroeconomic effects, which can be conceptually hard to comprehend and even harder to quantify, are referred to as "structural rebound", "macroeconomic rebound" (Barker, Dagoumas, and Rubin, 2009) or "transformational" rebound (Pohl, Hilty, and Finkbeiner, 2019; Börjesson Rivera, C. Håkansson, et al., 2014); they are often included in the larger category of "systemic transformations" brought about by digitalisation (Williams, 2011).

Beyond efficiency gains (and the energy or material savings they entail), other types of savings can also represent the trigger for rebound effects. In particular, rebound effects can emerge as a consequence of decreased transaction costs (i.e., monetary or non-monetary costs to obtain a product, evaluate it, and general market information), due to time savings (Binswanger, 2001) or even due to the lowered barrier to performing an activity such as driving a car (Coroamă and D. Pargman, 2020); the latter two yielding "time rebound" and "skill rebound" respectively. Given this variety of subtle effects and influence mechanisms, there is no generally agreed-upon taxonomy for indirect rebound effects. What distinguishes them from direct rebound effects is that the consumption increase occurs either for different products, instead of the product that was initially more efficiently produced, or through other means, such as time or transaction costs savings, rather than as a consequence of price reductions (Coroamă and D. Pargman, 2020).

2.5 Motivation

The thesis explores the role of digital interventions in realising energy savings by investigating the tensions that arise between expectations and outcomes in practice. More specifically, I am interested to understand the narratives of these interventions and of their potential among experts and research communities, and how these experts and research communities engage with and evaluate factors that can impact the interventions' effectiveness. Rebound effects, for example, have been established outside of HCI and computing but could significantly affect the outcomes of research in these fields.

In the field of SHCI, published critiques have already challenged the use of behaviour change technology, e.g., Hazas, Brush, and Scott, 2012; Ganglbauer, Reitberger, and Fitzpatrick, 2013; Joshi and T. C. Pargman, 2015. Being potentially one step ahead of the more technically-oriented research communities when it comes to empirical evaluations and reflections, analysing the SHCI literature presents a unique opportunity to understand their conclusions: has the SHCI community found strategies to resolve or bypass the tensions it uncovered? By focusing on the tensions between expectations and outcomes, my thesis can help to better understand when and how digital interventions can effectively realise energy savings.

Chapter 3

Methodology and study context

To explore the role of digital interventions in realising energy savings, I have opted for a mixed-methods approach that combines quantitative and qualitative research methods, including systematic literature reviews. Quantitative calculations were chosen to provide bounded estimates for the potential of the interventions. Qualitative studies enabled a contextualisation of the gathered data, capturing narratives and experiences around them. The literature reviews further complement these methods as they allowed for a systemic evaluation of how relevant concepts, trends and limitations have been considered, discussed and responded to by other researchers. In this chapter, I will first present the Lancaster University Bailrigg campus that I used as a case study environment for the empirical part of my thesis research and justify the mixed-method approach more thoroughly. I will then describe my research methods in more detail, present the energy data that I have used for my calculations and outline the recruitment process for my qualitative studies. The chapter concludes with a summary of how the described methods are distributed across the research studies that constitute the thesis.

3.1 The Lancaster University campus

I have been conducting the empirical part of my research on Lancaster University's Bailrigg campus, which had been previously used for "living laboratory" research on sustainable energy consumption (Bates and Friday, 2017); these studies form the basis of Chapters 4 and 5. The University is a medium-sized campus university in England, United Kingdom (UK), i.e., the University is situated on one site and contains student accommodation, teaching and research facilities, leisure and businesses all together on this site. Reflecting this diversity, some but not all of the buildings on campus are mixed-use (e.g., a single building may contain small businesses, offices and flats). The official "teaching term" times for students run from October until June, with short breaks in winter and spring. As there is no teaching during the summer break, a majority of the undergraduate students who usually live on campus leave, although postgraduate students and some international students may remain. During the COVID-19 pandemic, many campus buildings were closed. However, parts of the campus needed to be kept open as some of the students who lived on campus stayed in their accommodation (e.g., as they could not travel home). Some of the non-residential campus buildings could be accessed through a sign-up system. As relevant from an energy consumption perspective, the climate in the UK is defined as a humid temperate oceanic climate. This means that both summers and winters are relatively mild, usually within the range of 0°C to 25°C; extreme temperatures are rare—though as everywhere globally, once rare exceptional weather events are becoming more frequent.

The energy consumption on campus and related data are recorded in several data sets, which can be accessed through an Energy Information System (EIS). This system contains data sets from a Building Management System (BMS) for building management/control data and an Energy Monitoring System (EMS) for energy monitoring data; data from more modern energy meters is stored in a separate data set called *Synetica*. The EMS and Synetica data sets contain data from building main meters and individual floor-level and room-level meters with typically half-hourly resolution, which can be used to calculate and visualise the energy consumption for different buildings and spaces on campus over time. Newer campus buildings tend to have a more fine-grained metering systems than older campus buildings. In addition, the EIS contains room booking data, wind turbine energy production data, WiFi association data and descriptive information about the campus buildings, data loggers and sensors. These data sets are stored separately, although past projects have targeted the (automatic) combined use of data sets. Due to e.g., changes in metering systems and digital infrastructures over several decades, and periodic faults with meters, the EIS data are complex and contain gaps and errors. The data can also be difficult to understand (due to e.g., missing contextual data, unclear labelling and the need to manually cross-reference multiple data sets) and to handle (due to the size of the data sets).

3.2 Triangulation of methods in HCI

Mixed-method approaches are well-established in the research field of Human-Computer Interaction (HCI), in which my thesis research is mostly situated. To understand the benefits of triangulation in HCI research, the Development Oriented Triangulation (DOT) framework provides relevant groundwork. Created in 2013, the framework clusters available methods and outlines their strengths and necessary trade-offs (van Turnhout et al., 2013). It can be used to identify effective combinations of methods for a research problem (Turnhout et al., 2014). Focused on the *potential* of technology rather than the design of concrete artifacts, I argue that the DOT framework can still effectively be applied to my thesis research. More specifically, the framework is organised along three central trade-offs in HCI research, which can be addressed through triangulation (van Turnhout et al., 2013):

1. **Rigour or relevance**. This trade-off distinguishes between contribution to a concrete application domain versus available research: The former is addressed through relevance-focused research, when *"a researcher learns about and tries to improve an application domain (e.g., work practices in a hospital)"* (van Turnhout et al., 2013, p. 2). The latter is addressed in rigour-focused research, when *"the researcher learns from existing work (e.g., related solutions) and contributes new work (e.g., a novel approach to the problem)"* (van Turnhout et al., 2013, p. 2). Having arisen in a design research context, the trade-off applies to my research, however, without the aim to directly improve an application domain. Instead, I am using qualitative "field work" and quantitative "lab work" to get a complete understanding of the application domain, i.e., energy consumption and energy-saving interventions on Lancaster University's Bailrigg campus (relevance), and "library work", i.e., literature reviews, to obtain a complete picture of available work that is relevant to my research problem (rigour).

2. **Certainty or completeness**. This trade-off distinguishes between the concerns for precision of measurement (certainty) versus the system character of context (completeness). In order to cover both, my thesis research combines energy consumption calculations as a type of "lab work" with methods that help me understand the research context and contextualise the quantitative findings ("field work" and "library work"). It is thereby leaning more heavily towards completeness as a methodological choice to holistically explore the role of digital interventions for energy savings.

3. **Inspiration or data**. The last trade-off can be regarded as a pragmatic version of the prominent debate between positivism and phenomenology. While the aim of the former is to *"discover regularities in the objective reality through the scientific method"*, the latter includes studying *"the subjective experience of the researcher"* (van Turnhout et al., 2013, p. 3). For HCI research, this means that the researcher can either be seen as an active, reflexive participant who organises their work to strengthen their personal intuition (inspiration) or as someone who takes the role of a neutral observer (data). According to van Turnhout et al., 2013, p. 3, *"[i]n the long run most HCI projects require moments of personal researcher involvement and more distanced approaches, which makes*

triangulation desirable." In my thesis research, the qualitative methods, e.g., semi-structure interviews, rely on my active participation and have helped me gain an understanding of the campus energy context, which I used for the design of subsequent research (inspiration). The energy data analysis and literature reviews, however, were primarily designed with the intention to obtain replicable results independent of myself as the person who carried out the analysis (data).

3.3 Quantitative data

In order to quantify the energy consumption on campus and explore the energy-saving potential of digital interventions, I used campus-level and building-level electricity data from the EIS. Based on figures from February 2023 (Lancaster University, 2023), the University's annual electricity consumption is approximately 34,000,000 kWh, of which 55% are generated on campus (15% by the wind turbine and 40% by a Combined Heat and Power (CHP) engine); the remainder of the consumed electricity is sourced from the National Grid. This figure includes e.g., lighting, ventilation and operation of devices, servers and electrical building systems on campus, but excludes most of the heating.

1. **Campus-level data**. I obtained hourly campus-level electricity data for the time period 01/2016–01/2021 from the campus's energy manager who had compiled it from the EIS and the energy supplier. The data was visualised as line graphs, so it could be presented to and discussed by experts (see Chapter 5). Through informal communication, I learned that at least some of the values in the data set that appear to be unusually low or high are likely accurate. The energy manager explained that there exist three typical reasons for very low consumption values: (a) the University generates more electricity than it consumes so (close to) zero consumption can mean that the University has exported electricity; this is what the energy manager considered to be the most likely reason. Unfortunately, the exported power was not yet consistently measured during the time period I analysed due to missing meters (all available electricity export data has been factored in); (b) the occurrence of power cuts; and (c) data issues. The spikes in the data are more likely to represent inaccurate values: according to the energy manager, the campus's import capacity is roughly 8.5 Megawatts (MW), so they would expect its real consumption to be below 7.5 MW at any given time.

2. **Building-level data**. The building-level electricity data I used was obtained from the Synetica data set. The data had a measurement frequency of 10 minutes, which in its original form did not allow for a meaningful comparison

between the electricity consumption of campus buildings over longer time periods. For that reason, the data points for each day were summed up to create an aggregate value; zero values and data points that were seven times higher than the median value for each day were considered outliers and excluded from the aggregation. The data was visualised in the form of violin plots, which show the distribution of numerical data and allow for a comparison between data sets (see Section 5.3 for a detailed description of violin plots). In my case, this comparison was between years and thus phases of the COVID-19 pandemic (see Chapter 5).

3.4 Qualitative data

Especially since the beginning of the so-called third wave of HCI, qualitative research has played a prominent role in HCI research (Bødker, 2006) (see Section 2.3.1 for a detailed summary of the methodological developments in HCI). Many social and socio-technical phenomena cannot be easily quantified and require descriptions that are more nuanced. In addition, qualitative data can usefully complement and contextualise quantitative data (Clear, Mitchell Finnigan, et al., 2017; Widdicks, Bates, et al., 2017; Bates, Hazas, et al., 2014 provide examples of this in energy-focused Sustainable Human-Computer Interaction (SHCI) research). In this thesis, I use the following three types of qualitative data, each for a distinct purpose:

1. **Semi-structured interviews**. I chose semi-structured interviews as a method in my initial study (which was officially called *Human Context of Sensor Data Baseline Study* in the ethics approval document, participants consent form and participant information sheet) to capture the narratives and perspectives among experts regarding the role of digital interventions for energy savings, both on campus and more generally. Originating in the social sciences, storied and narrative-centred approaches have also commonly been used in HCI research (Golsteijn and Wright, 2013; Dourish, 2006; Tanenbaum, 2014). This is linked to the concept of "world making" through narrative by Bruner, 1987, i.e., the idea that people use stories to construct meaning and make sense of the world around them. In line with the argument by Golsteijn and Wright, 2013 that *"[...] narrative research is particularly useful for exploratory research projects, which seek to engage with experience and meaning-making processes of diverse individuals or groups"*, I focused on narratives in my interviews to capture how the expert participants understand and interpret energy-saving strategies and their key elements; the aim was not to look for an "objective truth". In addition, I used the interviews to gain a better understanding of the energy systems on campus and become aware of relevant initiatives and projects in order to guide

subsequent research. The semi-structured approach allowed me to adapt the focus of each interview slightly, in line with the participant's area of expertise, but to keep it structured enough to cover all relevant questions in each interview. An example protocol that I had prepared for one of the interviews can be seen in Appendix C.

2. **Jamboard study**. The Jamboard study was named after the platform on which is was conducted: Google Jamboard, which is a collaborative digital whiteboard tool. Users can create slide decks, similar to PowerPoint presentations, and share them with collaborators, who can edit the slides (by e.g., adding notes and comments). I used the Jamboard study for the contextualisation of graphs that show the electricity consumption of the University campus before and during the COVID-19 pandemic in order to better understand the energy-saving potential of digital interventions and the factors that limit it (see Chapter 5). Inviting experts to comment on the graphs and answer a related set of questions, the Jamboard platform enabled them to do this in their own time rather than to coordinate a time slot that was suitable for all participants.

3. **Focus group interview**. The focus group interview built on the Jamboard study by enabling a more detailed discussion about energy consumption on campus (before, after and during the COVID-19 pandemic), including energy-saving strategies, their potential and limiting factors. With different backgrounds and areas of expertise, the expert participants were able to comment on and add to each other's statements and suggestions. Their diversity of responses also provided me with additional details on the concepts and viewpoints that were mentioned in the Jamboard study.

3.4.1 Recruitment

All participants who feature in this thesis have expertise related to the topics of energy consumption and were affiliated with Lancaster University at the time when my research took place. Some but not all of the participants have actively investigated the energy consumption on campus and implemented energy-saving measures, including digital interventions. An overview of the participants, their areas of expertise and participation across studies can be found in Table 3.1. The expert participants' job titles are not listed in the table to ensure anonymity. The recruitment process for the different research studies was as follows:

- **Semi-structured interviews**. For the semi-structured interviews, I recruited 11 participants via email; they were selected based on their energy-related work experience and knowledge. Beginning with personal recommendations from within my research group, I subsequently asked participants who agreed to be interviewed if they could recommend other potential interviewees who could also contribute to the topic of my research. At the time of the interviews, all participants were affiliated with the University and familiar with its Bailrigg campus. The participant information sheet that was sent to the participants as part of the recruitment process and the consent form they signed before participating in the study can be found in Appendix A and Appendix B respectively.

- **Jamboard study and focus group interview**. For this study, the procedure was similar: I contacted experts based on their role and their energy-related work experience and knowledge; recommendations from both the semi-structured interviews and within my research group led to me to create an initial list of potential participants. After four participants had agreed to take part in the study and completed the Jamboard annotations, I invited them to the focus group interview, which two were able to join; a third participant was recruited for the focus group interview based on a recommendation by another participant. The participant information sheet and consent form for both parts of the study are included in Appendix D and Appendix E respectively.

3.5 Literature reviews

While the Lancaster University campus offered a relevant and accessible research environment, its energy data and the campus-based experts who worked on the topic of energy could only provide context-specific insights. To complement the quantitative and qualitative data described above, the initial plan was to conduct additional empirical studies, e.g., with non-expert campus users or on other university campuses. However, due to the COVID-19 pandemic, this plan could not be realised. Instead, I decided to use literature reviews to increase the data pool for my analysis. In line with the different aims of Chapters 6 and 7, I conducted two different types of literature reviews: Chapter 6 presents a systematic mapping study while Chapter 7 is based on two complementary targeted literature reviews. Together, they constitute the “library work” (van Turnhout et al., 2013) component of my thesis.

A systematic mapping study is a form of literature review that focuses on structuring a research area rather than on gathering and synthesising all published evidence (Petersen, Feldt, et al., 2008; Petersen, Vakkalanka, and Kuzniarz, 2015). Mapping studies are often useful to identify trends and opportunities for research that spans multiple fields, which matches my research aim in Chapter 6 to establish the prevalence of rebound effect considerations in energy efficiency research. With

Participant	**Expertise**	**Interview study**	**Jamboard study**	**Focus group**
E1	Energy research, energy systems, energy transitions	X		
E2	Energy system control and automation, building control	X		
E3	Energy research, digital sustainability research, design of energy systems	X		
E4	Energy research, energy policies, energy geographies	X		
E5	Development of infrastructure systems, building management and maintenance	X		
E6	Energy research, climate policies, climate modelling	X		
E7	Energy research, environmental design, research on the built environment	X		
E8	Architectural research, design of buildings, human-building interaction	X		
E9	Campus policies, energy research, urban infrastructures	X		
E10	Energy services, building operation and management, stakeholder engagement	X		
E11	Energy procurement, design of energy systems, stakeholder engagement	X	X	
E12	Building development, project management and delivery		X	X
E13	Energy and environmental management, building operation and maintenance		X	X
E14	Environmental management, impact assessments, sustainability interventions		X	
E15	Energy procurement, accounting			X

Table 3.1: Overview of expert participants, including their areas of expertise and participation across studies.

the emphasis on literature classification and identification of research gaps, mapping studies do not usually include a detailed analysis of all included publications; in my research for Chapter 6, I only carried out such an analysis for a small selected subset of articles.

In comparison, systematic reviews are focused on gathering and synthesizing evidence (Kitchenham et al., 2009), which enables the aggregation and comparison of findings across different studies. As the evaluation and quality assessment of the identified publications is a key focus, the depth and thus the effort required for a systematic review is larger than for mapping studies; this usually means that fewer studies are included in the review (Petersen, Feldt, et al., 2008). For the research I present in Chapter 7, the inclusion criteria were detailed and specific as the main research insights (regarding SHCI researchers' calls for changes in the field and their implementation) were obtained from qualitative analysis of *all* publications that were part of the two created corpora.

3.6 Data analysis

This section outlines the methodological approach taken to analyse the collected data described above.

- **Statistical analysis**. While there had been initiatives to create a dashboard that would allow users to reliably query a database with campus-level and building-level energy data, no such dashboard existed at the time of my research. Instead, the data was stored across different systems and databases; some of the data could be downloaded in the form of (very large) Excel spreadsheets. For my studies, I was able to overcome this difficulty by (a) obtaining campus-level data directly from the energy manager and (b) using and adapting existing Python scripts that were designed to obtain and visualise building-level data. The analysis of the obtained data was conducted manually, using R scripts and Excel spreadsheets. While automated approaches, such as change point analysis, could be applied to the data as future work, they were not part of my thesis research, which used a bottom-up approach alongside an analysis of the COVID-19 restriction timeline; the calculations are described in more detail in Chapter 5.

- **Thematic analysis**. The thematic analysis was applied to relevant publications that were identified as part of the literature review in Chapter 7, to the open-ended responses from the Jamboard study and to the transcripts from the semi-structured interviews and the focus group interview; the (clean verbatim) transcripts were created from either audio recordings (first six semi-structured interviews) or Microsoft Teams recordings (latter five semi-structured interviews and the focus group interview, which were conducted online after the onset of the COVID-19 pandemic). For the thematic analysis, I used a mostly bottom-up approach, similar to the one outlined in Braun and Clarke, 2006. This included the following steps: (a) transcription, if necessary, and familiarisation with the data; (b) highlighting and coding interesting passages across the data set; (c) collating the codes into potential themes; (d) iteratively refining the themes, their descriptions and how they relate to each other; and (e) a write-up of the analysis, including the selection of relevant quotes, with reference back to the research questions and analysis of the existing literature.

3.7 Roadmap

Across the following four chapters, which present my thesis research, the described methods have been applied as follows: For the study in **Chapter 4**, semi-structured interviews were used to capture the views of campus-based experts on digital energy-saving strategies and its key elements, including the role of building design, occupants and energy system automation. The research in **Chapter 5** also used the campus as a case study environment, this time with a focus on energy data and quantifications of energy consumption. As digital energy-saving interventions tend to target operational energy, the COVID-19 pandemic—during which buildings were largely unoccupied—presented a unique research opportunity to assess their potential. After establishing the baseload and consumption estimates, the Jamboard study and focus group interview were used to contextualise the findings and explore real-world factors that limit the estimated potential. Together, the two chapters form the empirical part of my research. They are complemented by the literature reviews in **Chapter 6** and **Chapter 7**. While Chapter 6 focuses on rebound effects as a socio-technical phenomenon that can be triggered by digital efficiency interventions, Chapter 7 targets digital behaviour change interventions and analyses by SHCI researchers on how to overcome the limitations of these interventions. What ties all four chapters together is that their HCI-informed research helps better understand the role of digital interventions for energy savings by exploring the potential tension between the narratives of these interventions, estimates of their energy-saving potential and complexity of real-world environments.

Chapter 4

Expert perspectives on key elements and strategies for energy savings

The contributions of this chapter are fully my own.

Digital interventions for energy savings share a number of elements that need to be considered in their design and affect their outcomes, namely the use of energy data, either manual or automatic; the interaction with building occupants (or users more generally); and the tailoring to the existing digital (building) infrastructure. Understanding how these elements and interventions are perceived and evaluated by experts provides an important foundation for subsequent research. In order to obtain this understanding, I opted to interview experts on energy use and systems from Lancaster University's Bailrigg campus, a setting that was accessible to me and that had a history of relevant energy-saving interventions and research projects, many of them related to the Energy Information System (EIS). This allowed me to hear about the motivation for and outcomes of these interventions and projects, as well as about the experts' perspectives on the different elements and digital energy-saving strategies more broadly (as described in Section 3.4, the aim of the study was to capture how the experts understand and interpret these elements and strategies rather than to look for an objective truth). While all participants had expertise regarding energy use, their areas of expertise were to some extent overlapping but also complementary, covering e.g., technical, behavioural and financial aspects. I refer to the interview participants as experts based on this accumulated knowledge; it should however be noted that their interpretations were shaped by their personal experiences and environments and do not necessarily reflect an objective reality.

In this chapter, I present the findings from eleven expert interviews, with a particular focus on the abovementioned elements, their role in past and current interventions and their potential to enable more energy savings in the future. The development of and vision for the EIS featured prominently in some of the interviews and are explicitly discussed in the section on automation and the use of data. The content of all three sections, namely, the intervention space, the role of energy system automation and the role of building occupants, highlights common narratives among the experts, key learnings from past projects, open questions and challenges. Based on this content, I conclude the chapter with a discussion on the most relevant findings, both for the studies I present in the subsequent three chapters and with regard to the role of digital technologies for energy savings.

4.1 Methods

To capture the perspectives and knowledge of campus-based experts on energy consumption and digital energy-saving strategies, including the role of automation, data, occupants, building design and digital infrastructure, I conducted eleven semi-structured interviews.

4.1.1 Semi-structured interviews

I interviewed each of the eleven expert participants individually (one-to-one) between July 2019 and June 2021. The first six interviews (P1–P5 and P11) were conducted in person on campus, while the latter five (P6–P10) were conducted online via Microsoft Teams (due to COVID-19 restrictions). Each interview was audio-recorded and lasted between 25 and 80 minutes. While some of the questions I posed remained the same in each interview, some were tailored to each participant's role and expertise or emerged freely during the conversation. The general themes across interviews were the following: (a) the potential of digital technologies for energy savings, covering both computational optimisation/automation and behaviour change approaches; (b) the role of data; (c) the role of building occupants; and (d) the impact of building design and infrastructures on energy consumption. To gain a better understanding of the energy systems on campus, I asked some of the participants with relevant knowledge to create and explain sketches of these systems during the interviews. After the interviews had ended, I transcribed the recordings and openly coded for themes across participants (see Section 3.6 for details).

4.1.2 Limitations

As all expert participants were affiliated with Lancaster University when I conducted the interviews, it is likely that their perspectives on energy consumption and (digital) energy-saving strategies have been shaped by their experiences on campus. While their common affiliation has allowed me to explore the campus as a case study environment in significant depth, features of its energy systems and buildings that are not representative of such environments may have collectively shaped the participants' perspectives on the topic. In addition, the variation in the participants' professional roles and thus their expertise—while all related to energy systems and consumption—means that I was not able to cover all subtopics with all participants in similar depth. None of these limitations should threaten the validity of my findings.

4.2 The intervention space

In the following three sections, I present the findings from the expert interviews I conducted, starting with those that capture the intervention space. More specifically, I use this section to summarise what according to the expert participants has been the underlying motivation for digital energy-saving interventions in buildings and describe the challenges that these interventions would need to successfully address in order to be effective; the two subsequent sections focus on the role of energy system automation and building occupants in the context of these interventions.

4.2.1 Building design as a key problem

Seven of the interviewed experts identify poor building design as a key problem for energy savings (E1, E5, E6, E7, E8, E10, E11). E11 explained that *"the buildings aren't particularly well designed [...]. They are not very energy efficient. They require a lot of active systems, heating or cooling, to keep them comfortable, or ventilation."* One of the reasons for this problem was described as the tendency of consultants to re-use specifications of previous buildings rather than to design a new building *"properly"* (E5). In addition, the experts criticise the building regulations and standards in the UK, which are not as tight and close to passive house standards as they should be (E5, E6, E10) due to lobbying efforts by contractors (E5). The experts thus call for a re-evaluation and improvements of these standards, including insulation standards, to align them better with those in Germany (E6) and Scandinavia (E8). Regardless of the reasons for their design, the experts agree that buildings need to change and that it is right to focus on them from an energy perspective: Buildings are *"really important"* (E6) and *"[w]hatever the targets anybody sets, the housing and building stock has got to be improved dramatically"* (E5). As a lot of energy consumption inherently depends on the buildings (E1), *"better design could make them more comfortable [...] and therefore minimise* energy consumption" (E11). In other words, a key measure to save energy will be to reduce the energy requirements of buildings (E5, E7).

One particular strategy to make existing buildings better are refurbishments (E5, E7, E8), which would allow for improvements to the buildings' air-tightness (E5, E8).

What needs to be kept in mind is that full air-tightness can cause problems with mold and condensation in very old buildings, so according to E8, the right balance needs to be found. What increases the importance of refurbishments is that *"so much building stock [...] is already here. So looking at new buildings, it's just a tiny proportion of all the buildings that exist. So mostly we have old buildings and particularly if you look at houses as well. [...] I think this is a massive problem we have to tackle. It's much easier to figure out how to design a new energy-efficient passive house"* (E8). Besides the technical challenges, E7 points out that refurbishments depend to a large extent on the availability of funding.

While the building design for new buildings is constantly moving towards greater levels of efficiency (E10), and new buildings allow for innovation around key materials, e.g., avoiding concrete and steel (E9), they are not necessarily an easy solution either. E9 emphasises that it is important to question whether new buildings are always needed or if it is possible to remodel, reuse or repurpose existing spaces. An increase in small meeting rooms for example could prevent small groups from using large spaces and thus save energy (E5). Another problem is that decision-makers cannot know *"what new technologies will come along in the next ten years that [they] should then be adopting that [they] haven't adopted yet"* (E10). E9 explained: *"You could develop today a carbon zero building on campus, but it will cost you a lot of money, and some of the technologies and approaches you use may well be out of date in ten years time and you might do it quite differently."* Building new buildings that are not net zero compatible would then mean to get locked into building structures for 80 years that are not fit for purpose (E6); a scenario the University has already experienced with its new Health Innovation Campus, which was argued is not *"fit for purpose"* (E6) with poor levels of air-tightness (E5). For this reason, E9 advises not to rush decisions for new buildings, which might soon backfire in this fast-changing area.

The current design and operation of buildings is argued to have a profound consequence: high energy consumption independent of the buildings' occupancy (E1, E6, E7, E9, E10). According to E10, a common misconception is to assume that if no one is in a building, then the building does not use any energy—which is never the case. Office buildings in particular have a high continuous load from e.g., standby devices and security systems that cannot be turned off (E7). This is consistent with E1's report of campus buildings whose energy consumption at midnight during Christmas time is about half of what it is when they are fully occupied. In this context E6, E7, E9 and E10 commented on the impact of the COVID-19 pandemic on the energy consumption in campus buildings[1]. Most notably they commented on the high consumption during lockdown periods; E10 explained it as follows: *"Certainly last March [...] we didn't just flick the master switch and turn those buildings off. Inevitably, most buildings have frost protection on, heating, they*

---

[1] E1–E5 and E11 were interviewed before the onset of the pandemic.

have electronic systems in them that are constantly running and monitoring things, they have emergency lighting, fire detection, backup systems, server rooms, etc. that all take power." This would mean that not occupying a building for a week will not save much energy unless there is a fundamental change in the way that a building is configured (E10) and highlight the importance of systems (E9). However, according to E6, there was also a political purpose behind running campus buildings as normal during the pandemic: *"[T]hey've made every possible effort, irrespective of the cost, to try and make the University look like it's open for business."*

4.2.2 The complexity behind energy systems and use

In the context of (campus) buildings' energy consumption, the experts describe several layers of complexity that would need to be factored into and addressed by energy-saving interventions. The first layer concerns the campus and its activities as a whole, *"which is perhaps different from other kinds of built environments [...] in terms of what's being powered, the kind of life that's being powered"* (E9). Because research requires energy but also brings in money, there can be an complicated push/pull dynamic of how to use energy and prioritise things (E3). On top of that, E4 describes *"pressures to always be producing more, to have more students, to have more staff, which inevitably have an impact on energy consumption as well."* In fact, many projects that increase student satisfaction also increase energy consumption, e.g., keeping the library open during the night and installing large screens (E4). Similar to the University campus, its buildings are characterised as *"ecosystem[s] made up of the building management system and the people [...]"* (E6) with dynamic patterns of behaviour and occupancy (E8). Even within the same building e.g., thermal conditions and thus occupants behaviour can differ significantly (E7).

Energy and building management systems are complex as well (E4, E8, E10, E11), which can make it hard to navigate them (E4). Only a few people might be able to do so (E8), and E8 predicts that *"as the systems become more complex potentially [you are] going to reduce even more the people that might even be willing to interact with them"*; a trend that could pose problems. E10 reports that *"[t]here are cases over the last [...] ten years if not longer of complicated building management systems that require a lot of human intervention to control them to provide occupancy satisfaction"* while E9 is concerned that staff members do not yet have the skillset that they need to operate buildings in the future. Required knowledge about faults in existing systems adds to the complexity (E2).

On the side of the building occupants, the complexity lies in the diversity of their energy-related needs, notably thermal and comfort needs (E2, E4, E8, E9, E11). Some of these needs are attributed to e.g., the occupants' gender (E8, E9), age (E9) and culture (E4, E8) and might not just differ between individuals but also for each occupant during the day (E11). For this reason, E8 considers the existing tendency to think of occupants as homogeneous *"a real problem"*: *"Actually looking at individual characteristics much more than assuming that there is an archetypal kind of occupant is probably one thing for me."* Due to these differences, the ambient temperatures that people consider to be reasonable are said to differ widely (E9) and make working in shared spaces challenging (E4, E7, E9, E11). Comfort needs to be negotiated in these spaces, which *"[...] might have to do with hierarchy, it might have to do with gender, it might have to do with age, so it is a matter of equality and how the space works in terms of hierarchy and function pretty much"* (E7). From E11's perspective, the goals is to minimise the overall level of complaints. Both E7 and E11 propose the idea to co-locate occupants in office buildings based on their thermal needs, i.e., to have warmer and colder offices.

The experts report that the behaviour of occupants is not only shaped by their individual characteristics but also external factors. This includes the buildings that the occupants live and work in (E6), their role-specific work patterns (E4) and interactions between occupants who might influence each other, e.g., by being receptive to each other's *"soft influence"* (E8). The number of people in an office and the office arrangements also change the thermal conditions in that space (E7, E8). In addition, occupants are said to behave differently at work versus at home (E2, E3, E4, E7, E9). This is largely attributed to the fact that they pay for energy at home but not at work (E2, E3, E4, E7, E9) which might give them a clearer understanding between the energy they are using and cost (E9) or make them care less about their consumption at work (E3). Another relevant factor could be that the responsiveness of the heating system is different on campus compared to domestic environments (E5).

4.2.3 The unaddressed rebound effect dynamic

Rebound effects featured prominently in the interview with E6 who considers them a key problem in the context of the University campus and the national climate change mitigation strategy. Regarding the latter, E6 said: *"A huge amount of the emissions reductions being promised are predicated on the assumption that efficiency improvements reduce emissions. [...] That's a false promise, because when you look behind every one of those promises, what they really are promising it for is to boost productivity. Therefore, that is Jevons paradox."* According to E6, the mechanism by which efficiency increases boost growth, leading to a bigger system and loss of all gains, applies to all efficiency improvements and should thus be *"our number one paranoia."* While the Jevons paradox can be beneficial from a social perspective, helping disadvantaged households to heat their homes, from a climate change mitigation perspective, they would eat up the savings achieved by e.g., making campus buildings more energy efficient (E6). To tackle this problem, E6 considers *"[it]* *unavoidable to want to make them more efficient, but [E6] would then want to have a discussion with the management of the University as to who should expect the profits."* The idea is that the growth opportunities do not need to materialise if the savings will not be re-invested but *give[n] away to poor people to make their lives better."*

E9 does not share E6's concern. As the participant with the most pronounced expertise in campus policies, I specifically asked E9 about rebound effects, who replied that the University does not have the luxury to be in a position where it would have to worry about it; according to E9, the level of control is limited and current discussions still evolve around fundamental questions about e.g., absolute temperatures and when to turn things on or off. E7 is also less concerned than E6; for E7 it is about focusing more on the positive (social) aspects of rebound effects rather than on the energy-saving reductions: *"It is quite bothering [estates] that they have to show only kilowatt hours saved or emission saved. And nobody is seeing actually that people might be more happy. We might not have achieved 50% changes, but productivity went up in office buildings, satisfaction went up, the health and well-being of our employees has been going up."*

4.3 The role of energy system automation

Given the high energy consumption associated with existing (campus) buildings, from an environmental perspective, there is a clear need to reduce this consumption. An established strategy with which people aim to achieve this—which does not require the refurbishment of existing buildings or construction of new buildings—is energy system automation. In the interviews I conducted, I asked the campus-based experts about their perspectives on and experiences with energy system automation.

4.3.1 Visions of seamless energy system automation

Many of the experts I interviewed have a positive view of energy system automation and what it could achieve (E1, E2, E3, E5, E8, E10, E11). The underlying vision they share tends to be of a system or building that seamlessly increases comfort and saves energy without requiring interventions from building users. E11 describes it as follows: *"I want the system, that essentially painlessly offers me the insights I'm after, which is where are my opportunities for improvement, where is my system not working [...]. And like I said, that must be painless."* E8 even associates the invisibility of such systems or buildings with the "calm technology" paradigm by Weiser and Brown, 1996 in which the interactions with them disappear: *"[I]f there was an algorithm that could just [manage a house] seamlessly behind the scenes and I didn't need to interact with it in any way whatsoever, it just intuitively knew what I wanted before I knew I wanted it, then that would be perfect"* (E8). For E5, the focus is on having automation in place that *"predicts"* a building without requiring intervention. These predictions would e.g., allow to pre-heat rooms before occupants arrive to make them more comfortable and to turn off systems when rooms are unoccupied to save energy (E5). Other envisioned benefits of energy system automation include the intelligent storage of energy in buildings to e.g., balance peaks (E8), support staff members in switching systems and devices off (E3) and provide actionable recommendations for energy management staff (E11).

If successful, several experts believe that energy system automation has the potential to make a real difference: Even though E3 is sceptical regarding the potential of Artificial Intelligence (AI) more generally, they believe that using it to optimise the University's heating schedule *"can have a very large impact, larger than 10% reduction in energy consumption used for heating. So there is a lot of practical advantages to that."* E11 also believes that an automated system with a high signal-to-noise ratio that offers prescriptive analytics would be impactful. A repeatedly mentioned strategy through which automation could achieve impact, including energy savings, is by linking systems together (E1, E2, E5). E5 describes it as follows: *"I mean my idea is [...] that we would be able to tie everything together, to room booking, to occupancy, to sensors [...] all done without really anyone intervening with it. I'd like to think we can get to a point as well where we predict a building."* This includes connecting substations together and using the data to makes rooms more comfortable and save energy (E5). E1 also believes that interfacing systems has *"great promises"*, especially linking the heating system with occupancy detection to avoid heating unoccupied rooms. Similarly, linking the lighting system and WiFi system would be beneficial to *"[...] only light up the room if there's an actual device near you"* (E1). Another idea for the campus specifically is to feed EIS data back into the main control system to control the temperature on-site (E2).

The targeted use and combination of data sets also plays a key role in the experts' vision (E2, E3, E5, E10, E11), including the integration of relevant data sets into automatic analyses (E11) and the combination of data sets to generate new insights (E11). Heating control systems on campus, for example, are not fed with occupancy or weather data *"[...] or any of the other factors that drive the internal sort of thermal comfort of a building. So, the control system can only take decisions based on a very limited set of data that comes from the part of the scope of the problem. Hence, we have uncomfortable buildings"* (E11). Occupancy data in particular is regarded as useful (E2, E3, E10, E11) as it could be used to automatically turn systems and devices off (E3). It could also be used automate the heating and cooling of rooms as according to E3, *"there's massive wastage because there's a lot of empty rooms or unoccupied."* Other ideas are to use occupancy data as input for the BMS (E2) and for air ventilation controls (E10). Regarding the weather data, the focus will be on replacing weather data from Manchester, which was used at the time of the interview, with local, more accurate weather data to optimise the campus buildings (E5).

Another application for energy data that is considered promising is predictive heating and predictive thermal comfort (E2, E11), i.e., for the system to make predictions about the heating or clothing that is required and adjust the output or forecast accordingly. While this has not yet been trialled on campus, E2 describes it as *"a good idea theoretically"* and E11 believes that is has the potential to stop buildings from overheating—a problem that several experts report (E3, E4, E11). Key challenges associated with it are *"the building of good models [and] to find good data"* (E11).

4.3.2 Challenges implementing automation

In contrast to the often "seamless" and "painless" visions of energy system automation described above, the only successful instantiation of it that was mentioned is automated lighting control, i.e., lights that get automatically turned on and off in response to occupancy (E1, E10); in one case the daylight levels are also considered. According to E1, the experience with this in the University context has been positive: *"We observe that spaces with switches tend to have a higher lighting energy consumption than spaces with motion sensor lights. But then this also has a limit because if you have a large space like the library and two people are in there, suddenly all the library is lit up."* Beyond the automatic lighting success, no other positive examples were given. Instead, the experts listed a large number of challenges and problems associated with the implementation and use of energy system automation.

Several experts commented on the slow progress with energy system automation and on how people tend to overestimate its potential (E1, E3, E7, E11). Despite feeling positive about the linking of systems for new insights, E1 is also concerned that decision-makers overestimate the potential of Artificial Intelligence (AI): *"[...] you have a system which has anything to do with AI and there people expect it to revolutionise. And in reality, it's not that. Maybe it can save 1% and then suddenly people start to be not so happy. However, I do think that the University is actually trying to use the information that we gather from the Energy Information System to optimise its heating schedule. And that potentially can have a very large impact [...]."* Similar to E1, E11 feels positive about energy system automation to painlessly offer insights—but is also concerned that the initiatives of senior management in the facilities department will not be successful as they do not know much about it. While E11 is working towards the automatic evaluation of energy consumption on campus and generation of actionable insights, it is *"slow"* and *"turning out to be a challenge."* E3 is even less optimistic: *"I have trouble seeing how automation will fix everything. I think it will just kind of make a new kind of crappy level"*; a sentiment E3 shares with E7 who does not think that the transition to using the Internet of

Things with prosumers and fully automated buildings is going to happen quickly. The term “prosumer” does thereby describe an individual who both consumes and produces a resource, in this context, energy.

Another challenge is related to the required maintenance and risk of failure of energy system automation technology. As automation technology becomes more interwoven into people’s lives and the fabric of society, the complexity increases, which is not necessarily considered (E3). This can also have negative consequences if the technology starts failing or breaking (E3); a scenario which is not unlikely given the reports of previous energy system failures, including *“quite a large failure rate of the TRVs [thermostatic radiator valves]”* (E2) and issues with temperature sensors that give incorrect readings (E2). E1 summarises it succinctly: *“[...] real-world systems have many problems.”* As buildings become more automated, the costs for maintenance and repair rise; a trend which has been observed before: *“[F]rom the simple things 30 years ago [...] that never failed, now you have solenoid-controlled devices on timers that do fail, that need batteries changing, or need maintaining or automatic radio-controlled thermostatic radiator valves fail or need batteries changing or need a greater level of electrical integration so that there is and can be a very high cost to the maintenance of highly automated systems. That’s great when they are working but when they stop working the costs to repair can be greater”* (E10). E10 explains that for this reason a simple system can sometimes still be cheapest.

As a key element of energy system automation, the storage, visualisation and accessibility of energy data also pose problems. Regarding its quantity, increasing amounts of collected data require a lot of storage: *“And then there’s always the question: When do you delete, start deleting some of that data that you don’t require? Or you just carry on collecting it”* (E2). The question might be even more difficult to answer because according to E11, it is difficult to know which data is valuable until you collect and analyse it. Visualising large quantities of energy data is not an easy task either, because it is very computationally intensive in that it requires a lot of memory processing power, and it needs to be done in a way that allows users to interpret millions of data points (E3). At the same time, it is regarded as an important task to make the data accessible (E3). Another issue that arises is that *“it’s useful to understand the system. But at the same time, now we start having data quantities where pure black box machine learning methods might become possible”* (E1). This tension also becomes apparent in E11’s responses, who would like to be presented the opportunities for improvement that the system uncovers and *[is] not actually interested in the rest of it.”* On the other hand, E11 says that they would want to be able to verify the results: *“Then I want to have the ability to interrogate any of those results to make sure that I can verify for myself that the pipeline is robust.”* For individual energy consumption data specifically, E4 is worried that it could be misinterpreted and lead to finger pointing.

Regarding the role of people, several experts agree that the automation of energy systems will require sufficient staff with technical expertise (E7, E9, E10), also to manually review the actions suggested by the system (E7). E9 explains that *"to develop a more intelligent campus, [...] intelligent buildings, [...] you not only need the technologies and the design, but you need the people who are going to be able to operate these buildings."*. E10 in particular is concerned that this will not be in place: *"And what the University and many organisations don't have is a large team of people to manage the automation of a building because once again that is an extremely costly resource."* What the experts agree on is that automated systems will to some extent keep humans in the loop, including the control systems.

4.3.3 The EIS case study

The EIS, which I introduce in Chapter 3, presents an interesting case study as one of its initial goals was to enable energy system automation on campus. E1, E2, E3, E5 and E11 have been involved in the design, development and/or use of the EIS and were able to share their thoughts and experiences during the interviews.

Originally, the EIS was set up to automatically find opportunities for improvement (E11), produce insights (E1) and make the campus smarter or more intelligent (E3) by gathering existing energy-related data and providing users with a tool to navigate and query it (E3). For E3, the EIS is about having all the data in one place, making it accessible and using it in meaningful ways. This includes the possibility for users to integrate their own tools and add qualitative data (E3). However, not all of this was realised or successful: *"You're supposed to be able to easily query the database but then it turns out the database is actually just files mostly, it's not actually a database"* (E3). Similarly, E1 reports that while the EIS was intended to inform high-level decisions, it *"[it] is not really enabling that"*. E3 adds that the automation-related goals have not been met: *"[Automation] is the idea of EIS phase two, which is closing the loop. So, phase one was all about getting the data and making it available and validating it. I think we've done some of some of those things"* (E3).

A key problem related to the EIS concerns the campus's energy data, which contains errors and gaps, the latter resulting in part from blackout events, that cannot be easily fixed (E1). E3 agrees that the data quality is likely poor, even though it difficult to know with certainty; in any case the data is described as poorly structured and poorly linked (E3), difficult to query (E11) and difficult to make accessible (E2). E11 summarises it as follows: *"[W]e had envisioned it to be very easily accessible, it's turned out being very much the opposite. The data is hard to access, hard to make sense of, it's full of errors and missing data and we've got scripts that can deal with a lot of but [...] we have to rerun it every time we need the data. It's a pain in the backside."* This means that the data needs to be cleaned and analysed, which no one is doing (E5). The amount of data also poses problems: According to E11, it is too much data to analyse manually, so the analysis needs to be automated. And to codify the metadata in a standardised way, the data needs to be stored differently (E11). What makes the analysis even more challenging is that the EIS was not *"built for live and raw data"* or *"made for reading lots of data all at once either, it's quite slow to write to the database"* (E3). Because the data has not been validated, it also remains unclear if visualisations would have led to better decisions (E3).

The experts mention additional challenges, including a lack of documentation for EIS scripts, which would benefit e.g., researchers who want to use the EIS, and poor standardisation of both EIS data and scripts (E1). There have been efforts to improve the latter but solutions that work for a specific subset often do not scale (E1). According to E11, there is also need for a robust processing pipeline for automated analyses that can deal with e.g., uncertainty: *"if your processing pipeline isn't robust, isn't scientific, you have high risk of false positives."* Other problems include the lack of a front end (E5) and the age of the system, which means that many new tools cannot be applied to it (E1). The reasons for this situation are manifold: E3 refers to *"political but also institutional kind of complexity"* around technological choices and *"[...] maybe just blindness to the limitations of the technologies."* According to E3, the goals for the EIS were too broad and *"[...] then instead of evaluating whether this technology was appropriate, scale up to the whole of campus, they just decided to use it."* While the EIS needs an *"analystic review"* (E5), there remain challenges regarding full access to the EIS for researchers who want to develop it further (E1).

Despite all these challenges, the experts still believe in the usefulness and potential of the EIS (E1, E2, E3, E5), given the right changes and investments. They also highlight some of the past and possible future achievements related to the EIS, the former including improved energy billing (E5). According to E5, the EIS *"[...] has got potential to be useful quite a bit"*; E3 agrees with this assessment: *"[it] has so much potential in my eyes and the eyes of a few others"*, focusing on its potential to be helpful through both automation and reporting. In line with the outlined problems, suggestions to improve the EIS and realise its potential include more standardisation (E1) and a better data scheme and data validation (E3). With this in place, which would require a significant investment (E3), the experts envision that the EIS could be used to communicate building performance to the building's occupants (E2), compare and benchmark buildings (E5) and flag erroneous data or systems (E3).

4.4 The role of occupants

In the context of digital interventions for energy savings, including energy system automation, I was also interested in the experts' perspectives on building occupants and their role. The subsections below summarise the experts' views on this topic.

4.4.1 Occupants regaining control

Several of the experts agree that the prevalent building design leaves occupants with little control over their surroundings, e.g., work and teaching spaces, and especially over the room temperature in these spaces (E3, E4, E7); a situation the occupants are unhappy about, especially if they have no control at all (E7, E8). E7 gives the following example: *"I've been in buildings that the thermostat is there but because they don't want people to tamper with the thermostat, it will have pretty much plastic cover and it will be screwed in. So you cannot really change the temperature other than violating it or calling someone [...] and usually people they won't bother to call. So what's going to happen is that [...] if you have access to the window, they will go and they open the windows."* However, even the opening of windows might be restricted due to e.g., concerns that people fall out of the windows or poor air quality outside (E7). E3 even goes as far as to describe it as an *"oppressor/oppressee kind of relationship almost"* in which occupants cannot control their environment. Instead, occupants want access to thermal controls to regulate their immediate surroundings (E7, E8): *"I think people don't like having no control at all"* (E8). This raises questions about the right amount of control to give to occupants and the balance between agency and external control (E7, E8, E9): *"There's a really interesting balance here [...] between the parameters of control and the parameters of agency [...]. But really, rather than seeing them as either or is, how do you marry them together in a hybrid?"* (E9). This question also covers occupants' interaction with sensor technology (E7).

Based on these observations, energy system automation, which takes away control from occupants (E3), could leave them dissatisfied: *"[...] you're gonna be inconveniencing some people at some point, and I think automation doesn't care about that and optimality isn't concerned with people's feelings either"* (E3). Looking at it from a different perspective, occupants *"could be a problem"* for successful energy system automation (E5). Regardless of the perspective, it is possible that *"[...] occupants end up complaining about the level of automation for their work environments, or they manually find ways to override the automation which will increase energy use"* (E10). This means that in highly automated buildings, occupancy satisfaction can be low because occupants have different views of what they consider comfortable working environments (E10). E10 specifically describes the case of an expensive automated building that was not able to provide the occupants with the environment they needed: *"It was a high cost project. It was iconic, one would say. And it was a very good building in terms of first impressions and wow factor but had created for the occupants a lot of problems with the internal environmental controls. And there was no doubt that the occupants of the building had lost faith in the environmental control. And some of those automated control systems became manually controlled, because occupant satisfaction was quite low."*

In terms of regaining control when the occupants are dissatisfied, the experts report a variety of strategies and workarounds. On campus, the use of electric heaters in offices, for example, is considered a key problem (E2, E7, E9, E10); acknowledging that it is hard to solve, E2 even describes the use of electric heaters as the most important barrier to reducing the energy consumption on campus. In addition, it can a social problem: *"[...] that office probably only got one temperature sensor on the wall which controls everything. So, if they are supplementing that with an electric heater, the thermostat thinks, 'oh the office is doing its job and it's nice and warm and [...] turns all the rest of the heating off.' The only person that then got heating is the person with the electric heater."* With regard to the origin of the problem, E7 offers the following perspective: *"The problem is why they felt that they need an extra heater because if the heater is there, it is their way of adapting to non-comfortable conditions pretty much."* Occupants who bring electric heaters are aware that they waste energy, but they prioritise comfort and they do not pay the bill; for them, the problem lies with their lack of control (E7). Besides the use of electric heaters, the opening of windows is also regarded as a problem (E2, E9, E10), partly in combination with turning up the radiator valves too high (E10). Through these measures, occupants can regain control, which the building engineers might not also be aware of (E6); at the same time they are *"defeating the object of the environmental control"* (E10).

In order to prevent workarounds by occupants, three experts suggest to either give occupants an illusion of control and/or the minimum amount of control that is necessary (E5, E7, E8). The underlying idea is that occupants feel comfortable in e.g., a wider range of temperatures if they believe that those are caused by their own decisions (E7)—so they will not disrupt the system (E8). E8, for example, proposes to give *"small amounts of control [to occupants] whilst still having the overall control in the hands of the building manager, the facilities manager, the client"* while E5 believes that the best strategy would be to automate the system but to *"have a boost function where you can boost the heating or hot water for an hour, something like that where an occupant could overwrite it for an hour and get a little bit of heat or cool or whatever. And then that goes back to standard operating system."*

4.4.2 Frustration about occupant behaviour

The workarounds described above are not the only cause of frustration that the experts report with regard to occupants' behaviour and conceptualisations. On the motivational side, occupants are believed to mostly care about their comfort, productivity and/or finances, rather than about sustainability (E3, E7): *"[T]hey will try to be comfortable and do their work. So they're not going to think efficiency. For them, probably efficiency will be an extra layer that comes after they have achieved comfort"* (E7). Their everyday context might be *"very different from this global idea of climate change"* (E3). On the behavioural side, the experts report frustration that few occupants turn down the heating when they leave offices, as unoccupied spaces get heated unless heating is turned off centrally (E11) and that occupants tend to only interact with building controls when they arrive at the office and when they leave and do not think of it in the meantime (E7). More generally, their energy-wasting behaviours, such as forgetting to close windows, are regarded as habitual (E7).

Related to this behaviour, the experts believe the occupants to have a number of relevant misconceptions and knowledge gaps. This includes the occupants not knowing how the heating systems (E2, E11) and thermostats (E5) work and thinking that *"if you turn the stat up full, you gonna get warm quicker"* (E5). In turn, E11 suspects that a lot people on campus do not know how to use the heating controls. According to E7, people in the office building environment have incorrect views on which behaviours waste energy—they think of electricity first, not heating, and *"cannot understand easily that heat, for example, is energy."* On a policy level, they are said be confident that the government is solving the climate crisis when seeing positive news headlines (E3) and to inaccurately believe that energy is expensive: *"[P]eople think that utilities are dear. And they're not. The cost of gas and electricity generally both in this country and in most parts of the world is, is very modest"* (E10).

The most frequently mentioned complaint is that occupants do not take responsibility for their own comfort (E5, E7, E9, E10, E11). According to the experts, occupants do not understand that they need to regulate their thermal needs through e.g., appropriate clothing (E5) rather than to blame the heating system if these needs are not met (E9, E11): *"[T]he biggest misconception in my opinion is that people think the heating system is solely and fully responsible to make them comfortable, at all times. Too hot, too cold, is gonna be the heating system"* (E11). There is a prevailing narrative that buildings should be warm enough so that occupants can only wear *"a short-sleeve shirt"* (E10) and do not need to change their clothes at any point: *"We should expect to be almost naked all the time if we want, and the temperature will be absolutely fine. And you can see how culturally constructed that is in terms of the acceptability. But all the normalcy of that as well"* (E9). So when they feel uncomfortable, people tend to personalise it and blame someone for it rather than to take responsibility (E9). E10 agrees that it is difficult to challenge the narrative that offices should be comfortable all year round and that occupants have no responsibility. At the same time, E10 encourages the education of occupants: *"[...] you can try working with occupants to be prepared for the environment in which they are working. [...] they shouldn't expect the office to be heated to a temperature where they could get down to a short-sleeve shirt [...]."*

Two experts specifically encourage a shift towards adaptive thermal comfort (E7, E11). Even though there are limited thermal comfort options in work places (E7) and the controls on campus are relatively poor (E11), they consider it important to think about how an adaptive thermal heating policy could get accepted (E11) and how adaptive thermal opportunities can be provided to occupants (E11).

4.4.3 Divided views on behaviour change interventions

When it comes to the importance of occupant behaviour for energy savings, the opinions of the experts differ to some extent. On the one hand, occupant behaviour is believed to have a significant impact on energy consumption on campus (E1, E2, E5, E7, E8). According to E2, *"[i]t would make a big difference"* if occupants turned down TRVs [thermostatic radiator valves], while E5 argues that *"keeping lights on in a meeting room or a lecture theatre or a seminar room from nine o'clock till five o'clock is wasting so much energy."* More generally, E5 believes that occupants make *"a massive difference"* for energy savings and that reducing the room temperature in offices would save a lot of energy and carbon. For E1, it depends on the specific actions: *"[I]f people are willing to stay in, I don't know, whatever their comfortable temperature is for everybody but 2°C below that temperature, that will have a massive impact. But if they turn their computer off overnight, maybe not so much."* As a result, E8 suggests that it might be helpful to explore ways for occupants to get immediate feedback on the consequences of their actions; E7 also believes that tracking and responding to energy wastage on an individual level would work best.

On the other hand, occupant behaviour is argued to often have limited impact (E1, E3, E11) and that it is difficult to make behaviour change interventions work (E3, E4): *"[W]e've been trying to do end-user energy feedback and behaviour change for years and all that happens is people have more stuff now or more complex ways of consuming energy"* (E3). According to E4, a lot of the focus remains on behaviour change interventions, but it is difficult to make them meaningful because people need energy for work and research. The impact of these interventions is also questioned by E11: *"[W]hen I look at the data that comes back from our buildings, it isn't the occupants driving [energy consumption]. So, we're doing the wrong thing, we've got the thin end the of the wedge. And that doesn't mean we shouldn't be doing it, we should, but we should be focusing elsewhere if we want to change energy consumption."* For this reason, several experts suggest to shift the focus from occupants to decision-makers (E6, E11), architects (E1) and high-level structures (E4). Decision-makers, for example, are regarded as key nodes in the system: *"[W]hen they change, everything changes"* (E6). For E11, the plan to save energy thus includes the following: *"[T]here's other stakeholder groups that decide what that energy bill is, and I have to find out who they are, what the strength of their relationship is with that energy consumption, and then I've got sort of more ammunition to try and influence them."*

When it comes to the education of occupants, the views are more nuanced. Many experts generally agree that it is positive to educate occupants (E2, E3, E4, E7, E10, E11) while also being aware that it is not always necessary or effective (E2, E3, E7, E11). According to E11, for example, behaviour change campaigns might not achieve many savings, but they educate students who *"leave the University and lead the rest of their lives with a little bit more knowledge around energy and energy efficiency."* For E4, the education of campus users is also important but depends on their roles and expectations. At the same time, information could be used to adjust certain expectations: *"Adjusting the expectations of occupants can be done and one of the ways that I've seen that done and worked with is to provide occupants with information themselves on what is happening in their environment"* (E10). Specific cases in which education is considered useful and necessary include interactions with air conditioning systems (E2), the timing of the heating system (E2), behaviour during heat waves (E7) and thermal comfort guides (E11). At the same time, occupants would not need to know how e.g., energy and heating systems works (E2, E11): *"[I]f you wanted to make people more aware then you could potentially do that for all of those complex systems, and it would simply be information overload"* (E11). It is also argued that they do not need the information (E2, E7) and that, except for experts, it will not help them make better decisions (E3): *"[E]specially in the University environment, I don't believe that people are not aware of sustainability, carbon offset emissions and they need education"* (E7).

Independent of the effectiveness of behaviour change interventions, several experts argue that it is not fair to focus on individuals (E3, E4, E7). One aspect of this is that occupants act within the context of their everyday lives where they need to e.g., get work done, and are shaped by personal and cultural factors (E3, E4, E7): *"Chasing every individual in the building to alter his behaviour? First of all, it's a bit unfair for the individual, because he has to live and react in an environment that it's not the optimal position for them, while they have also to perform their task. Plus it will be very hard to achieve what we calculate in terms of the background of these people and cultural expectations [...]"* (E7). For the University context in particular, there are pressures to publish, do lab work and grow research groups, which all impact energy consumption (E4). E3 also points out that targeting individuals will not change the underlying system: *"I think putting burden on the average individual just kind of makes people guilty. It's not going to kind of achieve a systemic change because energy is so cheap and when we consume energy, we don't think about glaciers melting or of rising water levels."* This is especially relevant as a lot of the energy consumption can be attributed to industry and commercial organisations (E3). In addition, it can be difficult for occupants to behave sustainably with e.g., old heaters, which makes E7 hesitant to put the blame on them: *"I'm against the option of it is the bad people and the good us."*

The final theme that emerges from the experts' responses is that occupants should be given space to participate in relevant conversations and decision-making processes (E3, E7) and that they should be actively considered in building design (E5, E6).

It is seen as problematic that e.g., researchers and building managers are *"dictating, not collaborating"* around people's environments (E3), including efforts to lower room temperatures (E7). While E3 acknowledges that it is not possible to engage with every single occupant, they *"should be given a space or an opportunity to participate"*, for example through forums and workshops (E3). For the design of buildings, the exclusion and non-consideration of occupants is also viewed as a problem; E6 discussed the *"fallacy of the engineer just thinking it's about actuators and ignoring the people"* while E5 describes how building designers and consultants do not consider occupants for new buildings. Instead, they tend to focus on standards and only engage with occupants when something has gone wrong but *"[...] it's too late then because then the building will need adaption from that point"* (E5). To address this problem, E5 recommends that building designers and consultants should speak to occupants before the construction of a building and rigorously complete post-occupant evaluations after the first twelve months of occupancy.

4.5 Discussion

In this chapter, I have presented the perspectives and insights of eleven campus-based experts around several key aspects of digital energy-saving interventions in buildings, i.e., the intervention space, automation technology and building occupants. From the interview analysis, a number of themes emerge, which I discuss in the following subsections.

4.5.1 Buildings as permanent energy consumers

All experts who spoke about the design of buildings agree that the standard building design is not sustainable from an energy consumption perceptive. Existing buildings need to be actively heated, cooled and ventilated, which stands in sharp contrast to the desired passive house standard (International Passive House Association, 2023). Compared to other European countries, the UK has some of the least energy-efficient buildings, which increases the need for active thermal management (Sivarajah, 2021). Taken together with the fact that existing buildings cannot easily be replaced with new buildings, it confirms the built environment as an important space for energy-saving interventions. This includes digital interventions as well as refurbishments; the latter can improve the buildings' air-tightness but often require a more significant financial investment. Interestingly, even if it was possible to focus on developing new buildings instead of refurbishing or retrofitting existing buildings, some of the experts are hesitant to do so at the current point in time because possibilities for developing more sustainable and energy-efficiency buildings are improving rapidly, and it might be better to wait until more technical innovations have entered the market. Given that the experts tend to describe the building industry as conservative and that at least one expert also reports difficulties with finding builders who are willing to implement solutions outside the industry norm, it could take additional time before these innovations are used for new buildings on a regular basis.

What was emphasised in multiple interviews is the buildings' high energy consumption *independent* of their occupancy. According to the experts, a common misconception is to believe that if no occupants are inside a building, the building consumes no or very little energy. Due to a high continuous load from systems and devices that cannot easily be turned off, e.g., standby devices, servers and security systems, this is not the case. To lower this baseload, there would need to be a fundamental change in the way a building is configured. Most of the experts' anecdotal evidence for this point stems from the COVID-19 pandemic: during its lockdown periods many campus buildings were largely unoccupied but continued to consume a significant amount of energy. While this indicates a limited energy-saving potential of digital behaviour change interventions, more research is needed for concrete estimates. I will return to this topic in Chapter 5.

4.5.2 Discordant views of occupants and behaviour change

With regard to the impact of occupant behaviour for energy savings, the experts' perspectives differ to some extent: While several experts consider mostly heating-related behaviour to be important, one expert argues that keeping lights on unnecessarily also wastes a substantial amount of energy. Another set of experts question the relevance of occupant behaviour from an energy consumption perspective and argues that the focus should shift to the behaviour of decision-makers and architects. Regardless of the expected impact, the experts report that it is difficult to make behaviour change interventions work within an environment in which people need energy for their work and research (to better understand these difficulties, future work could include interviews with external agencies, e.g., those running campaigns on behaviour change or reducing energy dependency). Acknowledging these difficulties, one expert believes that behaviour change campaigns can still be useful from an educational perceptive, even if they do not achieve the desired energy savings. In general, the experts' views regarding energy-specific education for campus users are positive. While the experts are aware that too much information can lead to information overload and that the amount of information needs to align with the recipient's level of expertise, they highlight specific cases and situations in which education for building occupants could be beneficial; this includes knowledge about the timing of the heating system and appropriate behaviour during heat waves.

Independent of the relevance of occupant behaviour for energy savings, many experts describe this behaviour critically and tend to assume that occupants care more about their own comfort and productivity than about sustainability—despite being aware that the circumstances can make to difficult for occupants to behave sustainably. Occupants are often seen as unaware of their responsibility to save energy, especially with regard to lowering room temperatures. According to these experts, occupants should regulate their own comfort *without* changing their environment, e.g., they should not use the heating system to feel warm but put on more clothing. However, this is not what the experts observe, especially in an office environment: occupants are argued to have inaccurate views about the impact of their behaviour, blame others when they are uncomfortable and do not understand how energy consumption works. From the perspective of digital energy-saving interventions, this critical view of occupants and problematisation of their behaviour explains the expressed desire to limit the occupants' control to the minimum amount necessary or even to an illusion of control through e.g., the automation of energy systems.

Efforts to limit occupants' control further can be seen as problematic for two reasons: fairness and effectiveness. The fairness aspect describes the pressure on occupants to save energy in an environment in which their main priority is to e.g., conduct lab work, complete coursework and publish research papers—activities which all require energy. In addition, their behaviour might be shaped by personal and cultural factors and restricted by the available infrastructure and control systems; invisible influences that the experts might not be aware of. To improve fairness, two experts actively propose to create spaces for occupants to participate in relevant conversations and decision-making processes, so that the relationship between experts and occupants can be centred around collaboration. Besides the fairness aspect, limiting the occupants' control of their environment is also likely ineffective from an energy-saving perspective. Many of the interviewed experts agree that taking control away from occupants tends to leave them dissatisfied and can motivate them to find strategies and workarounds to regain some of their control, including the use of electric heaters and opening of windows. These workarounds tend to reduce the effectiveness of the interventions that triggered them in the first place. As described in Chapter 2, such behaviour has previously been identified in the literature (Bedwell, Costanza, and Jewell, 2016).

4.5.3 Unevidenced faith in the potential of automation

In contrast to the behaviour-focused interventions, the majority of the experts describe positive and effective visions for the use of digital automation technologies for energy savings; these are mostly their own visions but also include those of decision-makers and other stakeholders. Many of the described visions focus on technical opportunities and how improvements, repairs or upgrades to existing technologies, e.g., linking systems for automation projects, the use of predictions to inform the responses of energy systems to outside conditions/temperatures, and the targeted application of AI, will eventually lead to energy savings. While not always articulated, these successful implementations also imply that building occupants behave as expected and do not "rebel" against the automation—a situation which has been described repeatedly during the interviews. In the experts' visions, a particular emphasis is put on the ease or seamlessness with which digital technologies can achieve the desired savings: rather than having to pick system settings manually, both building management staff who are responsible for the building as a whole and occupants who want their spaces to be comfortable could expect an algorithm to do the work with no or very little manual input; building management staff in particular could also expect the system to uncover the most important energy saving opportunities for them.

What is striking about these positive visions is that there exists little evidence so far that they can become a reality. The experts are aware of all the difficulties that would need to be overcome for digital energy-saving interventions to be successful and that there is no simple solution to enable this; they even present a large amount of anecdotal evidence, including severe problems with an "iconic" smart building on another university campus and issues with e.g., energy sensors, data storage and data quality on campus. In comparison, the only successfully implemented example of energy system automation that the experts report is that of automated lighting control—which comes with a limited saving potential. While these difficulties seem to shape the experts' evaluations of *other* people's, e.g., managers' and decision-makers' visions, of which the experts tend to critical (even when they are similar to their own visions), this is not the case for their own visions. In fact, it does not seem to be a problem for the experts' awareness of past and current difficulties to co-exist with their belief in the technologies' inherent potential and optimism for change. This becomes apparent again when analysing the EIS case study: even though the EIS did not achieve most of its goals, i.e., establishing a robust data processing pipeline, providing a database that is easy to access and query, and using the data for automation projects, the experts still believe in its potential and usefulness, given sufficient investments.

4.5.4 The ironies of energy system automation

In her widely cited paper *Ironies of Automation*, Bainbridge, 1983 critically reflects on the automation of industrial processes and identifies how automation tends to cause more problems for the human operator than it solves. The aim of automation is thereby to replace workers by automated systems that are designed to be more efficient and reliable. The workers are left to deal with parts of the system that cannot be automated or with system anomalies that the designer has not anticipated—to identify such anomalies, the workers (or human operators) will continuously monitor the system. What sounds straightforward on paper, does not necessarily translate into the real world. Presenting each issue that the automation causes the human operator as an irony, i.e., *"a combination of circumstances, the result of which is the direct opposite of what might be expected,"* the paper provides insight into the socio-technical challenges that come with system automation (Strauch, 2017). While the energy system automation I discuss in this thesis occurs outside an industrial context and is mainly targeting efficiency rather than reliability, the interviews nevertheless reveal similar ironies.

The first irony relates to the tensions between the experts' seamless visions of digital efficiency technologies and the increasing complexity inherent to energy systems and their automation; a tension that has also been described for e.g., digitally-supported agriculture (Rubambiza, Sengers, and Weatherspoon, 2022). The experts' views on energy system automation align in that the experts are aware of the complexity that comes with contextual factors, such as visible and invisible policies, diverse occupant needs and the technology itself; they also report a trend toward *more* complexity as digital building management systems and algorithms produce and process an increasing amount of energy data. Besides questions about the storage and presentation of this data, several experts note that the increasing complexity makes it difficult to understand the systems and their output, which can make people unwilling to interact with them and require specialised staff. It also increases the need for maintenance and repairs due to a higher risk that parts of the systems fail. Despite their awareness of these challenges, the experts continue to envision systems in which enough "intelligence" will lead to simplicity. Only one expert proposes to achieve simplicity through a return to simpler systems, which do not provide fine-grained monitoring and control of energy consumption, but are easier to understand and maintain.

The second irony relates to the experts' desire to want to stay in control without having to constantly monitor or oversee the system (which would defy the purpose of the automation). Instead, they would like to have enough knowledge and control to comprehend and verify the output while letting the system do the work most of the time. Given the large quantity of energy data that is used as input and the "black box" AI methods, it is unclear how the experts imagine such a verification to work. Bainbridge describes a similar irony for system failures: The more advanced an automated system is, the more critical will be the role of the human operator to mitigate the consequences of system failures. However, when intervention is needed, the operator requires skills that are no longer practised when the automated system runs smoothly, but that tend to worsen with non-use (Bainbridge, 1983). In the context of energy system automation, this means that when the the automated system becomes "invisible", as wished for by the experts, the energy management staff would interact with it less regularly and in case they want to verify the output (or repair the system), they will have less of an understanding how the system works. This comes on top of the increase in system complexity described above.

The third irony is less of an irony in the cognitive sense; instead it describes how an increase in energy efficiency through energy system automation can lead to *more* energy consumption overall when it triggers rebound effects. These effects, which I have described in more details in Section 2.4.3, were discussed by three of the experts during the interviews. While the experts acknowledged rebound effects, only one expert seemed concerned about it. The other two experts either highlighted the positive social consequences of rebound effects or argued that the University does not have the luxury to be in a position where it would need to worry about rebound effects. While rebound effects are difficult to measure, they have the potential to entirely mitigate savings achieved through digital energy-saving interventions. What can prevent rebound effects are sufficiency policies and consumption boundaries; Bierwirth and S. Thomas, 2015, for example, discuss how the combination of efficiency with sufficiency can maximise energy savings in buildings, taking into account both building design and use. I will return to the topic of rebound effects in a campus context in Chapter 5 and in a wider literature context in Chapter 6. I will also discuss the need for sufficiency policies and consumption boundaries in more detail in Chapter 8.

4.6 Summary

In this chapter, I have presented the findings from eleven semi-structured interviews with experts from Lancaster University's Bailrigg campus who possess expertise on energy consumption and interventions. To better understand the role of digital interventions in realising energy savings in buildings, I asked the experts about key elements, e.g., occupant behaviour, energy data, energy system automation, building design and digital infrastructure. In the context of my thesis, this interview study allowed me to explore (a) narratives among expert about the potential of digital energy-saving interventions, (b) past experiences the experts had with digital energy-saving interventions, including their reported effectiveness, both on campus and elsewhere, (c) how the occupants and their behaviour are perceived and evaluated by experts in the context of digital energy-saving interventions and (d) open questions and established tensions around digital energy-saving interventions.

My analysis shows that from an energy-saving perspective, the experts consider buildings an important and potentially impactful environment for digital interventions. The standard design of buildings means that the buildings consume large amounts of energy, independent of their occupancy. Regarding the two different strategies in which digital interventions could concretely be used to save energy, the experts' opinions differ: The unsuccessful outcome of past behaviour change interventions lets the experts convey hesitation about their usefulness, except for educational purposes (they disagree regarding the impact that the interventions could have if they *were* successful). Nevertheless, many of the experts seem to have the impression that they are working against the occupants and need to control their behaviour. The underlying narrative is that occupants do not sufficiently care about or even understand their energy consumption and would jeopardise the success of energy-saving projects. For digital efficiency interventions, the picture is different. Here, the majority of experts describe their energy-saving potential positively and imagine a future in which these interventions are used to seamlessly save energy—a future that stands in sharp contrast to the experts' reported experiences with past projects and their awareness of key challenges that have not been resolved.

Taken together, the findings in this chapter indicate hesitation among experts regarding digital behaviour change interventions but an overall positive view regarding energy system automation. Especially given the self-reported lack of successful examples for the latter and the identified ironies, which may undermine future success, it will be essential to better understand the limitations and relevant socio-technical factors that shape the outcome of these interventions.

Chapter 5

A COVID-19 case study: estimating the energy-saving potential of digital interventions

The contributions of this chapter that relate to the energy consumption analysis of individual campus buildings are largely based on published work, Bremer, Bates, et al., 2023. As the first author, I led the collaboration, writing and conceptual aspects of the analysis; Christian Remy and Oliver Bates were responsible for the technical implementation of the analysis. The contributions of this chapter that relate to the energy consumption analysis of the campus as a whole are fully my own.

In Chapter 4, I have presented the perspectives of campus-based experts on digital energy-saving interventions, including their energy-saving potential and key elements, e.g., occupant behaviour, energy data, energy system automation, building design and digital infrastructure. Despite their awareness of limiting factors, such as increasing technical complexity and workarounds by occupants, the experts consider the automated analysis and control of energy systems a key strategy to reduce the energy consumption of campus buildings. While several experts explained that the energy consumption exists independent of occupancy, the experts' views on the extent to which it is determined by occupant behaviour varied. In this chapter, I will investigate these perspectives on the potential of digital energy-saving interventions from a data angle. On the quantitative side, the chapter aims to estimate the *maximum* operational saving potential in buildings through their baseload and also the extent to which it can be realised. On the contextual side, I will explore the real-world factors that impede this realisation but also the role of the energy data itself for evaluating digital energy-saving interventions.

To achieve this, the COVID-19 pandemic has presented a unique research opportunity, namely, the absence of people from many non-domestic buildings, including those on Lancaster University's Bailrigg campus. Energy data from COVID-19 lockdown periods corresponds to a scenario in which people are taken "out of the loop", allowing insights into the energy consumption of buildings when they are (largely) unoccupied. More specifically, I am using campus energy data from lockdown periods for both daytime and nighttime consumption. The former can help to establish the extent to which operational energy consumption in buildings is linked to occupancy, which is relevant as digital interventions that target operational savings can only substantially lower the consumption of systems and devices that are used by occupants, as opposed to those that are "always on". The latter provides insights into the electricity baseload of buildings, i.e., their minimum electrical demand over a specified period (Luo et al., 2017), which can be used to estimate the operational saving potential. In a second step, I am using the data as a prompt for qualitative research with experts to identify the factors that determine (and restrict) the realisation of this potential.

Conceptually, the chapter considers the COVID-19 pandemic as a unique, grand-scale energy intervention in which "business as usual" was disrupted and people were largely removed from building premises. To understand the impact of this intervention on buildings' energy consumption, I present the findings from both campus-level and building-level electricity data analyses. The campus-level analysis focuses on historic consumption patterns and the impact of the first (strictest) lockdown period. The building-level analysis zooms in to uncover how the operational and baseload consumption changed in different campus buildings over the course of the pandemic. To better understand these quantitative insights, I have used visualisations of campus-level electricity consumption as prompts for a Jamboard study and focus group interview with experts, who were able to explain the observed consumption patterns. Based on the outcomes of these studies, I discuss the reported baseload values and the relationship between buildings' electricity consumption and occupancy. I conclude the discussion with a section on the attribution and drivers of energy consumption on campus—as indicators for the saving potential of digital interventions that target operational energy in buildings—and reflections on the role of energy data for evaluating digital energy-saving interventions.

5.1 Related COVID-19 energy research

Across the world, the COVID-19 pandemic has presented a unique opportunity for researchers to investigate the energy consumption of buildings during lockdown periods. In this context, university campuses have frequently been chosen as case study environments due the diversity of their buildings and the availability of energy data to the researchers. Compared to other building types, such as residential or commercial buildings, university campuses were (largely) unoccupied during lockdown periods, which makes them especially relevant for my own research. In fact, a study about COVID-19-related energy consumption changes in South Korea revealed that education and research facilities saw the largest average rate of change for both electricity and gas across the ten analysed building types (Kang et al., 2021). To better understand how this compares across universities, Table 5.1 provides an overview of studies that investigate the energy consumption impact of COVID-19 on university campuses as a whole or on a subset of campus buildings.

Paper	**Location**	**Buildings**	**Period**	**Findings**
H. Andrei et al., 2021	4 universities in Romania	Not specified	2019 – 2020	The electricity consumption of the four universities decreased by 8%, 21%, 36% and 60% in 2020 compared to 2019.
Birch et al., 2020	A "large" Russell group university (UK)	1 engineering building	03/2018 – 03/2020	For all unregulated energy submeters (for e.g., devices, servers), the electricity consumption decreased by 47% when comparing the first week of the March 2020 lockdown with the week prior to it.
Chaloeytoy, Inkarojrit, and Thanachareonkit, 2022	Chulalongkorn University (Thailand)	Not specified	08/2018 – 07/2021	Compared to the 2018/19 academic year, the electricity consumption in 2019/20 and 2020/21 decreased by 21% and 36%, respectively; changes were largest in academic and library buildings and smallest in research buildings.
Chihib et al., 2021	University of Almeria (Spain)	33 buildings	01/2011 – 12/2020	All building categories reduced their electricity consumption in 2020 compared with 2019; the savings varied from 2% to 44%; library buildings were impacted the most, research buildings the least.
Filimonau et al., 2021	Bournemouth University (UK)	Entire university campus	04/2018 – 06/2020	As part of more extensive carbon footprint calculations, the study shows that the electricity consumption for the campus from April to June decreased by 39% when comparing 2020 with 2019.

Gaspar et al., 2022	Universitat Politècnica de Catalunya-Barcelona Tech (Spain)	83 academic buildings across 9 campuses	02/2019 – 03/2021	Across all buildings, the energy consumption during COVID-19 was 4.3 Gigawatt hours (GWh) less than after COVID-19; buildings were using 47% less energy during strict lockdown periods.
Xuechen Gui et al., 2021	Griffith University (Australia)	122 buildings across 5 campuses	02/2019 – 02/2021	The energy savings during the COVID-19 academic year were 16% compared to the previous year; learning and administration were moved off campus while research remained on campus.
López-Sosa et al., 2021	13 state universities in Michoacán (Mexico)	Not specified	2019 – 2020	Electricity savings ranged from 10% to 90%; 9 out of 13 universities saved between 30% and 45%; the total average savings per month were 76.24 Megawatt hours (MWh).
Nasir et al., 2022	National University of Malaysia (Malaysia)	1 mixed research/office building	01/2019 – 12/2020	The comparison of the electricity pattern of 2019 with the lockdown period of 2020 shows that the Building Energy Index decreased by approximately 11%.
Spearing et al., 2021	University of Texas at Austin (USA)	5 buildings of different types	01/2020 – 11/2020	All buildings had lower average daily electricity demands in 2020 compared to 2019, ranging from 14% to 30% reductions; electricity use was less tightly coupled to occupancy than water use.
Tavakoli et al., 2023	University of Technology Sydney (Australia)	5 office buildings	01/2019 – 12/2021	Energy consumption was weakly correlated with occupant activity; per capita energy consumption increased during periods with reduced occupancy.

Xu et al., 2023	Twente University (Netherlands)	25 on-campus public buildings	01/2020 – 06/2022	During COVID-19, all building types, except for living (e.g., commercial) and academic buildings, reduced their electricity consumption; teaching buildings saw the largest average daily reduction with 1088 Kilowatt hours (kWh)/day.
Zhou et al., 2022	A university in Xi'an (China)	1 dormitory building	12/2021 – 01/2022	During a stay-at-home order the electricity consumption increased by 41%; the consumption showed backward shifts of morning peaks and forward shifts of evening peaks.

Table 5.1: Overview of research studies that analyse the impact of the COVID-19 pandemic on the energy consumption of university campuses.

As can be seen in Table 5.1, the range of energy savings on university campuses during COVID-19 is wide, starting as low as 2% (Chihib et al., 2021) and going all the way up to 90% (López-Sosa et al., 2021); most studies show savings between 15% and 50%. For academic buildings, such as libraries and teaching buildings, the consumption decrease tended to be largest, while research buildings (and in one case also "living buildings" for e.g., eating and shopping (Xu et al., 2023)) saw the smallest consumption changes (Chaloeytoy, Inkarojrit, and Thanachareonkit, 2022; Chihib et al., 2021; Xu et al., 2023).This was explained by the fact that research activities rely on e.g., laboratories and special equipment, which can only be used on campus, requiring researchers to return as soon as they were allowed. In addition, laboratories and special equipment tend to be energy-intensive, even when they are not is use (Xuechen Gui et al., 2021). In comparison, teaching and administrative work could be carried out online, allowing staff and students to engage in these activities while staying at home (Xuechen Gui et al., 2021). What should be noted is that while the possibility for staff and students to work online likely caused an energy consumption *decrease* on university campuses, it might also have led to a consumption *increase* in people's homes. The results by H. Andrei et al., 2021, who included household consumption in their study, support this theory: they found that *"in terms of electricity consumption, universities recorded a decrease during the pandemic, but there was an increase in household consumption for teachers and students."* Similarly, a case study of an individual dormitory building during a strict stay-at-home order period revealed a electricity consumption increase of 41% (Zhou et al., 2022).

Another important theme across Table 5.1 is the link between energy consumption and occupancy. As part of their analysis of the pandemic's impact on the energy consumption of office buildings, Tavakoli et al., 2023 found that during weekends, public holidays and time periods in which people were working from home, the per capita energy consumption increased significantly, translating into lower energy efficiency. Based on their results, they concluded that *"the changes in energy consumption due to COVID-19 in different UTS [University of Technology Sydney] faculties are not as strongly correlated with occupant activity"* (Tavakoli et al., 2023, p. 1). This was supported by another study, which looked at both electricity use and water use and found that electricity use was determined less by occupancy than water use (Spearing et al., 2021). From an electricity baseload perspective, one author group commented on *"the high environmental burden of buildings, regardless of whether they are occupied"* (Gaspar et al., 2022, p. 1); this was based on a weather-adjusted energy use analysis of 83 academic buildings, which were still using about 47% of what they typically consume during the strict lockdown period. Covering electricity use in the context of a carbon footprint estimation, Filimonau et al., 2021 reached a similar conclusion: *"the overall reduction of the BU's [Bournemouth University's] carbon footprint due to decreased use of utilities was lower than anticipated, i.e. 45% in the case of electricity [...]. This suggests that substantial amounts of energy are necessary to maintain University campuses even in the absence of staff and students."*

Of all these studies, only one actively included a qualitative contextualisation of energy data in their study design: to complement the energy data monitoring for a stay-at-home period in the dormitory building of a Chinese university, a survey was used to better understand the energy-consumption behaviour of its student residents (Zhou et al., 2022). While it is possible that other authors have contextualised their findings informally, they did not report this in their publications. This means that their proposed explanations and conclusions have not consistently been informed or verified by relevant stakeholders—a gap I am targeting with the mixed-method approach described below.

5.2 Research context and methods

To understand the maximum potential for energy savings on Lancaster University's Bailrigg campus, I began the study by analysing its total electricity consumption between January 2016 and December 2020. The focus on electricity was thereby determined by the availability of continuous hourly consumption values and the aim to establish the electricity baseload of buildings. In a second step, I presented campus-level electricity consumption graphs to experts in a Jamboard study and a focus group interview to understand the factors that determine energy consumption. As I was also interested in the electricity baseload of buildings (as a limiting factor of digital energy-saving interventions), I conducted an additional analysis of 19 campus buildings for which electricity data was available for the years 2019, 2020 and 2021. These were the years that captured different levels of occupancy during the different phases of the pandemic; due to historic changes in the systems that record and store energy data on campus, energy data for the period before 2019 was not consistently available for individual buildings. The COVID-19 timeline and four parts of the study are described in more detail below.

5.2.1 COVID-19 timeline

In the United Kingdom (UK), the first COVID-19 lockdown was announced on 23 March 2020 and came into force three days later (Institute for Government, 2022). The lockdown measures continued until 10 May 2020 when the restrictions started to get gradually lifted: on 15 June non-essential shops reopened, followed by indoor entertainment venues on 14 August. From an energy perspective, this "easing out of lockdown" coincided with the beginning of summer, the season with typically the lowest energy consumption due to reduced heating and lighting. After new restrictions in September 2020, the second national lockdown in England came into force on 5 November; it ended on 2 December. After the Christmas period, England entered its third national lockdown on 6 January 2021. From 8 March 2021 onward, the restrictions got lifted again: on 12 April non-essential retail and public buildings reopened, and on 19 July most legal limits and social contacts were removed. Based on this timeline, I divided the pandemic into four phases that correspond to the last four years (2019: pre-pandemic, 2020: height of the pandemic, 2021: transitioning out of the pandemic, 2022: return to "in person" operation).

To compare the energy consumption during the four phases of the pandemic, it was important to identify a suitable time window which (a) covered the full lockdown in spring/summer 2020; (b) was during teaching term times when students and staff are mostly expected to be present on campus in regular non-pandemic campus operation; and (c) excluded formal campus closure days over the Easter and Christmas breaks. This resulted in a five-week window for analysis starting on the last Monday in April and lasting for 35 days.[1] Figure 5.1 illustrates the positioning of the study window in the context of restriction periods on campus. It should be noted that during the second national lockdown period in England (5 November to 2 December 2020), the University continued a blended approach with both in-person and online teaching [2] in line with government announcements. This is why the period is coloured orange

---

[1] As mentioned in Section 3.3, the electricity consumption data that I used for my research does not include the bulk of the University's heating systems, so the impact of temperature differences across the selected years is assumed to be relatively minor.

[2] https://portal.lancaster.ac.uk/portal/news/article/new-national-restrictions-and-what-they-mean-for-you

rather than red in Figure 5.1. The onset of this partly-restricted (orange) period was marked by the re-opening of the main campus library on 6 July 2020[3].

5.2.2 Campus-level energy data analysis

For the campus-level analysis, which was conducted in February 2021, I used hourly electricity consumption values. The first data point I used in the analysis is from 16 January 2016 (no data was available from before 16 January 2016); the last data point is from 31 December 2020. There is a gap in the data between 13 August 2019 and 3 October 2019 due to a technical failure[4]. I visualised the data using R, so I could present it to the expert participants during the Jamboard study and the focus group interview. A formatted version of these graphs can be seen in seen in Figure 5.2.

Due to difficulties in distinguishing accurate from inaccurate outliers (see Section 3.3) as well as the fact that data quality presents a real-world limitation for digital energy-saving interventions and thus an important factor for my research, I decided to use the data as it was recorded for the Jamboard study and focus group, rather than to exclude what appeared to be outliers. This enabled the experts to comment on data quality in their Jamboard responses and focus group interview. For my calculations, I excluded values above the campus's consumption capacity of 7500 Kilowatts (kW), as these were most likely inaccurate (see Section 3.3). I first calculated the average electricity consumption on campus for each year. To better understand the impact of the COVID-19 pandemic, I then focused on each year's selected five-week period (see Section 5.2.1), for which I calculated the total electricity consumption.

5.2.3 Jamboard study

The Jamboard study, which took place between March and October 2021, was conducted to help contextualise and make sense of the campus-level electricity data and to inform the next steps of my research. The Jamboard contained a total of 11 slides: two slides with instructions, eight slides with questions (Q1–Q8) and a final "thank you" slide. After the participants agreed to participate and completed the necessary paperwork, they were sent a PDF document with the five campus-level electricity graphs (2016–2020; as in Figure 5.2) and the link to the Jamboard. They were each asked to go through the Jamboard slides in their own time, beginning on the first slide, and to follow the instructions on the slides. These instructions referred to the navigation of the Jamboard and the adding and saving of responses. To distinguish between the responses of different participants, I asked each of the

---

[3] https://portal.lancaster.ac.uk/portal/news/article/library-to-reopen-next-week

[4] Based on the design of the system, the expert I spoke to, who had been involved in setting up the EIS, considered it most likely that the technical failure occurred on a controller/sensor level.

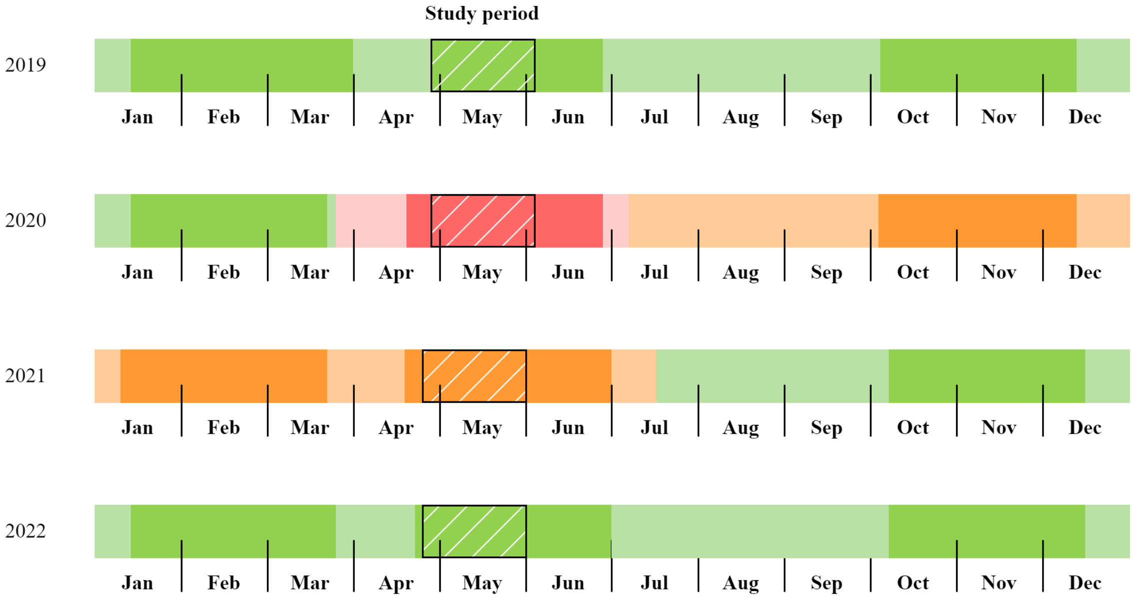
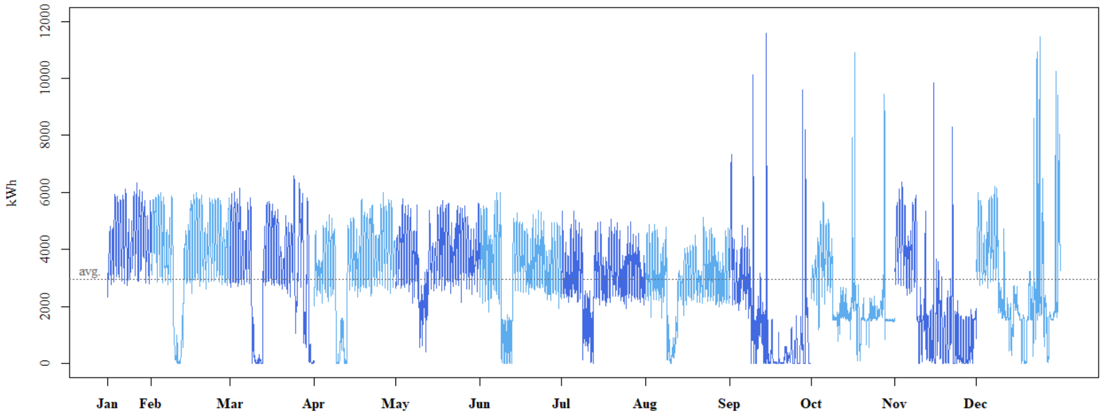
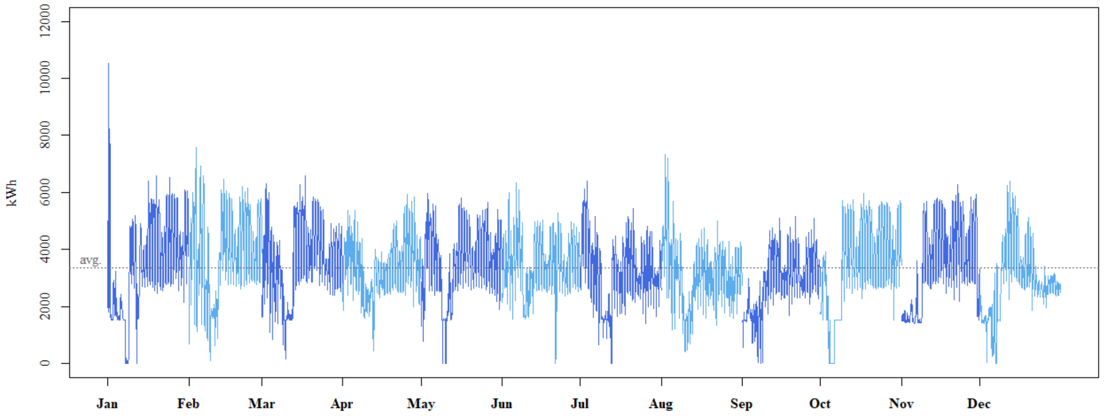


Figure 5.1: A visualisation of Lancaster University's academic calendar and restriction periods around the COVID-19 pandemic, i.e., during the years 2019, 2020, 2021 and 2022.

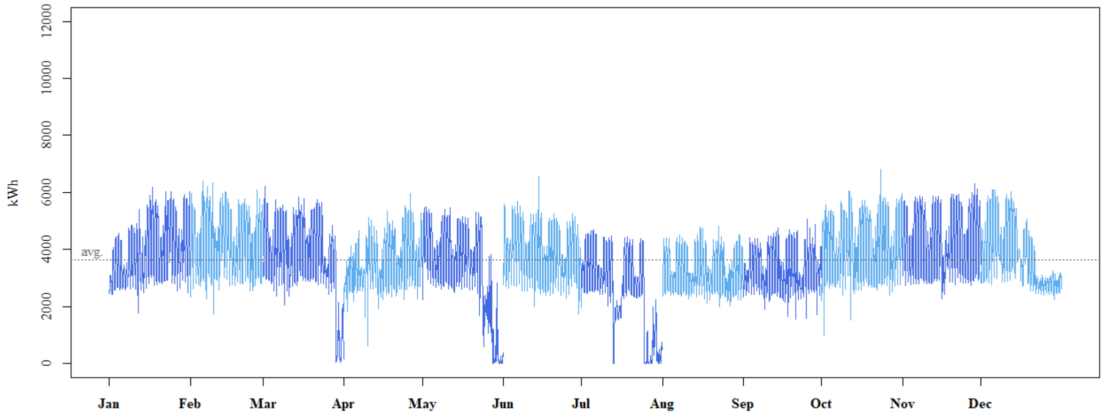
Note: In the graph, the rectangle with a black border illustrates the study period. The colour coding is as follows: Dark green slots indicate unrestricted term time periods, both before and after COVID-19; light green slots indicate unrestricted holiday periods. Dark red slots indicate fully restricted term time periods, during which teaching was conducted online; light red periods indicate fully restricted holiday periods. Dark orange slots represent partly restricted term time periods, during which the campus gradually re-opened and teaching occurred in blended form (in person and online); light orange periods indicate partly restricted holiday periods.



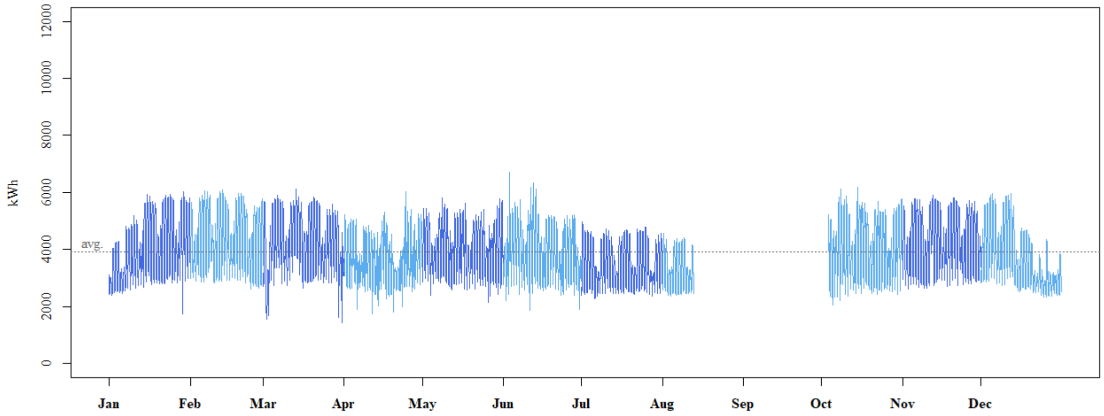
(a) Year: 2016



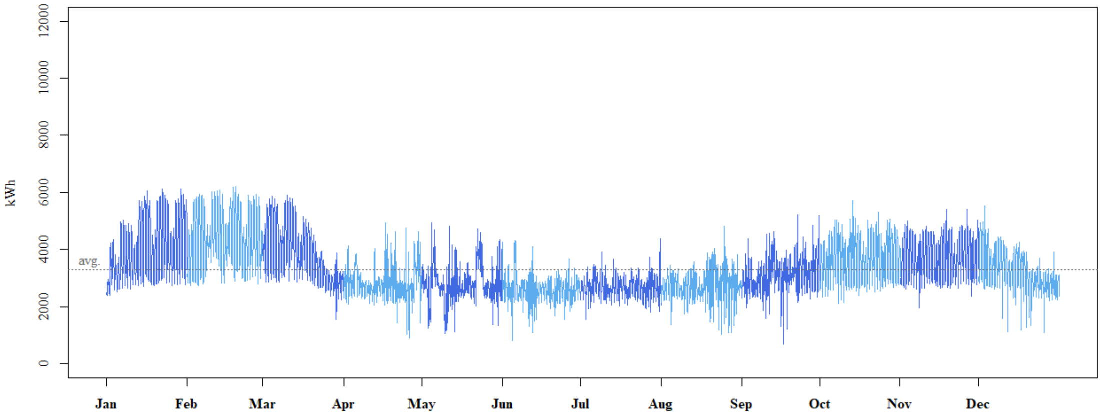
(b) Year: 2017



(c) Year: 2018



(d) Year: 2019



(e) Year: 2020

Figure 5.2: Figures 5.2a, 5.2b, 5.2c, 5.2d, and 5.2e show the total electricity consumption on Lancaster University's Bailrigg campus during the years 2016, 2017, 2018, 2019 and 2020, respectively. The colour coding distinguishes consecutive months. To allow for an easier comparison between years, each graph contains a grey line that indicates the average consumption.

participants to add their responses on (digital) sticky notes in a specific colour; the participants were encouraged to engage with any responses that had already been added by other participants.

Of the eight questions on the Jamboard slides, five (Q2–Q6) were directly related to the campus-level electricity graphs that the participants were sent in a PDF document. These questions covered consumption patterns, the impact of specific events/projects on campus and the limitations of the data for decision-making purposes; the participants were also asked if any of the data visualisations surprised them and to comment on the electricity consumption decrease during the first COVID-19 lockdown period. The remaining questions were about previous energy-saving projects/measures on campus, effective energy-saving strategies for the future (both technical and non-technical) and the barriers to implementing these strategies. I analysed the Jamboard responses together with the outcomes from the focus group interview, which is described below.

5.2.4 Focus group interview

After the Jamboard study had been completed, I conducted a focus group interview with three participants (October 2021). By fostering a discussion among the participants, it was intended to further contextualise the electricity consumption data and to build on the Jamboard study; the focus group covered three different topics: (a) factors that determine the energy demand on campus, including those that limit the energy-savings potential of (digital) interventions and that explain why realised savings do not always align with expected savings; (b) the campus history from an energy perspective, with a particular focus on the years 2016–2020, the impact of the COVID-19 pandemic on the energy consumption on campus and electricity baseload of buildings; and (c) the campus future from an energy perspective and the role of occupants, decision-makers, digital technology and infrastructure in it, as well as other relevant priorities.

During the focus group, which lasted one hour and was conducted and recorded via Microsoft Teams, the expert participants were shown a Miro board via slide share on which my supervisor Adrian Friday added notes from the discussion; the notes were colour-coded by participants. I had prepared the Miro board by adding (a) a conceptual graph of realised vs. expected energy savings from interventions for the first topic, (b) the 2016–2020 electricity graphs that the participants of the Jamboard study had been sent as a PDF document for the second topic, and (c) a table for the third topic to structure the participants' comments, with a column for each of the following: "people", "technology", "infrastructure", "decision-makers" and "other"; the Miro board also contained a descriptive heading for each topic.

The Miro board was used to guide the conversation, support my verbal explanations and capture key insights from the discussion as they relate to e.g., the electricity graphs. As I was moderating the focus group, I was not able to attend to the Miro board at the same time, which is why I relied on my supervisor for support. After the focus group had finished, I transcribed the focus group recording and analysed the transcription alongside the Jamboard responses by openly coding for themes across both studies (see Section 3.6 for details).

5.2.5 Building-level electricity data analysis

For the building-level analysis, I looked at 19 campus buildings for which I was able to obtain complete electricity data for the selected five-week period (see Section 5.2.1); 15 of these buildings also have complete electricity data for the corresponding time range in 2022. I used this data to calculate the changes in energy demand (both daytime and nighttime) that occurred as a result of adjustments to the building infrastructures and working practices made during the pandemic. A focus was on the buildings' baseload (estimated through the nighttime consumption), which can be regarded as the energy cost due to the equipment in the building and other "always on" electrical appliances in kitchens, offices, server rooms and embedded into the building fabric itself.

An overview of the buildings and corresponding data can be found in Table 5.2. I include the total energy consumption for the selected five-week time window in 2019 to illustrate the approximate scale of the building (larger buildings typically have higher energy demand). To find the effect of the pandemic, when many staff members and students were required to work or isolate at home, I compare the energy consumption in 2019 to that in 2020 during the same time window; the table includes the consumption during nighttime (midnight to 6am) to estimate a baseload, and the daytime consumption during peak work hours (10am to 5pm) when buildings are typically occupied (weekends excluded). In practice, operating hours for each type of building vary (e.g., lecture theatres may be in use until 7pm). For the daytime data comparison, I excluded weekends, assuming that non-residential spaces were in light use in a typical term week. The last three table columns illustrate the post-pandemic consumption change (from 2019 to 2021), using the same hours and weekend exclusions as for the first analysis.

5.2.6 Limitations

While COVID-19 provided a unique opportunity to study the campus with people taken "out of the loop", it was not intended as an energy intervention, meaning that energy savings were not the driver behind the changes and confounding variables were not controlled for. Air ventilation policies, for example, were introduced to reduce the virus load in indoor spaces, but also increased the energy demand due to heavier

		Total kWh	**2019 to 2020 change**			**2019 to 2021 change**		
#	**Building type**	**for 35 days in 2019**	**Total**	**Night time**	**Day time**	**Total**	**Night time**	**Day time**
1	Pre-school	4670	-70%	-32%	-93%	77%	190%	12%
2	Business space/meeting rooms	1458	0%	-1%	-16%	16%	8%	35%
3	Business space	751	-27%	0%	-44%	-7%	10%	45%
4	Offices/meeting rooms	12032	-4%	-10%	-1%	17%	6%	34%
5	Offices/meeting rooms	1520	-15%	-15%	9%	29%	24%	35%
6	Offices/meeting rooms	1536	5%	2%	81%	19%	4%	140%
7	Student residences	1433	-17%	-17%	-15%	7%	22%	-4%
8	Offices and laboratories	11670	-18%	37%	-58%	-8%	-13%	7%
9	Offices/meeting rooms	1025	-30%	-27%	-39%	-19%	-33%	-11%
10	Offices/hardware workshops	1256	-15%	-25%	-15%	-18%	-39%	-4%
11	Mix of offices and residential spaces	1774	-26%	-13%	-38%	-11%	-10%	-6%
12	Meeting rooms, event spaces	2162	-23%	-3%	-18%	-10%	-6%	1%
13	Offices, meeting rooms, event spaces	2116	-35%	-28%	-44%	-32%	-49%	-29%
14	Hotel building	4911	-68%	-31%	-86%	-60%	-32%	-74%
15	Sports facility	99786	-27%	16%	-31%	-65%	-57%	-67%
16	Offices/meeting rooms	8362	-45%	3%	-70%	-34%	-16%	-52%
17	Mix of offices and residential spaces	742	-7%	8%	-23%	-73%	-82%	-66%
18	Library	2162	-17%	-5%	11%	-11%	-8%	-3%
19	Student residences	1367	8%	20%	-6%	9%	8%	-1%

Table 5.2: Overview of selected buildings, their total energy consumption from 29 April to 2 June in 2019, and the savings observed during the initial lockdown periods (change from 2019 to 2020 by percentage) as well as the consumption increase after COVID-19 (change from 2019 to 2021 by percentage).

utilisation of the air ventilation systems. Differences in energy usage across buildings and time periods could also partly be due to changes that occurred independently of the COVID-19 pandemic (e.g., the type of equipment in a building, frequency of use patterns and changes in the building's structure and/or its size over time). An energy reduction on campus might then mean that the energy demand has to some extent *shifted* to people's homes in which they worked during lockdown periods; a trend that has observed in other places to varying degrees (Rouleau and Gosselin, 2021; Krarti and Aldubyan, 2021). Beyond my campus-specific findings, this would affect any conclusions drawn about the overall energy consumption impact of the pandemic.

Another limitation is the complexity and incompleteness of the energy data I worked with. While this is representative of many real-world environments, periods of missing data limited the choice of buildings for the building-level analysis. Taken together with the difficulties in identifying potentially incorrect data points (due to e.g., technical problems) and, for the campus-level analysis, the possibility that electricity exports reduce consumption values, it also reduces the quantitative accuracy of my calculations. I have used manual checks and informal conversations with the energy management team on campus to confirm that on the whole the data sets are accurate and can be used for quantitative analyses; for the campus-level analysis, the energy manager relied on the same data set for their work. These limitations should thus not threaten the validity of my findings.

For the Jamboard study and focus group interview, the relatively small number of participants limited the perspectives that were brought to the discussions. This was mainly due to the small participant pool from which I could draw, i.e., experts with in-depth knowledge of the energy consumption patterns and energy systems on campus (who were willing to give up some of their time to participate in my research despite their own busy work schedules). Fortunately, across the Jamboard study and focus group interview, the five experts who agreed to participate had complementary knowledge and together covered a large number of relevant perspectives (e.g., financial, University management, energy intervention management).

5.3 Electricity consumption changes on campus

Between 2016 and 2019, the mean electricity consumption on campus increased each year, starting with 2926 kWh in 2016 and rising up to 3910 kWh in 2019. The percentage increases were as follows: 13% in 2017, 8% in 2018 and 7% in 2019. In 2020, the mean consumption dropped to 3308 kWh, which is a decrease of 15% compared to 2019. It was, however, still higher than the mean value of 2017 and only 1% lower than mean value of 2018, both years without lockdown restrictions. For the total consumption during the selected five-week period, the impact of the first (strictest) lockdown period was more pronounced: compared to 3365 MWh in 2019, 2384 MWh in 2020 constituted a decrease of 29%. The fluctuations in the years prior did not see the same clear trend that was observed for the yearly mean consumption; the percentage changes for the total consumption during the selected five-week period were as follows: -6% in 2017, -8% in 2018 and 18% in 2019. The slight differences in start date (last Monday in April) and weather could be responsible for some of these variations.

5.3.1 Daytime consumption of individual buildings

Beyond the campus as a whole, I looked at the daytime electricity consumption of individual buildings to better understand how their operational consumption changed in line with the varying degrees of occupancy during the pandemic. As occupancy was low during COVID-19, especially during the first (strictest) lockdown period, my working hypothesis was that there would be a substantial drop in energy demand during this period, and that the "new normal" of home and hybrid working would keep the energy consumption below pre-pandemic levels. What the analysis of the 19 campus buildings actually shows is that the buildings can be clustered into four distinct categories based on their change in energy profile during working hours. These categories emerge from the combination of two dimensions: (a) whether there was a significant electricity *reduction* during the year 2020 (a decrease in energy consumption larger than 10% compared to 2019) and (b) whether there was a heightened electricity demand in 2021 (an increase of more than 10% compared to the pre-COVID-19 2019 level). Illustrated in Table 5.3, the categories of buildings can be described as follows:

(A) Buildings showing a significant electricity consumption reduction for 2020 and an electricity consumption increase in 2021 to levels higher than in 2019

(B) Buildings with an electricity demand increase in 2021 without a preceding reduction

(C) Buildings with an electricity consumption reduction in 2020 without a heightened consumption in 2021 to levels higher than in 2019

(D) Buildings for which neither energy savings were reported in 2020 nor an increase in 2021 (i.e., the consumption stayed roughly the same)

For each of these categories (the quadrants of Table 5.3), the visualisation of an exemplar building's consumption pattern can be seen below. Those buildings were chosen as exemplars for the respective quadrant and contain complete data for 2022 (e.g., while building 4 has a significantly larger footprint than the other two buildings in the second quadrant, their sensors yielded no data for 2022). It should be noted that

	Savings	**No savings**
Increase	(A) 1, 2, 3 Pre-school, business	(B) 4, 5, 6 Offices
No increase	(C) 7–17 Residences, offices/laboratories, offices, offices/residences, event spaces, hotel, sports facility	(D) 18, 19 Library, student residences

Table 5.3: Categorisation of campus buildings based on their aggregate daytime electricity consumption changes from 2019 to 2020 (savings/no savings) and from 2019 to 2021 (consumption increase/no increase).

no negative values were recorded for any of the building; violin plots are estimations of values in the data, and so when they go below zero, this means that there is a non-zero estimated probability of selecting a negative value from the data set.[5]

For categories A and B, Figure 5.3 plots the distribution of aggregate daily electricity use for representative buildings that saw an increase in energy consumption after the COVID-19 lockdown, with 16% daytime savings during the lockdown for the first building (Figure 5.3a), a mixed-use space with offices and businesses. The second building (Figure 5.3b), comprising offices and meeting rooms, saw no energy savings during lockdown working hours (but a small increase of 9%). Both buildings saw a 35% increase in energy consumption in 2021 (and subsequently a decrease again in 2022). For categories C and D, Figure 5.4 shows two buildings without a heightened energy consumption after lockdown, i.e., the values for 2021 did not exceed those of 2019. The library (Figure 5.4b) was one of only two buildings that did not see any savings (for weekday working hours) during lockdown, and also stayed relatively stable in the two years afterwards; it has to be noted that the total consumption did see a reduction of 17% during lockdown (see Table 5.2). The only other building that saw no consumption increase in 2021 and no savings in 2020 was a student residence. The majority of buildings, however, fell into the third category, such as the one displayed

---

[5] A violin plot combines a box plot and a kernel density plot; it should be read as follows: Based on a kernel density estimation, the width of each curve corresponds with the approximate frequency of data points in each region: wider sections of the violin plot represent a higher probability that members of the population will take on the given value; the narrower sections indicate a lower probability. The white dot in the centre shows the median while the thick gray bar in the center represents the interquartile range; the thinner gray line represents the rest of the distribution, except for data points that have been categorised as "outliers" using a method that is a function of the interquartile range.

in Figure 5.4a: a reduction of energy consumption during lockdown across the board, that continued post-COVID-19 or at least did not exceed pre-COVID-19 usage.

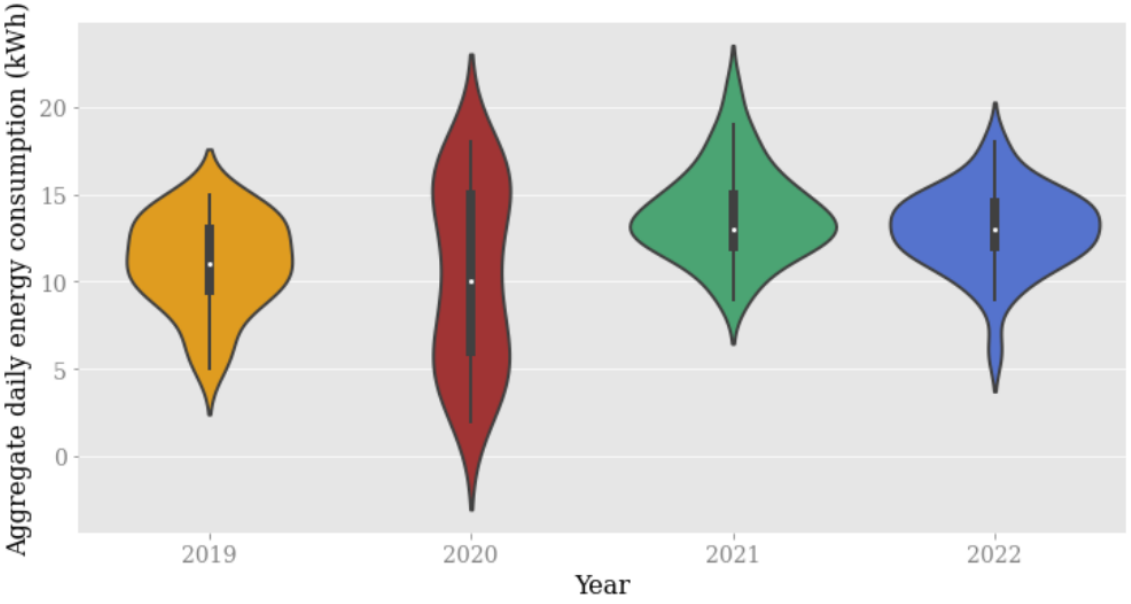
This third category (category C) captures the electricity consumption changes in 11 out of 19 buildings (see Table 5.3) and is the one that aligns with my working hypothesis. The category covers a variety of different buildings types, including a student residence, office buildings, a hotel and a building with sports facilities. Three additional buildings (those in category A), namely the pre-school and two buildings with business space/meeting rooms, also saw significant electricity savings in 2020. However, compared to the buildings in category C, these buildings subsequently recorded a consumption increase in 2021. Out of the 19 analysed buildings, five did not show significant daytime electricity savings in 2020: three office buildings, which still saw a consumption increase in 2021 (category B) and two buildings (a student residence and the main campus library), which showed no significant consumption changes during the pandemic (category D). Looking at the building types, this means that one clear trend emerges: an energy consumption increase in 2021 compared to 2019 only in non-residential buildings. A possible reason for this finding could be the instantiation of air ventilation policies in these buildings to protect occupants who use these buildings as shared work environments from the COVID-19 virus.

Across all buildings, Table 5.2 shows that the mean daytime consumption change from 2019 to 2020 was -26%, with a median change of -23%. This is slightly higher than the overall consumption change across buildings (mean: -23%, median: -18%) but slightly lower than the -29% campus-level consumption change over the same time period. Interestingly, the mean daytime consumption change from 2019 to 2021 was 0% (median: -3%) despite some ongoing COVID-19 measures and a blended approach to teaching during the summer term 2021. This indicates that any savings from reduced occupancy where neutralised by other factors; a topic I return to in the discussion (Section 5.5).

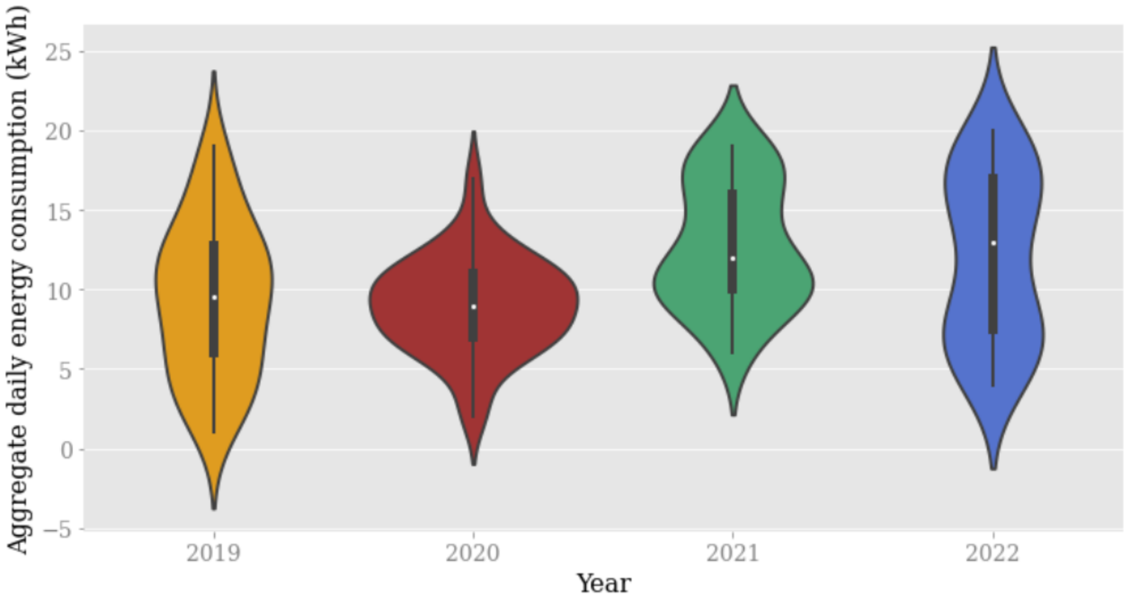
5.3.2 Nighttime consumption of individual buildings

To distinguish operational electricity consumption from end-use (e.g., building occupants using appliances) and continuous baseload consumption, the subsequent part of my analysis focuses on the buildings' nighttime consumption between midnight and 6am. Nighttime consumption is considered to approximate buildings' baseload as occupancy is low and the consumption is largely reduced to "always on" assets such as Information and Communication Technology (ICT) infrastructure (e.g., routers, switches, WiFi hotspots) used by occupants and for essential campus-wide systems.

To understand the nighttime consumption changes in the 19 selected buildings, I first ran the same analysis as for the daytime consumption. For the categorisation of buildings, a comparison of Table 5.3 and Table 5.4 shows that eight buildings were

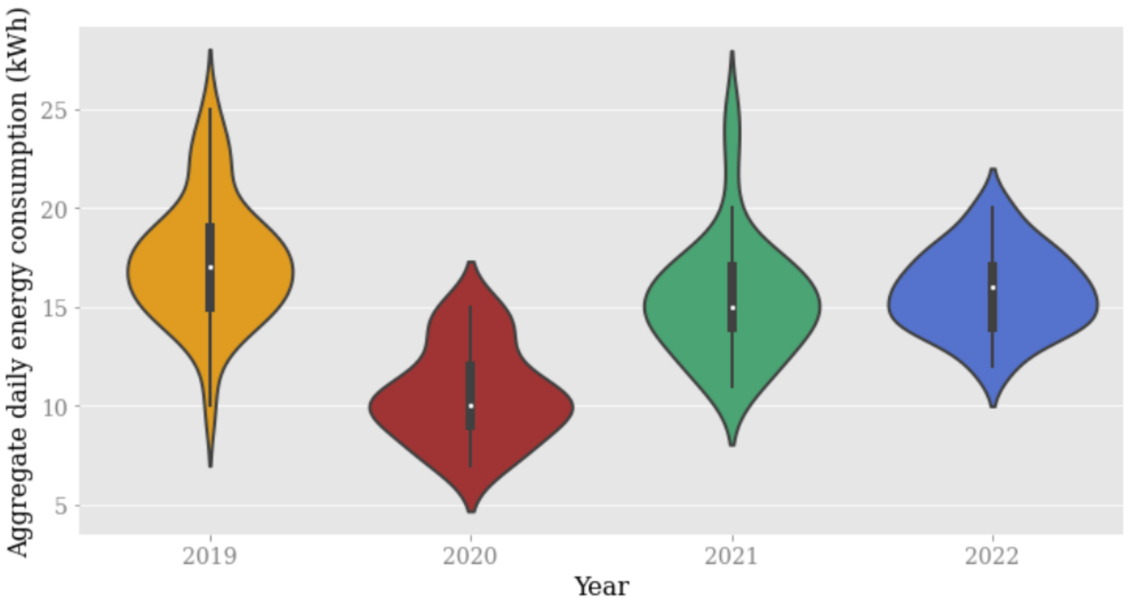


(a) Building 2, business space/meeting rooms

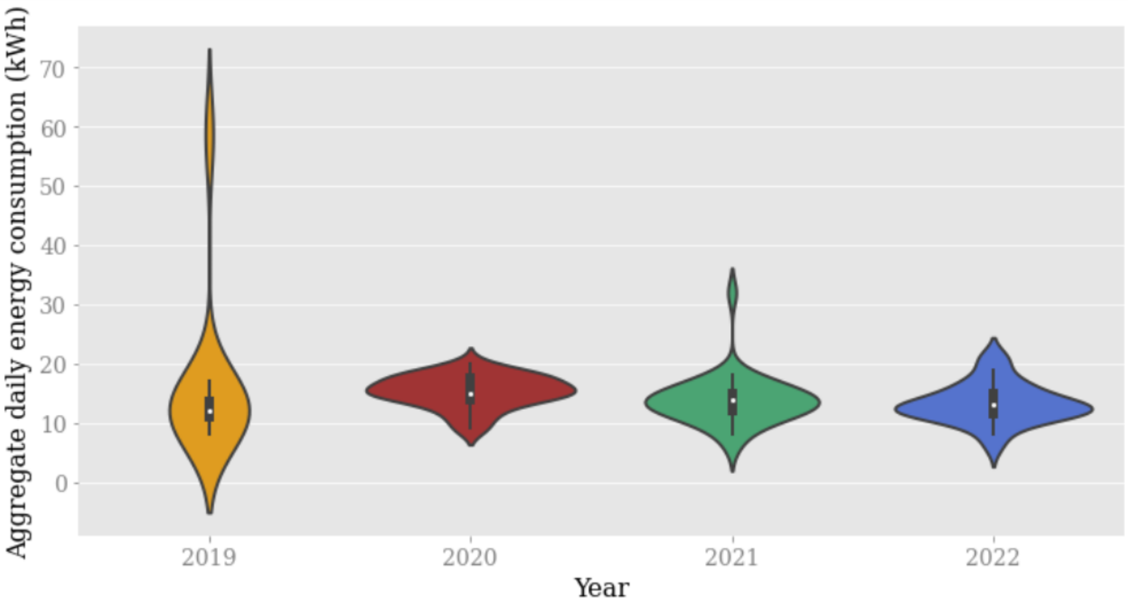


(b) Building 5, offices/meeting rooms

Figure 5.3: The electricity profiles of a building from category A (Figure 5.3a) with a significant electricity reduction in 2020 and subsequent increase in 2021 (compared to 2019) and of a building from category B (Figure 5.3b) where the electricity demand also increased compared to 2019, without significant savings in 2020.



(a) Building 11, mix of offices and residential spaces



(b) Building 18, library

Figure 5.4: The electricity profiles of building from category C (Figure 5.4a) with a significant electricity reduction in 2020 and return to 2019 consumption levels in 2021 and of a building from category D (5.4b) where the electricity demand in 2021 was again similar to that of 2019, but without savings in 2020.

		Baseload as % of total consumption		
#	**Building type**	**2019**	**2020**	**2021**
1	Pre-school	77%	178%	126%
2	Business space/meeting rooms	108%	107%	101%
3	Business space	53%	73%	63%
4	Offices/meeting rooms	106%	99%	96%
5	Offices/meeting rooms	125%	126%	120%
6	Offices/meeting rooms	104%	101%	90%
7	Student residences	78%	78%	90%
8	Offices and laboratories	84%	140%	79%
9	Offices/meeting rooms	93%	97%	77%
10	Offices/hardware workshops	89%	79%	67%
11	Mix of offices and residential spaces	75%	88%	77%
12	Meeting rooms, event spaces	65%	82%	68%
13	Offices, meeting rooms, event spaces	101%	112%	76%
14	Hotel building	48%	104%	82%
15	Sports facility	41%	64%	50%
16	Offices/meeting rooms	47%	88%	60%
17	Mix of offices and residential spaces	65%	74%	43%
18	Library	81%	94%	84%
19	Student residences	90%	100%	90%
			Average value	
		81%	**99%**	**81%**

Table 5.4: Overview of the 19 selected campus buildings' baseload consumption (approximated by multiplying their nighttime consumption, i.e., the combined total of what they consumed during each of the 35 6-hour midnight to 6am windows, by four) as a percentage of their total electricity consumption for the years 2019, 2020 and 2021.

assigned the same category for their daytime and nighttime consumption, while 11 buildings were assigned a different category. Based on Table 5.4, it can be seen that the largest category of buildings is not category C (electricity savings in 2020 but no heightened consumption in 2021) like for the daytime categorisation but category D (no electricity savings in 2020 and no heightened consumption in 2021). Instead of two buildings, category D now contains nine buildings, which cover a range of building types, including offices, student residences, sports facilities and the library. In other words, there were no significant consumption changes in 2020 or 2021 in almost half of the selected buildings' nighttime consumption. This indicates that the nighttime consumption of buildings was not impacted by changes in occupancy to the same degree as the operational daytime consumption. As this is, by definition, how the baseload consumption should behave, it supports my use of nighttime consumption values as a proxy for baseload.

With a mean of -10% (median: -10%), the nighttime consumption changes across all selected buildings from 2019 to 2020 were also significantly smaller than the daytime consumption changes. They were, however, non-zero, indicating that lockdown measures and reduced occupancy still had some effect. The nighttime consumption changes from 2019 to 2021 were even less pronounced, with a mean of -4% and a median of -8%. While this could indicate that the baseload in many buildings was approaching its pre-pandemic level, Table 5.1 shows that this was only the case for some buildings; others still reported a lowered nighttime consumption. In this context, Table 5.4 illustrates that four buildings experienced a heightened consumption in 2021 (as opposed to six buildings for the daytime consumption); three of these buildings were non-residential, supporting the daytime consumption trend that a heightened consumption in 2021 tended to occur in non-residential buildings.

The last part of my quantitative analysis involved the estimation of each building's baseload consumption as a percentage of its total electricity consumption. This was intended to provide further insights into the maximum saving potential of interventions that target operational energy consumption in buildings. As can be seen in Table 5.4, the lowest resulting value for any year and building was 41% (for building 15, a sports facility, in 2019) while the highest resulting value was 178% (for the pre-school in 2020). Values slightly above 100% are likely due to rounding errors, as many energy meters do not record exact numbers. However, this would not explain the 178% for the pre-school. Investigating this value further, I was able to rule out errors in the data as the main reason: the data appeared in itself consistent, showing regular spikes during the night. I then contacted a technician and employees of the pre-school; none of them could explain the spikes in the data. The only explanation the technician offered was related to the hot water tank in the plant room, which was monitored closely for temperature to avoid legionella bacteria, especially with young children using the water, and might have been coming on at night to keep

	Savings	**No savings**
Increase	(A) 1, 5, 7 Pre-school, offices, residences	(B) 3 Business
No increase	(C) 4, 9–11, 13, 14 Offices, offices/residences, hotel	(D) 2, 6, 8, 12, 15–9 Business, offices, offices/laboratories, event spaces, sports facility, offices/residences, library, residences

Table 5.5: Categorisation of campus buildings based on their aggregate nighttime electricity consumption changes from 2019 to 2020 (savings/no savings) and from 2019 to 2021 (consumption increase/no increase).

the temperature up. However, this should not have added a large load. On average, a building's baseload consumption was responsible for 81% of its total electricity consumption both in 2019 and 2021. In 2020, it accounted for roughly its entire consumption, with a coverage of 99%, indicating that the operational consumption was reduced as much as possible during the first (strictest) lockdown period.

The analysis indicates that during the strictest lockdown phase, most of the energy-consuming devices and systems in buildings that were kept on were indeed those that can be considered part of the buildings' (slightly lowered) baseload. For years without strict lockdown measures, the difference between nighttime and daytime consumption is more pronounced, indicating the impact of operational daytime consumption. Ranging from 0% to almost 60% for different buildings, the average values across buildings need to be interpreted with care. What can be said with relative certainty is that in most buildings, operational daytime electricity consumption, which is the consumption usually targeted by digital energy-saving interventions, does not constitute the majority of the building's electricity consumption.

5.4 Understanding energy demand on campus

To better understand the observed electricity consumption patterns and changes and what they mean for the potential of digital energy-saving interventions, I ran the Jamboard study and focus group interview with experts (using the campus-level graphs as prompts), for which I have described the procedures in Section 5.2.3 and Section 5.2.4, respectively. In this section, I present the outcomes of this research, with a particular focus on the relationship between energy consumption and occupancy, electricity baseload as a proxy for the maximum energy-saving potential of digital interventions, the factors that determine whether the potential can be realised and proposed strategies for lowering their impact.

5.4.1 The campus context from an energy perspective

Generally speaking, Lancaster University has invested in reducing the electricity consumption on campus: over the years, *"[t]here have been hundreds of projects"* (E14). Many of these projects have used technology to target energy efficiency, including high efficiency transformers, high efficiency lighting, variable speed drives, Building Management System (BMS) sensors and controls, improved Information Technology (IT) equipment, and virtualisation (E11). Information Technology (IT) systems are gradually replaced with lower energy use computers (E14). Two participants also commented on the significant investments into energy infrastructure and metering (E13, E15). In a campus-wide exercise, for example, additional metering has been installed *"in order to improve consumption mapping and pinpoint areas of high electrical consumption and review"* (E13). On the side of the campus users, policies and campaigns have been used to promote electricity saving (e.g., turning off lights and discouraging the use of electrical appliances in offices, such as toasters, kettles and fans) (E12); several engagement exercises elicited positive responses (E13).

What has made it difficult to evaluate interventions like these is that the campus has grown significantly (E13), including the addition of many new buildings (E11). This has impacted the campus's electricity consumption as *"each major development and numerous other refurbishments to existing buildings significantly increase electrical consumption as more and more electrical equipment requirements are required"* (E13). To accommodate these developments, the University increased the capacity of electrical supply to the campus from 7.5 to 11 Megavolt Amperes (MVA) (E13). The developments also need to be factored into consumption evaluations, leading E13 to conclude that it is *"a measure of the success / benefit of our on-site generation that [the electrical consumption has not increased]"*. Without the growth of campus, E13 suspects that the energy campaigns would have led to a consumption decrease. E11 framed the same outcome differently, suggesting a rebound effect mechanism: *"My hypothesis would be that energy efficiency gains are being off-set by growth, i.e. Jevons Paradox."*

In response to the campus-level graphs (see Figure 5.2, the experts point out weekly patterns (E11, E14) and the impact of the three academic terms each year during which students are taught on campus (E11, E14). They also note the drop in electricity consumption during vacation times when student occupancy on campus tends to be low, including summer, Easter and Christmas holidays (E11, E12, E14).

In addition to changes relating to the academic timetable, E12, E13 and E14 describe seasonal patterns that affect the consumption during summer and winter months. E13 explains the difference between years: *"The electrical consumption graph for 2016 indicates average consumption of 5–6MW with significant instances of peak winter consumption up to 10–12MW. This was a particularly bad winter and issues with the wind turbine performance meant less on-campus generation to off set [sic] consumption. Consumption settles for years 2017–2019 at circa 5–6MW [...]."* More generally, the experts describe how the overall consumption levels and peak demands have stayed broadly the same across the years (E11, E13), with one exception: COVID-19 lockdown periods (E11, E12, E13, E14).

5.4.2 Understanding energy consumption during COVID-19

I asked the experts to help me understand the electricity consumption during lockdown periods on campus. According to E13, the consumption rates didn't drop as much as expected due to two reasons: (a) electrical services for increased ventilation rates and (b) the continued operation of key services, such as pumped supplies and compliance related equipment. This explanation was supported by the other experts. E11 explained that COVID-19 response guidelines included the need for fresh air in buildings. Where buildings have mechanical ventilation, this meant running them at full capacity, which is more than normal and required more electricity. Heat recovery systems on air handling systems also had to be switched off (to minimise the cross-contamination risk), which further increased electricity demand, as heating pumps had to run harder and longer (E11). On the key services side, *"[m]uch of the electricity use on campus is embedded in systems that stay on—HVAC systems, computing, pumps etc [...]"* (E14). E11 also attributed the unresponsiveness of electricity consumption to lower occupancy during lockdown periods to the fact that the *"the majority of equipment was still running."* With equipment *unnecessarily* left on, energy wastage added to the consumption but was considered *"realitively [sic] minor"* by E11. What then hindered more drastic saving measures was that *"[t]he uncertainty of duration for COVID low occupancy rates on campus required campus to be operated in anticipation of a speedy return to normal operation [...]"* (E13).

Another important factor that limited the consumption reduction during lockdown periods was that a significant number of people continued to work and live on campus, including many students (E11, E12, E13). E11 explained that *"[r]emaining staff and students were spread out on campus, rather than concentrated in a few buildings. This means that almost all buildings still had to be serviced."* What made this even more problematic from an energy-saving perspective is that *"the University's energy systems do not have sensing or control granularity that enables a match with occupancy, either spatially or temporally"* (E11).

Generally speaking, the experts agreed that occupancy doesn't determine most of the electricity consumption on campus (E11, E12, E15). As E11 formulated it: *"[t]he occupancy related component of electricity consumption is much smaller than most people seem to assume."* This can be explained by the fact that many devices and services, such as fridges and student residences and University-wide servers, are never turned off (E15) and by the tendency for automated systems to not function as intended and to thus operate independent of whether they are actually needed (E12). According to E11, *"this poor relationship between occupancy and energy consumption also helps to explain why behaviour change campaigns focused on building occupants tend to significantly underdeliver."* When discussing the factors that determine the overall baseload, E13 explained that many *"chilled rooms and closed environment rooms and laboratories etc."* need to be cooled independent of the season and outside temperature, even in winter; this means that the baseload cannot be avoided. Without the aforementioned campus growth, it might have dropped, but as campus is growing, so is the consumption (E13).

5.4.3 Factors hindering energy savings

Based on what the experts reported, I wanted to better understand the real-world factors that impede the realisation of energy savings that are deemed possible according to models or quantitative estimates and thus expected as the outcome of interventions. In response, the experts listed a range of such factors that they have been confronted with on campus. The factors can be assigned to four broad clusters:

Limitations and failure of technology. With regard to this theme, the experts reported two distinct problems. The first problem is that in many cases, energy-related technology has actively failed. This was reported for energy meters (E15), data loggers (E13), lighting controls (E13), the wind turbine (E13) and energy systems as a whole, including BMS systems (E12). E15, for example, explained that *"the meters generally don't work very well. So, you have to get like nonsense data."* E13 reported similar experiences: *"[...] what I was finding was there was big gaps in the data because the data loggers were unreliable or we kept re-calibrating them and, in some places, replacing them, and there was a bit of an issue there."* This has led to frustration of needing to spend money on repairs rather than being able to invest it into new systems and devices (E13). The second problem is that while technology doesn't always actively fail, it still regularly doesn't deliver what it promises. Reporting on issues with control valves, E13 described it as follow: *"[...] often we find that the shiny presentation on the technology that 'how is it supposed to work' when you physically do it on the ground it doesn't quite translate"*; E13 added later: *"[...] like I said about technology with the lighting controllers, we have had stuff that promises things on the tin but when you open the tin it doesn't quite deliver."* In response, E13 suggested to take a step back away from the cutting-edge technology and focus on what is *"tried and tested."* E15 shares the scepticism and advocates for a careful approach in the context of heat pump installations.

A key theme across the experts' explanations of why technology fails or does not deliver is complexity. On the one hand, this relates to the complex task of modelling real world systems: *"[...] when you're looking at heating systems and energy usage, there are so many variables involved, all the things that they mentioned—users, weather, building performance, all of those things—and it's incredibly difficult to actually model"* (E15). On the other hand, it refers to the digital infrastructure and the technology itself. Being able to coordinate the different energy sources and systems on campus is challenging and *"you can quite often be running things in a sort of suboptimal way"* (E13). In addition, increasingly complex equipment is installed in buildings, e.g., complex lighting control systems (E13). Sometimes, the required technology also simply *"doesn't exist, or is not affordable. For example, automated, continuous data analysis of energy metering and contextual data"* (E11).

Missing, unreliable and unused data. The experts reported that missing and unreliable data was a problem for effective energy-saving interventions. E13 described instances were they found *"big gaps"* in the data and argued that *"[...] certainly from an operational perspective, part of the energy saving opportunities that we could capture, we don't because in some areas were not as informed from a data perspective as we could be."* In particular, they noted the need for actionable data: *"[...] that data that gives you that knowledge that enables action, that's the key thing, really"* (E13). E11 specifically called for data at the same spatial and temporal resolutions for both consumption and its key drivers in order to see if consumption is normal or exceptional, enable management action and target resources. However, even when sub-metering and accurate data was available, it was not always used. E15 described it as follows: *"[...] over the years we've invested a lot actually in sub-metering and systems that collate data and present data to us, but we never seem to quite do anything with it. It just seems to be like information data overload."* A focus for E13 was thereby to make alarms more actionable to reduce being *"overwhelmed with data."* E13 also emphasised the need for data contextualisation as data in isolation cannot necessarily outline the numerous contributory factors and may lead to incorrect assumptions or conclusions.

Occupant behaviour. The third challenge with regard to lowering the energy consumption on campus is behaviour change; a topic on which experts on campus *"have had loads of discussions over the years"* (E12). Occupant behaviour is mainly considered important by E12 and E13, as targets cannot be met if not everyone is involved (E13). E12 even describes the large number of people who are still *"a bit indifferent to [energy use, climate change and so on]"* as *"the biggest challenge,"* as they are too many compared to those who are committed and want to drive change.

E12 also reports that occupants sometimes don't behave as they are expected to and are interfering with the intended operation of buildings *"by doing whatever, opening windows, turning thermostats up, down, leaving you know things on, like switch lights on and so on."* E13 adds to this by describing situations in which occupants left windows open and then not returning to the room. Such behaviour tends to impacted by many different factors (E13); it also tends to be difficult to predict and cannot be controlled (E12). The experts posited that occupants do not want fully automated buildings (E12).

What adds to the challenge is that, based on the experts' experience, occupants have more energy awareness in their own homes. E13 describes it as follows: *"[...] you've got an awareness at home where you might not, you don't have on campus. You always think someone else will do it or 'I wouldn't want to do that, because who else is coming in the building now [...]'."* E12 argues that people are not taking as much responsibility for e.g., turning off the lights *"when they're not paying the bill."* Hybrid working and "hot desking", i.e., an organisational workspace system in which desks are used by different people at different times on an ad hoc basis, also bring new challenges with it, such the loss of ownership over office spaces (E13).

Lack of resources. Another obstacle to lowering the energy consumption on campus is a lack of resources. E11, E12 and E13 all mentioned budget constraints with regard to energy-saving strategies. This can mean that projects cannot be continued when the funding ends (E13) or that new projects cannot be initiated (E11, E13). E12 also addressed the *"difficult balance between the initial sort of capital investment cost versus cost in use and energy saving cost over the life of the building."* In response, E13 suggested to reduce the reliance on external funding and focus the limited resources that are available. What can complicate the situation is that funding is often only made available for detailed, advanced plans, which themselves require funding (E13), and that decision-makers tend to invest in projects that save money (E13). Besides financial constraints, the expert also pointed out a lack of time (E11, E12) and staff (E11, E13, E14, E15). Data analysis, for example, requires *"having resources, someone to actually analyse and work out where that data is telling us"* (E15).

5.4.4 Addressing the factors that hinder energy savings

To address some of the limiting factors to saving energy on campus, the experts call for a portfolio of strategies (rather than to focus on one strategy specifically), especially with regard to energy sources and the use of technology. According to E13 it's about the availability of different options; *"having a hybrid sort of approach gives you the resilience because it's not all or nothing."* This is also why E13 advocates for always having *"something in reserve."* This approach should be combined with the targeted use of resources that is based on the identification of e.g., relevant projects (E14) and poorly performing buildings (E13) and with investments into renewable energy. This includes the electrification of heating services (E11, E13), the diversification of renewable energy sources (E13) and the development of a solar farm (E13). These kinds of investments align with the University's high-level strategy (E13).

What is considered important across the University is good decision-making, including the prioritisation of sustainability in decisions taken at the top level. While E15 outlined the importance of robust financial modelling underpinning those decisions, E11 emphasised the importance of effective stakeholder engagement: *"[...] [key stakeholder groups that influence electricity consumption] should than be engaged in order to change their outlook, decision processes and social environment. My hypothesis is that the key stakeholder groups do not included [sic] building occupants (staff or students), but are rather the financial decision makers and various associated committees"*. In line with this suggestion, E11 believes that poor stakeholder targeting is the reason why behaviour-based projects have not been more effective—a suggestion that is potentially in tension with the call by E12 to *"educate the staff/students on the areas of highest consumption of electricity and ask them to help reduce (in context of Climate Emergency)"* as an effective strategy to save energy on campus. According to E13, energy and carbon savings need to be a priority across the University, including on a departmental and team level: *"We need to have it where, same as health and safety you know, you should be when you start doing a strategic plan, one of the first things on the bullet points should be, "Right, okay, what are we doing about carbon? And energy?"* This includes initiatives outside of facilities management (E13).

Another proposed strategy is the investment in energy system automation and optimised controls—although these come with challenges. E13 sees the benefits of this strategy: *"[...] the next step is to make sure we have proper optimised controls, so the buildings are really using the building management system, the BMS, to optimise energy heating systems to reflect the outside air temperature. [...] It's alert, it's an automated system and we haven't got that in place yet."*. In response to unexpected occupant behaviour, E12 adds: *"[...] we try and create automated systems to take out the human factor, but it's not always possible."* This call extends to the automatic and continuous analysis of energy-saving opportunities (E11) and continued automation of control systems (E14). The controls should be connected with the energy metering (E11) and learn to respond to changes in the environment (E13). At the same time, the experts are aware that it is difficult to link systems in an optimal way (E15) and that automated systems *"can often be not necessarily functioning as you would hope, and they're operating whether or not they need it"* (E12). Ironically, they are consuming energy themselves (E12). And from an occupant perspective, *"there has to be a level of control by the people that are operating the building, specifically in laboratories and so on"* (E12).

5.5 Discussion

In this chapter, I have estimated the maximum saving potential of interventions that target the operational energy consumption of buildings without changing existing energy systems by using campus energy data from the COVID-19 pandemic. I have also contextualised the data to better understand the real-world factors that hinder the realisation of this potential, and the strategies that are proposed by experts to address them.

5.5.1 The energy-saving potential in buildings

My first aim was to estimate the maximum energy-saving potential of interventions, including digital interventions, that target operational energy consumption in buildings. To do so, I focused on the buildings' baseload, which refers to their minimum electrical demand over a specific period. This means that digital interventions that target operational consumption, such as energy system automation and behaviour change interventions, can by definition only reduce the consumption down to this threshold. To approximate the baseload in 19 selected campus buildings, I used each building's nighttime consumption between 00:00am and 06:00am. As my analysis shows, in almost all of the analysed buildings, the 2020 nighttime consumption stayed either roughly equivalent to 2019 or saw a slight decrease (with a mean and median of -10%). Based on the assumption that the buildings' baseload cannot be lowered further than during a global pandemic, at least when the buildings need to stay habitable, this decrease can be regarded as the maximum possible decrease and the remaining consumption as the minimum consumption of a building. In turn, this means that the maximum operational saving potential can be estimated as the difference between the total consumption of a building and its baseload—I calculated this difference for the 19 campus buildings for the years 2019, 2020 and 2021. What I found were substantial variations across buildings and years: in 2019 and 2021, the years without strict lockdown policies, the operational consumption accounted for between 0% (in offices, business spaces and the pre-school) and over 50% (in offices, the hotel and sports facility); in both years the average across buildings was 19%. Given the large variation across buildings and the influence of rounding errors, this derived saving potential of around 20% must not be taken as a exact value but a rough estimate for the set of selected buildings.

I also looked at the campus as a whole. Based on my calculations, during the spring of 2020 (the period with the strictest lockdown measures) the overall electricity consumption on campus dropped by 29%, while the average decrease across the 19 selected campus buildings was slightly lower with 23%; numbers that align with findings from other university campuses, which mostly report savings of between 15% and 50% (see Section 5.1). While this consumption decrease is substantial, it still indicates that excluding people entirely from certain areas and buildings did not impact around 70% of the buildings' consumption. Together with the explanation by one of the experts that the continued operation of key services, such as pumped supplies and appliance-related equipment, was one of the key reasons why the consumption did not decrease further during the pandemic, it again highlights the significance of baseload. What should also be noted is that the savings did not continue during the less restricted periods: across the 19 selected buildings, the mean electricity consumption in spring 2021 was roughly equivalent to that in 2019 (before the pandemic). This indicates a weak link between electricity consumption and occupancy (which on campus was still low in spring 2021) and the influence of other factors.

Overall, the maximum energy-saving potential of interventions that target the operational energy consumption in the selected campus appears to be between 20% and 23%, depending on whether would be possible to (slightly) lower the baseload to lockdown levels even with occupants present. The 29% for the whole campus likely include some non-building-related savings, e.g., reduced charging of electric vehicles, lighting of outdoor spaces and use of large screens on the main plaza, and would thus overestimate the saving potential for individual buildings.

5.5.2 Realising energy savings in buildings

For multiple reasons, it would be difficult to realise this potential. One of the reasons is that digital energy-saving interventions will not remove occupants from buildings. The estimated 20% to 23% possible savings describe the *entire* operational day-time consumption in a building—which cannot be eliminated during non-pandemic times when occupants are present. Even if occupants remember to close windows when they leave a room and unused devices get turned off automatically, occupants still need devices and lighting *while* they work. In addition, going from zero occupants to one likely has a much larger impact on a building's electricity consumption than going from ten to one hundred because it means that all energy systems need to run to keep the building habitable. As the experts explained, this also prevented further energy reductions during lockdown periods, because the few people who remained on campus were spread across buildings. The poor energy system control capabilities the experts described add to the challenge, as in most buildings spaces cannot be selectively controlled. In the current situation, this means that reducing occupancy on campus would likely only have a minor effect on the energy consumption of buildings (except for the case in which the remaining occupants all live and work in the same building).

Additional factors that hinder energy savings and thus the realisation of the established saving potential were provided by the experts during my Jamboard study and focus group interview: limitations and failure of technology; missing, unreliable and unused data; occupant behaviour; and lack of resources. This builds on the findings from the expert interviews I have presented in Chapter 4. Limitations and failure of technology, for example, mirror the previously reported experiences with the EIS, and the narrative around occupants continues to be critical. Regarding the latter, two experts in particular expressed frustration about indifferent attitudes and careless actions of many occupants, such as leaving windows open and turning thermostats up. In response, one expert described ongoing efforts to take out the "human factor" by creating automated systems. In fact, despite the limitations and failure of technology, data issues, lack of resources and energy-wasting occupants behaviour, which can all limit the impact of energy system automation and optimised control, the experts suggested it as a key strategy to save energy on campus. This aligns with "seamless" but unevidenced visions from the expert interviews that I presented in Chapter 4. The experts imagine an ideal scenario in which energy system automation and optimised control would allow for the identification and realisation of energy-saving opportunities, quick adjustments to changes in the environment and a closer link between electricity consumption and occupancy. However, there remain open questions and tensions, regarding e.g., the agency of occupants to control energy systems and devices in buildings. Automation would have implications for campus users—bringing energy reduction into tension with those whose primary needs include learning and conducting research.

Another open question concerns the limited effectiveness of automation and efficiency measures on campus due to campus growth. As established in Section 5.3, between 2016 and 2019 the mean electricity consumption on campus increased by 25%. This means that the mean consumption in 2020, the year with the strictest lockdown policies, was roughly equivalent to the mean consumption in 2018, a year without lockdown restrictions. As the resources that were saved through past interventions were likely re-invested in a way that enabled and supported the growth of campus, e.g., enabling the development of new campus buildings, this can be regarded as an example of the "rebound effect"; a hypothesis that was shared by one of the experts who suspected *"that energy efficiency gains are being off-set by growth, i.e. Jevons Paradox."*

5.5.3 Reflecting on the role of energy data

The experts have highlighted multiple challenges regarding the use of energy data—which, interestingly, I also experienced in the context of my own energy consumption and baseload calculations. The first of theses challenges is the unavailability of relevant data. Rather than being able to select the buildings I wanted to analyse, I had to base my selection on the availability of energy data as the basis for my calculations.

As an apparent contradiction, I then also encountered the second challenge the experts reported: data overload. For me, this occurred on the building level rather than the campus level. For the buildings I was able to select, the electricity consumption was usually reported in 10-minute intervals, which for the main meter alone, added up to over 15,000 data points for each building's five-week period over three years (a fraction of the historic energy data for the whole campus). The daily aggregate that I visualised in form of violin graphs allowed for the comparison between buildings and the communication of overall consumption changes. As a trade-off, it did not capture finer-grained consumption patterns. Whatever the aggregation, the number of available data points explains why a lot of the energy data on campus does not get used for energy reduction purposes.

The last data-related challenge, unreliable data, can be even more problematic, as it can lead to incorrect conclusions. For example, being able to distinguish between normal and abnormal values and to explain patterns in the data (e.g., a heightened consumption in 2021) requires contextual knowledge, which can be difficult to obtain. In my study, I obtained the contextual knowledge from both informal conversations and formal studies with experts, who knew the data, buildings, metering system and historical context well. However, the availability of contextual knowledge cannot be assumed for all digital energy-saving interventions, which limits the confidence with which conclusions can be drawn. The need for contextual data also leads to a paradoxical situation: the more energy data is captured for analysis, the more data is needed to contextualise it. All of this data needs to be stored and analysed—which leads to a higher energy consumption and more complexity. What could be described as another "irony of energy system automation" (in addition to those described in Section 4.5.4) highlights the limitations of digital energy-saving interventions that are purely based on quantitative approaches.

5.5.4 Support for a policy-based approach

One of the initially surprising findings was the increased daytime energy consumption *after* the pandemic in 6 out of 19 campus buildings to levels higher than in pre-COVID-19 times. A closer look revealed that all of these buildings were non-residential (e.g., businesses, offices and the pre-school) and that the heightened electricity consumption in 2021 can be explained by COVID-19 policies that required increased air ventilation rates to reduce transmissions of the virus. According to the experts, where buildings had mechanical ventilation, it had to be run at full capacity, which was more than pre-pandemic and required additional electricity. Heat recovery systems on air handling systems also had to be switched off (to minimise the cross-contamination risk). Comparing the mean daytime consumption on campus in 2019 with 2021 across all analysed buildings, I found 0% difference despite some ongoing

COVID-19 measures and reduced occupancy (due to e.g., hybrid teaching) in 2021. This indicates that any savings from reduced occupancy were neutralised by other factors, such as policies, and that a policy-based approach to reductions might be more effective than an individual consumer behaviour approach.

One of the strategies the experts proposed to tackle the real-world factors that hinder energy savings, namely good decision-making across the University, also has elements of policy-making. The experts agreed that an effective approach requires solid decision-making with a focus on sustainability (environmental and financial) by those in charge as well as top-down initiatives on a departmental and team level. The former links back to the impact of policies that affect energy consumption, such as those described above: policies set the context for interventions and can provide incentives and pressures. Taken together with the weak link between electricity consumption and occupancy, one expert suggested a shift from behaviour change interventions to focused stakeholder targeting.

Lastly, policies can play an important role in preventing rebound effects, including the specific case of the Jevons paradox, where the effect is larger than 100% (Sorrell, 2009). As described above, I uncovered this case as part of my energy consumption calculations: the mean electricity consumption on campus increased each year between 2016 and 2019, despite a large number of energy-saving projects and interventions. As a well-established concept in the energy literature that describes a range of mechanisms counteracting efficiency savings, the campus growth example shows that rebound effects have the potential to limit the overall effectiveness of (digital) energy-saving interventions. When savings from successful interventions get re-invested in a way that increases the total energy consumption of e.g., the University campus, the situation might become more viable financially but not from a climate change mitigation perspective. Given the limited operational saving potential in buildings, it would be especially hard to rectify such a situation if it involves the construction of additional (non-passive) buildings. Here, global carbon constraint policies could be effective tools to prevent rebound effects (Freitag et al., 2021). I will discuss this in more detail in Section 6.3.4.

5.5.5 Summary

From an energy perspective, the COVID-19 pandemic has presented a unique research opportunity: the absence of most people from non-domestic buildings. In this chapter, I have focused on Lancaster University's electricity consumption during the pandemic to better understand the maximum operational saving potential in buildings, the extent to which it can be realised that the factors that can impede its realisation. In the context of my thesis, the analysis allowed me to explore (a) the electricity baseload in buildings that cannot be targeted by digital interventions that focus on operational savings, e.g., energy system automation and behaviour change interventions; (b) the operational electricity-saving potential of buildings that could be targeted by digital interventions; (c) the variation of that potential during COVID-19 (low-occupancy) periods and non-pandemic (regular occupancy) periods and (d) real-world factors that impact the energy consumption on a university campus with mixed-use buildings and proposed strategies to address them.

My analysis showed that across the analysed campus buildings, the maximum energy-saving potential of digital interventions in the selected campus buildings, such as behaviour change interventions, can be estimated to be between 20% and 23%. Due to a number of reasons, including the substantial energy requirement of even one occupant within a building, technical limitations and "imperfect" occupant behaviour, it is very unlikely that it could be fully realised. For the campus as a whole, the electricity consumption dropped by around 30% during the strictest lockdown period, aligning with calculations from other university campuses. However, what could also be observed was the continuous growth of the University campus and its total electricity consumption. From 2016 until 2019, the consumption grew by 25%, explaining why the mean consumption in 2020 (impacted by lockdown periods) was roughly equivalent to the mean consumption in 2018. This suggests a rebound effect, in which savings were re-invested into energy-consuming infrastructure, devices or services; a topic which I argue deserves more attention in the context of digital efficiency interventions in buildings.

During the COVID-19 pandemic, policies were able to reduce health risks in campus buildings and likely save lives. However, from an energy consumption perspective, my analysis shows that they had the opposite effect of what one might have hoped and expected to see. If one considers COVID-19 lockdown periods as an "extreme intervention" that permanently changed working practices, a desirable outcome might be a lasting reduction of campus energy demand instead of a return to pre-intervention or even higher levels. Instead, what I found was a weak link between electricity consumption and occupancy, which can explain a heightened electricity consumption in 2021: the negative impact of air ventilation policies mitigated all savings from reduced occupancy. This indicates that a policy-based approach would be able to save more energy than an approach that focuses on individual occupants.

Chapter 6

Rebound effect considerations in computing research on energy efficiency

The contributions of this chapter are largely based on published work, Bremer, Gujral, et al., 2023. As the first author, I led the collaboration, writing and analysis. I also carried out the literature searches, except for the SIGCHI library. The resulting paper contains a more detailed contribution breakdown in its Acknowledgements *section.*

> "Efficiency is doing the thing right. Effectiveness is doing the right thing."
> —PETER F. DRUCKER

In the electricity consumption analysis in Chapter 5, the experts who contextualised the electricity data explained how a continuous growth of the University campus had counteracted any possible efficiency savings (and over five years, even the changes brought about by the COVID-19 pandemic on the average yearly consumption); one expert referred to it as an instantiation of the Jevons paradox. As system optimisation through automation is a digital energy-saving strategy that the experts whose views I present in Chapters 4 and 5 consider to be especially promising, I want to explore such saving mitigations further. More specifically, I will focus on rebound effects, which I have described in detail in Section 2.4.3. These effects limit the resource-saving potential of efficiency interventions, including the energy-saving potential of digital interventions; linked to Peter F. Drucker's quote above: rebound effects can make energy efficiency ineffective. If computing researchers want to fully exploit the potential of efficiency interventions, they would need to accurately account for and, ideally, mitigate rebound effects. To what extent have they done this until now? And what kind of knowledge is needed for them to do so?

While the concept of rebound effects is not native to computing research, it affects the conclusions that can be drawn from studies in this field and thus the design of technology for energy savings. By ignoring rebound effects, there is a risk for energy research and interventions to become misdirected, and efficiency savings might backfire. If energy research informs decisions on a policy level, there is also a risk that policy makers direct their funding and reforms towards efficiency measures which ultimately might not bring the anticipated results, leading countries to miss critical climate and emission targets.

To explore the attention paid to rebound effects in computing research, this chapter investigates the prevalence of rebound effect considerations in the energy efficiency literature. I focus on smart home research as a representative domain in which energy efficiency research is prominently placed; in the context of my thesis, this aligns with the focus on energy use in *buildings* from Chapter 4 and Chapter 5. More specifically, while there exist a range of other smart contexts, i.e., smart cities and smart offices, smart homes are a particularly well-established area of research with a large body of available literature (significantly more than for smart buildings as the more general term) that allows me to continue my research on a building-level.[1]

In the upcoming sections, I present the results from a systematic literature mapping in four scientific databases for possible combinations of the keyword clusters "smart home", "energy efficiency" and "rebound effect". Through this mapping, I aim to establish to what extent (smart home) energy efficiency research in computing has considered rebound effects and how this compares to rebound effect considerations in energy efficiency research more generally. The mapping also allows me to identify relevant publications on rebound effects in the context of (smart home) energy efficiency interventions, in order to analyse how they can inform energy efficiency interventions in computing more generally.

Importantly, rebound effects stem from the interplay of technical characteristics with social, psychological, economic and cultural factors (Strengers, 2011a; Pierce, Schiano, and Paulos, 2010; Tirado Herrero, Nicholls, and Strengers, 2018) and can thus be described as socio-technical phenomena. As a research field in computing that studies such phenomena, the literature mapping includes a HCI corpus, besides the more technical computing databases. This decision was made because compared to researchers in other research fields, HCI researchers tend to focus more strongly on socio-technical phenomena; their existing research features critical engagements with smart energy and demand reduction, especially the expectations, experiences and attitudes of energy consumers, e.g., Strengers, 2014; R. H. Jensen, Strengers, Kjeldskov, et al., 2018; Hargreaves, Nye, and Burgess, 2010; Strengers, Kennedy,

---

[1] As rebound effects depend at least to some extent on the building in which they occur, it should be acknowledged that not all types of rebound effects will occur in all types of buildings and that some rebound effects that apply to smart homes might not apply to e.g., university campus buildings.

et al., 2019. This means that they are more likely to be able to offer insights on rebound effects to other computing communities and policy makers.

6.1 Motivation and methods

In the research field of energy policy, rebound effects are a firmly established concern (Safarzadeh, Rasti-Barzoki, and Hejazi, 2020). As the size of rebound effects varies significantly across contexts, a research goal in these fields is to identify causal factors that allow for concrete, context-specific estimations of rebound effects, to then direct and focus possible intervention points (Greening, Greene, and Difiglio, 2000; Wang, Han, and M. Lu, 2016). By understanding causal relationships and context-specific factors, it is argued that energy-focused research can be targeted and effective. The methods used to acquire this understanding include modelling and simulation (Wang, Han, and M. Lu, 2016; Nässén and Holmberg, 2009) as well as empirical studies (K. Chen et al., 2018; Haas and Biermayr, 2000) that take both macro-level policy perspectives and micro-level household perspectives into account. In the context of this work, researchers are encouraged to give *"due consideration to the full range of behavioural responses to technical efficiency improvements"* (Greening, Greene, and Difiglio, 2000, p. 390). After all, the actual energy consumption of a smart home is not determined by its technical components alone but must be understood as a socio-technical system.

A substantial part of the literature on smart homes, however, originates in engineering sciences; and although it has been shown that digital technologies are particularly prone to rebound effects—leading to the emergence of the term "digital rebound" (Coroamă and Mattern, 2019)—to my knowledge, it has not yet been analysed to what extent the computing and HCI communities at large, and that on smart homes in particular, have engaged with the concept of rebound effects. In 2011, Kaufman and Silberman, 2011 critically evaluated the research in sustainable HCI (SHCI): *"[P]roxies generally used in evaluation (e.g., less energy or water consumption) may be poor indicators of [persuasive or more efficient technologies'] effect on emissions because of effects outside the scope of analysis; in particular, direct and indirect rebound effects as described in the economic literature."* At this point, *"[t]he authors [were] not aware of studies examining the degree to which the effects of sustainable HCI technologies rebound"* (Kaufman and Silberman, 2011, p. 2). Assessing whether this has changed over the past decade, and how rebound effect considerations in HCI compare to those in computing more generally and, even broader, in all energy efficiency-related fields, has been a key motivation for the research underpinning this chapter. More specifically, I aim to establish the degree to which energy efficiency research in computing fields considers rebound effects, in order to evaluate the robustness of their results. I also aim to identify publications that have considered and discussed rebound effects in a smart home energy efficiency context to understand what their findings mean for the role of digital interventions in realising energy savings.

6.1.1 Procedure

To determine the engagement with rebound effects in smart home (and) energy efficiency research, I identified the publications in the following three research domains and their intersections: smart homes, energy efficiency and rebound effects; the domains and intersections are visualised in the Venn diagram in Fig. 6.1. Based on this mapping of sets, I was able to count the publications that consider rebound effects in computing's smart home (and) energy efficiency research and to also evaluate the relative frequency of attention to rebound effects in contrast to their larger research areas.

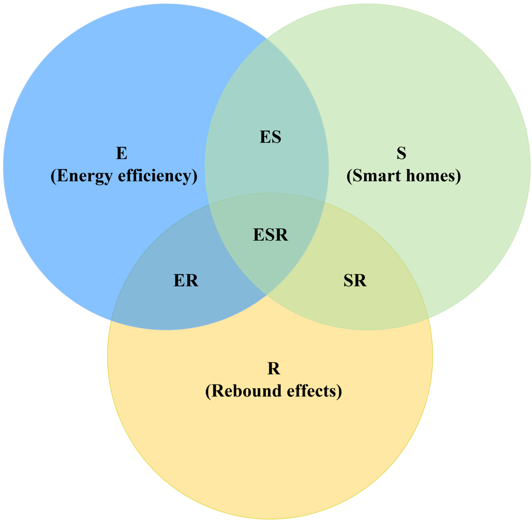


Figure 6.1: A visualisation of the seven keyword sets that were used in the literature searches. The sets are labelled with capital letters that represent the keywords which are included in each set.

The literature searches for each of the three research domains were conducted in multiple databases: general scientific databases (i.e., Scopus and ScienceDirect), general computing ones (i.e., IEEE Xplore and the ACM Guide to Computing Literature), and HCI-specific venues (i.e., conferences sponsored by the Special Interest Group on Computer–Human Interaction (SIGCHI) as well as the Proceedings of the ACM on Human-Computer Interaction (PACMHCI)). To identify the HCI-specific venues, the procedure was as follows: From SIGCHI's "upcoming conferences" website[2], all 2022 conferences were selected, which are 100% sponsored by SIGCHI: the Conference on Human Factors in Computing Systems (CHI) itself, 11 specialised conferences and 14 in-cooperation conferences (26 in total). From these, 6 were excluded because it was not possible to identify their collection of proceedings (Collective Intelligence Conference (CI), International Conference on Human Computer Interaction Theory and Applications (HUCAPP), Mensch und Computer (MuC)), their respective proceedings' website were not standalone searchable, but a search would yield results from the entire ACM full paper collection (International Learning Analytics and Knowledge Conference (LAK), International Audio Mostly Conference (AM)), or because they were not English-speaking (International Conference on Association Francophone d'Interaction Homme-Machine (IHM)). The resulting corpus, which I refer to as the "SIGCHI library", consisted of the all-time proceedings for the remaining 20 conferences (CHI, International Conference on Tangible, Embedded and Embodied Interaction (TEI), Conference on Creativity and Cognition (C&C), Conference on Designing Interactive Systems (DIS), International Conference on Interactive Media Experiences (IMX), Symposium on Engineering Interactive Computing (EICS), International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI), Recommender Systems Conference (RecSys), Conference on Mobile Human-Computer Interaction (MobileHCI), International Conference on Multimodal Interaction (ICMI), Conference on Computer Supported Cooperative Work (CSCW), Augmented Humans International Conference (AHS), Conference on Human Information Interaction and Retrieval (CHIIR), International Web for All Conference (W4A), Graphics Interface Conference (GI), International Conference on Advanced Visual Interfaces (AVI), International Conference on Conversational User Interfaces (CUI), International Workshop on Sensor-based Activity Recognition and Artificial Intelligence (iWOAR), Nordic Conference on Human-Computer Interaction (NordiCHI), and International Conference on the Internet of Things (IoT)) plus all volumes of the PACMHCI journal.

The literature search and mapping workflow is described in Fig. 6.2. To ensure the relevance of search terms, they were evaluated and tuned based on manual searches and sample checks. The final search terms used the following keywords and keyword combinations for the three different domains that are covered in the mapping (the content of Section 2.4.3 motivates the choice of search terms for rebound effects):

1. "smart home*"
2. "energy efficien*"
3. "rebound effect*" OR "Jevons paradox" OR "Khazzoom-Brookes postulate"

---

[2] https://sigchi.org/conferences/upcoming-conferences/

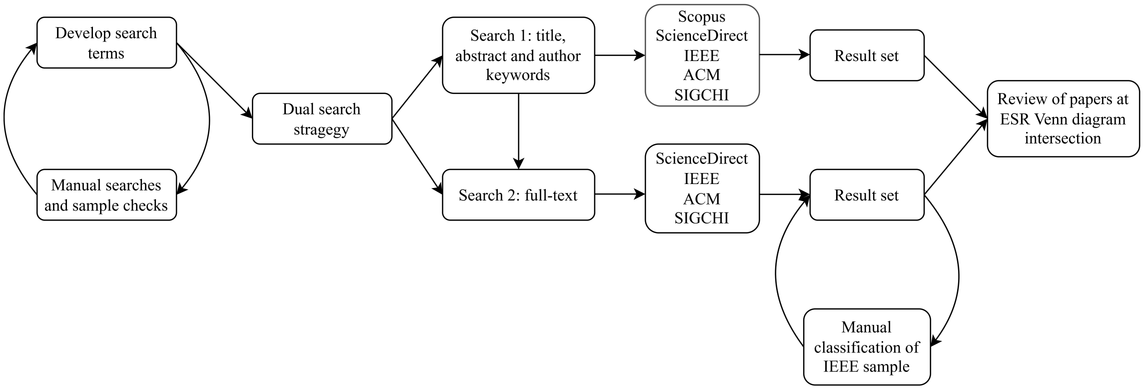


Figure 6.2: The literature mapping process.

Because ACM and ScienceDirect do not allow the use of wildcards as placeholders within quotation marks, the keywords/keyword combinations used there were as follows:

1. "smart home" OR "smart homes"
2. "energy efficient" OR "energy efficiency"
3. "rebound effect" OR "rebound effects" OR "Jevons paradox" OR "Khazzoom-Brookes postulate"

In a second step, I used the search terms to conduct searches in the four scientific databases mentioned above, namely Scopus, ScienceDirect, the ACM Full-Text Collection and IEEE Xplore. These databases were chosen to cover a representative proportion of archived literature within and beyond traditional computer science disciplines. For the searches—which were carried out in early 2022—I used a dual search strategy, meaning that the searches were conducted twice: (a) limited to the publications' titles, abstracts and keywords, referred to as *Search 1*, and (b) full-text searches (i.e., searching for the keywords anywhere in the publications), referred to as *Search 2*. In IEEE, titles, abstracts and keywords could not be selected as a set of fields due to a technical constraint, so my search covered the closest equivalent: "all metadata". The detailed list of search terms can be found in Appendix F.

The intention for the metadata-focused *Search 1* was to maximise the likelihood that the returned publications exhibit a focus on smart homes, energy efficiency and/or rebound effects, rather than to merely mention these terms in passing within a different context. However, the search could in principle omit papers that cover rebound effects but do not mention them in their title, abstract or keywords. I addressed this potential gap by combining the first search strategy with the second—which also enabled me to compare the number of search results for papers that focus on rebound effects (*Search 1*) and those that mention them but might not prioritise them (*Search 2*). Searching only in titles, abstracts and keywords (*Search 1*) might exclude publications that would thematically fit the search, so the full-text searches (*Search 2*) were intended as a strategy to rule out that the exclusion would skew the results. As Scopus does not store full texts, this was only possible for ScienceDirect, IEEE, ACM and SIGCHI.

Since the selected databases represent overlapping but distinct academic disciplines, computing percentages allowed for a comparison of rebound effect considerations among the selected databases. In particular, I considered the following two ratios for *Search 1* and *Search 2* to be the most relevant: (a) rebound effect considerations in the energy efficiency domain in general, and (b) rebound effect considerations in the energy efficiency domain for smart homes. The rebound effect considerations in the energy efficiency domain were calculated by:

$$R\, in\, E\, (\%) = (E \cap R) * 100/E \tag{6.1}$$

where E represents the number of papers in the energy efficiency domain, and $E \cap R$ denotes the number of papers in the energy efficiency domain that consider rebound effects. Similarly, rebound effect considerations in the energy efficiency domain for smart homes were expressed as:

$$R\, in\, E\, for\, S\, (\%) = (E \cap R \cap S) * 100/(E \cap S) \tag{6.2}$$

where $E \cap S$ represents the number of papers in the energy efficiency and smart homes domain, and $E \cap S \cap R$ denotes the number of papers at the intersection of energy efficiency and smart homes that pay attention to rebound effects. To refine and evaluate the search strategy, including the search terms, I conducted manual checks on the IEEE result sets, with emphasis on the number of "false positives" returned in the full-text searches, i.e., the number of returned papers that do not focus on smart homes, energy efficiency and/or rebound effects. As a database focused on engineering and computing, IEEE is highly relevant for smart home research and I considered its result set to be a representative sample for the research goals.

Finally, to understand and learn from the existing literature on rebound effects in smart home energy efficiency, I reviewed the papers that contain all keywords (area ESR in the Venn diagram in Fig. 6.1) in their titles, abstracts or keywords. For computing specifically (i.e., IEEE and ACM), there were no papers comprising all keywords in *Search 1* (by definition, this extends to ACM's SIGHCI subset), so I performed the same review on the SIGCHI papers containing all three keywords anywhere in the full text (i.e., for *Search 2*).

6.1.2 Limitations

Like for any systematic mapping study, there are some limitations. The databases do not cover all existing literature on smart homes, energy efficiency and rebound effects. This means that I might have missed some of the published work in these domains. Second, it is unclear to what extent the result sets from the different databases for each search overlap (with the exception of the SIGCHI library, an ACM subset by design). Lastly, due to the reliance of specific keywords as indicators for both awareness and research focus, it is likely that the presented result sets are affected by a small number of false positives (i.e., papers that include specific keywords, but do not engage in an analysis of the subject) and false negatives (i.e., papers that cover the subject area but do not use the search terminology, such as papers covering energy efficiency and consumption without using the term “energy efficient”). For example, one of the 6 SIGCHI results in the ESR set of *Search 2* turned out to be the full proceedings of CSCW’17, which contain all keywords spread across different papers. Nonetheless, the covered databases are among the most comprehensive sources available, and combined, the number of missed papers should be small. In addition, full-text search and manual verification address false positives, the terminology of rebound effects is well established and the identified trends are unlikely to be affected by minor shifts in time or coverage. Therefore, these limitations do not threaten the validity of the findings.

6.2 Rebound effects in the scientific literature

In this section, I present the quantitative results of all searches. I then discuss and compare the attention to rebound effects in computing to the attention they receive in the broader scientific literature. I also analyse the content of the papers that were returned for the most relevant intersections.

6.2.1 Overview

Based on the focused *Search 1* that took into account only titles, abstracts and author keywords, it can be seen that energy efficiency is a vast area of research across all fields, with Scopus alone returning almost a quarter-million papers (see Table 6.1, row 1). In IEEE and ScienceDirect, the numbers are slightly lower but still substantial with around 66,000 and 40,000 search results for “energy efficiency” respectively. ACM’s full-text database returned almost 7,000 results, while the lowest number of results was returned for the SIGCHI library, with only 33 papers that mention energy efficiency in their title, abstract or keywords. Smart home research is more evenly distributed, with approximately 15,000, 7,000, 1,000 and 1000 papers appearing in *Search 1* for the four large databases, and 200 in ACM's SIGCHI subset. By contrast, the number of papers mentioning "rebound effects" is limited to a few thousand at most, almost all of which appear outside of the computing databases: Scopus, ScienceDirect, IEEE and ACM contain 2,714, 1,114, 79, and 7 papers respectively, and SIGCHI does not contain any (see Table 6.1, row 3).

Row	Set	Scopus	ScienceDirect	IEEE	ACM	SIGCHI
1	E	249,167	39,663	66,196	6,842	33
2	S	15,502	1,113	7,070	1,149	200
3	R	2,714	1,114	79	7	0
4	ES	895	93	367	47	3
5	ER	**607 (0.24%)***	**337 (0.84%)***	**17 (0.02%)***	**1 (0.01%)***	**0**
6	SR	5	1	1	0	0
7	ESR	**4 (0.45%)****	**1 (1.07%)****	**0**	**0**	**0**

* as per Eq. 6.1 ** as per Eq. 6.2

Table 6.1: Results from Search 1 (titles, abstracts or author keywords).

Looking at the intersections for *Search 1*, it is clear that energy efficiency in smart homes has received considerable attention across all databases. For the *ES* set, Scopus returned almost 900 results, followed by IEEE and ScienceDirect with 367 and 93 results, respectively. The same is not true for rebound effects: In ACM, there are no papers at the intersection of "smart homes" and "rebound effects", as shown in Table 6.1, row 6. Similarly, only one paper was found in IEEE, whereas 5 papers were found in Scopus.

Proportionally, the highest percentage of papers on "energy efficiency" that mention "rebound effects" can be found in Scopus (0.24%) and ScienceDirect (0.84%), with several hundreds of publications (see Table 6.1, row 5). This degree of rebound consideration in energy efficiency work does not extend to the computing literature: as row 5 in Table 6.1 shows, for general energy efficiency, the ratio of papers focusing on rebound effects is only 0.02% and 0.01% for IEEE and ACM, respectively—one to two orders of magnitude lower than in the two general literature databases (i.e., 1 to 2 papers in 10,000 respectively, compared with more than 2 and 8 papers in 1,000). Strikingly, not a single paper in the field of computing (neither IEEE nor ACM) simultaneously encompasses all three topics based on *Search 1*. Scopus and ScienceDirect yield 4 papers and 1 paper, respectively (see Table 6.1, row 7).

Row	Set	ScienceDirect	IEEE	ACM	SIGCHI
1	E	212,029	170,243	18,928	278
2	S	7,641	25,977	5,078	777
3	R	11,779	797	98	23
4	ES	2,540	5,544	694	41
5	ER	**3,612 (1.7%)***	**251 (0.14%)***	**43 (0.23%)***	**10 (3.60%)***
6	SR	113	39	16	8
7	ESR	**92 (3.62%)****	**25 (0.45%)****	**12 (1.73%)****	**6 (14.63%)****

* as per Eq. 6.1 ** as per Eq. 6.2

Table 6.2: Results from Search 2 (full-text).

Perhaps computing papers engage with rebound effects but consider them important only within the context of discussing work in the body of text? The results from *Search 2* show that this is unlikely. As Table 6.2 documents, they are broadly consistent with the findings above, for both the energy efficiency literature in general and the smart home research field in particular; the discrepancy between the general literature (as reflected in the ScienceDirect database) and computing remains. ScienceDirect papers show an order of magnitude larger representation of rebound effects than IEEE, with ACM in between. For instance, in the thousands of ScienceDirect papers on "energy efficiency", 1.7% mention "rebound effect". In contrast, IEEE and ACM yield fewer papers—251 (0.14%) and 41 (0.22%), respectively (see Table 6.2 row 5).

6.2.2 Rebound effects in HCI research

The SIGCHI library represents a clear outlier compared to the other databases. For *Search 2*, the relative considerations of rebound effects among both general energy efficiency research and smart home energy efficiency research, is one order of magnitude above that of ACM (see Table 6.2, rows 5 and 7). It is also the only computing database in which the engagement surpasses (by a factor of 3-5) the one from ScienceDirect. However, it should be noted that these percentages play out on a low overall level: Of the over 30,000 papers of the SIGCHI library (see Appendix G), only 278 mention energy efficiency in their full text; and from the relatively substantial number of 777 smart home papers in SIGCHI, 41 address the energy efficiency of smart homes. Of those 278 papers in set *E* and 41 papers in set *ES*, relatively high percentages (3.60% and 14.63%, respectively) mention rebound effects; this is a much larger percentage than the 0.45% in IEEE and 1.73% in ACM overall.

This raises the question how exactly the papers returned in *Search 2* for the ESR set engage with the concept of rebound effects. Table 6.3 summarises the papers from the SIGCHI library that mention the smart home, energy efficiency and rebound effect keywords in their full texts[3]. A closer reading reveals that these papers refer to rebound effects but do not place them at the core of their analysis. For example, a recent study of smart meters in households discusses energy savings at length but only mentions rebound effects in passing: In some situations *"users wanted to heat the house a bit more than they would do normally in order to benefit from low prices (typically termed the rebound effect)"* (Alan et al., 2016, p. 5270). The participants were focusing more on pricing than efficiency. Another publication posed an open question about rebound effects as an afterthought, *"How to deal with rebound effects, to ensure efficiency gains are not used in additional emissions elsewhere?"* (Ahlers, 2020, p. 3). The paper in Table 6.3 that engages with rebound effects most profoundly is the one by D. Pargman and Raghavan, 2014, who provide conceptual frameworks for contributions to sustainability in HCI. I will return to their paper in the discussion (Section 6.3).

6.2.3 Learning from rebound research in smart homes

What can be learned from the small number of papers that *focus* on rebound effects in a smart home energy efficiency context? To answer this question, I reviewed the papers from the general literature which *centrally* address rebound effects. These papers, listed in Table 6.4, have all been published since 2017. Together with the insight that they aim to answer fundamental research questions (e.g., *"Does the rebound effect exist in smart homes and what is the size of the rebound effect?"* (K. Chen et al., 2018, p. 267)), it becomes apparent that the topic has only recently started to receive attention and that many important, especially more nuanced questions have not yet been addressed. The computing communities in particular do not seem to have this on their agenda, as none of the papers in Table 6.4 was published at a computing venue.

The papers point to some interesting behavioural dynamics, effect sizes and gaps in the literature, with potentially high relevance for HCI. Walzberg et al., 2020, for example, conducted an in-depth analysis of rebound effects, including the distinction between direct and (especially causal factors and dynamics of) indirect effects in smart homes, and the importance of suitable metrics for smart electricity management. The authors suggest that *"[w]hile RE [the rebound effect] does not cancel out all the benefits*

---

[3] The table lists 5 instead of 6 papers, as one of the results turned out to be the full proceedings of CSCW'17, which contain the keywords, but spread across different papers.

Year	Paper	Summary description
2013	Rodden et al., 2013	In this study, the authors explore UK consumers' attitudes towards future smart energy infrastructures that combine smart meters with software agents. Using a demonstration and animated sketches for their research, they provide design guidelines to address an identified distrust of energy companies. The rebound effect is briefly mentioned within the motivation of the research.
2014	D. Pargman and Raghavan, 2014	This paper features a wide-ranging discussion of sustainability in HCI and contrasts a set of conceptual frameworks for sustainability to reorient SHCI on a new, more ecological foundation. A well-referenced discussion of rebound effects is part of a broader critique of SHCI research that draws tight boundaries around its object of interest.
2016	Alan et al., 2016	The empirical study described in this paper includes a month-long observation of how residents used smart thermostats to control the heating in their homes, comparing the effects of three design variations to understand the implications of a set of design choices. The rebound effect is mentioned in passing.
2019	Stevens et al., 2019	This co-design study investigates how people use their travel and activity time, as well as their visions for making use of time in driverless cars. As part of the study, the participants were encouraged to engage with interior designs for these cars. The rebound effect is mentioned in the context of value of time theories.
2020	Ahlers, 2020	This position paper discusses open questions and existing challenges around urban mobility integration, with a focus on sustainability and emission reductions. Rebound effects are listed as part of these open questions/challenges.

Table 6.3: SIGCHI papers that contain the smart home, energy efficiency and rebound effect keywords in their full text.

Year	Paper	Summary description
2017	Kumar and Mani, 2017	Citing rebound effects as an important motivation, the authors conducted a life-cycle assessment to evaluate occupancy sensors for lighting loads in office buildings; based on case studies they also examined the role of designers in this context. Guided by their findings and relevant literature, the authors propose a model framework for smart homes and their components.
2018	K. Chen et al., 2018	This study performed experiments with student participants using software simulations of smart homes to better understand the occurrence of rebound effects in smart homes. Based on the obtained results, the authors offer recommendations for rebound effect mitigation.
2019	Beltram, Christensen, and R. Li, 2019	The paper outlines the results from field tests in which heating algorithms were employed in Danish apartments for flexible demand; one particular objective of these algorithms was to reduce rebound effects. User feedback was gathered and the algorithms were refined during the study, leading to better system performance.
2020	Walzberg et al., 2020	In this study, agent-based model simulations were run to assess the rebound effect in smart homes, with emphasis on the impact of contextual aspects of electricity, such as environmental impacts, cost and demand. The results show that the choice of metric (economic or environmental) is strongly linked to the size of occurring rebound effects.

Table 6.4: Scopus papers containing the smart home, energy efficiency and rebound effect keywords in their title, abstract or author keywords.

of energy efficiency, it should nonetheless be avoided when possible to maximize the contribution to sustainability." (Walzberg et al., 2020, p. 10); this implies that smart home efficiency gains do not result in backfire. The authors advise and promote the consideration of factors that decrease rebound effects in smart home design, especially related to user behaviours that tend to trigger them during certain periods. In another study that investigates rebound effects in smart homes, student participants were invited to use smart home software simulations (K. Chen et al., 2018). For both of their experimental setups, the results show significant rebound effects. However, as the authors were using simulations rather than energy data gathered in a real-world smart home context, the ecological validity of this study is low, which is not acknowledged by the authors; follow-up work is needed to confirm the findings outside of a lab setting. The only study in Table 6.4 that was carried out with occupants in the context of their everyday life is the one by Beltram, Christensen, and R. Li, 2019. While their iteratively improved algorithms led to an average peak demand reduction of 68%, it is unclear to what extent a reduction of rebound effects contributed to this result.

6.3 Discussion

Investigating the prevalence of rebound effect considerations in energy efficiency research in general and in smart home energy efficiency research in particular, the literature mapping described in this chapter consisted of two searches: the focused *Search 1* took into account only titles, abstracts and author keywords, while *Search 2* examined full texts. Covering the general scientific literature available in Scopus and ScienceDirect, computing publications as reflected in the IEEE and ACM databases, and HCI-specific publications, both searches show that rebound effects are overall poorly represented in smart home and energy efficiency research. There are, however, differences between the general literature and the technical literature: the attention to rebound effects in the latter is about one order of magnitude lower. For *Search 2*, the database with the—by a clear margin—highest *relative* considerations of rebound effects among both general energy efficiency research and smart home energy efficiency research is the SIGCHI library; around 15% of HCI papers that reference energy efficiency and smart homes also mention rebound effects.

A review of the HCI papers that constitute those 15% revealed that while the authors were aware of rebound effects, they mostly did not place rebound effects at the centre of their research or discussions. This was to be expected, given that the papers were returned in *Search 2*, the full-text search. To gain insights from papers that *focus* on rebound effects, energy efficiency and smart homes, I also conducted a review of the Scopus papers that were returned for the ESR intersection in *Search 1*. The review uncovered a critical lack of empirical research on rebound effects.

6.3.1 The need for empirical research on rebound effects

The lack of empirical research on rebound effects in the papers at Scopus' ESR intersection aligns with previous research findings. As Darby, 2018, p. 143 notes *"there is a striking contrast between the many research papers that* estimate *potential benefits from smart appliances/systems on the basis of simulations or trials in carefully controlled laboratory conditions and the handful that report on* measured *performance and acceptability in real-life conditions."* This gap in the literature has been argued to deserve prompt attention, given the "highly empirical nature" of rebound effects (Saunders, 2000). The deployment of technology does not happen in an (easily modelled) vacuum but is situated within the complicated everyday lives of people who are themselves shaped by cultures, demands and individual differences—which constitutes a key reason for why energy efficiency measures backfire (see for example the paper by Walzberg et al., 2020 in Table 6.4).

As the literature mapping revealed, research covered by ACM and IEEE, the computing databases, has shown the least relative engagement with rebound effects across all of the included databases—even though many energy efficiency interventions originate in technical fields. Communicating the socio-technical nature of rebound effects and relevant research findings from real-world contexts to all technically-oriented fields, as well as to policy makers and other stakeholders, could prevent at an early stage misleading research outputs and thus potentially misled policy measures and incentives as a result of incomplete analyses; measures that are critical for the reduction of GHG emissions. This is especially important in view of the vast amount of energy efficiency research that has been conducted: Scopus returned almost a quarter-million papers for *Search 1* alone. A systematic stream of research is needed to develop guidelines and conceptual frameworks to account for rebound effects both reactively and prospectively:

1. A posteriori, frameworks and empirical methods are needed to measure the size of rebound effects in real interventions.
2. A priori, tools are needed to evaluate the *potential* for rebound effects in given circumstances. Mitigation strategies are essential at all times, but in particular before technology is designed and deployed.

For both a posteriori and a priori challenges, it is important to understand what factors trigger rebound effects, in which contexts and to what extents. Here, literature in the ER intersection, i.e., literature on rebound effects in energy efficiency work outside of smart homes, could provide a meaningful starting point to identify the different contexts in which rebound effects have been discussed. Some of the open questions from a computing perspective might have already been addressed in these contexts.

6.3.2 Using systems thinking to study rebound effects

For various methodological reasons, assessing the indirect effects of digitalisation (both the environmentally beneficial and detrimental ones) is challenging (Coroamă, Bergmark, et al., 2020), and rebound effects are no exception: *"Environmental impacts that arise when technologies co-evolve with everyday practices are not easily predictable. This seems to be one reason why the existing literature [...] contains relatively few or vague recommendations to policy makers and other stakeholders"* (Börjesson Rivera, Gunnarsson-Ostling, et al., 2012 as cited in D. Pargman and Raghavan, 2014, p. 643). The different factors and mechanisms that drive rebound effects (see Section 2.4.3 for details) add to the complexity of the required research, though this does not mean that the research is not important. The paper by D. Pargman and Raghavan, 2014 that was returned for SIGCHI's ESR intersection in *Search 2* (see Table 6.3) agrees with this assessment: *"The fact that these are difficult problems and that few recommendations exist is however not a good enough reason to not take these factors into account when we design and deploy ICT systems"* (D. Pargman and Raghavan, 2014, p. 643).

To deal with complexity in sustainability research, a shift from computational thinking to system-level thinking has been encouraged among technologists: *"[C]omputational thinking tends to see the world in terms [of] a series of problems (or problem types) that have computational solutions (or solution types). Sustainability, on the other hand, demands a more systemic approach, to avoid technological solutionism, and to acknowledge that technology, human behaviour and environmental impacts are tightly inter-related."* (Easterbrook, 2014, p. 236). Representing such an approach, systems thinking is well-established and has been used in a range of fields. It takes into account the different components of a system, as well as their relationships (Checkland, 1999; Meadows, 2008) putting emphasis on the resulting dynamics and feedback loops instead of studying each system component in isolation.

In the context of rebound effects, systems thinking can be used to evidence the problematic tendency in the computing literature towards automation and optimisation without prior understanding of their social and environmental consequences (Easterbrook, 2014)—a tendency that is reflected in the literature mapping results I present in Section 6.2. Exposing the problems with techno-solutionism, i.e., the idea that digital innovations can simply be applied to fix global problems (Morozov, 2013; Lindtner, S. Bardzell, and J. Bardzell, 2016), this tendency often leads to a growing dependency on unsustainable ICT infrastructure (Easterbrook, 2014). In addition, systems thinking can be used to enable the successful application of efficiency strategies in an emission-constraint context: A recent publication reports the results of a transdisciplinary workshop with 19 experts to uncover the challenges of addressing rebound effects in digital innovation processes and associated policy (Widdicks, Lucivero, et al., 2023). The authors conclude that to adequately address ICT-related rebound effects, a systems thinking approach is required in which efficiency is understood as one solution among many—on the basis that emission constraints are in place, e.g., caps on GHG emissions.

6.3.3 Starting points to understand rebound systemically

To fully capture the mechanisms behind rebound effects and create rigorous theoretical frameworks, it is important to identify relevant factors and understand how they shape user behaviour (Turner, 2013). Potential factors and thus interesting starting points for this research include energy supply and demand responses (Turner, 2013), building types (Guerra Santin, 2013) and personal values (Seebauer, 2018). Preist, Schien, and E. Blevis, 2016 provide a useful lens to better understand both the mechanisms behind wasteful behaviour leading to an increasing ICT footprint, and design principles and strategies to address these mechanisms. These reflections could be extended to mechanisms behind indirect rebound and induce a shift towards more radically sustainable design practices.

Using their qualitative skills, HCI and other socio-technical researchers can also make important contributions by further exploring and speculating about potential impacts of smart home technologies, including their undesirable consequences, within and beyond the constraints of contemporary technologies and social life, e.g., Soden, Pathak, and Doggett, 2021; Rosson and Carroll, 2009; Ilstedt and Wangel, 2014. This is reflected in the call by Börjesson Rivera, C. Håkansson, et al., 2014, p. 112 to use a scenario methodology (among other methodological approaches) to assess second-order effects, including rebound effects, which can be particularly difficult to quantify: *"One option is to build scenarios on possible ICT futures based on certain assumptions and then assess the environmental impacts on first and second order level. Such an analysis would not quantify actual impacts, but could be useful in identifying potential impacts by using environmental systems analysis tools in combination with scenario methodology."* Identifying such impacts can feed back into systemic conceptualisations of rebound effects and inform empirical work.

Structural rebound is especially complex and poses a particular challenge for researchers. To identify and explain structural rebound, the focus on "leverage points" constitutes a promising approach (Penzenstadler et al., 2018). Leverage points *"are places within a complex system (a corporation, an economy, a living body, a city, an ecosystem) where a small shift in one thing can produce big changes in everything."* (Meadows, 1999, p. 1); examples include the goals of the system and the structure of information flows. Once identified, the design of systems and interfaces enables the exploration and potential use of leverage points, e.g., in order to change feedback loops and the intent of the system and stakeholders (Penzenstadler et al., 2018). In this context, prototyping allows for evaluations without infrastructure cost (Pierce and Paulos, 2012). Researchers can also draw on guidance for the application of systems thinking approaches and systemic design methods to support the development of more sustainable interactive systems (Nathan et al., 2008; Bornes, Letondal, and Vingerhoeds, 2022); a topic I will return to in Chapter 8.

6.3.4 Combining efficiency with sufficiency

While socio-technical research on rebound effects can produce valuable insights into the extent to which these effects occur, as well as their potential patterns and boundaries, the research is unlikely to offer simple solutions independent of policy changes. Looking across sectors, it becomes clear that the ongoing digitalisation has not substantially mitigated the existing environmental problems—likely due to the resulting rebound effects and their potential to outweigh digitalisation's benefits. As Santarius, 2017 notices, *"Humanity's ecological footprint keeps growing although we have already digitalized significant parts of our economy and society over the past years. It seems that digitalization is not relaxing but rather reshaping societal metabolism in a way that tends to rebound on global energy and resource demand [...]."* A paper fittingly subtitled *Why Digitalization Will Not Redeem Us Our Environmental Sins* adds: *"Digitalization is unlikely to be the environmental silver bullet it is sometimes claimed to be. On the contrary, the way digitalization changes society, making it ever faster, more connected, and allowing us unprecedented levels of efficiency might in fact lead to a backfire [...]. For most manifestations of digitalisation [...] a strong digital rebound seems to be the rule rather than the exception"* (Coroamă and Mattern, 2019, p. 7).

Digitalisation-triggered rebound does thereby occur both within the ICT sector and outside it, in society and economy at large. The former is represented by e.g., the induced material and energy consumption of smart technologies such as those deployed in smart homes. It is also reflected in Koomey's law (Koomey, Berard, et al., 2011) that shows that the exponential efficiency gains of computation (as reflected by the well-known Moore's law (Schaller, 1997)) have not led to close-to-zero energy consumption for computation, but to an equally exponential growth in the complexity of computations performed—in other words, a direct rebound effect of 100%.

Together with other factors, rebound effects contradict the idea that digitalisation and other technical innovations can "dematerialise" economic activity from resource consumption so that the economy can keep growing while its material footprint remains constant or shrinks. According to the available evidence, *"it is safe to say that the type of decoupling acclaimed by green growth advocates is essentially a statistical figment"* (Parrique et al., 2019, p. 32), (Haberl et al., 2020; Vadén et al., 2020; Wiedmann et al., 2015; Hickel and Kallis, 2020). Rebound effects are one of seven factors that stand against the feasibility of absolute decoupling.

Together, these insights reinforce the message that a more profound shift is needed to create truly sustainable societies (Mann, Bates, and Maher, 2018; Knowles, 2014; D. Pargman and Raghavan, 2014; Hickel, 2020; Nardi, 2019); they also confirm the importance of recognising and evaluating the impacts of technology-focused interventions systemically.

In line with the outcomes from the expert workshop mentioned above (Widdicks, Lucivero, et al., 2023), Freitag et al., 2021, p. 25 explain that *"[i]f a global carbon constraint was introduced, we could be certain that rebound effects would not occur, meaning that productivity improvements through ICT-enabled efficiencies both within the ICT sector and the wider economy would be realised without a carbon cost."* In other words, the only known conditions under which rebound effects do not occur are conditions of constraints. This means that the combination of efficiency and sufficiency strategies offers conditions in which digital interventions can bring their intended environmental benefits (Hilty, Lohmann, and Huang, 2011). When technical efficiency concurs with limited input resources, real progress can be made towards long-term sustainable resource usage. Digital technologies can then be used to replace or improve existing activities without stimulating additional activities.

6.4 Summary

Rebound effects are a well-established concept in the energy literature with the potential to significantly reduce the energy-saving potential of digital energy efficiency interventions. In this chapter, I have analysed to what extent energy efficiency research has engaged with rebound effects, using smart homes as a relevant application area; the selected databases covered the general literature, the computing literature, as well as HCI-specific publications. In the context of my thesis, the analysis allowed me to explore (a) the prevalence of rebound effect considerations in energy efficiency research, (b) how this prevalence compares across disciplines and for smart home focused vs. general energy efficiency research, (c) the research insights from publications that address rebound effects in a smart home energy efficiency context and (d) potential contributions that the HCI community and other socio-technical research communities could make to increase researchers' and policy makers' understanding of rebound effects.

My analysis shows that energy efficiency is a vast area of research, in which rebound effects are overall poorly represented. The lowest engagement with rebound effects was found in the technical literature—about one order of magnitude lower compared to the general literature—even though many energy efficiency interventions originate in these fields; this applies to both smart home focused and general energy efficiency research. The most frequent mention of rebound effects was observed in the HCI corpus, which aligns with the field's socio-technical focus. A closer review of the papers that address rebound effects in a smart home energy efficiency context revealed that they were recently published outside of computing venues and mostly address fundamental research questions with non-empirical methods. Here, I call research communities with relevant expertise to assesses rebound effect sizes, patterns and constraints, engage in system-level thinking and raise awareness among researchers and policy makers.

Such work is critical because rebound effects constitute a key reason for why efficiency strategies need to be combined with sufficiency measures (e.g., emission constraints) to become effective resource-saving and thus emission-saving tools. With a quantified understanding of rebound effects, technologists and policy makers will be under pressure to acknowledge that digital interventions alone will not substantially mitigate the environmental problems humanity is facing and thus to enact relevant constraints.

Chapter 7

Critiques of behaviour change technology in sustainable HCI

The contributions of this chapter are largely based on published work, Bremer, Knowles, and Friday, 2022. As the first author, I am also the primary contributor of the figures, findings and analysis. As co-authors, my supervisors guided the work and conclusions and edited an earlier version of the paper.

In the three previous chapters, I have identified several limiting factors around digital energy-saving interventions. These includes (a) the limited effectiveness of behaviour change interventions (which was described by the interviewed experts in Chapter 4 and quantified within the context of campus buildings in Chapter 5); (b) the focus on individual users and frustration with their "non-rational" behaviour—even though the users experience contradicting pressures in everyday life and have limited capacity for action; and (c) missing engagement with longer-term behavioural mechanisms (such as rebound effects, see Chapter 6). Similar reflections have raised concern in the Sustainable Human-Computer Interaction (SHCI) community, which emerged around 2007, when it largely focused on the design of behaviour change technology for sustainability interventions (DiSalvo, Sengers, and Brynjarsdóttir, 2010). As described in more detail in Chapter 2, the resulting research was centred around the design and use of technology that is intended to make its (mostly individual) users behave more sustainably, for example by giving them feedback on their energy consumption. Keen to help mitigate climate change and related problems that have arisen outside the field of computing, behaviour change projects have presented opportunities for HCI researchers to use their expertise towards the promotion of sustainability.

As the field progressed, an increasing number of critique papers challenged the effectiveness of these projects. Around 15 years after the emergence of SHCI, this presents a unique research opportunity to understand the impact of these critiques and if they have led to significant shifts in the research that has been conducted. In other words, with the existing evidence that the resource-saving potential of behaviour change technology is limited, and the historic availability of this knowledge in SHCI, analysing developments in the field can help answer the following questions: Have the alternative approaches proposed in behaviour change critiques led to more effective digital interventions? If so, what kinds of interventions are these?

To answer these questions, this chapter explores how SHCI researchers have responded to critiques arising from the community, and whether this has opened up new territory for impactful research. After presenting a more detailed motivation for this work, I describe the two corpora on which the work is based. Using the first *critique corpus*, I summarise a number of key critiques in SHCI in terms of the alternative research directions that they propose and analyse to what extent these proposals can be achieved with a traditional HCI skillset. Next, based on the second *critique adoption corpus*, I survey SHCI publications at CHI between 2019 and 2021, comparing the recent landscape of SHCI to the one mapped in 2010 (DiSalvo, Sengers, and Brynjarsdóttir, 2010) in order to reflect on the impact of these critiques. The aim of this chapter is not to judge SHCI contributions as right or wrong or to diminish the wide range of contributions in the field; instead, the aim is to understand the shifts that have occurred in the SHCI landscape and the insights they offer as to how HCI can effectively contribute to sustainability and to energy-savings efforts more specifically.

7.1 Motivation and methods

SHCI has seen significant critical engagement with its publications, with a number of key critiques emerging that challenge the assumptions of the field. For example, many researchers have called for a move away from designs which effect individual behaviour change, which—as established by DiSalvo, Sengers, and Brynjarsdóttir, 2010—is deeply ingrained in traditional SHCI research. Critics challenged the notion that people are "rational consumers" capable of engaging with the feedback provided to make more informed choices (Strengers, 2014) and also argued that persuasive sustainability interventions tend to overestimate individuals' capacity for action (Brynjarsdóttir et al., 2012): *"Even the best designed and most well intended PT [persuasive technology] application to foster sustainable behaviour cannot persuade users to engage in the desired behaviours if the circumstances are not allowing or supporting them"* (Ganglbauer, Reitberger, and Fitzpatrick, 2013, p. 64). Other critics questioned the effectiveness of individual behaviour change, for example arguing that, *"when evaluated 'in the wild', the scale of reduction achieved tends to be limited to less than 10 percent (of, say, household electricity or water) and is not proven to be long-lasting"* (Hazas, Brush, and Scott, 2012, p. 14), and (perhaps more fundamentally) challenged the belief that *"by merely changing practices at an individual level one can do away with unsustainability"* (Joshi and T. C. Pargman, 2015, p. 37).

Based on these concerns, there were calls to move *"beyond persuasion"* (Preist, Busse, et al., 2013), and in general, the community began to fundamentally reflect on their role and that of digital technologies for sustainability. Mankoff, 2012 asked, *"What percentage, really, would even global adoption of any of our projects create?"*, while others more explicitly urged the community to *"develop a reflective awareness for situations in which computational technologies may be inappropriate or potentially harmful"* (Baumer and Silberman, 2011, p. 2271) and realise that *"while there will always remain problems for computer researchers and professionals to solve, not all problems are necessarily best solved by the application of ICT/computing power or 'high-tech' solutions [...]"* (D. Pargman and Raghavan, 2014, p. 644). Sufficient time having passed, it is now possible to analyse the published critiques and subsequent SHCI research to understand if the community has been able to internalise the critiques without stretching beyond reasonable competencies of the discipline (see Chapter 2 for a detailed history of HCI and the associated competencies). In order to do that, this chapter relies on the two corpora that are described below.

7.1.1 The critique corpus

The first step of the analysis was to establish a corpus of SHCI critiques. The aim thereby was to bring together a representative set of publications that at their core aim to reform the direction and approaches of the field, rather than to provide an exhaustive list of papers criticising aspects of SHCI. To locate these publications, I carried out online searches in Google Scholar and the ACM Digital Library using the keyword "sustainable HCI". I also drew on the reference lists of the 2017 book *Digital Technology and Sustainability* by Hazas and Nathan, 2018. A publication was defined as an SHCI critique when one of its key contributions was to present a fundamental problem or gap in the SHCI literature and to ask the community to respond in a certain way. If incorporated, I also included its reference list and the articles that cite it in the search. This approach was used to handle the diversity of possible publication venues and make the corpus as comprehensive as possible.

A challenge I faced when establishing the corpus was in drawing the distinction between an SHCI critique to include and simply an SHCI-related publication. Many papers clearly either did or did not fit the criteria above, but for others, the decision was more nuanced. Overtly critical papers that reviewed the past literature and offered a new call to action, were easily included. I also included papers situated or more critical of work in a particular domain drawing on particular analysis or specific literature, that offered a call to shape research differently going forward. However, I excluded papers that reviewed SHCI literature to identify genres, trends or under-explored areas without actively criticising the existing research, e.g., Goodman, 2009; Hansson, Cerratto Pargman, and D. Pargman, 2021; DiSalvo, Sengers, and Brynjarsdóttir, 2010. Papers had to be in some sense "pivotal" and reflective with a call to the community to adjust course. I made these decisions as carefully as possible, taking into account both the content and language of the paper, paying particular attention to statements about the paper's core contribution(s). I also discussed the papers for which a decision was more difficult with my supervisors. In each included critique I checked that I could pinpoint at least one section in the paper that critically addresses SHCI research and one call to action.

The final corpus, which can be found in Appendix H, included 35 SHCI critiques. Without enforcing constraints on publication dates at the time of the research (spring 2021), the critiques span the period from 2009 to 2018. Figure 7.1 illustrates the distribution, frequency and publication venues of each of these. As the visualisation highlights, the critique timeline can be divided into: (a) a build-up phase from 2009 until 2013, where a handful of critiques were published each year; (b) a significant peak in the number of critiques published, spanning 2014 and 2015 across multiple venues—15 (43%) of the critiques in our corpus stem from these two years; and (c) a cool-down phase from 2016 onward with significantly fewer new critiques. Looking at the publication venues, it can be seen that the largest number of critiques by frequency (13) were published at CHI, followed by Interactions (7).

The key question driving the analysis was, *what are they asking HCI researchers to do?* The critiques each identify certain flaws in the then-current SHCI approach, and while they are often less prescriptive about what needs to be done instead, they do hint at the importance of developing new competencies within the SHCI community. To identify these competencies, I applied a thematic analysis to the critique paragraphs and calls to action that had already been located in each paper; established themes were iteratively refined to form the final competency categories. The following section shows the outcome of this analysis. Here, I provide a sketch of what the critiques have encouraged HCI researchers to focus on—in order to produce more effective research outputs—and which competencies they need for this. I hold for the moment the larger discussion around the adaptation to global change and "collapse" (Tomlinson, Patterson, et al., 2012; E. Blevis and S. Blevis, 2010), which assumes a more fundamental and unavoidable climate-induced change to society, returning to these in the discussion.

7.1.2 The critique adoption corpus

To explore the integration of the critiques within the SHCI community and to understand whether any clear trends were observable, I developed a corpus of relevant SHCI publications for analysis from CHI proceedings between 2019 and 2021.

Figure 7.1: The distribution of SHCI critiques by year and publication venue. The size of the circles (radius) is proportional to the number of included papers (shown in each circle).

Limiting the analysis to CHI was intended to track changes within a specific research community, for which CHI was chosen as the originating and preeminent venue for SHCI research. This does mean, however, that the analysis pertains only to the CHI community, reflecting the work of researchers who publish at CHI and reviewers and programme committee members serving CHI who collectively determine which SHCI works get published. I chose 2019 as the starting point, as this allowed approximately a decade since the emergence of the subfield—arguably enough time for a period of reflection, impact and change—to avoid overlap with the critique corpus, and three years of proceedings to provide a sufficient sized sample of current literature without over-representation of any one conference proceeding.

An initial set of publications was generated by searching the ACM Guide to Computing Literature via the ACM Digital Library using the keywords "sustainability" and "sustainable". Focusing on research articles, I obtained 568 results. I then manually checked the search results for relevance. In line with the criteria in DiSalvo, Sengers, and Brynjarsdóttir, 2010, I decided that for a paper to be regarded as an SHCI paper, one of its main contributions had to be sustainability-related. Papers that did not explicitly present sustainability as a key motivator for their research were excluded, even when the outcomes of their research were making contributions to sustainability. To match the critique corpus, papers had to target sustainability in an environmental/ecological sense, either exclusively or besides other kinds of sustainability (e.g., economic, social) to be included in the corpus. After manually checking the search results against these criteria, 27 papers remained, which constituted the critique adoption corpus: 7 from 2019, 8 from 2020 and 12 from 2021. The corpus can be found in Appendix I.

7.2 Proposed research directions for SHCI

In what follows I present the results of the critique corpus analysis in order to understand what SHCI researchers are being asked to do, and how this might align with or exceed what can be regarded as a traditional HCI skillset.

7.2.1 Calls for multidisciplinary expertise and collaboration

To avoid staying in its own knowledge bubble, the SHCI community has been asked to acquire knowledge from outside of HCI and to collaborate more widely (Silberman, Nathan, et al., 2014) and across disciplines (J. Chen, 2016), including collaborations with computer scientists and community organisations (Silberman, 2015) as well as practitioners in government, business, civil society and activist movements (Silberman, Nathan, et al., 2014). This is intended as an opportunity to learn from each other, to make SHCI research more impactful and to increase the community's understanding of the roots of current sustainability challenges, including the broader ecological, economic, social, political and historical contexts. Bendor, 2018 concludes that *"we must seek allies and become allies to others. If sustainability is a 'bigger than self' issue (Crompton, 2010), we too should grow both internally (by adding members) and externally (by assuming our place within Third Wave HCI)."*

HCI has always drawn from other disciplines—including psychology, sociology and information sciences—which allows for its unique understanding of humans, computers and the situatedness of their interactions. For SHCI specifically, researchers also require additional, sustainability-related expertise, as publications in this space regularly reference the work of orthogonal sciences, including climate science (e.g., GHG emissions (Jacobs et al., 2013; Preist, Schien, and Shabajee, 2019), carbon footprints (Clear, Hazas, et al., 2013; Preist, Schien, and E. Blevis, 2016)), ecology (e.g., biodiversity (Dema, Brereton, Esteban, et al., 2020; Moran et al., 2014)), hydrology (Hirsch and Anderson, 2010), air quality (Aoki et al., 2009; Kim and Paulos, 2010) and life-cycle analysis (Bonanni et al., 2010)). Given the relevance of this expertise, it would be counterproductive to question the benefits of multidisciplinary knowledge for SHCI research. But asking the community to become experts in further disciplines, such as economics and political science, there is a risk that they have to spread themselves very thin. Even without that additional workload, there already exists a steep learning curve for those entering SHCI: learning about and keeping up with new developments in environmental fields needs to be done alongside readings on technological innovation and disciplines that have traditionally informed HCI work. The behavioural sciences have especially been emphasised, and how a deep understanding of users' values, emotions and inherent psychology is essential for SHCI (Brynjarsdóttir et al., 2012; M. Håkansson and Sengers, 2013; Knowles, L. Blair, Coulton, et al., 2014). It has even been argued that *"without addressing the underlying psychology that perpetuates our current state of unsustainability, there is little that computing can hope to achieve"* (Knowles and Eriksson, 2015).

7.2.2 Calls for a shared understanding of sustainability

In the midst of its multidisciplinary curriculum, the SHCI community has been encouraged to reach a shared understanding, definition or framing of sustainability. Observations that *"definitions of sustainability in the sustainable HCI literature have become so broad as to become meaningless"* (D. Pargman and Raghavan, 2014, p. 638) are potentially in tension with concern about adopting an overly narrow definition of sustainability (Brynjarsdóttir et al., 2012), e.g., the calls that *"[f]uture HCI research must take a more comprehensive view of the environmental, social, and economic facets that make up sustainability"* (Dillahunt, 2014, p. 1) and to adopt a holistic view of sustainability and *"go beyond being 'about' being green"* (M. Håkansson and Sengers, 2013, p. 2733). Further contributions have encouraged the community to understand sustainability as a supply (rather than a demand) problem (Knowles, L. Blair, Coulton, et al., 2014) and *"[u]nsustainability [not as] a problem to be solved, but a complex and multifaceted condition with which we must grapple"* (Baumer and Silberman, 2011, p. 2273).

Linked to the discussion on how to arrive at a sufficiently meaningful definition of sustainability is the repeated call to specify sustainability goals and metrics and to carry out evaluations, e.g., Knowles, Bates, and M. Håkansson, 2018; Silberman and Tomlinson, 2010; J. Chen, 2016. Portrayed as essential for progress in the field, such measurements of impact are argued to increase SHCI's relevancy and scientific basis (Silberman and Tomlinson, 2010) and to *"promote research to practitioners outside the field [...] [and] help other researchers contribute to sustainability and gain acceptance for their work in the SHCI community"* (Remy et al., 2017, p. 104). To combat "feel-good motivations" that are insufficient for the environmental crisis, projects could be evaluated against a checklist for impact (Mankoff, 2012)—not an easy task as *"the proxies generally used in evaluation (e.g., less energy or water consumption) may be poor indicators of such systems' effect on emissions because of effects outside the scope of analysis; in particular, direct and indirect rebound effects as described in the economic literature"* (Kaufman and Silberman, 2011, p. 1). Moreover, it has been noted that a focus on specifying goals and metrics in relation to authors' own particular definition of sustainability has divided the community, keeping it stuck in debates about what sustainability *is* or *should be* (Knowles, Bates, and M. Håkansson, 2018). Instead, Knowles, Bates, and M. Håkansson, 2018 suggest orienting the field around climate change as a "big tent" for the myriad concerns of interest to SHCI.

Sustainability has always been a contested concept (Davison, 2001), and so agreeing on a shared framing or definition is undoubtedly a challenging task. Even without considering philosophical contributions from outside of SHCI, the critiques show the diversity of conceptualisations that are already promoted within the SHCI community; some of them are potentially in conflict with each other. There are, however, clear benefits should the community succeed in tackling this challenge: establishing a coherent SHCI agenda and metrics for evaluation would provide valuable guidance for both established researchers and those entering the field.

7.2.3 Calls for systems thinking

As the discussions within and outside of SHCI show, sustainability is an intricate concept with significant underlying complexity (Baumer and Silberman, 2011; Davison, 2001; Dillahunt, 2014). With this awareness, at the heart of many critiques sits what members of the community called for in 2014: *"Move beyond simple models to grapple with the full multi-scalar complexity of 'wicked' sustainability problems"* (Silberman, Nathan, et al., 2014, p. 68). Simple models do thereby link to computational thinking, which is rooted in the belief that with a toolbox of (algorithmic) methods, computer scientists are able to solve the worlds' problems by applying the correct solution (type) to any particular problem (type). In lieu of such solutionism, a more systemic approach has been called for: *"[T]he failure to think systemically is a critical weakness in our understanding of the transformations needed to achieve sustainability"* (Easterbrook, 2014, p. 236); as a means to overcome this "systems thinking *provides the necessary bridge from computational thinking to sustainability practice [...]"* (Easterbrook, 2014, p. 235). A shift from problems and solutions to situations and interventions, for example, *"could beneficially be applied in numerous areas of HCI research and practice, and resonates with work in the 'third wave' of HCI research [...]"* (Baumer and Silberman, 2011, p. 2273). On a methodological level, it has been argued that *"[t]he processes that give rise to the issues indexed by the term* sustainability *are larger in time, space, organizational scale, ontological diversity, and complexity than the scales and scopes addressed by traditional HCI design, evaluation, and fieldwork"* (Silberman, Nathan, et al., 2014, p. 67). Consequently, those in SHCI should *"[d]o research that considers longer time scales"* (Silberman, Nathan, et al., 2014, p. 68).

Many critiques address the need for SHCI research to be contextually embedded.

It should acknowledge that consumption is shaped by infrastructures, technologies and institutions (Strengers, 2011a) and that sustainability is balanced with other concerns and practices (M. Håkansson and Sengers, 2013). The inter-personal dynamics in social settings like households add another layer of complexity. Here, *"HCI designers can learn from the vast amount of social, cultural and anthropological research discussing how practices change in everyday life [...]"* (Strengers, 2011a, p. 2142). And because the focus of consumption practices is often non-environmental, *"it might not be useful to focus on consumption or the environment at all"* (Strengers, 2011a, p. 2142). In general, the community has been asked to think outside the box, and reimagine and create new approaches to tackle challenges of resource and carbon reduction (Hazas, Brush, and Scott, 2012). Macrostructures (Mollenbach, Hoff, and Hornbæk, 2012) and retrofitting (Weeks, Delalonde, and Preist, 2014), for example, are said to deserve attention. Other suggestions include *"having 'enough' as a central design theme for applications that support communication and information access"* (M. Håkansson and Sengers, 2013, pp. 2725–2726), to reconfigure what is old and new (M. Håkansson and Sengers, 2014) and to *"focus on a generative, positive theme of more to counter limits: more community, more shared activity, more collaboration, more shared moral sense of sustainability, more neighborliness, more empowerment"* (Xinning Gui and Nardi, 2015). Or not to design at all. To better understand when technology is and is not appropriate as a solution, it could be useful to present prototypes and abandoned alternatives alongside final designs, and the reasons for why those options were not pursued (Baumer and Silberman, 2011).

As researchers come to HCI through a diverse mix of disciplinary backgrounds, parts of the community might not currently find themselves fully trained and equipped to excel at systems thinking. For those with an HCI education, it has been shown that there are gaps in the curriculum which leave graduates ill-prepared to take on the challenges they face: a lack of e.g., (perceived or real) knowledge, resources and relevance regularly prevents the integration of sustainability principles and practices into the computing curriculum (Mann, Muller, et al., 2010). And even when these factors are eliminated, it is not necessarily clear how to best achieve a smooth and profound integration across modules that "touches" students (Eriksson and D. Pargman, 2014). The above critiques call for a redesign of the HCI curriculum to enable SHCI researchers to be able to think in ways needed to tackle sustainability. The critiques also raise questions about the path away from "solutionism" when designing technology solutions is what HCI as a discipline has largely evolved to do and about the feasibility to conduct research over long timescales, given the desired publication timescales.

7.2.4 Calls to support system change and activism

Emerging from more holistic thinking, a frequent call is to design for system change instead of individual behaviour change. This includes efforts to support activism and mass movements (e.g., Ganglbauer, Reitberger, and Fitzpatrick, 2013; Knowles, Bates, and M. Håkansson, 2018) as well as to influence institutions, infrastructures and policies (Silberman, Nathan, et al., 2014). The main idea is that interactive technologies can be used to address broader levels of community engagement (Joshi and T. C. Pargman, 2015) and societal transformation (Ganglbauer, Reitberger, and Fitzpatrick, 2013) rather than to target each user only within the context of their personal life: *"if research disciplines (ICT4S, HCI, Ubicomp) are to successfully progress towards a more sustainable future they must begin to consider limits to growth and more regularly attempt at more radical, more impactful changes (e.g., designing for non-reliance, a zero carbon future for non-negotiable), instead of putting the majority of its efforts into low(er) impact persuasion (e.g., attending to the impacts of background tasks)"* (Hazas, Clear, et al., 2015, p. 11).

This does not mean that persuasion should be abandoned. Rather, the aim is to apply the accumulated knowledge around persuasive technology more fruitfully: *"By focusing not on connecting people* to *their actions and their consequences, but on connecting people* through *their actions and their consequences, we can approach persuasive technologies as ones whose intent is to persuade people of the effectiveness of collective action and of their own positions within those collectives"* (Dourish, 2010, p. 7). Supporting people to engage in activist behaviours (Ganglbauer, Reitberger, and Fitzpatrick, 2013) is thereby seen as a particularly promising strategy as these behaviours, together with major lifestyles changes, *"are ultimately the behaviours that have the potential for significant impacts for sustainability (Knowles, L. Blair, Coulton, et al., 2014)"* (Knowles, L. Blair, Walker, et al., 2014, p. 1041). This is mirrored in the suggestion that high-impact areas (indoor climate, travel, food, and purchases) *"might be most effectively addressed in conjunction with policy initiatives and broader public support"* because they *"are so technologically, socially, and culturally mediated"* (Hazas, Brush, and Scott, 2012, p. 17). Such calls raise important questions, like those about the attribution of responsibility (Dourish, 2010) and protection of democracy: *"Can we identify ways to activate individuals and communities without jeopardizing that which makes democracy worth protecting, that is, without bringing to life some grotesque version of a (more or or less) benevolent eco-dictatorship?"* (Bendor, 2018, p. 84).

The critiques highlight the potential impact gain by redirecting efforts towards system change. In part recognising the endemic pace of innovation and uptake of research, they argue that SHCI should support or amplify the voices of activists, communities and larger groups to bring about and accelerate this change, cf. Aoki et al., 2009. However, this raises new questions for SHCI researchers as to their position, role and responsibility in this, if they want to successfully and fairly support system-level change. Besides the challenge to ensure that the developed systems allow activists and communities to democratically promote their personal sustainability priorities, rather than those of the designers, SHCI researchers might find themselves in a difficult position when the institutions that support their research do not support their activism. And while building knowledge, relationships and trust takes time, there is also a risk that these engagements cannot be maintained over longer time periods, leaving groups that come to depend on SHCI researchers without digital support.

7.2.5 Calls to re-imagine the economy, with limits to growth

Questions about responsibility and system change also emerge in the discussions of the SHCI community on economic sustainability, another pillar of the popular three-pillar conception of sustainability, besides environmental and social (Purvis, Mao, and D. Robinson, 2019). Economic concerns have arguably not received enough attention in SHCI (Dillahunt, 2014) (and HCI more generally (Ekbia and Nardi, 2015)), which hampers the community's ability to address sustainability holistically.

Where "the market" and "nature" have been *"construed as natural facts rather than as social ones"* (Dourish, 2010, p. 2), questioning such framings can open up new areas for engagement and research. (The design of) information technologies, which act as a lens through which we perceive contexts and systems can, thus, play a critical role in driving change (Dourish, 2010). This belief is echoed in the discussion on (ecological and social limits to economic) growth: *"Coming out of our roles as technology specialists aiming to produce knowledge and novel technologies in the service of increasing economic growth or shareholder value is an opportunity to reassess the centrality of technology in our work. Technology is extremely powerful, and our facility with it gives us relatively unique powers"* (Silberman, 2015). To make a positive difference, the community has been encouraged to focus *"on a) ecological limits, b) creating designs and artifacts that do not further a cornucopian paradigm, and c) fundamental human needs"* (Raghavan and D. Pargman, 2017, p. 786) and to design disintermediated human-computer systems, which *"can have the dual benefit of improving societal sustainability while decreasing inequality and the political economy problems that are prevalent today"* (Raghavan and D. Pargman, 2017, p. 793). To begin to address the fundamental tension *"between sustainability and the aim of economic growth that supports and orients, if implicitly, the industry of which HCI is part"* (Silberman, Nathan, et al., 2014, p. 69), another call was for a new model for the digital economy, with *"technologies relying less on instrumental purposes of efficiency connected with corporate profit [...] (motivated by research paradigms grounded in the belief of infinite economic growth) and relying more on volitional and value-laden* *aspects underlying people's use of technologies"* (Knowles, Bates, and M. Håkansson, 2018, p. 4, quoting Klein, 2015).

The finiteness of natural resources and tension between sustainability and economic growth has led to SHCI community to ask fundamental questions about current economic systems and limits to growth. Questions that have profound implications for sustainability work. But re-imagining and designing for new economic models and potentially degrowth within a system that is built upon economic growth is difficult. It requires much imagination, intricate knowledge of political and economic systems and the confidence—as non-economists by training—to apply this knowledge towards ideas that are far from uncontroversial. It is not clear to what extent SHCI can affect economic systems that are being fueled by so many outside forces.

7.3 Adoption of proposed directions in SHCI

Raghavan and D. Pargman, 2017, p. 793 observed that *"[w]hile some of this [Sustainable HCI and Sustainable Computing] work has offered well-grounded critique, it has often fallen short on practical advice and on suitable techniques that are concrete enough to be actionable."* This observation raises important questions about the practicability and tangibility of published SHCI critiques. In the following section, I explore the extent to which the SHCI community has been able to translate their advice into action and what difficulties they have faced in the process. As can be seen in Section 7.2, many of the analysed critique papers have encouraged SHCI researchers to draw from disciplines that are not commonly part of an HCI education. Here, it will be especially interesting to see if insights from these disciplines have made SHCI projects more impactful.

7.3.1 Knowledge creation instead of behaviour change

A key shift within the SHCI literature at CHI is the one away from (frequently criticised) individual behaviour change approaches towards research that at its core aims to bring about a deeper understanding of sustainability issues and interventions among communities and decision-makers. The underlying scientific insights are obtained through a variety of methods, often those that involve the presence of community members, like ethnographic (e.g., Rifat, Prottoy, and S. I. Ahmed, 2019; S. Liu, S. Bardzell, and J. Bardzell, 2019; Landwehr, Engelbutzeder, and Wulf, 2021; J. Bardzell, S. Bardzell, and Light, 2021) and co-design activities (e.g., Heitlinger, Bryan-Kinns, and Comber, 2019; Dema, Brereton, Esteban, et al., 2020; Heitlinger, Houston, et al., 2021; Meena et al., 2020). While interventions can make a difference and set an example (e.g., Dema, Brereton, Esteban, et al., 2020; Shakeri and McCallum, 2021), the focus tends to be on the knowledge created during the research or design process and during subsequent reflections. This is mirrored in a lack of traditional quantitative impact evaluations in favour of qualitative descriptions and in a large number of non-interventional studies (e.g., Widdicks, Hazas, et al., 2019; Wilkins, Chitchyan, and Levine, 2020; Soden and Kauffman, 2019; Jacques, 2020; Hamm et al., 2021; Biggs and Desjardins, 2020): with the goal to create knowledge, many studies explore existing environments and systems without the need to alter them. Instead, a key contribution of these studies can be to explicitly open up research and design spaces for impactful follow-up work (within and outside of academia), e.g., Widdicks, Hazas, et al., 2019; Rifat, Prottoy, and S. I. Ahmed, 2019; S. Liu, S. Bardzell, and J. Bardzell, 2019; J. Bardzell, S. Bardzell, and Light, 2021.

The shift shows that the SHCI community has responded to several calls from critics, namely to stop focusing on individual behaviour change research, to design with and for communities and to think contextually. The nature of the resulting research, however, can make it difficult to measure its impact. This leads to the question (which the SHCI community has grappled with previously) of how it can verify that its efforts will eventually create measurable impact. If its current work focuses on generating contextual understanding and opening up research and design spaces, there is a risk that the question of impact is simply passed on to the next generation of SHCI researchers.

7.3.2 Speculation instead of prescription

With the shift from behaviour change towards awareness raising also comes a shift in the underlying approach from prescription to reflection and speculation. As described above, DiSalvo, Sengers, and Brynjarsdóttir, 2010 classified 45% of their corpus as persuasive technology. This is not echoed in the critique adoption corpus, which contains only one study that uses an openly persuasive approach (Shakeri and McCallum, 2021); a few other studies have an indirect persuasive element as they encourage reflection (Cho, Devendorf, and Voida, 2021), support learning (Dema, Brereton, and Roe, 2019; Dema, Brereton, Esteban, et al., 2020) or raise awareness (Shaikh et al., 2021). What can be seen instead is a substantial amount of speculative design (e.g., Biggs and Desjardins, 2020; Wu and Devendorf, 2020; Heitlinger, Houston, et al., 2021; Snow et al., 2021; Cho, Devendorf, and Voida, 2021). Often participatory, such design research is more experimental and possibility-oriented in nature and aims to expand the research community's horizon and encourage reflection. It thereby forgoes a more stringent behavioural assessment—one that underpins traditional persuasive work. The design principles in the paper by Biggs and Desjardins, 2020, p. 6 succinctly capture this orientation: *"First, we aimed to resist design directions that sought to 'solve' climate change or change the behavior of research participants. Second, we wanted to validate and* *integrate the practices of Seattle's everyday cyclists [...]. Finally, we wanted to design for noticing and awareness as a way to allow nuanced, open ended narratives about intersections of cycling and sea level rise to form from participant's histories of situated practice as Seattle cyclists. The High Water Pants embody these tenets."*

Back in 2012, Brynjarsdóttir et al., 2012 highlighted how persuasion narrows our vision of sustainability; the critique adoption corpus indicates a turning point. The shift towards speculative design research enables SHCI researchers to not impose their understanding of sustainability and sustainable behaviour onto others, including their participants. Avoiding such prescriptions allows them to continue their work outside of behaviour change projects; it can also make the resulting outputs more inclusive and practice-oriented. At the same time there remains the aspiration for impact and the question if speculations will suffice.

7.3.3 Holistic perspectives instead of simple metrics

The papers in the critique adoption corpus frequently view environmental and other kinds of sustainability, notably social and economic sustainability, as interlinked. Thus, they tend to be addressed together, rather than researched separately, to allow for a deeper understanding of all aspects and their interplay (e.g., Rifat, Prottoy, and S. I. Ahmed, 2019; Willis et al., 2020; Heitlinger, Bryan-Kinns, and Comber, 2019; Heitlinger, Houston, et al., 2021; Dema, Brereton, and Roe, 2019; Landwehr, Engelbutzeder, and Wulf, 2021). Detailed reflections on the characteristics and meaning of specific contexts, objects and practices illustrate the community's holistic and systemic ways of thinking. The methodological choices indicate this too: for research with a substantial human element, authors tend to integrate one or several qualitative methods in their study design, including the aforementioned ethnography, interviews (e.g., Wilkins, Chitchyan, and Levine, 2020; Snow et al., 2021; Soden and Kauffman, 2019) and workshops (e.g., Meena et al., 2020; Heitlinger, Bryan-Kinns, and Comber, 2019; Widdicks, Hazas, et al., 2019). This does not mean that quantitative methods are absent from recent SHCI research, but rather that they are used to evaluate technical systems, not human ones. Calculations of energy demand and/or GHG emissions (Widdicks, Hazas, et al., 2019; Preist, Schien, and Shabajee, 2019; Jacques, 2020) fall into this category.

The holistic research perspectives that can be seen in recent SHCI work answer to critics' calls to move away from overly narrow definitions of sustainability and to embrace systems thinking. As environmental concerns remain on the agenda, they are studied in context, not isolation. This aligns with third-wave thinking and prevents oversimplifications, for example in decision-making processes. However, acting on the findings while honouring the captured complexity comes with new challenges: When introducing computational interventions into complex contexts it remains important not to fall prey to computational thinking. This in turn raises the question of how SHCI researchers can realise impact from the knowledge created through their research if computational interventions are not the solution.

7.3.4 Diverse explorations beyond resource consumption

While DiSalvo, Sengers, and Brynjarsdóttir, 2010 did not specify the frequency with which the papers in their corpus targeted specific aspects of sustainability (e.g., energy consumption, waste reduction), Brynjarsdóttir et al., 2012 established such a categorisation for the persuasive technology literature they analysed. They found that half the papers addressed energy consumption, a quarter focused on other types of resource consumption and the remaining quarter targeted sustainable transportation, air quality, CO_2 emissions or went beyond a single topic. (As persuasive technology only describes one type of SHCI research, comparisons should be made with caution.) What can be seen in the critique adoption corpus is that energy has remained a key theme (e.g., Widdicks, Hazas, et al., 2019; Shaikh et al., 2021; Snow et al., 2021; Meena et al., 2020; Wilkins, Chitchyan, and Levine, 2020), although the research approaches and contexts have changed, as described above. A subcluster of energy-related research explores the carbon footprint and, more generally, the (un)sustainability of digital technologies. This includes online services (Preist, Schien, and Shabajee, 2019; Widdicks, Hazas, et al., 2019), web development (Willis et al., 2020), machine learning (Shaikh et al., 2021) and digital materials (Meena et al., 2020) and can be conceptualised as work on sustainability *in* design rather than sustainability *through* design (Mankoff et al., 2007). Beyond energy, topics of interests include biodiversity (Heitlinger, Bryan-Kinns, and Comber, 2019; Dema, Brereton, and Roe, 2019; Dema, Brereton, Esteban, et al., 2020; Biggs and Desjardins, 2020), food (Heitlinger, Bryan-Kinns, and Comber, 2019; Shakeri and McCallum, 2021; Heitlinger, Houston, et al., 2021; Cho, Devendorf, and Voida, 2021) and agriculture (Heitlinger, Bryan-Kinns, and Comber, 2019; S. Liu, S. Bardzell, and J. Bardzell, 2018; J. Bardzell, S. Bardzell, and Light, 2021; Landwehr, Engelbutzeder, and Wulf, 2021), fabrication (Wu and Devendorf, 2020; Song and Paulos, 2021; S. Liu, S. Bardzell, and J. Bardzell, 2019), sea-level rise (Soden and Kauffman, 2019; Biggs and Desjardins, 2020), and (e-)waste (Rifat, Prottoy, and S. I. Ahmed, 2019; Wu and Devendorf, 2020).

The list of research topics reveals that the SHCI community has embraced sustainability research beyond energy and resource consumption. This shows the versatility of SHCI work and answers to calls for innovation, outside-the-box thinking and agenda expansion in SHCI (e.g., Norton et al., 2017; Dillahunt, 2014; Raghavan, Nardi, et al., 2016), thereby embracing topics such as fabrication, food and biodiversity. At the same time, the SHCI community has been moving away from concrete climate change mitigation efforts. While this does not mean that it cannot make other meaningful contributions to sustainability—environmental and otherwise—is does raise questions as to whether in its 15 years of reflection, the SHCI community has not found concrete approaches beyond behaviour change to use their skillset in the global effort to preserve the habitability of this planet.

7.4 Discussion

Established around 2007, the SHCI community now has a history of self-critical evaluation of its direction. Using this history, in this chapter I have analysed the SHCI critique landscape to better understand what they ask of and suggest for the community, and ultimately if the critiques have led to more effective digital sustainability interventions. My analysis shows a substantial expansion of knowledge and skills required of SHCI researchers. In addition to expertise in what can be regarded as "traditional" core areas of HCI, like interface design, user psychology and technological innovation, SHCI researchers have been asked to be well-versed in various aspects of sustainability sciences, philosophy and economy. And they have been urged to engage in systems thinking, activism and cross-disciplinary collaborations. Given that HCI already spans multiple disciplines, each with its own literature and methodological toolkit, acquiring additional expertise and keeping up with developments in all relevant fields is clearly a challenging task: not only does it have implications for researchers in and entering the field, their epistemology and engagement with communities, but it also suggests a curriculum redesign to equip students with the skills and ways of thinking they require.

Positively, the critique adoption analysis indicates that the critiques have shaped the nature of subsequent research. This means that the SHCI community brings adaptability and communication skills to the table, besides its shared passion for "doing good" (Bates, V. Thomas, and Remy, 2017). More specifically, the community has acknowledged the limitations of persuasive, individual-focused projects and moved towards more diverse, qualitative and speculative SHCI research. Viewed through a historical lens, SHCI research has shifted from second-wave approaches towards those anchored in the third wave, and has found creative ways to capture the complexity of (un)sustainability and broaden the SHCI agenda to topics including biodiversity, food and fabrication. Within a broader framing of sustainability that does not hone in on climate change, the story my analysis tells shows progress and diverse explorations. In addition, my findings indicate that the analysed critique papers have reached their intended audience and that any non-implementation of their calls is not due to these calls not being heard.

7.4.1 Impact of SHCI research

When analysing the results of this chapter through the climate change mitigation lens that underpins my thesis work, it needs to be noted first that sustainability is of course more than just climate change. In this sense, I do not wish to discard projects that are engaging with communities and stakeholders effectively, and are having various positive impacts to learning, theory and practice; or those that are helping to explore, provoke, or enhance the global understanding of sustainability in other ways. Similarly, I understand that it is possible to argue in favour of incremental progress. However, given the urgency, importance and existential threat of climate change—and urgent need for direct, evaluable paths to help mitigate this—my analysis does not indicate that the SHCI community has found them. In others words, the most useful role that digital technology design can play in climate change mitigation efforts, and energy saving efforts more specifically, seems mostly centred around qualitative explorations, speculations and provocations, at least in the current context.

While qualitative research has allowed the SHCI community to embrace sustainability's complexity, it also appears to have decreased the ability to measure its impact; a development which makes it difficult to assess the difference that the research has made to climate change and to understand if the SHCI community is on a trajectory toward more effective interventions. Similar considerations about impact have undoubtedly played a role in many of the critiques I have presented in this chapter. As Mankoff, 2012, p. 16 put it: *"I've seen the same concern crop up in various forms in reviews and on thesis committees I've been privy to: how much of an impact do sustainability projects really have, and does it justify the cost, time, and effort put into them?"* The recently published SHCI research partly circumvents these concerns by focusing on outcomes that are not quantifiable (e.g., opening up design spaces). However, without concretely specifying how these outcomes would get the community closer to creating measurable impact, this does not solve the underlying problem.

Aware of the urgency and potential consequences, the SHCI community has invested its time and energy to help tackle the climate crisis; a big challenge considering that it originates from and is fuelled outside of HCI. The lack of effective contributions to climate change mitigation—even after 15 years of discussions—indicates that technologists cannot be expected to do the work of policy makers. Even if SHCI researchers would find ways to acquire all the skills that are called for and be fully equipped to take on the underlying structural challenges to society, it is not them but the policy makers that can implement these changes. The belief that it is policies which will enable societal transformations is also present in the SHCI community, as it underpins several of the calls presented in Section 7.2, namely those for activism, support of system change and re-imagination of economic models.

7.4.2 Introducing green policy informatics

The need for systemic changes does not mean that SHCI researchers cannot or should not contribute, but it means that there is a need to challenge the narrative that climate change is an individual behaviour change problem, with digital technologies as the solution (a narrative I identified across the studies in Chapters 4, 5 and 6). SHCI work to date has assumed that policy makers will fail to implement some form of constraint (Tomlinson, Silberman, et al., 2012), e.g., an extraction cap, emissions taxes or limits on consumption; and under those conditions, it seems that the ways in which SHCI researchers can effectively apply their skills towards climate change mitigation—without acquiring expertise in other disciplines—are limited. However, if more ambitious climate policies were in place, SHCI researchers could constructively apply a more traditional HCI skillset to help realise those policies in a whole host of domains. I call this pathway "green policy informatics".

In green policy informatics, HCI has a clearer role in working towards and staying within the emission constraints set by policy makers. This could provide new focus for SHCI. The community could help ensure digital systems bring needed transparent accounting and accountability, support complex decision making under uncertainty and enable the deconstruction of popular myths about the energy and carbon impacts of everyday life. As discussed in Chapter 6, efficiencies delivered by computing can lead to wide-ranging rebound effects, where efficiency gains counter-intuitively result in an *increase* in carbon emissions. However, in a world where there are limits set to energy and resources, an efficiency gain becomes an important means of staying within this budget. In the words of Freitag et al., 2021, p. 3, *"[...] the only ways to harness emission savings from efficiencies may be through a constraint on consumption (as like Covid-19 has temporarily imposed), or a carbon constraint (such as a carbon tax or a cap on emissions)."* In such a context, digital technologies can replace or improve existing activities *without* stimulating additional, resource-consuming activities.

This means that previously discounted avenues of design may have new value under green policy informatics: "Smart" solutions (e.g., for homes, cities; a well-established area of research according to the literature mapping in Chapter 6) and persuasive technologies could make a valuable contribution—as long as due consideration is given to the cost-benefit ratio to ensure they deliver more emissions reductions than they cost, both in terms of operational as well as embodied cost (Horner, Shehabi, and Azevedo, 2016). Visualisation can usefully be applied to track compliance with emissions targets at various scales, for example adding clarity to the complex dynamics of multiple emission sources. Interface design and usability will be in high demand given the many levels and actors throughout society at which sustainability must be considered, as digital systems are introduced to streamline and transition operations across the global economy. An important (and comfortable) role for SHCI can even include making sure that the systems developed to support a radical transition are user-centred. Experts, for example, require carefully designed building management and urban planning systems, whereas individuals would benefit from intuitive digital systems for public transport and energy demand management. On the decision-making side, climate services—which are systems that provide climate and climate-related information to inform decision making-around the world—feature diverse interactions between technologies and a variety of user groups and require user-centred designs (Rigby and Preist, 2023). SHCI already has third-wave skills for requirements gathering, participatory design, and understanding the implications of climate measures in different contexts and for different populations.

This includes disadvantaged populations, who might be disproportionately affected by the introduced constraints, as they spend larger shares of their income on energy costs (World Economic Forum, 2022; Williams III et al., 2015). Even with e.g., regressive carbon pricing, it will be critical to avoid lower-income households having to bear a disproportionate share of the burden. Designing with and for these populations can provide them with tools to articulate their needs and to access e.g., compensation schemes. By helping to establish such customised digital communication channels between policy makers and their constituents and visualising the social implications of climate policies as they become apparent, SHCI researchers cannot only contribute to an effective but also a fair implementation of constraint policies.

7.4.3 Realistic SHCI contributions

That starting from an alternative assumption can open up a different space for SHCI has been shown before: Collapse informatics (Tomlinson, Silberman, et al., 2012) did just this by preparing for the case in which humanity is unsuccessful in preventing climate change in advance of societal collapse caused by its effects. Similarly, what I am proposing as new territory for SHCI is closely aligned with suggestions made by E. Blevis and S. Blevis, 2010, p. 29, when they encouraged SHCI researchers to contribute towards *"the design of digital networking and interactive technologies that can help people at various levels—as individuals, small groups, governments, and global bodies—plan and prepare for the orderly adaptation to these effects."* These are reasonable and realistic contributions to ask of SHCI if what the community is responsible for is not system change, but facilitating an effective digital transition. With this in mind, it is possible to circle back, this time better understanding the contributions SHCI researchers can make not only in preparation for but also to avoid collapse.

I do not intend to imply that bringing about or enacting such policies is without its challenges or that SHCI researchers should simply trust politicians to implement the required changes. Rather, as Dourish, 2010, p. 8 reflects: *"interactive systems are also lenses through which we encounter the world [...],"* framed by broader social, political and economic processes. As such, SHCI researchers have a potentially critical role in addressing the urgent problems of environmental sustainability. Starting from an alternative assumption does not mean that their work to date loses its value: sustainability has multiple dimensions, and through e.g., the expansion of their research agenda and thought-provoking digital design, the SHCI community can shape people's understanding of the topic. Besides, all of HCI's holistic design skills will be required to get the message of green policy informatics across to policy makers. Several of the calls presented in Section 7.2, most notably those for activism, support of system change and re-imagination of economic models, provide valuable starting points for this endeavour. While this kind of politically-focused research might push SHCI researchers out of their comfort zone, it can provide a shared vision: Rather than framing the climate change debate as an individual behaviour change or a technologists' problem, policy makers need to meet their responsibility when it comes to climate change mitigation and implementation of socially, economically and environmentally just and sustainable systems. A context with more ambitious climate policies would then allow the SHCI community to focus on what they do best, contributing their expertise to wider collaborations.

7.5 Summary

In this chapter, I have analysed two corpora—a corpus with SHCI critique papers and a corpus with recent SHCI publications at CHI—in order to understand if, in response to behaviour change critiques, the SHCI community has found effective strategies to contribute to environmental sustainability and to climate change mitigation more specifically. In the context of my thesis, this analysis has allowed me to explore: (a) expert suggestions of how the design of digital technologies could contribute to energy and emission savings, (b) the challenges that arise for researchers who want to implement these suggestions, (c) the limitations of digital behaviour change interventions for climate change mitigation in the current context and (d) how these interventions could be more impactful in a different context.

My analysis shows that in order to make impactful contributions to sustainability, SHCI researchers have been called to acquire expertise in disciplines outside of HCI (e.g., ecology, economics) and engage in activities that aim to change the current system (e.g., activism, re-imagination of economic models). Given that HCI is itself interdisciplinary, this let me conclude that SHCI researchers would need to stretch significantly beyond their existing competencies to implement these suggestions. In the second part of my analysis, I looked at recent SHCI publications at CHI to understand if the SHCI landscape has shifted in response to the critiques, compared to the SHCI landscape in 2010 (DiSalvo, Sengers, and Brynjarsdóttir, 2010). I found that the SHCI community has moved away from behaviour change interventions towards projects that are more qualitative, thematically diverse and holistic. These results indicate that the SHCI community has listened to the critiques and embraced third-wave thinking. However, it also indicates that the SHCI community has not discovered effective, evaluable approaches to use their skillset toward climate change mitigation.

Taken together, the findings in this chapter indicate that SHCI researchers have been asked to do the work of policy makers and drive the structural changes that are necessary; in the current context, the impact that SHCI researchers can have as technologists is limited. Changing the underlying assumption that policy makers will establish more ambitious climate policies in the form of e.g., emission taxes or consumption caps, I propose green policy informatics as a pathway that allows SHCI researchers to make a reasonably scoped contribution; this includes the design of digital technologies that support complex decision-making, track compliance with emission targets and awareness raising. Beyond diverse (design) explorations and speculations, green policy informatics does thereby allow SHCI researchers to use their traditional design and research skills to help facilitate a smoother and more effective transition to a carbon-constrained future—but it is policy makers who must set this transition in motion.

Chapter 8

Conclusions

This chapter summarises the main contributions of the thesis. I revisit the research aims and describe how the conclusions of Chapters 4, 5, 6 and 7 contribute new understandings that achieve these aims. In a second step, I pull together core themes that emerged across chapters and connect their key messages to generate additional insights. I conclude the chapter with a section on relevant future work and research directions that build on the presented findings.

8.1 Review of contributions

The aim of the thesis was to explore the role of digital interventions for energy savings from an HCI perspective with a particular focus on energy use in buildings. The foci: (a) the narratives relating to digital interventions enabling energy savings in buildings among experts in the energy domain, (b) the theoretical energy-saving potential of digital interventions in buildings, (c) the contextual factors that impact the realisation of this potential, (d) the extent to which energy efficiency research in and beyond smart homes considers rebound effects and (e) the identification of strategies in the Sustainable Human-Computer Interaction (SHCI) community to overcome the limitations of digital behaviour change interventions. Through this exploration, the thesis contributes the following key research findings:

1. **Chapter 4** uncovered a shared optimism among experts with regard to the potential of digital energy-saving interventions, in particular building automation projects, which stands in sharp contrast to the experts' own experiences with past projects; the latter tend to be viewed as unsuccessful due to both technical problems and uncooperative occupant behaviour.
2. **Chapter 5** used longitudinal energy data to show that the energy-saving potential of digital interventions in campus buildings is on average limited to

20% to 23% of the buildings' electricity consumption. However, this potential is unlikely to be reached as it is calculated on the basis of energy data from COVID-19 lockdown periods when buildings were largely unoccupied. A contextualisation of the data with experts highlighted additional challenges without simple solutions, including the responses from occupants, limitations and failure of technology and limited resources. Across the longitudinal analysis, the data indicated that the growth of the University campus outweighed savings from interventions.

3. **Chapter 6** was partly motivated by the campus growth from Chapter 5, investigating a problem that can occur when digital interventions successfully realise energy savings: rebound effects. The investigations in the form of a literature mapping showed that rebound effect considerations are rare in the smart home energy efficiency literature and the energy efficiency literature more generally. More specifically, they range from 0.01% to 3.60% across four large scientific databases.

4. **Chapter 7** analysed critiques and recent publications in the field of SHCI; this is a field in which digital behaviour change interventions used to be prominently represented and have since been discussed and reflected on by SHCI researchers. The analysis revealed that in order to implement the calls in the critique papers, SHCI researchers would need to acquire new skills in a whole host of domains. This means that without policy interventions, SHCI researchers face clear limitations in their efforts to advance environmental sustainability by applying a traditional HCI skillset.

Taken together, the research I have presented across the four chapters suggests that digital energy-saving interventions in buildings are not a sufficient strategy to mitigate the urgent climate crisis. This is not to say that the underlying efficiency approach is consistently ineffective: both intelligent controls and thoughtful user behaviour can reduce energy wastage in a variety of situations. Instead, what I argue is that within the current context, these reductions are neither reliable nor significant enough to represent a solution. Accounting for 34% of the global energy demand in 2021 (United Nations Environment Programme, 2022), buildings are a major climate change contributor. Based on this statistic, let us consider a best-case scenario: if it was possible to use digital interventions to consistently reduce the demand by 20% across all existing buildings, this would would lower the global energy demand to around 93% of its current value and buildings' global demand contribution to around 29%, assuming that the demand in all other sectors stayed the same. While this would not be nearly enough to solve the climate crisis, it could make a meaningful difference. The problem, however, is that this best-case scenario can be considered highly unlikely.

First of all, the calculated energy-saving potential in buildings is based on energy consumption data from mostly *empty* buildings. With occupants inside a building, as is almost always the case outside of lockdown periods, the consumption will rise even if energy wastage is avoided, as occupants need energy to stay comfortable and carry out work and other activities. What adds to the challenge is that the interventions are introduced within a real-world context that tends to be characterised by e.g., technical complexity, unpredictable occupant behaviour and limited resources; all of these factors widen the gap between the on-paper potential and actual savings. But the perhaps most fundamental problem are the cultural and political drivers that counteract and likely outgrow saving strategies; these drivers include but are not limited to efforts to prioritise "business as usual", personal comfort and business growth. In the following sections, I will discuss these challenges and the undue reliance on technological solutions for energy-savings in more detail.

8.2 Challenging popular narratives

My research has shown that using digital technologies for energy savings is not an easy win—even if it can initially appear that way and dominates expert thinking. Given the urgency of the climate crisis and slow progress towards global use of clean energy (Energy Institute, 2023), digital technologies can spark "seamless" visions of a sustainable future that does not require radical change: The experts I spoke to on Lancaster University's Bailrigg campus showed deep concern about energy consumption and climate change (Chapter 4 and Chapter 5) and clearly articulated their realistic hope for e.g., energy system automation to significantly lower the energy consumption on campus. The large number of energy efficiency publications across fields, often tied to a vision of energy-efficient smart homes (Chapter 6), and early enthusiasm in SHCI to contribute to climate change mitigation through the design of behaviour change technology (Chapter 7) tell a similar story. In no part of my research have I encountered a lack of concern about climate change or a lack of desire to help mitigate it. However, when digital energy-saving technologies are chosen as the main pathway to achieve this, my research has shown that the current narratives of their potential can be problematic when they e.g., underestimate the baseload consumption of buildings, ignore rebound effects and lack a systemic view.

8.2.1 The paradox of complexity

When digital technologies are introduced to save energy, estimates of their saving potential tend to be positively correlated with the complexity of the technologies (Naylor, Gillott, and Lau, 2018; Reinisch et al., 2011; Hughes and Dhannu, 2008); this means that increasingly complex digital technologies tend to be called for to save more energy. A review of building control technologies for energy savings, for example, came to the following conclusion: *"The observable gap between designed and actual energy performance across a range of building types highlights the need for more complex and responsive building controls"* (Naylor, Gillott, and Lau, 2018, p. 7). The experts who participated in my research tended to share this perception, regarding both energy data and digital technologies. In their visions of successful energy system automation, fine-grained data from multiple systems would be used to feed advanced algorithms in order to make accurate predictions. Despite being aware of the challenges that arise when the amount of data and technical complexity increases, the experts continued to associate this increase with a more "seamless" reality in which digital technologies would enable large-scale energy efficiency and a reduction in the work required by the experts themselves.

The contrast between these visions and the associated challenges leads to a paradoxical situation: The experts ask for more fine-grained energy data to gain new insights—but struggle with "data overload" and questions around data storage. They envision advanced algorithms that make accurate predictions based on millions of data points—while wanting to keep the ability to manually verify these predictions. They would like to install comprehensive sensing and control systems in campus buildings—being fully aware that these systems require specialised and frequent maintenance and repair efforts. The more complex a digital system becomes, the more expertise is required to understand, programme and interact with it, reducing the number of people who are competent doing so. As system components are linked in complex ways, incorrect mental models can even lead to severe consequences: as described by Bainbridge, 1983, the most successful automated systems that have the lowest demand for manual interventions entail the greatest need for human operator training. When designing digital interventions for energy savings, this paradox of complexity can turn seamless visions into a seamful reality.

8.2.2 Technological optimism

Despite their awareness of the (quite fundamental) challenges that come with energy system automation, the majority of experts who participated in my research firmly believe that this approach has the potential to save a substantial amount of energy. Without much concrete evidence that it can successfully be implemented in this setting, the experts tend to envision very concretely how data sources and systems could be linked in order to save energy in campus buildings. This is not to say that these interventions cannot be successful. However, it seems naive to assume that they will be—even more so when considering the paradox of complexity described above. In this sense, the experts' views can be associated with technological optimism, which is a well-established concept in the literature that describes the unjustified belief that technological progress will fix existing problems (Krier and Gillette, 1985). In the context of climate change mitigation, this means rapid emission reductions (Lamb et al., 2020; Peeters et al., 2016). As part of the discourses of climate delay—which are discourses that acknowledge climate change, but justify inaction or inadequate efforts—technological optimism has been characterised as follows: *"We should focus our efforts on current and future technologies, which will unlock great possibilities for addressing climate change"*, which falls into the category *Disruptive change is not necessary: push for non-transformative solutions* (Lamb et al., 2020, p. 2). While the description is mainly associated with *energy* technologies, e.g., clean energy productions and carbon storage, my research supports the coverage of *digital* technologies as well.

The concept of technological optimism has been identified across disciplines: In the environmental sciences, "technophilic optimism" describes the assumption that future technological improvements can outpace historical experience (Mitchell, 2012); in the psychology literature, a corresponding cognitive bias called the "technology effect" exists (Clark, Robert, and Hampton, 2016). Here, the proposed theory is that *"[...] constant exposure to advances in technology has resulted in an implicit association between technology and success that has conditioned decision makers to be overly optimistic about the potential for technology to drive successful outcomes"* (Clark, Robert, and Hampton, 2016, p. 87). This would explain why the experts who participated in my studies argued in favour of previously unsuccessful digital interventions despite being deeply concerned about climate change: it is not because they want to delay climate change mitigation but because their minds heuristically overestimate the potential of e.g., energy system automation. Similarly, it is likely that the wave of behaviour change projects in SHCI and energy efficiency research in the technical and general literature arose from researchers' genuine desire to contribute to climate change mitigation. Limiting real-world factors and mechanisms, such as "non-rational" user behaviour and rebound effects, can be difficult to anticipate—which of course does not mean that they can be ignored once identified.

From a societal perspective, technological optimism can be associated with the cultural movement of modernism, which aims to improve life through technical means (a similar link has been identified between persuasive sustainability and modernism, cf. Brynjarsdóttir et al., 2012). In this sense, technological optimism likely is not simply the result of individuals' blind faith but of a wider cultural framing with a deep-rooted belief in progress through industrialisation and technological advancement.

8.2.3 Problematisation of users and their behaviour

In contrast to the widespread optimism regarding automation technology stands the problematisation of technology users and their behaviour. Many of the experts who participated in my research described the behaviour that occupants on campus engage in to be more comfortable, e.g., opening windows and using electric heaters, as unnecessary, frustrating obstacles on the path to less energy consumption; one expert explicitly described the occupants themselves as a problem for successful energy system automation. Reporting regular occurrences of that behaviour, a narrative that emerged among the experts was the occupants' lack of engagement with sustainability and unwillingness to contribute: rather than helping to save energy, the occupants were believed to first and foremost care about their own comfort and productivity. Interestingly, most of the experts showed awareness of the occupants' different thermal and energy-related needs that are shaped by e.g., the occupants' gender, cultural backgrounds and workplace dynamics. A few experts even mentioned the tension between the pressure on campus-based individuals to e.g., complete their work, study, grow lab groups and publish articles (which are activities that all require energy) and the pressure to reduce their energy consumption. This dynamic can also be observed on the level of the University as an institution: installing new screens and opening the library at night increase student satisfaction—but also add to the energy bill.

Analysing HCI researchers' perceptions of users of digital energy technologies in (smart) homes, Strengers, 2014, p. 27 noticed a duality between the two strategies I have focused on in my thesis, namely behaviour change and automation: *"In contrast to the vision of the active consumer [who engages with energy feedback], the strategy of automation assumes that humans are primarily lazy, too busy, or simply uninterested in managing their energy data."* A slightly different perspective (albeit also a negative one) on the perception of humans in the context of automation is given by Bainbridge, 1983, p. 775, who argues that *"[t]he designer's view of the human operator may be that the operator is unreliable and inefficient"*; this aligns with the tendency of the campus-based experts to express a desire for taking the building occupants "out of the loop". What these perspectives have in common is that they reduce technology users to rather simplified personas. Similar to the technological complexity behind energy system automation, human complexity and diversity is not fully acknowledged either, potentially because it is hard to mentally conceptualise and design for multi-faceted user groups. However, this does not mitigate the reality in which occupants might care deeply about climate change mitigation, but have to prioritise productivity to not lose their jobs; and where their engagement with energy data might depend on their mental load and energy literacy.

8.3 The importance of policies

Policies define the setting into which digital energy-saving interventions are introduced and in which they operate. In many ways, policies can be regarded as the rules for playing the global game called climate change mitigation—one that humanity must not lose. Through policies, decision-makers can demand sustainable architecture and prevent rebound effects, but also drive growth and enable unsustainable investments. This means that policies hold the potential to increase or reduce the complexity that characterises digital energy-saving interventions in the current context; the latter through e.g., a combination of efficiency and sufficiency strategies (see Chapters 6 and 7). Perhaps most notably, policies implicitly shift the responsibility from individuals and technologists, whose energy-saving margins are often slim (as shown for mixed-use campus buildings in Chapter 5), to policy makers and larger organisations. Due to their high energy consumption and lasting structures, my research has in also highlighted the importance of policies for buildings. This concerns the design of new buildings, refurbishments of existing buildings and even their operation, as the impact of air circulation policies during COVID-19 onto campus buildings' energy consumption has shown.

8.3.1 Digital interventions as a political act

In the current context, which is not characterised by ambitious climate policies (and can thus e.g., trigger underacknowledged rebound effects), the energy-saving potential of digital interventions tends to be limited. For this reason, the interventions can problematically represent a political act or an unspoken articulation to continue business as usual in a way that does not invite discussion (unless they are helping people to live under specified constraints like carbon taxes or extraction caps; see Section 8.3.3). The underlying idea that technology has a political dimension and can act as a lens for our perception of the world is already well-established (Dourish, 2010; Ekbia and Nardi, 2015) and has even been suggested as a core element of a fourth wave in HCI (Ashby et al., 2019). In 2010, for example, Dourish, 2010, p. 8 offered a reflection on the relationship between sustainability and HCI, and with it on the intertwining of design and politics: *"Political, social, cultural, economic, and historical contexts have critical roles to play, not only because they shape our experience with information technologies, but also, and even more, because information technologies in contemporary life are sites at which these contexts are themselves developing."*

Given people's and even experts' tendency towards technological optimism, the saving potential of digital technologies needs to be carefully weighed against their potentially re-assuring presence that conveys their ability to effectively save energy; when this presence leads e.g., buildings occupants to reduce their own energy-saving efforts, it can fuel rebound effects. In other words, a risk that comes with the introduction of digital technologies for energy savings is the underlying expectation that they solve the problem for which they are intended. Both decision-makers who introduce the technology and individuals living and working in spaces shaped by it can easily develop the impression that it takes away some of their own responsibility.

By continuously relying on digital energy-saving interventions, we are reinforcing the belief that it can be relied upon. In this sense, the interventions are not only fuelling rebound effects but also technological optimism. In addition, digital energy-saving interventions often target individual users, by e.g., persuading them to consume less energy, implying that it is the users' responsibility to mitigate climate change—when the problems tend to be structural (Joshi and T. C. Pargman, 2015). Continuous use of digital energy-saving interventions can thus re-emphasise this allocation of responsibility.

8.3.2 Policy interventions for buildings, not occupants

My calculations have shown that the energy consumption of campus buildings is only weakly linked to occupancy, which aligns with what the experts reported during the interviews and also with findings in the literature (Tavakoli et al., 2023; Spearing et al., 2021; Gaspar et al., 2022). Most of buildings' energy consumption can be attributed to their baseload, which cannot be meaningfully targeted by behaviour change interventions or energy system automation. Fundamentally, this means that reducing the energy consumption of buildings is not an individual behaviour change problem or an efficiency problem more generally. Instead, we need to target the buildings themselves, which, from both a global and national energy consumption perspective, are major energy consumers and difficult to change once built.

The apparent benefit of digital energy-saving interventions, and in particular energy system automation, for existing buildings is that they tend to be cheaper and easier to install than refurbishments. However, the high baseload of buildings and the identified limitations and complexities mean they cannot be regarded as an effective enough strategy and might even fuel technological optimism. This means that refurbishments of existing buildings and new passive-house standard buildings are the best option that is currently available. The building stock in the United Kingdom (UK) needs to substantially reduce its energy requirements, which is unlikely to happen quickly without targeted policies: given the substantial investments that are required to refurbish a building and the long time period until these investments pay off financially, the past decades have shown that building owners are unlikely to refurbish their buildings voluntarily (Guardian, 2022). Standards like the Building Research Establishment Environmental Assessment Method (BREEAM) (BRE Group, 2023) and Leadership in Energy and Environmental Design (LEED) (U.S. Green Building Council, 2023), for example, provide frameworks for assessing and certifying the sustainability and energy requirements of buildings. Requiring these certifications can help drive energy efficient building practices. Policies can also offer financial incentives, tax breaks, grants or subsidies to offset the costs of refurbishments; these incentives can make it easier for building owners to make these investments. What remains important is that regulations are updated regularly to help raise the minimum energy performance standards. As the the campus-based experts emphasised, best practices, materials and technologies for new building are improving fast.

8.3.3 The need for sufficiency and constraint policies

Unfortunately, none of the energy-saving policies or interventions for buildings can be expected to make a significant difference towards climate change mitigation if they are triggering rebound effects. As long as savings get re-invested into unsustainable projects and fossil-fuel-driven growth, this will likely hold back the overall progress. An example for this could be seen on Lancaster University's campus: the growth of the campus and addition of new buildings likely offset energy savings that were achieved through projects and interventions (see Chapter 5). Given that the University is a place for research and education, which benefit individuals and society, its expansion can well be seen as a positive development from a social perspective. However, from a climate change mitigation perspective, it is the opposite. In fact, had the University decided to neither grow its campus nor implement energy-saving interventions, it would likely consume less energy overall.

In order to create a context in which digital energy-saving interventions can make a meaningful contributions *without* the risk to trigger rebound effects, I argue in favour of a combination of efficiency with sufficiency strategies in the form of relevant policies. I have described the underlying idea and provided supporting references in Section 6.3.4; I have then built on this idea in Chapter 7 by proposing green policy informatics as a pathway for SHCI researchers that is characterised by constraint policies. This pathway highlights potential new ways in which HCI researchers could use their traditional design and user research skills to contribute towards climate change mitigation. This is not to say that constraint policies and consumption boundaries will be an easy win. Similar to how digital energy-saving interventions can lead to unintended consequences, constraint policies might too. From both a social and economic perspective, there are risks that need to be addressed and potentially responded to, e.g., carbon pricing disproportionately affecting disadvantaged members of society (World Economic Forum, 2022; Williams III et al., 2015). However, given the urgency of the situation and failure by any of the previously used strategies to significantly lower carbon emissions, it appears to be the most promising approach. And recent literature can provide guidance: Callmer and Bradley, 2021, for example, offer a framework for sufficiency politics based on public policy in Sweden, highlighting the need to *"[...] formulate clear goals that serve to set environmental limits, for instance, in the form of carbon budgets, and then steer toward well-being for the inhabitants within these limits"* (Callmer and Bradley, 2021, p. 194). Alongside this goal-setting, policies can be used to support a cultural reorientation that might help shift the focus toward more sufficiency-oriented ways of meeting needs.

For the use and design of buildings, existing sufficiency research can also be built upon. Responding to the trend that growing floor space, e.g., living area per person, tends to counteract efficiency gains, Lorek and Spangenberg, 2019 recommend that instead of focusing primarily on the energy consumption of buildings, it makes sense to shift the attention towards a concept of sustainable homes. And Bierwirth and S. Thomas, 2015 make concrete suggestions of how sufficiency can be applied to building design, including the creation of smaller, flexible and shared spaces.

A context with constraints would likely reduce the complexity that characterises digital energy-saving interventions in the current context by shifting the responsibility from individual users to policy makers and preventing rebound effects. However, it would not necessarily take away the complexity inherent to the implementation of the digital technologies themselves. This includes questions around maintenance, data storage and operator training. If we want to meaningfully use digital energy-saving interventions in a constrained context, we need to be realistic about what they can and cannot achieve, consider their footprints and tackle the problems that can reduce their effectiveness.

8.4 Future work

In this section I will discuss possible avenues for follow-on research that build on the findings I have presented and discussed in this thesis. As I consider sufficiency and constraint policies as the most promising strategy to increase the effectiveness of digital energy-saving interventions and prevent rebound effects, this section largely focuses on work that can help support, prepare and make a case for their implementation. At the same time, it will be paramount to acknowledge and tackle the challenges (related to e.g., material wear, data storage and operator training) that are inherently part of digital energy-saving interventions and grow with increasing complexity, independent of the policy context. With new technical, social and political developments, the role of digital technologies for energy savings continues to evolve, and more research will be required to capture the changing role over time. The following list of research directions should be seen as a starting point to deepen the understanding from this thesis but also to reflect on prominent narratives and strategies in fields where digital energy-saving technologies are researched and employed, including the field of HCI.

8.4.1 Empirical research on rebound effects

The lack of studies on rebound effects that focus on occupants in the context of their everyday life presents a problematic gap in the literature than can be addressed by empirical research. In particular, empirical knowledge on rebound effects is needed to accurately and systemically estimate and evaluate the outcomes of digital energy efficiency interventions and to raise awareness about rebound effects that get triggered by them. When it comes to the identification of rebound patterns and constraints in the real world, the HCI community would be particularly well-equipped to carry out this research due its history in uncovering the nuanced ways in which socio-technical factors undermine energy savings. To address the lack of empirical work, HCI researchers can also use their knowledge of in-situ research (Rogers and Marshall, 2017; Carroll and Rosson, 2013; Carroll and Rosson, 2013; Consolvo et al., 2007), which can help other disciplines understand the impact of rebound effects by studying situated behaviours.

Across the different types of rebound, important research goals will be to better understand the causal factors of rebound effects and to identify and evaluate *rebound patterns* that can inform research and design. For example, rebound effects are enabled and shaped by features such as flexible uses, the potential for new types of uses that create induced demand, and resource savings that can be redeployed for other activities (Coroamă and D. Pargman, 2020). On the other hand, they are constrained by factors such as natural caps or limits on objectives, such as comfortable temperature zones for human living or existing real-estate costs (Coroamă and Mattern, 2019). In many cases, natural caps exist that place constraints on the size of the rebound effects we can expect. Research in energy policy provides conceptual guidance for methods and macro-level views (Saunders, Tsao, et al., 2012) that can structure and inform this research. For example, there is a difference between lighting efficiency gains and heating gains in that lighting has additional uses and therefore is subject to induced demand, whereas heating is limited by people's temperature comfort zones.

Among the methods that can be used to estimate rebound effects are carefully designed quasi-experimental approaches (Azevedo, 2014) and living lab research; for the latter, *"experts have confirmed that Living Labs contain the potential to observe complex demand systems of users within experimental designs, encompassing indirect rebound effects in terms of expenditure as well as time use"* (Buhl et al., 2017, p. 592). Both methods align closely with the current skillset of HCI researchers and would allow them to study the outcome of strategies and interventions that might trigger rebound effects, such as the introduction of smart home systems (Alan et al., 2016). In some cases, their findings could feed into interdisciplinary collaborations.

8.4.2 Addressing technological optimism

The authors of the psychology study on how perceptions of technology drive excessive optimism, Clark, Robert, and Hampton, 2016, p. 87, who coined the term "technology effect", describe the implications of their research as follows:

> *"Excessive optimism that technology will result in success can have negative consequences. Individual investment decisions, organizational decisions to invest in R&D, and societal decisions to explore energy and climate change solutions might all be impacted by biased beliefs about the promise of technology."*

Future work should target this bias and the negative consequences that are associated with it, not least because it can be accompanied by the unsupported claim that technological progress requires only market-based incentives, rather than regulation (Lamb et al., 2020). This work might include research on how to design e.g., artefacts and interfaces for decision-makers that encourage critical reflections, a better understanding of the mechanisms that drive technological optimism, and research on the extent to which different people are affected by it. Case studies of situations in which technological optimism is present or absent could guide this research. In an energy consumption context, it could be informed by the role and digital literacy of the user and their exposure to digital energy-saving interventions. More generally, Clark, Robert, and Hampton, 2016 propose a list of psychological variables to consider, including individual-level variables such as investment experience or risk taking, cognitive load, investment experience and tolerance for ambiguity. In order to reduce the technology effect, the literature on bias mitigation (Bonaccorsi, Apreda, and Fantoni, 2020; Whitehead and Cherry, 2007) could provide valuable guidance, also for design projects.

8.4.3 Critical thinking as an HCI asset

With its roots in human factors engineering and information processing, the HCI research community has become increasingly interested in the context of interactions and their social, cultural and political aspects (Bødker, 2006), including in a sustainability context (Sengers, Boehner, and Knouf, 2009). The resulting research methods and critical evaluations in its SHCI subfield have fundamentally shaped this thesis: The combination of quantitative energy data research with qualitative contextualisations and the identification of prominent narratives enabled me to better understand the data itself and to contrast the expected and realistic energy-saving potential of digital interventions. My reviews of the existing literature then uncovered the SHCI community's significant critical engagement with socio-technical factors and mechanisms that can undermine the success of digital sustainability interventions; this includes their considerations of rebound effects to a much larger degree any other research community included in my mapping, as well as their conversations around the limitations of behaviour change interventions.

Despite some SHCI researchers' frustration with the limited contributions their traditional skillset has allowed them to make towards climate change mitigation, I want to highlight the value of their expertise—both in the green policy informatics scenario I introduced in Chapter 7 but also in the current situation. In comparison to many other technical research communities, HCI researchers have well-honed critical thinking skills that allow them to take a step back and question existing approaches: as I have uncovered in Chapter 7, after just 15 years, the SHCI research presented at CHI is very different from the research the field focused on initially. I do not want to distract from the difficulty of the situation in which HCI researchers have implicitly and unfairly been asked to do the work of policy makers; instead, I want to suggest that the critical reflections that have led to this realisation (which are at the heart of this thesis too) could provide benefit beyond HCI. Many institutions and communities still argue that efficiency projects and lifestyle changes of individuals are a silver bullet for climate change mitigation. The more awareness there exists for the limitations of these approaches, the more pressure can be put on decision-makers, who are ultimately responsible for creating a more sustainable system.

8.4.4 Becoming systems thinkers

In line with previously published research (e.g., Bedwell, Costanza, and Jewell, 2016; Tirado Herrero, Nicholls, and Strengers, 2018; Beltram, Christensen, and R. Li, 2019), my research has highlighted the complexity that characterises the deployment of digital technologies for energy-saving purposes; this includes unintended consequences, such as workarounds by occupants, increased maintenance requirements and rebound effects. These consequences are, however, not consistently acknowledged: as my research has shown, there exists a tendency among both academic and non-academic experts to ignore or deprioritise them in decision-making. Examples include a decision-maker's description of rebound considerations as a "luxury" and their absence from most energy efficiency research, as well as the visions for seamless energy system automation on campus despite major difficulties with the EIS.

In the current situation, which is not characterised by constraint policies, technologists need to navigate the complexity that surrounds their sustainability interventions and shapes long-term outcomes. A way of thinking that can help to grasp and design for this complexity is system thinking. As one of the calls by SHCI researchers that I have identified in Chapter 7, systems thinking can help to challenge a computational mindset (Easterbrook, 2014). Instead of focusing solely on individual elements, it takes a holistic approach to see how those elements work together to create a larger whole. For this, researchers can draw on guidance for the application of systems thinking approaches and systemic design methods to support the development of more sustainable interactive systems (Nathan et al., 2008; Bornes, Letondal, and Vingerhoeds, 2022), including a systemic design methodology (Bornes, 2023). Another concrete starting point to apply systems thinking towards sustainability are feedback loops, where the outputs of a system feed back into the system and influence future behaviour (Arnold and Wade, 2015). Feedback loops can be positive (reinforcing) or negative (balancing), and they play a significant role in shaping system behaviour. Besides feedback loops, a promising systems thinking strategy for HCI researchers specifically is to design for leverage points. This involves the identification of strategic areas where small changes can lead to significant and lasting positive impacts on the overall sustainability of a system. Originally introduced as a concept by Meadows, 1997, a systems thinker, in her essay *Leverage Points: Places to Intervene in a System*, leverage points could e.g., help to identify and explain rebound effects (Penzenstadler et al., 2018).

As much as we need to move away from techno-solutionism (Kneese, 2023), it should be noted that system thinking is the opposite of what technologists are commonly trained to do (Mann, Muller, et al., 2010)—implying that the their curricula need to change.

8.4.5 Developing green policy informatics

Significant research potential also lies in the development and refinement of the concept of green policy informatics, which I initially propose in Chapter 7. On the policy side of things, it would be helpful to better understand the different constraints that exist, e.g., carbon pricing, resource budgets and limits on consumption, and the local contexts in which relevant constraints have been introduced/trialled (e.g., as of May 2023, 23% of global greenhouse gas emissions are covered by 73 carbon pricing instruments (The World Bank, 2023)). Case studies of these contexts or engagement with possible scenarios, such as those discussed in Freeman, 2018, could reveal research and design opportunities for HCI but also uncover challenges related to the use and introduction of digital technologies.[1]

Linking green policy informatics with the existing research on energy efficiency technologies, that I have mapped in Chapter 6, another focus could be to scope opportunities for collaboration between HCI researchers and engineers or more technically-oriented researchers. For example, how do smart technologies need to be designed that they do no lead to adverse reactions by their users? And how can we accurately quantify (and visualise) the operational and embodied costs of digital technologies? Answering such questions collaboratively could lead to a quicker uptake of the results and recommendations, especially by the technical communities.

---

[1] As materials and research that relate to policy-making are often published and distributed outside of commercial or academic channels, grey literature, e.g., reports, working papers, government documents and white papers, should be included in this analysis.

Finally, I want to encourage SHCI research to engage in activities around futures thinking, design fiction and co-design activities of future scenarios. Collaboratively imagining the future could be a powerful tool to further develop the concept of green policy informatics and help designers engage with the politics and scales of systems change that are difficult to imagine in our current systems. Guided by the literature on critical design (Dunne and Raby, 2013), speculation (Elsden et al., 2017), adversarial design (DiSalvo, 2015), and design fiction (Blythe, 2014), it will be important to reflect on the concrete ways in which technologists can contribute in a carbon-constrained future, the challenges they might face and how these challenges can be overcome. In fact, a recent review of speculative design in SHCI found that it is a growing research area but that *"longstanding issues in sustainable HCI regarding the tension between individual consumer choices and societal-scale solutions do not seem as prevalent in this body of work"* (Soden, Pathak, and Doggett, 2021, p. 196). Speculative design activities in the context of green policy informatics could fill that gap.

8.5 Concluding remarks

If we want to successfully mitigate climate change, we need to be honest with ourselves that digital energy efficiency strategies are not a "quick fix" for larger structural problems that drive energy demand. While it is a compelling narrative to buy into, especially if the alternative means fundamental changes to the growth-oriented, consumer-centric way society and business operate, relying on these technologies will backfire—in a way that that could make our planet uninhabitable. This is not to say that efficiency improvements cannot meaningfully contribute to emission reductions, but rather that we need to be careful about the message they are sending and the cultural and political drivers that often counteract and likely outgrow the savings they achieve (by e.g., triggering rebound effects). In this regard, the expected role of digital interventions in achieving energy savings through efficiency improvements is one characterised by widespread yet mostly undue optimism: optimism about both their energy-saving potential and the likelihood of realising it. Especially the agency of users and impact of their behaviour get frequently overestimated.

The good news is that the role of digital energy-saving technologies could be different if the context changes and sufficiency or constraint policies are introduced. Without the risk to trigger rebound effects, technologists could use their skills to realise energy savings by enabling a more efficient use of systems and devices; they could thus help to increase the output from limited resources while the world transitions to renewable energy sources. In such a context, the presence of digital technologies would no longer constitute a unspoken articulation to continue business as usual, and technologists could focus on what they do best. That said, it is important to remember that ambitious climate policies will not magically solve the problems and ironies that are inherent to the use of automation and behaviour change technologies. There remain open questions about e.g., data storage, algorithm verification, operator training and user agency. We need to keep tackling these questions from a systems thinking perspective, apply empirical design and evaluation methods and continue to challenge our own mental models. Should we succeed, digital technologies can become an important part of the solution to climate change, allowing future generations to build the lives they deserve.

Appendix A

Expert interviews: participant information sheet

School of Computing
& Communications
Lancaster University

PARTICIPANT INFORMATION SHEET

For further information about how Lancaster University processes personal data for research purposes and your data rights please visit our webpage: www.lancaster.ac.uk/research/data-protection

I am a PhD student at Lancaster University and I would like to invite you to take part in a research study about the human context of sensor data.

Please take time to read the following information carefully before you decide whether or not you wish to take part.

What is the study about?

This study aims to investigate what different people know and think about sensor data collection and use on campus.

Why have I been invited?

There are no special requirements for participants, apart from being based on Lancaster University's Bailrigg campus.

I would be very grateful if you would agree to take part in this study.

What will I be asked to do if I take part?

You will be asked to take part in an informal interview in which you will be encouraged to talk about your experiences with and opinion towards sensor data collection and use on campus. You might also be asked to draw sketches to visualize some of your answers.

The interview may last up to an hour and will be arranged at a convenient time to suit you. The interview will be recorded and later transcribed. Quotations from what you say during the interview and any of the sketches you create may be used in publications, but they will be anonymised.

What are the possible benefits from taking part?

Taking part in this study will allow you to share your experiences with and opinion towards sensor data collection and use on campus. This will contribute to our understanding of the role of sensor data in decision-making in smart cities and help us create tools to reveal challenges in smart city data.

Do I have to take part?

No. It is completely up to you to decide whether or not you take part. Your participation is voluntary and you are free to withdraw at any time, without giving any reason. If you decide not to take part in this study, this will not affect your position in the university and your relations with your employer.

What if I change my mind?

As explained above, you are free to withdraw at any time and if you want to withdraw, I will extract any data you contributed to the study and destroy it. Data means the information, views, ideas, sketches etc. that you and other participants will have shared with me. However, it is difficult and often impossible to take out data from one specific participant when this has already been anonymised or pooled together with other people's data. Therefore, you can only withdraw up to 6 weeks after taking part in the study.

What are the possible disadvantages and risks of taking part?

It is unlikely that there will be any major disadvantages to taking part in the study. You would need to invest roughly one hour of your time for the interview.

Will my data be identifiable?

After the interview, only I, the researcher conducting this study, and my research team will have access to the data you share with me. The research team are mainly based in the School of Computing and Communications (SCC) at Lancaster University.

Research Team:

Kelly Widdicks (PhD student, SCC)
Adam Tyler (PhD student, SCC)
Kathlyne New (PhD student, SCC)
Dr Oliver Bates (SCC)
Dr Mike Hazas (SCC)
Professor Adrian Friday (SCC)
Professor Richard Harper (SCC)
Novri Suhermi (PhD Student, Mathematics and Statistics)
Jan Bastiaans (Energy Manager, Facilities)

I will keep all personal information about you (e.g., your name and other information about you that can identify you) confidential, that is I will not share it with others. I will anonymise any audio recordings and hard copies of any data. This means that I remove any personal information.

How will my data be stored?

Your data will be stored in encrypted files (that is no-one other than me, the researcher will be able to access them) and on password-protected computers. I will store hard copies of any data securely in locked cabinets in my office. I will keep data that can identify you separately from non-personal information (e.g., your views on a specific topic).

In accordance with university guidelines, I will keep the data securely for a minimum of ten years.

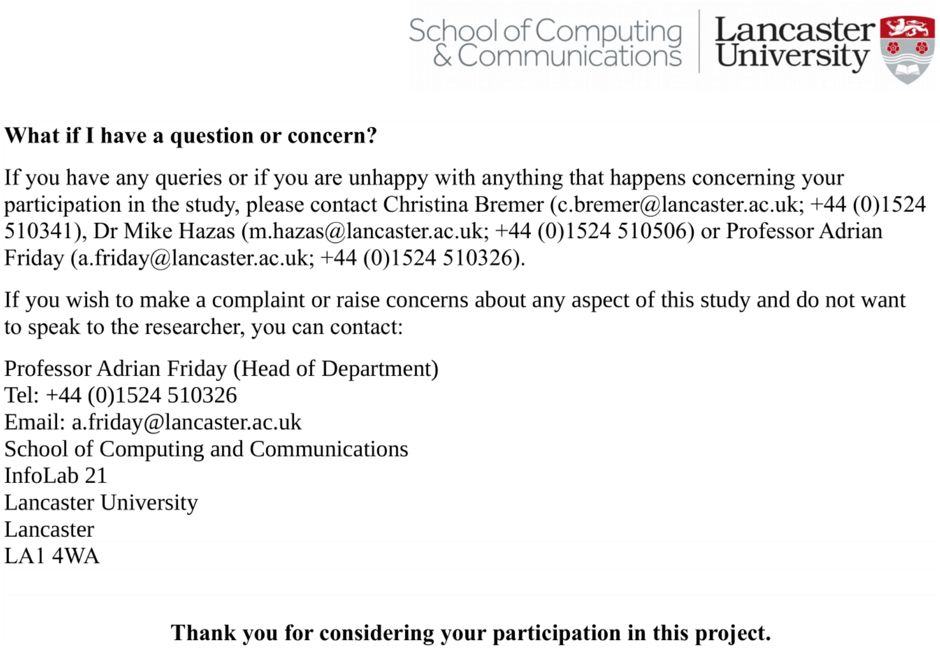
How will we use the information you have shared with us and what will happen to the results of the research study?

The only ways in which I will use the data you have shared with me is for academic purposes and to inform policy-makers. This will include my PhD thesis and other publications, for example journal articles. I may also present the results of my study at academic conferences or workshops.

When writing up the findings from this study, I would like to reproduce some of the views and ideas you shared with me. When doing so, I will only use anonymised quotes so that although I will use your exact words, you cannot be identified in our publications.

Who has reviewed the project?

This study has been reviewed and approved by the Faculty of Science and Technology Research Ethics Committee.



School of Computing & Communications | Lancaster University

What if I have a question or concern?

If you have any queries or if you are unhappy with anything that happens concerning your participation in the study, please contact Christina Bremer (c.bremer@lancaster.ac.uk; +44 (0)1524 510341), Dr Mike Hazas (m.hazas@lancaster.ac.uk; +44 (0)1524 510506) or Professor Adrian Friday (a.friday@lancaster.ac.uk; +44 (0)1524 510326).

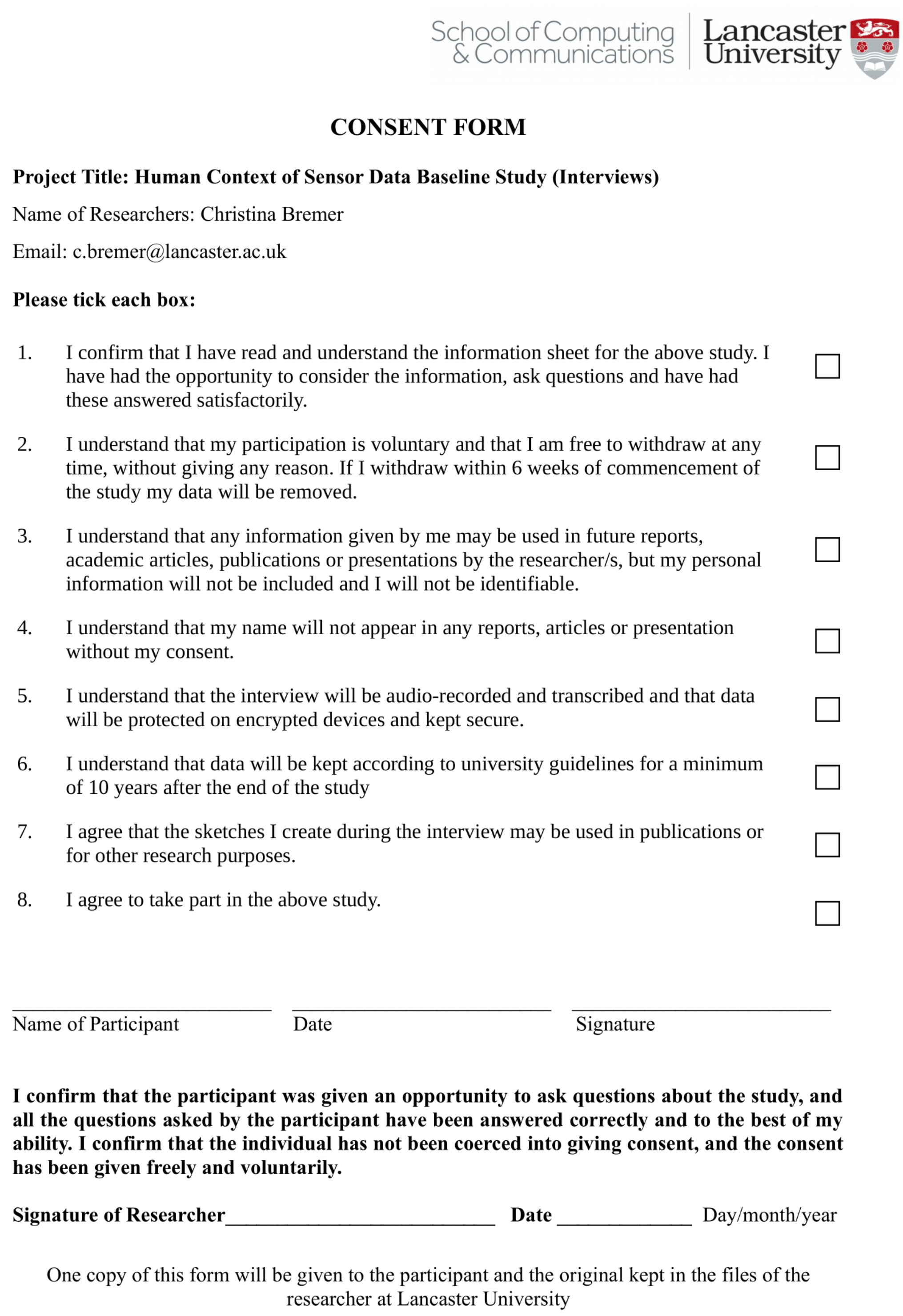
If you wish to make a complaint or raise concerns about any aspect of this study and do not want to speak to the researcher, you can contact:

Professor Adrian Friday (Head of Department)
Tel: +44 (0)1524 510326
Email: a.friday@lancaster.ac.uk
School of Computing and Communications
InfoLab 21
Lancaster University
Lancaster
LA1 4WA

Thank you for considering your participation in this project.

Appendix B

Expert interviews: participant consent form



School of Computing & Communications | Lancaster University

CONSENT FORM

Project Title: Human Context of Sensor Data Baseline Study (Interviews)

Name of Researchers: Christina Bremer

Email: c.bremer@lancaster.ac.uk

Please tick each box:

1. I confirm that I have read and understand the information sheet for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason. If I withdraw within 6 weeks of commencement of the study my data will be removed. ☐
3. I understand that any information given by me may be used in future reports, academic articles, publications or presentations by the researcher/s, but my personal information will not be included and I will not be identifiable. ☐
4. I understand that my name will not appear in any reports, articles or presentation without my consent. ☐
5. I understand that the interview will be audio-recorded and transcribed and that data will be protected on encrypted devices and kept secure. ☐
6. I understand that data will be kept according to university guidelines for a minimum of 10 years after the end of the study ☐
7. I agree that the sketches I create during the interview may be used in publications or for other research purposes. ☐
8. I agree to take part in the above study. ☐

__________________________ __________________________ __________________________
Name of Participant Date Signature

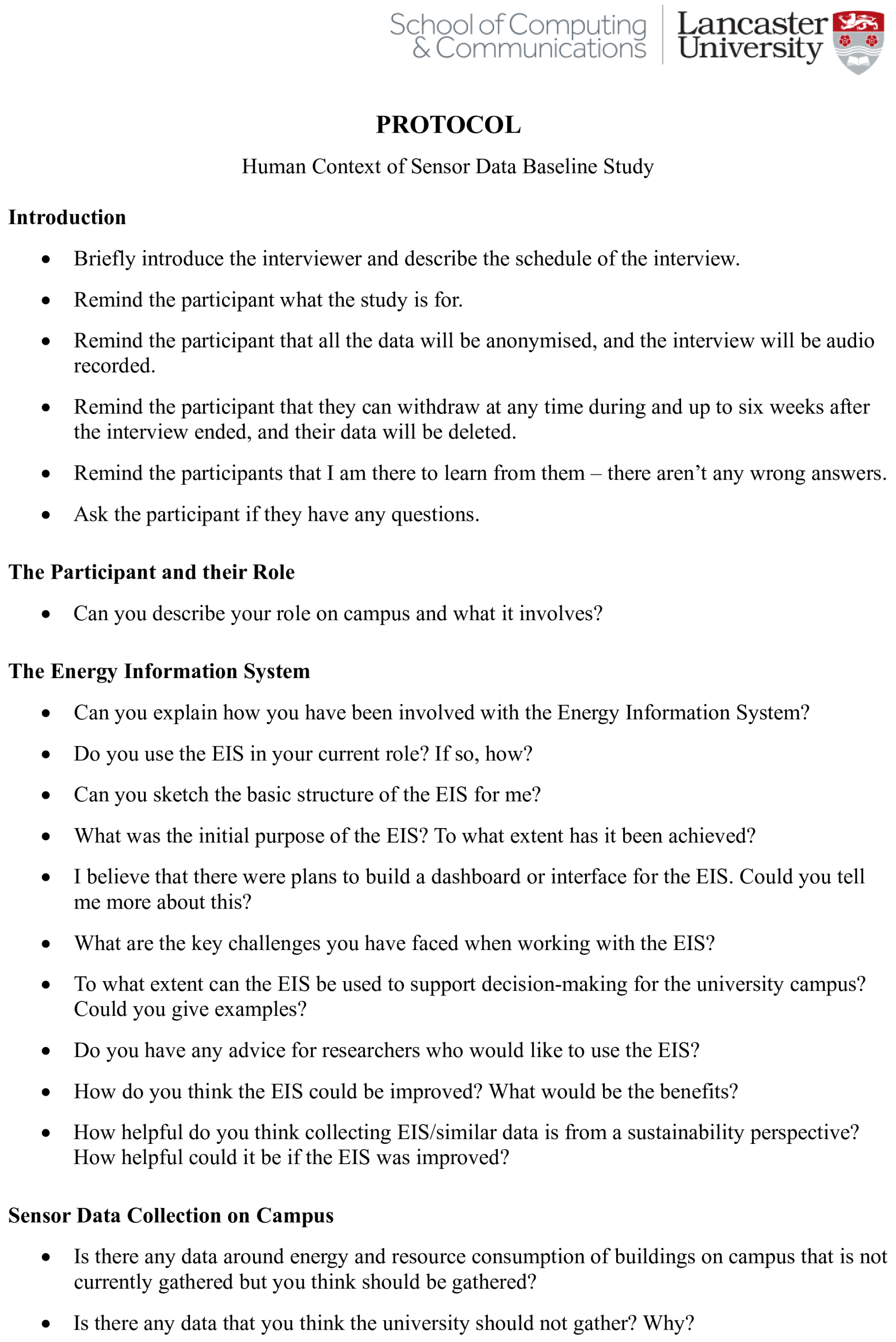
I confirm that the participant was given an opportunity to ask questions about the study, and all the questions asked by the participant have been answered correctly and to the best of my ability. I confirm that the individual has not been coerced into giving consent, and the consent has been given freely and voluntarily.

Signature of Researcher___________________________ **Date** _____________ Day/month/year

One copy of this form will be given to the participant and the original kept in the files of the researcher at Lancaster University

Appendix C

Expert interviews: example protocol



School of Computing & Communications | Lancaster University

PROTOCOL

Human Context of Sensor Data Baseline Study

Introduction

- Briefly introduce the interviewer and describe the schedule of the interview.
- Remind the participant what the study is for.
- Remind the participant that all the data will be anonymised, and the interview will be audio recorded.
- Remind the participant that they can withdraw at any time during and up to six weeks after the interview ended, and their data will be deleted.
- Remind the participants that I am there to learn from them – there aren't any wrong answers.
- Ask the participant if they have any questions.

The Participant and their Role

- Can you describe your role on campus and what it involves?

The Energy Information System

- Can you explain how you have been involved with the Energy Information System?
- Do you use the EIS in your current role? If so, how?
- Can you sketch the basic structure of the EIS for me?
- What was the initial purpose of the EIS? To what extent has it been achieved?
- I believe that there were plans to build a dashboard or interface for the EIS. Could you tell me more about this?
- What are the key challenges you have faced when working with the EIS?
- To what extent can the EIS be used to support decision-making for the university campus? Could you give examples?
- Do you have any advice for researchers who would like to use the EIS?
- How do you think the EIS could be improved? What would be the benefits?
- How helpful do you think collecting EIS/similar data is from a sustainability perspective? How helpful could it be if the EIS was improved?

Sensor Data Collection on Campus

- Is there any data around energy and resource consumption of buildings on campus that is not currently gathered but you think should be gathered?
- Is there any data that you think the university should not gather? Why?

Energy Consumption on Campus

- In your opinion, what would be the key measures to reduce the energy consumption on campus?
- Are you aware of any misconceptions around the understanding of energy among campus users?
- How actively do you think campus users should be educated on the energy systems and energy usage on campus?
- How much of a difference do you think that behaviour change of campus users could make in terms of energy consumption? (I mean students and staff rather than people who are involved in the decision-making processes around energy.)
- How much potential do you see in the automation of the energy systems, for example the heating system?
- Do you foresee any challenges related to the automation of energy systems on campus?
- Are you aware of any initiatives or projects that aim to reduce the energy consumption on campus – or did so in the past?

Summary

- Is there anything else you want to say? Do you have any questions?
- Thank the participant for taking the time for this interview and that they were willing to share your insights with me.
- Considering the subject of the interview, do you know anyone else with expertise whom I could ask if they would be willing to get interviewed by me?

Appendix D

Jamboard study and focus group: participant information sheet

School of Computing & Communications | Lancaster University

PARTICIPANT INFORMATION SHEET

For further information about how Lancaster University processes personal data for research purposes and your data rights please visit our webpage: www.lancaster.ac.uk/research/data-protection

I am a PhD student at Lancaster University and I would like to invite you to take part in a research study about the human context of sensor data.

Please take time to read the following information carefully before you decide whether or not you wish to take part.

What is the study about?

This study aims to investigate what different people know and think about sensor data collection and use on campus.

Why have I been invited?

There are no special requirements for participants, apart from being based on Lancaster University's Bailrigg campus.

I would be very grateful if you would agree to take part in this study.

What will I be asked to do if I take part?

You will be asked to annotate graphs that visualise sensor data collected on campus. Subsequently, you will be asked to take part in a focus group in which you will be encouraged to talk about your experiences with and opinion towards sensor data collection and use on campus.

The focus group may last up to an hour and will be arranged at a convenient time to suit you. The focus group will be recorded and later transcribed. Quotations from what you say during the focus group may be used in publications, but they will be anonymised.

What are the possible benefits from taking part?

Taking part in this study will allow you to share your experiences with and opinion towards sensor data collection and use on campus. This will contribute to our understanding of the role of sensor data in decision-making in smart cities and help us create tools to reveal challenges in smart city data.

Do I have to take part?

No. It is completely up to you to decide whether or not you take part. Your participation is voluntary and you are free to withdraw at any time, without giving any reason. If you decide not to take part in this study, this will not affect your position in the university and your relations with your employer.

What if I change my mind?

As explained above, you are free to withdraw at any time. During and after the focus group, it will not be possible for you to withdraw your data. You will be reminded beforehand that due to the nature of the group discussion, once the focus group has been completed, data cannot be withdrawn.

What are the possible disadvantages and risks of taking part?

It is unlikely that there will be any major disadvantages to taking part in the study. You would need to invest roughly one hour of your time for the focus group.

Will my data be identifiable?

After the focus group, only I, the researcher conducting this study, and my research team will have access to the data you share with me. The research team are mainly based in the School of Computing and Communications (SCC) at Lancaster University.

Research Team:

Iman Hussain (PhD student, SCC)
Matthew Marsden (PhD student, SCC)
Adam Tyler (PhD student, SCC)
Kathlyne New (PhD student, SCC)
Dr Kelly Widdicks (SCC)
Dr Oliver Bates (SCC)
Dr Bran Knowles (SCC)
Professor Adrian Friday (SCC)
Professor Richard Harper (SCC)
Novri Suhermi (PhD Student, Mathematics and Statistics)
Jan Bastiaans (Energy Manager, Facilities)

I will keep all personal information about you (e.g., your name and other information about you that can identify you) confidential, that is I will not share it with others. I will anonymise any audio recordings and hard copies of any data. This means that I remove any personal information.

You will be asked not to disclose information outside of the focus group and with anyone not involved in the focus group without the relevant person’s express permission.

How will my data be stored?

Your data will be stored in encrypted files (that is no-one other than me, the researcher will be able to access them) and on password-protected computers. I will store hard copies of any data securely in locked cabinets in my office. I will keep data that can identify you separately from non-personal information (e.g., your views on a specific topic).

In accordance with university guidelines, I will keep the data securely for a minimum of ten years.

How will we use the information you have shared with us and what will happen to the results of the research study?

The only ways in which I will use the data you have shared with me is for academic purposes and to inform policy-makers. This will include my PhD thesis and other publications, for example journal articles. I may also present the results of my study at academic conferences or workshops.

When writing up the findings from this study, I would like to reproduce some of the views and ideas you shared with me. When doing so, I will only use anonymised quotes so that although I will use your exact words, you cannot be identified in our publications.

Who has reviewed the project?

This study has been reviewed and approved by the Faculty of Science and Technology Research Ethics Committee.

What if I have a question or concern?

If you have any queries or if you are unhappy with anything that happens concerning your participation in the study, please contact Christina Bremer (c.bremer@lancaster.ac.uk), Dr Bran Knowles (b.h.knowles1@lancaster.ac.uk) or Professor Adrian Friday (a.friday@lancaster.ac.uk).

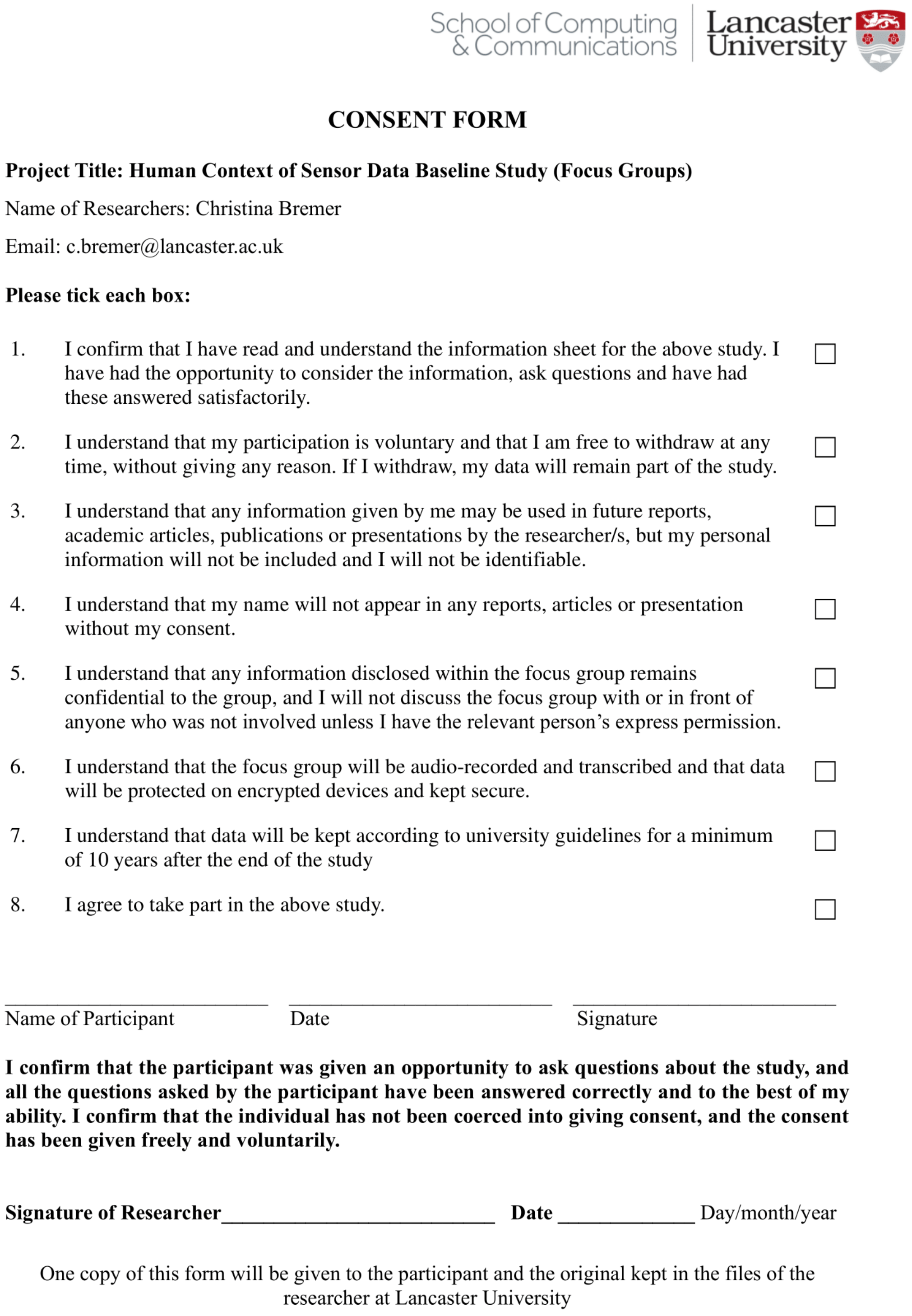
If you wish to make a complaint or raise concerns about any aspect of this study and do not want to speak to the researcher, you can contact:

Professor Adrian Friday (Head of Department)
Tel: +44 (0)1524 510326
Email: a.friday@lancaster.ac.uk
School of Computing and Communications
InfoLab 21
Lancaster University
Lancaster
LA1 4WA

Thank you for considering your participation in this project.

Appendix E

Jamboard study and focus group: participant consent form



School of Computing & Communications | Lancaster University

CONSENT FORM

Project Title: Human Context of Sensor Data Baseline Study (Focus Groups)

Name of Researchers: Christina Bremer

Email: c.bremer@lancaster.ac.uk

Please tick each box:

1. I confirm that I have read and understand the information sheet for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason. If I withdraw, my data will remain part of the study. ☐
3. I understand that any information given by me may be used in future reports, academic articles, publications or presentations by the researcher/s, but my personal information will not be included and I will not be identifiable. ☐
4. I understand that my name will not appear in any reports, articles or presentation without my consent. ☐
5. I understand that any information disclosed within the focus group remains confidential to the group, and I will not discuss the focus group with or in front of anyone who was not involved unless I have the relevant person's express permission. ☐
6. I understand that the focus group will be audio-recorded and transcribed and that data will be protected on encrypted devices and kept secure. ☐
7. I understand that data will be kept according to university guidelines for a minimum of 10 years after the end of the study ☐
8. I agree to take part in the above study. ☐

________________________ ________________________ ________________________
Name of Participant Date Signature

I confirm that the participant was given an opportunity to ask questions about the study, and all the questions asked by the participant have been answered correctly and to the best of my ability. I confirm that the individual has not been coerced into giving consent, and the consent has been given freely and voluntarily.

Signature of Researcher________________________ **Date** ____________ Day/month/year

One copy of this form will be given to the participant and the original kept in the files of the researcher at Lancaster University

Appendix F

Search terms for the rebound effect literature mapping

ACM

Search 1

S. Title:("smart home") OR Abstract:("smart home") OR Keyword:("smart home") OR Title:("smart homes") OR Abstract:("smart homes") OR Keyword:("smart homes")

E. Title:("energy efficient") OR Abstract:("energy efficient") OR Keyword:("energy efficient") OR Title:("energy efficiency") OR Abstract:("energy efficiency") OR Keyword:("energy efficiency")

R. (Title:("rebound effect") OR Abstract:("rebound effect") OR Keyword:("rebound effect") OR Title:("rebound effects") OR Abstract:("rebound effects") OR Keyword:("rebound effects") Title:("jevons paradox") OR Abstract:("jevons paradox") OR Keyword:("jevons paradox") OR Title:("khazzoom-brookes postulate") OR Abstract:("khazzoom-brookes postulate") OR Keyword:("khazzoom-brookes postulate"))

ES. (Title:("energy efficient") OR Abstract:("energy efficient") OR Keyword:("energy efficient") OR Title:("energy efficiency") OR Abstract:("energy efficiency") OR Keyword:("energy efficiency")) AND (Title:("smart home") OR Abstract:("smart home") OR Keyword:("smart home") OR Title:("smart homes") OR Abstract:("smart homes") OR Keyword:("smart homes"))

SR. (Title:("smart home") OR Abstract:("smart home") OR Keyword:("smart home") OR Title:("smart homes") OR Abstract:("smart homes") OR Keyword:("smart homes”)) AND (Title:(“rebound effect”) OR Abstract:(“rebound effect”) OR Keyword:(“rebound effect”) OR Title:(“rebound effects”) OR Abstract:(“rebound effects”) OR Keyword:(“rebound effects”) Title:(“jevons paradox”) OR Abstract:(“jevons paradox”) OR Keyword:(“jevons paradox”) OR Title:(“khazzoom-brookes postulate”) OR Abstract:(“khazzoom-brookes postulate”) OR Keyword:(“khazzoom-brookes postulate”))

ER. (Title:(“energy efficient”) OR Abstract:(“energy efficient”) OR Keyword:(“energy efficient”) OR Title:(“energy efficiency”) OR Abstract:(“energy efficiency”) OR Keyword:(“energy efficiency”)) AND (Title:(“rebound effect”) OR Abstract:(“rebound effect”) OR Keyword:(“rebound effect”) OR Title:(“rebound effects”) OR Abstract:(“rebound effects”) OR Keyword:(“rebound effects”) Title:(“jevons paradox”) OR Abstract:(“jevons paradox”) OR Keyword:(“jevons paradox”) OR Title:(“khazzoom-brookes postulate”) OR Abstract:(“khazzoom-brookes postulate”) OR Keyword:(“khazzoom-brookes postulate”))

ESR. (Title:(“energy efficient”) OR Abstract:(“energy efficient”) OR Keyword:(“energy efficient”) OR Title:(“energy efficiency”) OR Abstract:(“energy efficiency”) OR Keyword:(“energy efficiency”)) AND (Title:(“smart home”) OR Abstract:(“smart home”) OR Keyword:(“smart home”) OR Title:(“smart homes”) OR Abstract:(“smart homes”) OR Keyword:(“smart homes”)) AND (Title:(“rebound effect”) OR Abstract:(“rebound effect”) OR Keyword:(“rebound effect”) OR Title:(“rebound effects”) OR Abstract:(“rebound effects”) OR Keyword:(“rebound effects”) Title:(“jevons paradox”) OR Abstract:(“jevons paradox”) OR Keyword:(“jevons paradox”) OR Title:(“khazzoom-brookes postulate”) OR Abstract:(“khazzoom-brookes postulate”) OR Keyword:(“khazzoom-brookes postulate”))

Search 2

S. AllField:(“smart home”) OR AllField:(“smart homes”)

E. AllField:(“energy efficient”) OR AllField:(“energy efficiency”)

R. AllField:(“rebound effect”) OR AllField:(“rebound effects”) OR AllField:(“jevons paradox”) OR AllField:(“khazzoom-brookes postulate”)

ES. (AllField:(“energy efficient”) OR AllField:(“energy efficiency”)) AND (AllField:(“smart home”) OR AllField:(“smart homes”))

SR. (AllField:(“smart home”) OR AllField:(“smart homes”)) AND (AllField:(“rebound effect”) OR AllField:(“rebound effects”) OR AllField:(“jevons paradox”) OR AllField:(“khazzoom-brookes postulate”))

ER. (AllField:("energy efficient") OR AllField:("energy efficiency")) AND (AllField:("rebound effect") OR AllField:("rebound effects") OR AllField:("jevons paradox") OR AllField:("khazzoom-brookes postulate"))

ESR. (AllField:("energy efficient") OR AllField:("energy efficiency")) AND (AllField:("smart home") OR AllField:("smart homes")) AND (AllField:("rebound effect") OR AllField:("rebound effects") OR AllField:("jevons paradox") OR AllField:("khazzoom-brookes postulate"))

IEEE

Search 1

S. ("All Metadata":"smart home*")

E. ("All Metadata":"energy efficien*")

R. ("All Metadata":"rebound effect*") OR ("All Metadata":"jevons paradox") OR ("All Metadata":"khazzoom-brookes postulate")

ES. ("All Metadata":"energy efficien*") AND ("All Metadata":"smart home*")

SR. ("All Metadata":"smart home*") AND ("All Metadata":"rebound effect*" OR "All Metadata":"jevons paradox" OR "All Metadata":"khazzoom-brookes postulate")

ER. ("All Metadata":"energy efficien*") AND ("All Metadata":"rebound effect*" OR "All Metadata":"jevons paradox" OR "All Metadata":"khazzoom-brookes postulate")

ESR. ("All Metadata":"smart home*") AND ("All Metadata":"energy efficien*") AND ("All Metadata":"rebound effect*" OR "All Metadata":"jevons paradox" OR "All Metadata":"khazzoom-brookes postulate")

Search 2

S. ("Full Text Only":"smart home*")

E. ("Full Text Only":"energy efficien*")

R. ("Full Text Only":"rebound effect*") OR ("Full Text Only":"jevons paradox") OR ("Full Text Only":"khazzoom-brookes postulate")

ES. ("Full Text Only":"energy efficien*") AND ("Full Text Only":"smart home*")

SR. (“Full Text Only”:“smart home*”) AND (“Full Text Only”:“rebound effect*” OR “Full Text Only”:“jevons paradox” OR “Full Text Only”:“khazzoom-brookes postulate”)

ER. (“Full Text Only”:“energy efficien*”) AND (“Full Text Only”:“rebound effect*” OR “Full Text Only”:“jevons paradox” OR “Full Text Only”:“khazzoom-brookes postulate”)

ESR. (“Full Text Only”:“smart home*”) AND (“Full Text Only”:“energy efficien*;;) AND (“Full Text Only”:“rebound effect*” OR “Full Text Only”:“jevons paradox” OR “Full Text Only”:“khazzoom-brookes postulate”)

Scopus

Search 1

S. TITLE-ABS-KEY (“smart home*”)

E. TITLE-ABS-KEY (“energy efficien*”)

R. TITLE-ABS-KEY (“rebound effect*” OR “jevons paradox” OR “khazzoom-brookes postulate”)

ES. TITLE-ABS-KEY (“energy efficien*” AND “smart home*”)

SR. TITLE-ABS-KEY (“smart home*” AND (“rebound effect*” OR “jevons paradox” OR “khazzoom-brookes postulate”))

ER. TITLE-ABS-KEY (“energy efficien*” AND (“rebound effect*” OR “jevons paradox” OR “khazzoom-brookes postulate”))

ESR. TITLE-ABS-KEY (“energy efficien*” AND “smart home*” AND (“rebound effect*” OR “jevons paradox” OR “khazzoom-brookes postulate”))

Search 2

It is not possible to conduct full-text searches for Scopus.

ScienceDirect

Search 1

S. Title, abstract, keywords: “smart home” OR “smart homes”

E. Title, abstract, keywords: “energy efficient” OR “energy efficiency”

R. “rebound effect” OR “rebound effects” OR “jevons paradox” OR “khazzoom-brookes postulate”

ES. Title, abstract, keywords: (“energy efficient” OR “energy efficiency”) AND (“smart home” OR “smart homes”)

SR. Title, abstract, keywords: (“smart home” OR “smart homes”) AND (“rebound effect” OR “rebound effects” OR “jevons paradox” OR “khazzoom-brookes postulate”)

ER. Title, abstract, keywords: (“energy efficient” OR “energy efficiency”) AND (“rebound effect” OR “rebound effects” OR “jevons paradox” OR “khazzoom-brookes postulate”)

ESR. Title, abstract, keywords: (“energy efficient” OR “energy efficiency”) AND (“smart home” OR “smart homes”) AND (“rebound effect” OR “rebound effects” OR “jevons paradox” OR “khazzoom-brookes postulate”)

Search 2

S. (“smart home”) OR (“smart homes”)

E. (“energy efficient”) OR (“energy efficiency”)

R. (“rebound effect”) OR (“rebound effects”) OR (“jevons paradox”) OR (“khazzoom-brookes postulate”)

ES. ((“energy efficient”) OR (“energy efficiency”)) AND ((“smart home”) OR (“smart homes”))

SR. ((“smart home”) OR (“smart homes”)) AND ((“rebound effect”) OR (“rebound effects”) OR (“jevons paradox”) OR (“khazzoom-brookes postulate”))

ER. ((“energy efficient”) OR (“energy efficiency”)) AND ((“rebound effect”) OR (“rebound effects”) OR (“jevons paradox”) OR (“khazzoom-brookes postulate”))

ESR. ((“energy efficient”) OR (“energy efficiency”)) AND ((“smart home”) OR (“smart homes”)) AND ((“rebound effect”) OR (“rebound effects”) OR (“jevons paradox”) OR (“khazzoom-brookes postulate”))

Appendix G

Mapping results for the SIGCHI library

Conference		**CHI**	**TEI**	**C&C**	**DIS**	**IMX**	**EICS**	**AutomotiveUI**	**RecSys**	**MobileHCI**	**ICMI**	**CSCW**	**AHs**	**CHIIR**	**W4A**	**GI**	**AVI**	**CUI**	**iWOAR**	**NordiCHI**	**IoT**	**PACMHCI**	**Total**
All papers		20714	289	85	730	297	53	846	144	178	402	2862	137	32	181	505	296	22	26	1080	260	1483	**30622**
Search 1																							
	E	10	0	0	1	0	0	2	2	3	0	1	0	1	0	0	0	0	0	2	10	1	**33**
	S	95	6	1	18	1	2	1	0	3	13	5	1	2	2	0	5	2	4	10	19	10	**200**
	R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	ES	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**3**
	ER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	SR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	ESR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Search 2																							
	E	100	8	5	23	0	4	15	3	27	13	14	1	13	1	0	3	0	4	8	31	5	**278**
	S	346	28	5	85	6	18	3	2	37	39	26	6	8	6	0	15	13	6	34	47	47	**777**
	R	11	0	0	3	0	0	1	0	1	0	3	0	0	0	0	1	0	0	1	1	1	**23**
	ES	19	1	0	5	0	0	0	1	1	3	1	0	0	0	0	1	0	0	2	7	0	**41**
	ER	4	0	0	0	0	0	0	0	1	0	3	0	0	0	0	0	0	0	1	1	0	**10**
	SR	5	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	**8**
	ESR	3	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	**6**

Table G.1: Mapping results for the SIGCHI library.

Appendix H

The SHCI critique corpus

Year	**Author(s)**	**Title**	**Venue (abb.)**
2009	Wong, J.	Prepare for Descent: Interaction Design in our New Future	Workshop at CHI
2010	Blevis, E., & Blevis, S.	Hope for the Best and Prepare for the Worst: Interaction Design and the Tipping Point	Interactions
2010	Dourish, P.	HCI and Environmental Sustainability: The Politics of Design and the Design of Politics	DIS
2010	Silberman, M. S., & Tomlinson, B.	Toward an Ecological Sensibility: Tools for Evaluating Sustainable HCI	CHI Extended Abstracts
2011	Baumer, E. P. S., & Silberman, M. S.	When the Implication Is Not to Design (Technology)	CHI
2011	Kaufman, S. J., & Silberman, M. S.	Rebound Effects in Sustainable HCI	Workshop at CHI
2011	Strengers, Y.	Designing Eco-Feedback Systems for Everyday Life	CHI
2012	Brynjarsdóttir et al.	Sustainably Unpersuaded: How Persuasion Narrows Our Vision of Sustainability	CHI
2012	Hazas et al.	Sustainability Does Not Begin with the Individual	Interactions
2012	Mankoff, J.	HCI and Sustainability: A Tale of Two Motivations	Interactions
2012	Møllenbach et al.	HCI and Sustainability: The Role of Macrostructures	CHI Extended Abstracts
2012	Tomlinson et al.	What If Sustainability Doesn't Work Out?	Interactions

Table H.1: SHCI critique corpus. Page 1.

Year	**Author(s)**	**Title**	**Venue (abb.)**
2013	Ganglbauer et al.	An Activist Lens for Sustainability: From Changing Individuals to Changing the Environment	Persuasive
2013	Håkansson, M., & Sengers, P.	Beyond Being Green: Simple Living Families and ICT	CHI
2014	Bates et al.	Towards an Holistic View of the Energy and Environmental Impacts of Domestic Media and IT	CHI
2014	Dillahunt, T.	Toward a Deeper Understanding of Sustainability within HCI	Workshop at CHI
2014	Easterbrook, S.	From Computational Thinking to Systems Thinking: A conceptual toolkit for sustainability computing	ICT4S
2014	Håkansson, M., & Sengers, P.	No Easy Compromise: Sustainability and the Dilemmas and Dynamics of Change	DIS
2014	Knowles et al.	Patterns of Persuasion for Sustainability	DIS
2014	Knowles et al.	Rethinking Plan A for Sustainable HCI	CHI
2014	Pargman, D., & Raghavan, B.	Rethinking Sustainability in Computing: From Buzzword to Non-negotiable Limits	NordiCHI
2014	Silberman et al.	Next Steps for Sustainable HCI	Interactions
2014	Strengers, Y.	Smart Energy in Everyday Life: Are You Designing for Resource Man?	Interactions
2014	Weeks et al.	Sustainable HCI and Encouraging Retrofitting	Workshop at NordiCHI
2015	Bates et al.	Exploring (un)sustainable growth of digital technologies in the home	ICT4S

Table H.2: SHCI critique corpus. Page 2.

Year	**Author(s)**	**Title**	**Venue (abb.)**
2015	Gui, X., & Nardi, B.	Foster the" mores", counter the "limits"	First Monday
2015	Joshi, S., & Pargman, T. C.	In Search of Fairness: Critical Design Alternatives for Sustainability	Critical Alternatives
2015	Knowles, B., & Eriksson, E.	Deviant and guilt-ridden: Computing within psychological limits	First Monday
2015	Silberman, M. S.	Information systems for the age of consequences	First Monday
2016	Chen, J.	A Strategy for Limits-aware Computing	LIMITS
2017	Raghavan, B., & Pargman, D.	Means and Ends in Human-Computer Interaction: Sustainability through Disintermediation	CHI
2017	Remy et al.	The Limits of Evaluating Sustainability	LIMITS
2018	Bendor, R.	Sustainability, Hope, and Designerly Action in the Anthropocene	Interactions
2018	Knowles et al.	This Changes Sustainable HCI	CHI
2018	Liu et al.	Out of Control: Reframing Sustainable HCI Using Permaculture	LIMITS

Table H.3: SHCI critique corpus. Page 3.

Appendix I

The SHCI critique adoption corpus

Year	**Author(s)**	**Title**
2019	Dema et al.	Designing Participatory Sensing with Remote Communities to Conserve Endangered Species
2019	Heitlinger et al.	The Right to the Sustainable Smart City
2019	Liu et al.	Symbiotic Encounters: HCI and Sustainable Agriculture
2019	Preist et al.	Evaluating Sustainable Interaction Design of Digital Services: The Case of YouTube
2019	Rifat et al.	The Breaking Hand: Skills, Care, and Sufferings of the Hands of an Electronic Waste Worker in Bangladesh
2019	Soden, R., & Kauffman, N.	Infrastructuring the Imaginary: How Sea-level Rise Comes to Matter in The San Francisco Bay Area
2019	Widdicks et al.	Streaming, Multi-Screens and YouTube: The New (Unsustainable) Ways of Watching in the Home
2020	Biggs, H. R., & Desjardins, A.	High Water Pants: Designing Embodied Environmental Speculation
2020	Dema et al.	Designing in the Network of Relations for Species Conservation: The Playful Tingtibi Community Birdhouse
2020	Jacques, J. T.	CHI 2020: Right Here, Right Now? A bottom-up approach to estimating the carbon emissions from more than twenty years of CHI conference travel
2020	Meena et al.	PV-Tiles: Towards Closely-Coupled Photovoltaic and Digital Materials for Useful, Beautiful and Sustainable Interactive Surfaces
2020	Tomlinson, B.	Suffering-Centered Design
2020	Wilkins et al.	Peer-to-Peer Energy Markets: Understanding the Values of Collective and Community Trading
2020	Willis et al.	Low Power Web: Legacy Design and the Path to Sustainable Net Futures

Table I.1: SHCI critique adoption corpus. Page 1.

Year	**Author(s)**	**Title**
2020	Wu, S., & Devendorf, L.	Unfabricate: Designing Smart Textiles for Disassembly
2021	Bardzell et al.	Wanting To Live Here: Design After Anthropocentric Functionalism
2021	Biggs et al.	Watching Myself Watching Birds: Abjection, Ecological Thinking, and Posthuman Design
2021	Cho et al.	From The Art of Reflection to The Art of Noticing: A Shifing View of Self-Tracking Technologies' Role in Supporting Sustainable Food Practices
2021	Hamm et al.	What Makes Civic Tech Initiatives To Last Over Time? Dissecting Two Global Cases
2021	Hansson et al.	A Decade of Sustainable HCI: Connecting SHCI to the Sustainable Development Goals
2021	Heitlinger et al.	Algorithmic Food Justice: Co-Designing More-than-Human Blockchain Futures for the Food Commons
2021	Landwehr et al.	Community Supported Agriculture: The Concept of Solidarity in Mitigating Between Harvests and Needs
2021	Shaikh et al.	EnergyVis: Interactively Tracking and Exploring Energy Consumption for ML Models
2021	Shakeri, G., & McCallum, C. H.	Envirofy your Shop: Development of a Real-time Tool to Support Eco-friendly Food Purchases Online
2021	Snow et al.	Neighbourhood Wattch: Using Speculative Design to Explore Values Around Curtailment and Consent in Household Energy Interactions
2021	Song, K. W., & Paulos, E.	Unmaking: Enabling and Celebrating the Creative Material of Failure, Destruction, Decay, and Deformation
2021	Wall et al.	Scrappy: Using Scrap Material as Infill to Make Fabrication More Sustainable

Table I.2: SHCI critique adoption corpus. Page 2.

References

Abrahamse, Wokje et al. (2005). "A review of intervention studies aimed at household energy conservation". In: *Journal of Environmental Psychology* 25.3, pp. 273–291.

Ahlers, Dirk (2020). "Challenges of Sustainable Urban Mobility Integration". In: *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services*, pp. 1–3.

Al Dakheel, Joud et al. (2020). "Smart buildings features and key performance indicators: A review". In: *Sustainable Cities and Society* 61, p. 102328.

Alam, Muhammad Raisul, Mamun Bin Ibne Reaz, and Mohd Alauddin Mohd Ali (2012). "A review of smart homes—Past, present, and future". In: *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 42.6, pp. 1190–1203.

Alan, Alper T et al. (2016). "It is too hot: An in-situ study of three designs for heating". In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 5262–5273.

Alavi, Hamed S et al. (2019). "Introduction to Human-Building Interaction (HBI): Interfacing HCI with Architecture and Urban Design". In: *ACM Transactions on Computer-Human Interaction (TOCHI)* 26.2, pp. 1–10.

Alcott, Blake (2005). "Jevons' paradox". In: *Ecological Economics* 54, pp. 9–21.

Andrei, Horia et al. (2021). "Energy Consumption, Pandemic Period and Online Academic Education: Case Studies in Romanian Universities". In: *7th International Symposium on Electrical and Electronics Engineering (ISEEE)*. IEEE, pp. 1–6.

Aoki, Paul M et al. (2009). "A vehicle for research: using street sweepers to explore the landscape of environmental community action". In: *Proceedings of the 2009 CHI Conference on Human Factors in Computing Systems*, pp. 375–384.

Arnold, Ross D and Jon P Wade (2015). "A definition of systems thinking: A systems approach". In: *Procedia computer science* 44, pp. 669–678.

Ashby, Simone et al. (2019). "Fourth-wave HCI meets the 21st century manifesto". In: *Proceedings of the Halfway to the Future Symposium 2019*, pp. 1–11.

Azevedo, Inês L (2014). "Consumer end-use energy efficiency and rebound effects". In: *Annual Review of Environment and Resources* 39.1, pp. 393–418.

Bainbridge, Lisanne (1983). “Ironies of automation”. In: *Analysis, Design and Evaluation of Man–Machine Systems*. Elsevier, pp. 129–135.

Bang, Magnus, Carin Torstensson, and Cecilia Katzeff (2006). “The powerhhouse: A persuasive computer game designed to raise awareness of domestic energy consumption”. In: *International Conference on Persuasive Technology*. Springer, pp. 123–132.

Bannon, Liam J (1991). “From human factors to human actors: The role of psychology and human-computer interaction studies in system design”. In: *Design at work: Cooperative Design of Computer Systems*. Elsevier, pp. 25–44.

Barbu, Anca-Diana, Nigel Griffiths, and Gareth Morton (2013). *Achieving energy efficiency through behaviour change: what does it take?* URL: `https://www.osti.gov/etdeweb/biblio/22094230`.

Bardzell, Jeffrey, Shaowen Bardzell, and Ann Light (2021). “Wanting To Live Here: Design After Anthropocentric Functionalism”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–24.

Barker, Terry, Athanasios Dagoumas, and Jonathan Rubin (2009). “The macroeconomic rebound effect and the world economy”. In: *Energy Efficiency* 2.4, pp. 411–427.

Bates, Oliver and Adrian Friday (2017). “Beyond data in the smart city: repurposing existing campus IoT”. In: *IEEE Pervasive Computing* 16.2, pp. 54–60.

Bates, Oliver, Mike Hazas, et al. (2014). “Towards an holistic view of the energy and environmental impacts of domestic media and IT”. In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*, pp. 1173–1182.

Bates, Oliver, Vanessa Thomas, and Christian Remy (2017). “Doing good in HCI: Can we broaden our agenda?” In: *Interactions* 24.5, pp. 80–82.

Baumer, Eric and M Six Silberman (2011). “When the implication is not to design (technology)”. In: *Proceedings of the 2011 CHI Conference on Human Factors in Computing Systems*, pp. 2271–2274.

Becker, Vincent et al. (2018). “Estimating the savings potential of occupancy-based heating strategies”. In: *Energy Informatics* 1.S1, p. 52.

Bedwell, Ben, Enrico Costanza, and Michael O Jewell (2016). “Understanding energy consumption at work: Learning from arrow hill”. In: *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing*, pp. 1337–1348.

Beltram, Lucas, Morten Herget Christensen, and Rongling Li (2019). “Demonstration of heating demand peak shaving in smart homes”. In: *Journal of Physics: Conference Series* 1343.1, p. 012055.

Bendor, Roy (2018). “Sustainability, hope, and designerly action in the anthropocene”. In: *Interactions* 25.3, pp. 82–84.

Berkhout, Frans and Julia Hertin (2001). “Impacts of information and communication technologies on environmental sustainability: Speculations and evidence”. In: *Report to the OECD, Brighton* 21.

Berkhout, Peter H G, Jos C Muskens, and Jan W Velthuijsen (2000). “Defining the rebound effect”. In: *Energy Policy* 28.6-7, pp. 425–432.

Bielek, Boris and Milan Bielek (2012). “Environmental Strategies for Design of Sustainable Buildings in Technique of Green Eco-Architecture”. In: *Journal of Civil Engineering and Architecture* 6.7, p. 892.

Bierwirth, Anja and Stefan Thomas (2015). “Almost best friends: sufficiency and efficiency; can sufficiency maximise efficiency gains in buildings?” In: *ECEEE Summer Study Proceedings*. Europ. Council for an Energy Efficient Economy.

Biggs, Heidi R and Audrey Desjardins (2020). “High Water Pants: Designing Embodied Environmental Speculation”. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–13.

Binswanger, Mathias (2001). “Technological progress and sustainable development: what about the rebound effect?” In: *Ecological Economics* 36.1, pp. 119–132.

Birch, Christina et al. (2020). “Electrical consumption in the Higher Education sector, during the COVID-19 shutdown”. In: *2020 IEEE PES/IAS PowerAfrica*. IEEE, pp. 1–5.

Blevis, Eli (2007). “Sustainable interaction design: invention & disposal, renewal & reuse”. In: *Proceedings of the 2007 CHI Conference on Human Factors in Computing Systems*, pp. 503–512.

Blevis, Eli and Shunying Blevis (2010). “Hope for the best and prepare for the worst: Interaction design and the tipping point”. In: *Interactions* 17.5, pp. 26–30.

Blythe, Mark (2014). “Research through design fiction: narrative in real and imaginary abstracts”. In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*, pp. 703–712.

Bødker, Susanne (2006). “When second wave HCI meets third wave challenges”. In: *Proceedings of the 4th Nordic Conference on Human-Computer Interaction: changing roles*, pp. 1–8.

— (2015). “Third-wave HCI, 10 years later—participation and sharing”. In: *Interactions* 22.5, pp. 24–31.

Bonaccorsi, Andrea, Riccardo Apreda, and Gualtiero Fantoni (2020). “Expert biases in technology foresight. Why they are a problem and how to mitigate them”. In: *Technological Forecasting and Social Change* 151, p. 119855.

Bonanni, Leonardo et al. (2010). “Small business applications of sourcemap: a web tool for sustainable design and supply chain transparency”. In: *Proceedings of the 2010 CHI Conference on Human Factors in Computing Systems*, pp. 937–946.

Börjesson Rivera, Miriam, Ulrika Gunnarsson-Ostling, et al. (2012). “Guidance on Sustainable Social Practices with ICT”. In: *A literature review.*

Börjesson Rivera, Miriam, Cecilia Håkansson, et al. (2014). “Including second order effects in environmental assessments of ICT”. In: *Environmental Modelling & Software* 56, pp. 105–115.

Bornes, Laetitia (2023). “A Methodology and a Tool to Support the Sustainable Design of Interactive Systems: Adapting systemic design tools to model complexity in interaction design”. In: *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–5.

Bornes, Laetitia, Catherine Letondal, and Rob Vingerhoeds (2022). “Could Systemic Design Methods Support Sustainable Design Of Interactive Systems?” In: *Relating Systems Thinking and Design 2021 Symposium*.

Braesemann, Fabian and Andrew Baum (2020). “PropTech: Turning real estate into a data-driven market?” In: *Available at SSRN 3607238*.

Braun, Virginia and Victoria Clarke (2006). “Using thematic analysis in psychology”. In: *Qualitative Research in Psychology* 3.2, pp. 77–101.

BRE Group (2023). *BREEAM technical standards.* URL: `https://bregroup.com/products/breeam/breeam-technical-standards/`.

Bremer, Christina (2020a). “Not (B)interested? Using Persuasive Technology to Promote Sustainable Household Recycling Behavior”. In: *Persuasive Technology. Designing for Future Change: 15th International Conference on Persuasive Technology*. Springer, pp. 195–207.

— (2020b). “When Mental Models Grow (C)old: A Cognitive Perspective on Home Heating Automation”. In: *IEEE Pervasive Computing* 19.4, pp. 48–52.

— (2021). “A Smart Approach?: Raising Uncomfortable Questions about Building Automation in the Workplace”. In: *Automation Experience at the Workplace, workshop at CHI 2021*.

— (2022). “Efficiency Technology as a Political Act”. In: *Towards a Material Ethics of Computing: Addressing the Uneven Environmental Stakes of Digital Infrastructures, workshop at CHI 2022*.

Bremer, Christina, Oliver Bates, et al. (2023). “COVID-19 as an Energy Intervention: Lockdown Insights for HCI”. In: *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–7.

Bremer, Christina, Harshit Gujral, et al. (2023). “How Viable are Energy Savings in Smart Homes? A Call to Embrace Rebound Effects in Sustainable HCI”. In: *ACM Journal on Computing and Sustainable Societies* 1.1, pp. 1–24.

Bremer, Christina, George Kamiya, et al. (2023). “Assessing Energy and Climate Effects of Digitalization: Methodological Challenges and Key Recommendations”. In: *nDEE Framing Paper Series*.

Bremer, Christina, Bran Knowles, and Adrian Friday (2022). “Have We Taken On Too Much?: A Critical Review of the Sustainable HCI Landscape”. In: *CHI Conference on Human Factors in Computing Systems*, pp. 1–11.

Bruner, Jerome (1987). “Life as narrative”. In: *Social Research*, pp. 11–32.

Brynjarsdóttir, Hrönn et al. (2012). “Sustainably unpersuaded: how persuasion narrows our vision of sustainability”. In: *Proceedings of the 2012 CHI Conference on Human Factors in Computing Systems*, pp. 947–956.

Buckman, Alex H, Martin Mayfield, and Stephen B M Beck (2014). “What is a smart building?” In: *Smart and Sustainable Built Environment* 3.2, pp. 92–109.

Buhl, Johannes et al. (2017). “Rebound effects in Living Labs: Opportunities for monitoring and mitigating re-spending and time use effects in user integrated innovation design”. In: *Journal of cleaner production* 151, pp. 592–602.

Callmer, Åsa and Karin Bradley (2021). “In search of sufficiency politics: the case of Sweden”. In: *Sustainability: Science, Practice and Policy* 17.1, pp. 194–208.

Carroll, John M and Mary Beth Rosson (2013). “Wild at home: The neighborhood as a living laboratory for HCI”. In: *ACM Transactions on Computer-Human Interaction (TOCHI)* 20.3, pp. 1–28.

Chaloeytoy, Kittiwoot, Vorapat Inkarojrit, and Anothai Thanachareonkit (2022). “Electricity Consumption in Higher Education Buildings in Thailand during the COVID-19 Pandemic”. In: *Buildings* 12.10, p. 1532.

Checkland, Peter (1999). “Systems thinking”. In: *Rethinking management information systems*, pp. 45–56.

Chen, Jay (2016). “A strategy for limits-aware computing”. In: *Proceedings of the Second Workshop on Computing Within Limits*, pp. 1–6.

Chen, Ko-jung et al. (2018). “Influence of rebound effect on energy saving in smart homes”. In: *Cross-Cultural Design. Applications in Cultural Heritage, Creativity and Social Development: 10th International Conference, Proceedings*. Springer, pp. 266–274.

Chen, Xi, Hongxing Yang, and Lin Lu (2015). “A comprehensive review on passive design approaches in green building rating tools”. In: *Renewable and Sustainable Energy Reviews* 50, pp. 1425–1436.

Chihib, Mehdi et al. (2021). “Impact of the COVID-19 Pandemic on the Energy Use at the University of Almeria (Spain)”. In: *Sustainability* 13.11, p. 5843.

Cho, Janghee, Laura Devendorf, and Stephen Voida (2021). “From The Art of Reflection to The Art of Noticing: A Shifting View of Self-Tracking Technologies’ Role in Supporting Sustainable Food Practices”. In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–7.

Clark, Brent B, Christopher Robert, and Stephen A Hampton (2016). “The technology effect: how perceptions of technology drive excessive optimism”. In: *Journal of Business and Psychology* 31, pp. 87–102.

Clear, Adrian K, Mike Hazas, et al. (2013). “Domestic food and sustainable design: a study of university student cooking and its impacts”. In: *Proceedings of the 2013 CHI Conference on Human Factors in Computing Systems*, pp. 2447–2456.

Clear, Adrian K, Samantha Mitchell Finnigan, et al. (2017). "'I'd Want to Burn the Data or at Least Nobble the Numbers' Towards Data-mediated Building Management for Comfort and Energy Use". In: *Proceedings of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing*, pp. 2448–2461.

Consolvo, Sunny et al. (2007). "Conducting in situ evaluations for and with ubiquitous computing technologies". In: *International Journal of Human-Computer Interaction* 22.1-2, pp. 103–118.

Coroamă, Vlad C, Pernilla Bergmark, et al. (2020). "A Methodology for Assessing the Environmental Effects Induced by ICT Services: Part I: Single Services". In: ICT4S2020. Bristol, United Kingdom: Association for Computing Machinery, pp. 36–45.

Coroamă, Vlad C and Friedemann Mattern (2019). "Digital Rebound – Why Digitalization Will Not Redeem Us Our Environmental Sins". In: *Proc. of the 6th Int. Conf. on ICT for Sustainability (ICT4S)*. Lappeenranta, Finland.

Coroamă, Vlad C and Daniel Pargman (2020). "Skill rebound: On an unintended effect of digitalization". In: *Proceedings of the 7th International Conference on ICT for Sustainability*. Bristol United Kingdom: ACM, pp. 213–219.

Costanza, Enrico, Joel E Fischer, et al. (2014). "Doing the laundry with agents: a field trial of a future smart energy system in the home". In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*, pp. 813–822.

Costanza, Enrico, Sarvapali D Ramchurn, and Nicholas R Jennings (2012). "Understanding domestic energy consumption through interactive visualisation: a field study". In: *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*, pp. 216–225.

Crompton, Tom (2010). *Common Cause: The Case for Working with Our Cultural Values*. URL: `https://assets.wwf.org.uk/downloads/common_cause_report.pdf`.

Dalton, Ruth et al. (2020). "HabiTech: Inhabiting Buildings, Data & Technology". In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–8.

Dankwa, Nana Kesewaa (2020). "Investigating Smart Home Needs for Elderly Women Who Live Alone. An Interview Study". In: *International Conference on Human-Computer Interaction*. Springer, pp. 32–38.

Darby, Sarah J (2018). "Smart technology in the home: time for more clarity". In: *Building Research & Information* 46.1, pp. 140–147.

Darwazeh, Darwish et al. (2022). "Review of peak load management strategies in commercial buildings". In: *Sustainable Cities and Society* 77, p. 103493.

Davison, Aidan (2001). *Technology and the contested meanings of sustainability*. Suny Press.

de Leon Barido, Diego Ponce et al. (2018). “Opportunities for behavioral energy efficiency and flexible demand in data-limited low-carbon resource constrained environments”. In: *Applied Energy* 228, pp. 512–523.

Dema, Tshering, Margot Brereton, Michael Esteban, et al. (2020). “Designing in the network of relations for species conservation: The playful Tingtibi community birdhouse”. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–14.

Dema, Tshering, Margot Brereton, and Paul Roe (2019). “Designing participatory sensing with remote communities to conserve endangered species”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–16.

Dileep, GJRE (2020). “A survey on smart grid technologies and applications”. In: *Renewable Energy* 146, pp. 2589–2625.

Dillahunt, Tawanna (2014). “Toward a deeper understanding of sustainability within HCI”. In: *Workshop on Sustainability. What have we learned.*

DiSalvo, Carl (2015). *Adversarial design.* MIT Press.

DiSalvo, Carl, Phoebe Sengers, and Hrönn Brynjarsdóttir (2010). “Mapping the landscape of sustainable HCI”. In: *Proceedings of the 2010 CHI Conference on Human Factors in Computing Systems*, pp. 1975–1984.

Dix, Alan (2017). “Human–computer interaction, foundations and new paradigms”. In: *Journal of Visual Languages & Computing* 42, pp. 122–134.

Domingues, Pedro et al. (2016). “Building automation systems: Concepts and technology review”. In: *Computer Standards & Interfaces* 45, pp. 1–12.

Dourish, Paul (2006). “Implications for design”. In: *Proceedings of the CHI conference on Human Factors in computing systems*, pp. 541–550.

— (2010). “HCI and environmental sustainability: the politics of design and the design of politics”. In: *Proceedings of the 8th ACM Conference on Designing Interactive Systems*, pp. 1–10.

Duarte, Emanuel Felipe and M Cecília C Baranauskas (2016). “Revisiting the Three HCI Waves: A Preliminary Discussion on Philosophy of Science and Research Paradigms”. In: *Proceedings of the 15th Brazilian Symposium on Human Factors in Computing Systems*. ACM, p. 38.

Dunne, Anthony and Fiona Raby (2013). *Speculative everything: design, fiction, and social dreaming.* MIT Press.

Easterbrook, Steve (2014). “From computational thinking to systems thinking”. In: *The 2nd international conference ICT for Sustainability (ICT4S), Stockholm.*

Eirinaki, Magdalini et al. (2022). “Real-time recommendations for energy-efficient appliance usage in households”. In: *Frontiers in Big Data* 5, p. 972206.

Ekbia, Hamid and Bonnie Nardi (2015). “The political economy of computing: The elephant in the HCI room”. In: *Interactions* 22.6, pp. 46–49.

Elsden, Chris et al. (2017). "On speculative enactments". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 5386–5399.

Energy Institute (2023). *Statistical Review of World Energy.* URL: `https://www.energyinst.org/exploring-energy/resources/news-centre/media-releases/ei-statistical-review-of-world-energy-energy-system-struggles-in-face-of-geopolitical-and-environmental-crises`.

Eriksson, Elina and Daniel Pargman (2014). "ICT4S Reaching Out: Making sustainability relevant in higher education". In: *ICT4S*.

European Commission (2015). *Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation.* Brussels.

Filimonau, Viachaslau et al. (2021). "The carbon footprint of a UK University during the COVID-19 lockdown". In: *Science of the Total Environment* 756, p. 143964.

Fogg, Brian J (2002). "Persuasive technology: using computers to change what we think and do". In: *Ubiquity* 2002.December, p. 2.

Ford, Rebecca et al. (2017). "Categories and functionality of smart home technology for energy management". In: *Building and Environment* 123, pp. 543–554.

Foster, Derek, Shaun Lawson, Mark Blythe, et al. (2010). "Wattsup? Motivating reductions in domestic energy consumption using social networks". In: *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries*, pp. 178–187.

Foster, Derek, Shaun Lawson, Jamie Wardman, et al. (2012). ""Watts in it for me?" design implications for implementing effective energy interventions in organisations". In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*, pp. 2357–2366.

Fraternali, Piero et al. (2017). "enCOMPASS — An integrative approach to behavioural change for energy saving". In: *2017 Global Internet of Things Summit (GIoTS).* Geneva, Switzerland: IEEE, pp. 1–6.

Freeman, Rachel (2018). "A theory on the future of the rebound effect in a resource-constrained world". In: *Frontiers in Energy Research* 6, p. 81.

Freitag, Charlotte et al. (2021). "The climate impact of ICT: A review of estimates, trends and regulations". In: *arXiv preprint arXiv:2102.02622*.

Froehlich, Jon (2009). "Promoting energy efficient behaviors in the home through feedback: The role of human-computer interaction". In: *Proc. HCIC Workshop.* Vol. 9, pp. 1–11.

Froehlich, Jon, Leah Findlater, and James Landay (2010). "The design of eco-feedback technology". In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*, pp. 1999–2008.

Galvin, Ray (2015). "The rebound effect, gender and social justice: a case study in Germany". In: *Energy Policy* 86, pp. 759–769.

Ganglbauer, Eva, Wolfgang Reitberger, and Geraldine Fitzpatrick (2013). “An activist lens for sustainability: From changing individuals to changing the environment”. In: *International Conference on Persuasive Technology*. Springer, pp. 63–68.

Gaspar, K et al. (2022). “Assessing the impact of the COVID-19 lockdown on the energy consumption of university buildings”. In: *Energy and Buildings* 257, p. 111783.

Geelen, Daphne et al. (2012). “Exploring the use of a game to stimulate energy saving in households”. In: *Journal of Design Research 14* 10.1-2, pp. 102–120.

Gillingham, Kenneth et al. (2013). “The rebound effect is overplayed”. In: *Nature* 493.7433, pp. 475–476.

Golsteijn, Connie and Serena Wright (2013). “Using narrative research and portraiture to inform design research”. In: *Human-Computer Interaction–INTERACT 2013: 14th IFIP TC 13 International Conference, Cape Town, South Africa, September 2-6, 2013, Proceedings, Part III 14*. Springer, pp. 298–315.

Goodman, Elizabeth (2009). “Three environmental discourses in human-computer interaction”. In: *CHI’09 Extended Abstracts on Human Factors in Computing Systems*, pp. 2535–2544.

Gram-Hanssen, Kirsten and Susse Georg (2018). “Energy performance gaps: promises, people, practices”. In: *Building Research & Information* 46.1, pp. 1–9.

Greening, Lorna A, David L Greene, and Carmen Difiglio (2000). “Energy efficiency and consumption — the rebound effect — a survey”. In: *Energy Policy* 28.6, pp. 389–401.

Grudin, Jonathan (2017). “From tool to partner: The evolution of human-computer interaction”. In: *Synthesis Lectures on Human-Centered Interaction* 10.1, pp. i–183.

Guardian, The (2022). *The Guardian view on the future of buildings: make do and mend*. URL: `https://www.theguardian.com/commentisfree/2022/apr/17/the-guardian-view-on-the-future-of-buildings-make-do-and-mend`.

Guerra Santin, Olivia (2013). “Occupant behaviour in energy efficient dwellings: evidence of a rebound effect”. In: *Journal of Housing and the Built Environment* 28.2, pp. 311–327.

Gui, Xinning and Bonnie Nardi (2015). “Foster the ‘mores’, counter the ‘limits’”. In: *First Monday*.

Gui, Xuechen et al. (2021). “The impact of COVID-19 on higher education building energy use and implications for future education building energy studies”. In: *Energy and Buildings* 251, p. 111346.

Gunhan, Suat (2019). “Analyzing sustainable building construction project delivery practices: builders’ perspective”. In: *Practice periodical on structural design and construction* 24.1, p. 05018003.

Gustafsson, Anton and Magnus Gyllenswärd (2005). “The power-aware cord: energy awareness through ambient information display”. In: *CHI’05 Extended Abstracts on Human Factors in Computing Systems*, pp. 1423–1426.

Haas, Reinhard and Peter Biermayr (2000). “The rebound effect for space heating: Empirical evidence from Austria”. In: *Energy Policy* 28.6-7, pp. 403–410.

Haberl, Helmut et al. (2020). “A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights”. In: *Environmental Research Letters* 15.6. Publisher: IOP Publishing, p. 065003.

Hafez, Fatma S et al. (2023). “Energy efficiency in sustainable buildings: a systematic review with taxonomy, challenges, motivations, methodological aspects, recommendations, and pathways for future research”. In: *Energy Strategy Reviews* 45, p. 101013.

Håkansson, Maria and Phoebe Sengers (2013). “Beyond being green: simple living families and ICT”. In: *Proceedings of the 2013 CHI Conference on Human Factors in Computing Systems*, pp. 2725–2734.

— (2014). “No easy compromise: Sustainability and the dilemmas and dynamics of change”. In: *Proceedings of the 2014 Conference on Designing Interactive Systems*, pp. 1025–1034.

Hamm, Andrea et al. (2021). “What Makes Civic Tech Initiatives To Last Over Time? Dissecting Two Global Cases”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–17.

Hansson, Lon Åke Erni Johannes, Teresa Cerratto Pargman, and Daniel Pargman (2021). “A Decade of Sustainable HCI: Connecting SHCI to the Sustainable Development Goals”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–19.

Hargreaves, Tom, Michael Nye, and Jacquelin Burgess (2010). “Making energy visible: A qualitative field study of how householders interact with feedback from smart energy monitors”. In: *Energy Policy* 38.10, pp. 6111–6119.

Hargreaves, Tom, Charlie Wilson, and Richard Hauxwell-Baldwin (2018a). “Learning to live in a smart home”. In: *Building Research & Information* 46.1, pp. 127–139.

— (2018b). “Learning to live in a smart home”. In: *Building Research & Information* 46.1, pp. 127–139.

Harrison, Steve, Deborah Tatar, and Phoebe Sengers (2007). “The three paradigms of HCI”. In: *Alt. Chi. Session at the CHI Conference on on Human Factors in Computing Systems*, pp. 1–18.

Hasselqvist, Hanna et al. (2022). “Exploring Renewable Energy Futures through Household Energy Resilience”. In: *CHI Conference on Human Factors in Computing Systems*, pp. 1–18.

Hazas, Mike, AJ Bernheim Brush, and James Scott (2012). “Sustainability does not begin with the individual”. In: *Interactions* 19.5, pp. 14–17.

Hazas, Mike, Adrian K Clear, et al. (2015). “Exploring (un)sustainable growth of digital technologies in the home”. In: *Proceedings of EnviroInfo and ICT for Sustainability 2015*.

Hazas, Mike and Lisa P Nathan (2018). *Digital Technology and Sustainability: Engaging the Paradox*. Routledge New York.

Hedin, Björn et al. (2017). “The energy piggy bank—A serious game for energy conservation”. In: *2017 Sustainable Internet and ICT for Sustainability (SustainIT)*. IEEE, pp. 1–6.

Heitlinger, Sara, Nick Bryan-Kinns, and Rob Comber (2019). “The right to the sustainable smart city”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–13.

Heitlinger, Sara, Lara Houston, et al. (2021). “Algorithmic Food Justice: Co-Designing More-than-Human Blockchain Futures for the Food Commons”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–17.

Hickel, Jason (2020). *Less is More: How Degrowth Will Save the World*. Penguin Random House.

Hickel, Jason and Giorgos Kallis (2020). “Is Green Growth Possible?” In: *New Political Economy* 25.4, pp. 469–486.

Hilty, Lorenz M and Bernard Aebischer (2015). “ICT for sustainability: An emerging research field”. In: *ICT innovations for Sustainability*, pp. 3–36.

Hilty, Lorenz M, Peter Arnfalk, et al. (2006). “The relevance of information and communication technologies for environmental sustainability–a prospective simulation study”. In: *Environmental Modelling & Software* 21.11, pp. 1618–1629.

Hilty, Lorenz M, Wolfgang Lohmann, and Elaine M Huang (2011). “Sustainability and ICT-an overview of the field”. In: *Notizie di POLITEIA* 27.104, pp. 13–28.

Hirsch, Tad and Ken Anderson (2010). “Cross currents: water scarcity and sustainable CHI”. In: *Extended Abstracts of the 2010 CHI Conference on Human Factors in Computing Systems*, pp. 2843–2852.

Horner, Nathaniel C, Arman Shehabi, and Inês L Azevedo (2016). “Known unknowns: indirect energy effects of information and communication technology”. In: *Environmental Research Letters* 11.10, p. 103001.

Hughes, Roy F and Sunny S Dhannu (2008). “Substantial energy savings through adaptive lighting”. In: *2008 IEEE Canada Electric Power Conference*. IEEE, pp. 1–4.

Ilstedt, Sara and Josefin Wangel (2014). “Altering expectations: How design fictions and backcasting can leverage sustainable lifestyles”. In: *DRS (Design Research Society) 2014: Design’s Big Debates-Pushing the Boundaries of Design Research. Umeå, Sweden.*

Institute for Government (2022). *Timeline of UK coronavirus lockdowns, March 2020 to December 2021*. `https://www.instituteforgovernment.org.uk/sites/`

`default/files/2022-12/timeline-coronavirus-lockdown-december-2021.pdf`.

International Energy Agency (2019a). *Emissions savings*. URL: `https://www.iea.org/reports/multiple-benefits-of-energy-efficiency/emissions-savings`.

— (2019b). *Energy efficiency and digitalisation*. URL: `https://www.iea.org/articles/energy-efficiency-and-digitalisation`.

— (2020). *Energy Efficiency 2020*. URL: `https://www.iea.org/reports/energy-efficiency-2020`.

— (2021). *World Energy Outlook 2022*. Tech. rep. URL: `https://www.iea.org/reports/world-energy-outlook-2022`.

— (2022a). *Buildings*. Tech. rep. URL: `https://www.iea.org/reports/buildings`.

— (2022b). *Cimate change: Energy sector is central to efforts to combat climate change*. URL: `https://www.iea.org/topics/climate-change`.

— (2023). *Behavioural Changes*. URL: `https://www.iea.org/energy-system/energy-efficiency-and-demand/behavioural-changes`.

International Passive House Association (2023). *Passive House certification criteria*. URL: `https://passivehouse-international.org/index.php?page_id=150`.

International Telecommunication Union (2018). *ITU-T Recommendation L.1450 (09/2018): Methodologies for the assessment of the environmental impact of the information and communication technology sector*. URL: `https://www.itu.int/rec/T-REC-L.1450`.

Ishihara, Yukio et al. (2015). "Domestic Electricity Consumption Visualized as Flowing Tap Water to Raise the Feeling of Waste". In: *International Conference on Human-Computer Interaction*. Springer, pp. 546–550.

Jacobs, Rachel et al. (2013). "A conversation between trees: what data feels like in the forest". In: *Proceedings of the 2013 CHI Conference on Human Factors in Computing Systems*, pp. 129–138.

Jacques, Jason T (2020). "CHI 2020: Right Here, Right Now? A bottom-up approach to estimating the carbon emissions from more than twenty years of CHI conference travel". In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–13.

Jahn, Marco et al. (2010). "The Energy Aware Smart Home". In: *2010 5th International Conference on Future Information Technology*. Busan, Korea (South): IEEE, pp. 1–8.

Jakobi, Timo et al. (2017). "The catch(es) with smart home: Experiences of a living lab field study". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 1620–1633.

Janakiraman, Shamila, Sunnie Lee Watson, and William R Watson (2018). "Using game-based learning to facilitate attitude change for environmental sustainability". In: *Journal of Education for Sustainable Development* 12.2, pp. 176–185.

Jensen, Rikke Hagensby, Yolande Strengers, Jesper Kjeldskov, et al. (2018). "Designing the desirable smart home: A study of household experiences and energy consumption impacts". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pp. 1–14.

Jensen, Rikke Hagensby, Yolande Strengers, Dimitrios Raptis, et al. (2018). "Exploring Hygge as a desirable design vision for the sustainable smart home". In: *Proceedings of the 2018 Designing Interactive Systems Conference*, pp. 355–360.

Jensen, Victor Vadmand and Rikke Hagensby Jensen (2023). "Exploring Values of Energy Justice: A Case Study of a Burgeoning Energy Community". In: *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–9.

Jevons, William Stanley (1865). *The Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-mines*. Macmillan and Co.

Jia, Liyan and Lang Tong (2016). "Dynamic pricing and distributed energy management for demand response". In: *IEEE Transactions on Smart Grid* 7.2, pp. 1128–1136.

Jiang, Li, Da-You Liu, and Bo Yang (2004). "Smart home research". In: *Proceedings of 2004 International Conference on Machine Learning and Cybernetics (IEEE Cat. No.04EX826)*. Vol. 2. Shanghai, China: IEEE, pp. 659–663.

Johnson, Daniel et al. (2017). "Gamification and serious games within the domain of domestic energy consumption: A systematic review". In: *Renewable and Sustainable Energy Reviews* 73, pp. 249–264.

Joshi, Somya and Teresa Cerratto Pargman (2015). "In search of fairness: critical design alternatives for sustainability". In: *Proceedings of the Fifth Decennial Aarhus Conference on Critical Alternatives*, pp. 37–40.

Kang, Hyuna et al. (2021). "Changes in energy consumption according to building use type under COVID-19 pandemic in South Korea". In: *Renewable and Sustainable Energy Reviews* 148, p. 111294.

Katzeff, Cecilia, Loove Broms, et al. (2013). "Exploring sustainable practices in workplace settings through visualizing electricity consumption". In: *ACM Transactions on Computer-Human Interaction (TOCHI)* 20.5, pp. 1–22.

Katzeff, Cecilia, Åsa Nyblom, et al. (2012). "User-centred design and evaluation of EnergyCoach–an interactive energy service for households". In: *Behaviour & Information Technology* 31.3, pp. 305–324.

Kaufman, Samuel J and M Six Silberman (2011). “Rebound effects in sustainable HCI”. In: *Sustainable Interaction Design in Professional Domains, workshop at CHI 2011.* Citeseer.

Kavousian, Amir, Ram Rajagopal, and Martin Fischer (2013). “Determinants of residential electricity consumption: Using smart meter data to examine the effect of climate, building characteristics, appliance stock, and occupants’ behavior”. In: *Energy* 55, pp. 184–194.

Khazzoom, J Daniel (1980). “Economic Implications of Mandated Efficiency in Standards for Household Appliances”. In: *The Energy Journal* 1.4, pp. 21–40.

Kim, Sunyoung and Eric Paulos (2010). “InAir: sharing indoor air quality measurements and visualizations”. In: *Proceedings of the 2010 CHI Conference on Human Factors in Computing Systems*, pp. 1861–1870.

King, Jennifer and Christopher Perry (2017). *Smart buildings: Using smart technology to save energy in existing buildings.* Amercian Council for an Energy-Efficient Economy Washington, DC, USA.

Kitchenham, Barbara et al. (2009). “Systematic literature reviews in software engineering–a systematic literature review”. In: *Information and software technology* 51.1.

Klein, Naomi (2015). *This changes everything: Capitalism vs. the climate.* Simon and Schuster.

Kneese, Tamara (2023). *Death glitch: How techno-solutionism fails us in this life and beyond.* Yale University Press.

Knowles, Bran (2014). “Cyber-sustainability: towards a sustainable digital future”. PhD thesis. Lancaster: Lancaster University.

Knowles, Bran, Oliver Bates, and Maria Håkansson (2018). “This changes sustainable HCI”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pp. 1–12.

Knowles, Bran, Lynne Blair, Paul Coulton, et al. (2014). “Rethinking plan A for sustainable HCI”. In: *Proceedings of the 2014 CHI Conference on Human Factors in Computing Systems*, pp. 3593–3596.

Knowles, Bran, Lynne Blair, Stuart Walker, et al. (2014). “Patterns of persuasion for sustainability”. In: *Proceedings of the 2014 Conference on Designing Interactive Systems*, pp. 1035–1044.

Knowles, Bran and Elina Eriksson (2015). “Deviant and guilt-ridden: Computing within psychological limits”. In: *First Monday.*

Knowles, Bran, Kelly Widdicks, et al. (2022). “Our house is on fire: The climate emergency and computing’s responsibility.” In: *Communications of the ACM* 65.6, pp. 38–40.

Kohlenberg, Robert, Thomas Phillips, and William Proctor (1976). “A Behavioral Analysis of Peaking in Residental Electricity-Energy Consumers”. In: *Journal of Applied Behavior Analysis* 9.1, pp. 13–18.

Koomey, Jonathan G, Stephen Berard, et al. (2011). “Implications of Historical Trends in the Electrical Efficiency of Computing”. In: *IEEE Annals of the History of Computing* 33.3, pp. 46–54. DOI: `10.1109/MAHC.2010.28`.

Koomey, Jonathan G, H Scott Matthews, and Eric D Williams (2013). “Smart everything: Will intelligent systems reduce resource use?” In: *Annual Review of Environment and Resources* 38, pp. 311–343.

Kotilainen, Kirsi (2019). “Energy prosumers’ role in the sustainable energy system”. In: *Affordable and Clean Energy*. Springer, pp. 1–14.

Krarti, Moncef and Mohammad Aldubyan (2021). “Review analysis of COVID-19 impact on electricity demand for residential buildings”. In: *Renewable and Sustainable Energy Reviews* 143, p. 110888.

Krier, James E and Clayton P Gillette (1985). “The un-easy case for technological optimism”. In: *Mich. L. Rev.* 84, p. 405.

Kumar, Tarun and Monto Mani (2017). “An Energy-Neutrality based Evaluation into the Effectiveness of Occupancy Sensors in Buildings: An integrated Life-cycle Study”. In: *Proceedings of 33rd PLEA International Conference: Design to Thrive, PLEA 2017*. Edinburgh: NCEUB 2017 - Network for Comfort and Energy Use in Buildings, pp. 2579–2586.

Kvist Svangren, Michael et al. (2020). “Investigating one-time actions for domestic energy reduction: the case of district heating”. In: *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society*, pp. 1–11.

Lamb, William F et al. (2020). “Discourses of climate delay”. In: *Global Sustainability* 3.

Lancaster University (2023). *Where does our electricity come from and what are our carbon emissions?* URL: `https://www.lancaster.ac.uk/sustainability/news/where-does-our-electricity-come-from-and-what-are-our-carbon-emissions?redir=1`.

Landwehr, Marvin, Philip Engelbutzeder, and Volker Wulf (2021). “Community Supported Agriculture: The Concept of Solidarity in Mitigating Between Harvests and Needs”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–13.

Li, Han et al. (2021). “Characterizing patterns and variability of building electric load profiles in time and frequency domains”. In: *Applied Energy* 291, p. 116721.

Lim, SCJ and BT Tee (2018). “A Preliminary Review of Building Informatics for Sustainable Energy Management”. In: *Journal of Physics: Conference Series*. Vol. 1019. 1. IOP Publishing, p. 012032.

Lindtner, Silvia, Shaowen Bardzell, and Jeffrey Bardzell (2016). “Reconstituting the utopian vision of making: HCI after technosolutionism”. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 1390–1402.

Liu, Szu-Yu, Shaowen Bardzell, and Jeffrey Bardzell (2018). “Out of control: reframing sustainable HCI using permaculture”. In: *Proceedings of the 2018 Workshop on Computing within Limits*, pp. 1–8.

— (2019). “Symbiotic encounters: HCI and sustainable agriculture”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–13.

López-Sosa, Luis Bernardo et al. (2021). “COVID-19 pandemic effect on energy consumption in state universities: Michoacan, Mexico Case Study”. In: *Energies* 14.22, p. 7642.

Lorek, Sylvia and Joachim H Spangenberg (2019). “Energy sufficiency through social innovation in housing”. In: *Energy Policy* 126, pp. 287–294.

Luo, Xuan et al. (2017). “Electric load shape benchmarking for small-and medium-sized commercial buildings”. In: *Applied Energy* 204, pp. 715–725.

Lutolf, Remo (1992). “Smart home concept and the integration of energy meters into a home based system”. In: *Seventh international conference on metering apparatus and tariffs for electricity supply 1992*. IET, pp. 277–278.

Mankoff, Jennifer (2012). “HCI and sustainability: a tale of two motivations”. In: *Interactions* 19.3, pp. 16–19.

Mankoff, Jennifer et al. (2007). “Environmental sustainability and interaction”. In: *Extended Abstracts of the 2007 CHI Conference on Human Factors in Computing Systems*, pp. 2121–2124.

Mann, Samuel, Oliver Bates, and Raymond Maher (2018). “Shifting the maturity needle of ICT for Sustainability”. In: *ICT4S2018. 5th International Conference on Information and Communication Technology for Sustainability*, pp. 209–226.

Mann, Samuel, Logan Muller, et al. (2010). “Computing and sustainability: evaluating resources for educators”. In: *ACM SIGCSE Bulletin* 41.4, pp. 144–155.

Martin, Böckle and Yeboah-Antwi Kwaku (2019). “Designing at the intersection of gamification and persuasive technology to incentivize energy-saving”. In: *Digital Transformation for a Sustainable Society in the 21st Century: 18th IFIP WG 6.11 Conference on e-Business, e-Services, and e-Society, I3E 2019, Trondheim, Norway, September 18–20, 2019, Proceedings 18*. Springer, pp. 316–328.

Meadows, Donella H (1997). “Places to Intervene in a System (in increasing oder of effectiveness)”. In: *Whole Earth.*

— (1999). “Leverage points: Places to intervene in a system”. In.

— (2008). *Thinking in systems: A primer.* chelsea green publishing.

Meena, Yogesh Kumar et al. (2020). “PV-Tiles: Towards Closely-Coupled Photovoltaic and Digital Materials for Useful, Beautiful and Sustainable Interactive

Surfaces". In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–12.

Melo, Gustavo Costa Gomes de et al. (2021). "A low-cost IoT system for real-time monitoring of climatic variables and photovoltaic generation for smart grid application". In: *Sensors* 21.9, p. 3293.

Mencarini, Eleonora et al. (2023). "HCI for Climate Change: Imagining Sustainable Futures". In: *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–6.

Merz, Hermann, Thomas Hansemann, and Christof Hübner (2009). *Building automation.* Springer.

Midden, Cees et al. (2008). "Using persuasive technology to encourage sustainable behavior". In: *Sustainability WS Pervasive* 113, pp. 83–86.

Mitchell, Ronald B (2012). "Technology is not enough: Climate change, population, affluence, and consumption". In: *The Journal of Environment & Development* 21.1, pp. 24–27.

Mitchell Finnigan, Samantha (2020). "A Foundation for HabiTech: Three Case Studies in the Built Environment". In: *HabiTech Workshop at CHI 2020.*

Mollenbach, Emilie, Jens Hoff, and Kasper Hornbæk (2012). "HCI and sustainability: the role of macrostructures". In: *CHI'12 Extended Abstracts on Human Factors in Computing Systems*, pp. 2159–2164.

Moran, Stuart et al. (2014). "Listening to the forest and its curators: lessons learnt from a bioacoustic smartphone application deployment". In: *Proceedings of the 2014 CHI Conference on Human Factors in Computing Systems*, pp. 2387–2396.

Morozov, Evgeny (2013). *To save everything, click here: The folly of technological solutionism.* Public Affairs.

Mylonas, Georgios et al. (2021). "Using gamification and IoT-based educational tools towards energy savings—some experiences from two schools in Italy and Greece". In: *Journal of Ambient Intelligence and Humanized Computing*, pp. 1–20.

Nardi, Bonnie (2019). "Design in the Age of Climate Change". In: *She Ji: The Journal of Design, Economics, and Innovation* 5.1, pp. 5–14.

Nasir, Sharifah Nurain Syed et al. (2022). "Lockdown impact on energy consumption in university building". In: *Environment, Development and Sustainability*, pp. 1–20.

Nässén, Jonas and John Holmberg (2009). "Quantifying the rebound effects of energy efficiency improvements and energy conserving behaviour in Sweden". In: *Energy Efficiency* 2.3, pp. 221–231.

Nathan, Lisa P et al. (2008). "Envisioning systemic effects on persons and society throughout interactive system design". In: *Proceedings of the 7th ACM Conference on Designing Interactive Systems*, pp. 1–10.

Naylor, Sophie, Mark Gillott, and Tom Lau (2018). “A review of occupant-centric building control strategies to reduce building energy use”. In: *Renewable and Sustainable Energy Reviews* 96, pp. 1–10.

Nembrini, Julien and Denis Lalanne (2017). “Human-building interaction: When the machine becomes a building”. In: *IFIP Conference on Human-Computer Interaction*. Springer, pp. 348–369.

Nishant, Rohit, Thompson SH Teo, and Mark Goh (2014). “Energy efficiency benefits: is technophilic optimism justified?” In: *IEEE Transactions on Engineering Management* 61.3, pp. 476–487.

Norton, Juliet et al. (2017). “A grand challenge for HCI: food + sustainability”. In: *Interactions* 24.6, pp. 50–55.

Pargman, Daniel and Barath Raghavan (2014). “Rethinking sustainability in computing: From buzzword to non-negotiable limits”. In: *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational*, pp. 638–647.

Parrique, Timothée et al. (2019). “Decoupling debunked – Evidence and arguments against green growth as a sole strategy for sustainability”. In: *Evidence and arguments against green growth as a sole strategy for sustainability. A study edited by the European Environment Bureau EEB*.

Peeters, Paul et al. (2016). “Are technology myths stalling aviation climate policy?” In: *Transportation Research Part D: Transport and Environment* 44, pp. 30–42.

Peffer, Therese et al. (2011). “How people use thermostats in homes: A review”. In: *Building and Environment* 46.12, pp. 2529–2541.

Penzenstadler, Birgit et al. (2018). “Software engineering for sustainability: Find the leverage points!” In: *IEEE Software* 35.4, pp. 22–33.

Pérez-Lombard, Luis, José Ortiz, and David Velázquez (2013). “Revisiting energy efficiency fundamentals”. In: *Energy Efficiency* 6, pp. 239–254.

Petersen, Kai, Robert Feldt, et al. (2008). “Systematic mapping studies in software engineering”. In: *12th International Conference on Evaluation and Assessment in Software Engineering (EASE) 12*, pp. 1–10.

Petersen, Kai, Sairam Vakkalanka, and Ludwik Kuzniarz (2015). “Guidelines for conducting systematic mapping studies in software engineering: An update”. In: *Information and Software Technology* 64, pp. 1–18.

Pierce, James, Chloe Fan, et al. (2010). “Some consideration on the (in) effectiveness of residential energy feedback systems”. In: *Proceedings of the 8th ACM Conference on Designing Interactive Systems*, pp. 244–247.

Pierce, James and Eric Paulos (2012). “Beyond energy monitors: interaction, energy, and emerging energy systems”. In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*, pp. 665–674.

Pierce, James, Diane J. Schiano, and Eric Paulos (2010). “Home, Habits, and Energy: Examining Domestic Interactions and Energy Consumption”. In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*. CHI ’10, pp. 1985–1994.

Pinder, Charlie et al. (2018). “Digital behaviour change interventions to break and form habits”. In: *ACM Transactions on Computer-Human Interaction (TOCHI)* 25.3, pp. 1–66.

Pohl, Johanna, Lorenz M Hilty, and Matthias Finkbeiner (2019). “How LCA contributes to the environmental assessment of higher order effects of ICT application: A review of different approaches”. In: *Journal of Cleaner Production* 219, pp. 698–712.

Preist, Chris, Daniela K Busse, et al. (2013). “POST-SUSTAINABILITY: a CHI sustainability community workshop”. In: *CHI’13 Extended Abstracts on Human Factors in Computing Systems*, pp. 3251–3254.

Preist, Chris, Daniel Schien, and Eli Blevis (2016). “Understanding and mitigating the effects of device and cloud service design decisions on the environmental footprint of digital infrastructure”. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 1324–1337.

Preist, Chris, Daniel Schien, and Paul Shabajee (2019). “Evaluating sustainable interaction design of digital services: The case of YouTube”. In: *Proceedings of the 2019 CHI cConference on Human Factors in Computing Systems*, pp. 1–12.

Purvis, Ben, Yong Mao, and Darren Robinson (2019). “Three pillars of sustainability: in search of conceptual origins”. In: *Sustainability Science* 14.3, pp. 681–695.

Raghavan, Barath, Bonnie Nardi, et al. (2016). “Computational agroecology: Sustainable food ecosystem design”. In: *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, pp. 423–435.

Raghavan, Barath and Daniel Pargman (2017). “Means and ends in human-computer interaction: Sustainability through disintermediation”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 786–796.

Rasmussen, Majken K et al. (2017). “Exploring the flexibility of everyday practices for shifting energy consumption through clockcast”. In: *Proceedings of the 29th Australian Conference on Computer-Human Interaction*, pp. 296–306.

Rau, Pei-Luen Patrick et al. (2015). “Promote energy conservation in automatic environment control: a comfort-energy trade-off perspective”. In: *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*, pp. 1501–1506.

Reddy, BV Venkatarama (2004). “Sustainable building technologies”. In: *Current Science*, pp. 899–907.

Reinisch, Christian et al. (2011). “Thinkhome energy efficiency in future smart homes”. In: *EURASIP Journal on Embedded Systems* 2011, pp. 1–18.

Remy, Christian et al. (2017). "The limits of evaluating sustainability". In: *Proceedings of the 2017 Workshop on Computing Within Limits*, pp. 103–110.

Rifat, Mohammad Rashidujjaman, Hasan Mahmud Prottoy, and Syed Ishtiaque Ahmed (2019). "The breaking hand: Skills, care, and sufferings of the hands of an electronic waste worker in Bangladesh". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–14.

Rigby, Jacob M and Chris Preist (2023). "Towards User-Centred Climate Services: the Role of Human-Computer Interaction". In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–14.

Rodden, Tom A et al. (2013). "At home with agents: exploring attitudes towards future smart energy infrastructures". In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*, pp. 1173–1182.

Rogers, Yvonne and Paul Marshall (2017). "Research in the Wild". In: *Synthesis Lectures on Human-Centered Informatics* 10.3, pp. i–97.

Romero, Marcelo et al. (2020). "Towards a characterisation of smart systems: A systematic literature review". In: *Computers in Industry* 120, p. 103224.

Rosson, Mary Beth and John M Carroll (2009). "Scenario-based design". In: *Human-Computer Interaction*. CRC Press, pp. 161–180.

Rouleau, Jean and Louis Gosselin (2021). "Impacts of the COVID-19 lockdown on energy consumption in a Canadian social housing building". In: *Applied Energy* 287, p. 116565.

Rubambiza, Gloire, Phoebe Sengers, and Hakim Weatherspoon (2022). "Seamless Visions, Seamful Realities: Anticipating Rural Infrastructural Fragility in Early Design of Digital Agriculture". In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, pp. 1–15.

Saad Al-Sumaiti, Ameena, Mohammed Hassan Ahmed, and Magdy M. A. Salama (2014). "Smart Home Activities: A Literature Review". In: *Electric Power Components and Systems* 42.3-4, pp. 294–305.

Safarzadeh, Soroush, Morteza Rasti-Barzoki, and Seyed Reza Hejazi (2020). "A review of optimal energy policy instruments on industrial energy efficiency programs, rebound effects, and government policies". In: *Energy Policy* 139, p. 111342.

Santarius, Tilman (2017). *Digitalization, Efficiency and the Rebound Effect*. URL: `https://www.degrowth.info/blog/digitalization-efficiency-and-the-rebound-effect`.

Santin, Olivia Guerra, Laure Itard, and Henk Visscher (2009). "The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock". In: *Energy and buildings* 41.11, pp. 1223–1232.

Sardianos, Christos et al. (2019). "'I Want to... Change': Micro-moment based Recommendations can Change Users' Energy Habits". In: *SMARTGREENS*, pp. 30–39.

Saunders, Harry D (1992). "The Khazzoom-Brookes Postulate and Neoclassical Growth". In: *The Energy Journal* 13.4. Publisher: International Association for Energy Economics, pp. 131–148.

— (2000). "A view from the macro side: rebound, backfire, and Khazzoom–Brookes". In: *Energy Policy* 28.6, pp. 439–449.

Saunders, Harry D, Jeffrey Y Tsao, et al. (2012). "Rebound effects for lighting". In: *Energy Policy* 49.0, pp. 477–478.

Schaller, Robert R (1997). "Moore's law: past, present and future". In: *IEEE Spectrum* 34.6, pp. 52–59.

Schwartz, Tobias et al. (2015). "What people do with consumption feedback: a long-term living lab study of a home energy management system". In: *Interacting with Computers* 27.6, pp. 551–576.

Seebauer, Sebastian (2018). "The psychology of rebound effects: Explaining energy efficiency rebound behaviours with electric vehicles and building insulation in Austria". In: *Energy Research & Social Science* 46, pp. 311–320.

Sengers, Phoebe, Kirsten Boehner, and Nicholas Knouf (2009). "Sustainable HCI meets third wave HCI: 4 themes". In: *CHI 2009 workshop*. Vol. 4.

Shackel, Brian (1959). "Ergonomics for a computer". In: *Design* 120, pp. 36–39.

Shaikh, Omar et al. (2021). "EnergyVis: Interactively Tracking and Exploring Energy Consumption for ML Models". In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–7.

Shakeri, Gözel and Claire H McCallum (2021). "Envirofy your Shop: Development of a Real-time Tool to Support Eco-friendly Food Purchases Online". In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–10.

Shove, Elizabeth (2003). *Comfort, cleanliness and convenience: the social organisation of normality*. Berg.

Silberman, M Six (2015). "Information systems for the age of consequences". In: *First Monday*.

Silberman, M Six, Lisa P Nathan, et al. (2014). "Next steps for sustainable HCI". In: *Interactions* 21.5, pp. 66–69.

Silberman, M Six and Bill Tomlinson (2010). "Toward an ecological sensibility: tools for evaluating sustainable HCI". In: *Extended Abstracts of the 2010 CHI Conference on Human Factors in Computing Systems*, pp. 3469–3474.

Siniak, Nikolai et al. (2020). "The impact of proptech on real estate industry growth". In: *IOP Conference Series: Materials Science and Engineering*. Vol. 869. 6. IOP Publishing, p. 062041.

Sivarajah, Sankar (2021). *The UK has some of the least energy-efficient housing in Europe – here's how to fix this.* URL: `https://theconversation.com/the-uk-`

has-some-of-the-least-energy-efficient-housing-in-europe-heres-how-to-fix-this-151609.

Snow, Stephen et al. (2021). “Neighbourhood Wattch: Using Speculative Design to Explore Values Around Curtailment and Consent in Household Energy Interactions”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–12.

Soden, Robert and Nate Kauffman (2019). “Infrastructuring the Imaginary: How Sea-level Rise Comes to Matter in The San Francisco Bay Area”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–11.

Soden, Robert, Pradnaya Pathak, and Olivia Doggett (2021). “What we speculate about when we speculate about sustainable HCI”. In: *ACM SIGCAS Conference on Computing and Sustainable Societies*, pp. 188–198.

Song, Katherine W and Eric Paulos (2021). “Unmaking: Enabling and Celebrating the Creative Material of Failure, Destruction, Decay, and Deformation”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–12.

Sorrell, Steve (2009). “Jevons’ Paradox revisited: The evidence for backfire from improved energy efficiency”. In: *Energy Policy* 37.4, pp. 1456–1469.

Spagnolli, Anna et al. (2011). “Eco-feedback on the go: Motivating energy awareness”. In: *Computer* 44.5, pp. 38–45.

Spearing, Lauryn A et al. (2021). “Human–infrastructure interactions during the COVID-19 pandemic: Understanding water and electricity demand profiles at the building level”. In: *ACS Es&t Water* 1.11, pp. 2327–2338.

Stevens, Gunnar et al. (2019). “Using time and space efficiently in driverless cars: Findings of a co-design study”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–14.

Stieglitz, Stefan et al. (2023). “The potential of digital nudging to bridge the gap between environmental attitude and behavior in the usage of smart home applications”. In: *International Journal of Information Management* 72, p. 102665.

Strauch, Barry (2017). “Ironies of automation: Still unresolved after all these years”. In: *IEEE Transactions on Human-Machine Systems* 48.5, pp. 419–433.

Strengers, Yolande (2008). “Challenging comfort & cleanliness norms through interactive in-home feedback systems”. In: *Proceedings of Green Pervasive Workshop at Pervasive Persuasive.*

— (2011a). “Designing Eco-Feedback Systems for Everyday Life”. In: *Proceedings of the CHI Conference on Human Factors in Computing Systems.* CHI ’11. Vancouver, BC, Canada: Association for Computing Machinery, pp. 2135–2144.

— (2011b). “Negotiating everyday life: The role of energy and water consumption feedback”. In: *Journal of Consumer Culture* 11.3, pp. 319–338.

— (2014). “Smart energy in everyday life: are you designing for resource man?” In: *Interactions* 21.4, pp. 24–31.

Strengers, Yolande, Mike Hazas, et al. (2020). “Pursuing pleasance: Interrogating energy-intensive visions for the smart home”. In: *International Journal of Human-Computer Studies* 136, p. 102379.

Strengers, Yolande, Jenny Kennedy, et al. (2019). “Protection, productivity and pleasure in the smart home: emerging expectations and gendered insights from Australian early adopters”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–13.

Tabassum, Madiha, Tomasz Kosinski, and Heather Richter Lipford (2019). “” I don’t own the data”: End User Perceptions of Smart Home Device Data Practices and Risks”. In: *Fifteenth symposium on usable privacy and security (SOUPS 2019)*, pp. 435–450.

Tanenbaum, Theresa Jean (2014). “Design fictional interactions: why HCI should care about stories”. In: *Interactions* 21.5, pp. 22–23.

Tavakoli, Sara et al. (2023). “Impact of COVID-19 Pandemic on Energy Consumption in Office Buildings: A Case Study of an Australian University Campus”. In: *Sustainability* 15.5, p. 4240.

The World Bank (2023). *State and Trends of Carbon Pricing 2023*. URL: `http://hdl.handle.net/10986/39796`.

Tirado Herrero, Sergio, Larissa Nicholls, and Yolande Strengers (2018). “Smart home technologies in everyday life: do they address key energy challenges in households?” In: *Current Opinion in Environmental Sustainability* 31, pp. 65–70.

Tomlinson, Bill, Donald J Patterson, et al. (2012). “What if sustainability doesn’t work out?” In: *Interactions* 19.6, pp. 50–55.

Tomlinson, Bill, M Six Silberman, et al. (2012). “Collapse informatics: augmenting the sustainability & ICT4D discourse in HCI”. In: *Proceedings of the 2012 CHI Conference on Human Factors in Computing Systems*, pp. 655–664.

Tsao, Jeffrey Y et al. (2010). “Solid-state lighting: an energy-economics perspective”. In: *Journal of Physics D: Applied Physics* 43.35. Publisher: IOP Publishing, p. 354001.

Turner, Karen (2013). “‘Rebound’ effects from increased energy efficiency: a time to pause and reflect”. In: *The Energy Journal* 34.4.

Turnhout, Koen van et al. (2014). “Design patterns for mixed-method research in HCI”. In: *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational*, pp. 361–370.

U.S. Department of Energy (2017). *The Influence of Occupancy on Building Energy Use Intensity and the Utility of an Occupancy-Adjusted Performance Metric*. URL: `https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26019.pdf`.

U.S. Energy Information Administration (2023). *Glossary*. URL: `https://www.eia.gov/tools/glossary/?id=B`.

U.S. Green Building Council (2023). *LEED rating system*. URL: `https://www.usgbc.org/leed`.

Uddin, Moslem et al. (2018). "A review on peak load shaving strategies". In: *Renewable and Sustainable Energy Reviews* 82, pp. 3323–3332.

United Nations Environment Programme (2022). *CO_2 emissions from buildings and construction hit new high, leaving sector off track to decarbonize by 2050: UN*. URL: `https://www.unep.org/news-and-stories/press-release/co2-emissions-buildings-and-construction-hit-new-high-leaving-sector`.

Vadén, T et al. (2020). "Decoupling for ecological sustainability: A categorisation and review of research literature". In: *Environmental Science & Policy* 112, pp. 236–244.

Van Dronkelaar, Chris et al. (2016). "A review of the energy performance gap and its underlying causes in non-domestic buildings". In: *Frontiers in Mechanical Engineering* 1, p. 17.

Van Thillo, L., S. Verbeke, and A. Audenaert (2022). "The potential of building automation and control systems to lower the energy demand in residential buildings: A review of their performance and influencing parameters". In: *Renewable and Sustainable Energy Reviews* 158, p. 112099.

van Turnhout, Koen et al. (2013). "Tradeoffs in design research: development oriented triangulation". In: *27th International BCS Human Computer Interaction Conference (HCI 2013)*, pp. 1–6.

Walzberg, Julien et al. (2020). "Should we fear the rebound effect in smart homes?" In: *Renewable and Sustainable Energy Reviews* 125, p. 109798.

Wang, Zhaohua, Bai Han, and Milin Lu (2016). "Measurement of energy rebound effect in households: Evidence from residential electricity consumption in Beijing, China". In: *Renewable and Sustainable Energy Reviews* 58, pp. 852–861.

Weeks, Christopher, Charles Delalonde, and Chris Preist (2014). "Sustainable HCI and Encouraging Retrofitting". In: *Is there a European strand of sustainable HCI?* Citeseer.

Weiser, Mark and John Seely Brown (1996). "Designing calm technology". In: *PowerGrid Journal* 1.1, pp. 75–85.

Whitehead, John C and Todd L Cherry (2007). "Willingness to pay for a green energy program: a comparison of ex-ante and ex-post hypothetical bias mitigation approaches". In: *Resource and Energy Economics* 29.4, pp. 247–261.

Widdicks, Kelly, Oliver Bates, et al. (2017). "Demand around the clock: time use and data demand of mobile devices in everyday life". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 5361–5372.

Widdicks, Kelly, Mike Hazas, et al. (2019). “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*, pp. 1–13.

Widdicks, Kelly, Federica Lucivero, et al. (2023). “Systems Thinking and Efficiency under Emissions Constraints: Addressing Rebound Effects in Digital Innovation and Policy”. In: *Patterns*.

Wiedmann, Thomas O et al. (2015). “The material footprint of nations”. In: *Proceedings of the National Academy of Sciences* 112.20. Publisher: Proceedings of the National Academy of Sciences, pp. 6271–6276.

Wilkins, Denise J, Ruzanna Chitchyan, and Mark Levine (2020). “Peer-to-peer energy markets: Understanding the values of collective and community trading”. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–14.

Williams, Eric D (2011). “Environmental effects of information and communications technologies”. In: *Nature* 479.7373, pp. 354–358.

Williams, Eric D and H Scott Matthews (2007). “Scoping the potential of monitoring and control technologies to reduce energy use in homes”. In: *Proceedings of the 2007 IEEE International Symposium on Electronics and the Environment*. IEEE, pp. 239–244.

Williams III, Roberton C et al. (2015). “The initial incidence of a carbon tax across income groups”. In: *National Tax Journal* 68.1, pp. 195–213.

Willis, Max et al. (2020). “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*, pp. 1–14.

Wilson, Charlie, Tom Hargreaves, and Richard Hauxwell-Baldwin (2017). “Benefits and risks of smart home technologies”. In: *Energy Policy* 103, pp. 72–83.

World Economic Forum (2022). *What are the advantages and challenges of a carbon tax?* URL: `https://www.weforum.org/agenda/2022/02/what-a-carbon-tax-can-do-and-why-it-cannot-do-it-all`.

World Meteorological Organization (2022). *WMO Provisional State of the Global Climate 2022*. Tech. rep. URL: `https://library.wmo.int/index.php?lvl=notice_display&id=22156#.ZB2Fy_bP3b1`.

Wu, Shanel and Laura Devendorf (2020). “Unfabricate: Designing Smart Textiles for Disassembly”. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–14.

Xu, Sheng et al. (2023). “Impact of the COVID-19 on electricity consumption of open university campus buildings–The case of Twente University in the Netherlands”. In: *Energy and Buildings* 279, p. 112723.

Yang, Jie Chi, Kun Huang Chien, and Tzu Chien Liu (2012). “A digital game-based learning system for energy education: An energy Conservation PET.” In: *Turkish Online Journal of Educational Technology-TOJET* 11.2, pp. 27–37.

Yang, Rayoung and Mark W Newman (2013). “Learning from a learning thermostat: lessons for intelligent systems for the home”. In: *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing*, pp. 93–102.

Zavadskas, Edmundas Kazimieras et al. (2017). “Sustainable decision-making in civil engineering, construction and building technology”. In: *Sustainability* 10.1, p. 14.

Zhan, Sicheng and Adrian Chong (2021). “Building occupancy and energy consumption: Case studies across building types”. In: *Energy and Built Environment* 2.2, pp. 167–174.

Zhang, Yan et al. (2018). “Rethinking the role of occupant behavior in building energy performance: A review”. In: *Energy and Buildings* 172, pp. 279–294.

Zhao, Dong et al. (2017). “Interaction effects of building technology and resident behavior on energy consumption in residential buildings”. In: *Energy and Buildings* 134, pp. 223–233.

Zhou, Tingting et al. (2022). “Analysis of the influence of the stay-at-home order on the electricity consumption in Chinese university dormitory buildings during the COVID-19 pandemic”. In: *Energy and Buildings* 277, p. 112582.

Zou, Patrick XW et al. (2018). “Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives”. In: *Energy and Buildings* 178, pp. 165–181.