ESTIMATING THE HANDPRINTS OF NETWORK TECHNOLOGIES TO MAKE INFORMED BUSINESS DECISIONS

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September 2023
ACEEE Report

ACEEE
Smart Energy. Clean Planet. Better Lives.

Contents

About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

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Acknowledgments

This report was made possible through the generous support of Cisco Systems, Inc. The authors gratefully acknowledge the external reviewers, internal reviewers, and colleagues who supported this report. External expert reviewers included Steven Harper from Intel Corporation (retired) and Lawrence Plumb. External review and support do not imply affiliation or endorsement. Internal reviewers included Andrew Hoffmeister, Avi Mersky, and Pavitra Srinivasan. Last, we would like to thank Mariel Wolfson for developmental editing, Ethan Taylor for managing the editing process, Phoebe Spanier for copy editing, Roxanna Usher for proofreading, Kate Doughty for graphics design, and Mark Rodeffer and Nick Roper for their help in launching this report.

Suggested Citation

Fadali, L., J. Eisen, and N. W. Esram. 2023. *Estimating the Handprints of Network Technologies to Make Informed Business Decisions*. Washington, DC: American Council for an Energy-Efficient Economy. www.aceee.org/research-report/b2304.

Data and Licensing Information

Executive Summary

KEY FINDINGS

Information and communication technologies (ICT)—data, programs, and equipment used for computing and telecommunications, such as mobile phones, laptops, software applications, and ethernet—have long been recognized for their potential to reduce emissions by precisely managing and coordinating energy use in applications such as bike sharing, avoiding food waste, telecommuting, grid management, and many others. These applications could collectively eliminate more emissions than ICT generates.

- Most ICT-provided energy and emissions benefits are enabled and enhanced by communication networks, which allow systems to be optimized holistically. This could mean integrating different systems, such as a building's room reservation and energy systems, so that rooms use minimal energy when empty. It could also mean optimizing a larger network of similar systems, such as coordinating the energy use of many homes for the benefit of the electrical grid.
- ICT can potentially save additional energy and emissions through *network effects*, where, for example, 10 users can save more than 10 times the energy saved by one user.
- However, we found such network effects do not occur without technology or policy to capture them, and large numbers of uncoordinated ICT can even lead to negative effects such as sharp spikes in electricity demand or rebound effects.
- Unlike a carbon footprint, which estimates the detrimental impact on the climate that is inherent to a product or service over its lifetime, a carbon handprint is an estimate of the potential decrease (or increase) in emissions that a product may enable in *another* process, business, or industry.
- An analysis of approximately 6 million homes in Texas for the year 2028 shows the handprint of network-enabled smart thermostats could range from 0.52 to 1.35 million metric tons (6.5–17%) of emissions avoided in 2028, the equivalent of the emissions from electricity to power 100,000–260,000 homes in 2022.
- Handprint estimates for individual ICT solutions range from less than 5% to over 100% of emissions being avoided in a particular application. One major reason for the uncertainty is variability in how real people interact with ICT. Other sources of uncertainty related to human behavior are rebound effects and levels of adoption.
- To address these large uncertainties, data sharing, field studies, and agreed-upon ways of calculating handprints are needed for both existing and future solutions.
- To ensure ICT solutions function as intended, companies should fully consider a wide range of users' attitudes, including product usability, the need to educate

some users, and the imperative to build trust in the face of privacy and security concerns, both real and perceived.

- User convenience is a non-energy benefit that may be even more important for the adoption of new technologies than energy and emissions benefits.
- Companies can and should use handprint estimates to help guide business strategy and the use of research and development (R&D) dollars to avoid detrimental climate impacts and protect environmental resources.

Information and communication technologies (ICT)—the data, software, and equipment used for computing and telecommunications—have been foundational to the growth of our economy in recent decades and are helping to transform and optimize entire sectors such as transportation, industry, and buildings. ICT solutions have become so pervasive as to be central to businesses far beyond core ICT companies such as Intel or Apple. Whether integrating smart thermostats in smart buildings or providing mobility solutions such as ride-hailing apps or bike-sharing services, ICT solutions have a wide range of applications that utilize responsive and adaptive technologies and systems.

While many components are required for ICT to function, communication networks—the software and hardware that enable communication and information *sharing* between multiple devices—are a bedrock. Networks link individual devices together so that they can operate efficiently and optimally as a system. Networks can also create synergistic *network effects*, where 100 users of the network reap benefits that are more than 100 times the benefit to one user. For example, if only a few people used email, they would each avoid some energy and emissions associated with paper production, but when email is widely used, the need for printers and copiers is also reduced and their associated energy and emissions can be avoided in addition to the savings from paper. Companies can develop ICT products and services that could help shrink their end users' carbon footprints—the handprint effect This report examines the handprint concept in depth using communications networks as an example. We examine how communication networks could play a role in reducing future carbon emissions while recognizing that networks are only one of many integral components of ICT that are needed to reduce carbon emissions.

A carbon footprint, or the detrimental impact on the climate that is inherent to a product or service over its lifetime, has been used by companies and organizations to understand, track, and reduce greenhouse gas (GHG) emissions and other environmental degradation. Significant increases in equipment and operational efficiency have allowed ICT companies to massively decrease the footprints of their own activities. And while important progress has been made on this front (in part due to the development and enforcement of international standards for quantifying and reporting GHG emissions), there are additional opportunities for companies to evaluate their emissions beyond their carbon footprints. The handprint concept has emerged over the last 10–20 years as a complementary method to estimate the potential benefit or detriment a product or service can have at a broader societal level.

A beneficial carbon handprint, also referred to as "Scope 4 emissions" or "avoided emissions," is generated when a company offers a new solution with a lower carbon footprint than the baseline solution, or when a company enables its end users to reduce the footprint of their existing products or processes relative to business as usual. For example, well-insulated buildings can lead to energy savings and avoided emissions over a building's lifetime. These reduced emissions do not appear in the insulation's footprint but will be greater than the emissions associated with producing and installing the insulation itself, thus benefitting the climate overall.

By making processes more efficient than they would be otherwise, ICT has the potential to create a large positive handprint. Previous research has been conducted on the handprint of the core ICT industry in the United States and abroad. We review these assessments in our literature review and explore their complicated nature, highlighting the numerous uncertainties that arise when conducting a handprint analysis (e.g., usage patterns, time of use and regional discrepancies, life-cycle stages, determining which use cases to include, level of adoption). It is critical that companies compute a handprint in addition to their footprint, rather than instead of it, to obtain a more transparent and comprehensive understanding of their overall contribution to the problems and solutions associated with climate change. The purpose of reporting these calculations is to motivate companies to minimize their footprints while also making business decisions that maximize their beneficial handprints.

Various methodologies have been developed to estimate handprint effects. Determining how and to which parties to attribute emissions savings can be a key consideration for a handprint analysis. To further unpack frameworks for handprints and the notion of attribution, we develop an illustrative example of a potential carbon handprint, using smart thermostats as the network-enabled ICT solution. Our analysis found that in the year 2028, smart thermostats could reduce emissions by 0.52 to 1.35 million metric tons (6.5–17%) in Texas homes heated with electricity. For this calculation of possible emissions reductions from smart thermostats, we limit our attention to five major players involved in the smart thermostat scenario to explore five different methods of attributing credit for the emissions reductions among players.

CONCLUSIONS AND RECOMMENDATIONS FOR THE ICT INDUSTRY

Our research highlights that by improving system-level efficiencies, ICT solutions can reduce emissions and have a beneficial handprint effect on society at large. Nonetheless, to understand and avoid overstating the potential benefits when conducting or evaluating handprints, companies, investors, and other stakeholders must make note of numerous uncertainties and potential side effects of ICT that may occur, such as rebound effects (where efficiency gains are counteracted by increased consumption due to more accessible technology, or where the money and time saved are used for inefficient purposes that offset the efficiency gains from ICT). Quantifying the amount of energy and emissions savings from handprint analyses can produce a wide range of results given all the uncertainties and the particular methodology used when formulating each estimate. Despite some of these concerns, developing handprint calculations is of major value and can help influence companies to take further action on addressing climate change.

In addition to supporting the use and maturity of the handprint concept, we suggest the following:

- Companies should account for widely varying customer motivations for adopting a product or service. Customers may be more motivated by convenience than climate or environmental factors in making day-to-day decisions, and this may affect whether and how they use the product or service.
- ICT companies should prioritize creating products and services that optimize usability, compatibility, and interoperability, and they should account for how users interact with these solutions in the real world.
- Policymakers and other stakeholders should work with companies when deploying solutions at scale to maximize the performance and efficiency of ICT and minimize potential adverse rebound effects.
- The ICT industry can be a key player in delivering smart solutions that help mitigate the impacts of climate change. Encouraging the practice of carbon handprinting will help prioritize the research and development of products and services with emissions benefits.

Introduction

Energy efficiency has substantially improved for equipment over the past few decades, but system-level efficiency remains an area with enormous potential. Many improvements in system efficiency could be enabled by information and communication technologies (ICT), which offer a variety of applications across a wide range of industries including smart thermostats in smart buildings; grid management systems for utilities; energy and supply chain optimization tools in industrial smart manufacturing; mobility solutions such as bike sharing or mobility-as-a-service applications for personal transportation; improved management of food production and distribution supply chains, and reduction of food waste; energy and system optimization tools in data centers and cloud computing in the information services industry; solutions for optimizing electric motor systems; telecommuting and collaboration tools for workers; and many others. These solutions are usually coordinated and connected by a particular kind of ICT: communication networks.

ICT and its applications have expanded rapidly over recent decades, and ICT plays a key role in our increasingly complex and interconnected global economy and energy systems. In the early 2000s, the growing energy consumed by data centers led to some concern; for example, a 2008 study projected ICT's share of global greenhouse gas emissions would be as high as 14% in 2020 (Pickavet et al. 2008).[1] This concern led to efforts such as The Green Grid and the Global eSustainability Initiative (GeSI) that aimed to reduce energy use in ICT [2] so that while demands for computational power have indeed grown enormously, the electrical power demands for computing have grown modestly. Today, the share of global emissions attributed to ICT is estimated to be only 1.8–3.9%, despite a 15-fold increase in data traffic since 2010 (IEA 2021).

In part, ICT's share of global emissions is much lower than past projections because the efficiency of equipment has increased tremendously. The shift toward mobile devices has played a major role in driving device efficiency, as mobile form factors demand efficiency to regulate heat and extend battery life. Estimates indicate that computing equipment has historically doubled in efficiency roughly every year and a half (Koomey et al. 2010). For example

- Chip processors' performance and speed have exponentially increased while power consumption has decreased

[1] Pickavet et al.'s definition of ICT includes computers, data centers, networking equipment, and other ICT devices (excluding smart phones).

[2] www.thegreengrid.org, gesi.org

- Efficient LED TVs and monitors have replaced their energy-intensive plasma and CRT counterparts
- Routers are consuming less energy while supplying more bandwidth (Freitag et al. 2021): for example, Cisco's 8201 router consumes 96% less energy per year than its predecessor NCS 6008 while supplying 35% more bandwidth (Cisco 2021)

Operational efficiency gains have also played a role in lowering network emissions by allowing for automated network management; more precise management of maintenance issues, upgrades, and equipment replacements; and requiring less labor to support the physical infrastructure of networks (Macaulay 2016). These efficiency gains are impressive but may be hard to continue if the low-hanging efficiency fruit has already been picked.

In addition to implementing equipment and operating efficiency, traditional ICT companies top the list of corporate renewable energy purchasers and many have made major commitments to reduce their greenhouse gas emissions under their corporate environmental, social, and governance (ESG) plans.[3] For example, to meet their "net-zero by 2030" goal, IBM plans to procure 75% of the electricity it consumes worldwide from renewable sources by 2025, and 90% by 2030 (IBM 2022). By 2023 SAP[4] aims to be carbon neutral in its own operations, "which includes all direct (Scope 1), indirect (Scope 2), and selected categories of value chain (Scope 3) carbon emissions, such as business flights, employee commuting, and external data centers (co-locations and hyperscalers)" (SAP 2022), as defined in the GHG Protocol and discussed in the literature review. Cisco also plans to have net-zero emissions for Scopes 1 and 2 by 2025, and net-zero emissions for Scopes 1, 2, and 3 by 2040 (Cisco 2021). Intel has pledged to reach 100% renewable energy across their global manufacturing operations by 2030 and committed to net-zero GHG emissions for Scopes 1 and 2 by 2040 (Intel 2022). In addition to these individual company goals, the International Telecommunication Union (ITU), the United Nations body for information and telecommunication technologies, in collaboration with GeSI, Global System for Mobile Communications Association (GSMA),[5] and the Science-Based Targets Initiative (SBTi), has laid out pathways for data centers and mobile and fixed networks to achieve a 45% emissions reduction by 2030 (ITU 2020).

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[3] According to the Clean Energy Buyers Association (CEBA), the top five companies for renewable energy purchases in 2021 were Amazon, Meta, Verizon, Google, and Microsoft. https://cebuyers.org/blog/clean-energy-buyers-association-announces-top-10-u-s-energy-customers-in-2021/

[4] Originally Systemanalyse Programmentwicklung (System Analysis Program Development), later abbreviated to SAP.

[5] Originally the Groupe Spéciale Mobile.

The ICT industry continues to face challenges in meeting its emissions goals, including managing computationally intensive applications such as machine learning and cryptocurrency mining,[6] and proliferating connected devices including the Internet of Things. However, the industry has also provided a hopeful lens for the potential positive impact of ICT-enabled applications on other industries. ACEEE and others have projected that the application of ICT by end-use customers in the economy can reduce energy and greenhouse gas emissions by more than is emitted in manufacturing and operating ICT equipment (Laitner and Ehrhardt-Martinez 2008). We call this reduction in emissions a beneficial handprint effect, also referred to as "Scope 4 emissions" or "avoided emissions" (Elliott, Srinivasan, and Hoffmeister 2022).

Many components are required for ICT to reduce emissions; for instance, microchips are present in every digital device, and software is required for these devices to function. At a more macro level, communication networks are also pervasive in enabling ICT to reduce emissions, and a portion of ICT's overall handprint could be attributable to their operation. ACEEE's past research suggests that communications networks contribute to this handprint in two ways. First, communications are essential to operating ICT-enabled systems that collect data from end-user facilities and connect computers to share the data, enable controls, and optimize operations at the end-user facilities. In addition, the number of possible connections in a network grows proportionally with the square of the number of connected users of the system (e.g., for 10 users there are 45, or approximately $10^2/2$ possible connections, and for 100 users there are 4,950, or approximately $100^2/2$ possible connections, etc.). These interconnections between users offer the potential for improved efficiencies and optimization that can reduce energy use and GHG emissions faster than the number of networked users grows. Thus, networks are an often unseen enabler for industrial sectors (including ICT itself) to become more efficient.

Because of its leadership, the ICT industry has been a favorite of the ESG[7] investing or sustainable investment community for many years. Now, both the sustainable investment community and ICT company customers and employees are increasingly interested in greenhouse gas reporting. To meet their obligations to address the climate crisis for the sake of their stakeholders and of humanity, the ICT industry's challenge, put simply, is to minimize its footprint and maximize its beneficial handprint. This study aims to highlight the relevance and value of handprints to greenhouse gas reporting as well as the importance of system-level optimization. We consider the example of the energy and emissions reductions enabled

[6] In addition to being extraordinarily energy-intensive, cryptocurrency mining also generates large amounts of e-waste (Digiconomist 2023). E-waste and water use are major concerns for the ICT industry as a whole but are particularly acute for cryptocurrency mining.

[7] ESG stands for environment, social, and governance criteria that may be used in stock selection (in addition to traditional company fundamentals that are otherwise the basis for investment decision making).

by communication networks in our effort to create a consistent framework for evaluating the downstream carbon impacts of intelligent technologies and attributing credit to the enablers. Such a framework will provide a new lens for companies and investors to prioritize their technology development and investments. We hope this will be a useful example for the ICT industry and its customers, the GHG reporting community, and the ESG investment community.

Background

In this section, we will describe our terminology, summarize how ICT-based intelligent efficiency can help drive energy and emissions reductions, discuss the greenhouse gas emission reporting framework for companies, and provide a more in-depth review of the handprint concept.

WHAT WE MEAN BY ICT AND NETWORKING

Information and communication technologies encompass everything used for computing and telecommunication, such as computers, phones, routers, wires, data, and software, including component parts. ICT could include the people that facilitate these technologies (for example, by programming or troubleshooting equipment), but our emphasis is generally on software, devices, and data (JISC 2012). We note that other authors may consider only subsets of this broad category when referring to ICT; this issue is discussed further in the literature review.

By a network, we mean a system that includes more than one device capable of communicating with other devices on the network, along with the infrastructure such as wires and routers that enable devices to communicate. (However, we note that estimates of energy and emissions from networking found in the literature and included in this report generally do not include the contribution of end-use devices such as personal computers or mobile phones.) A network could be wired or rely on wireless technology such as 5G and could be limited to one geographic area (a local area network, or LAN) or many geographic areas (wide area network, or WAN). Networks are a subset of ICT.

In this report, we use "communication networks" to include both local and wide-area networks, but our thinking is more focused on the role of wide-area networks because they are capital and energy intensive, and thus have a larger role to play in reducing emissions.

INTELLIGENT EFFICIENCY

The term *intelligent efficiency* was introduced by ACEEE in the mid-2000s to describe a holistic, systems-based approach to energy efficiency enabled by the adaptive, predictive, and networked capabilities of ICT. Other terms for this include "active efficiency" (Alliance to

Save Energy) and "digitalization efficiency" (International Energy Agency).[8] Intelligent efficiency relies on a complex alignment of networks that link information between devices, large datasets, and analytic software tools that convert data into information used for decision making to enable energy savings. Technological developments such as the internet of things (IoT), big data, data analytics, digital twins, and machine learning have begun to improve the monitoring, optimization, and control of facilities and organizations that can lead to greater savings and more efficient end-use energy consumption, but much more remains unrealized.

ACEEE has explored the benefits and penetration of intelligent efficiency across various sectors of the economy. Buildings, manufacturing, transportation, government services, and the electrical grid are some areas where companies and governments have achieved significant savings and cut emissions. The US Department of Energy's (DOE's) Smart Grid Investment Grant Program's projects, for example, saved over 15,000 tons of CO_2 emissions as well as over $300 million in operational and maintenance costs over three years (DOE 2016). In homes, smart thermostats use machine learning and data in the cloud to identify occupancy patterns and temperature preferences, automatically adjusting the heating or air-conditioning for the optimal setting. Overall, ACEEE estimated that the energy cost savings of intelligent efficiency technologies for the commercial and manufacturing sectors alone could exceed $90 billion per year (Rogers et al. 2013).

Importantly, intelligent efficiency systems can reduce or eliminate the degradation of energy savings over time. A common example of this decline in savings occurs at the whole-building level with building automation systems (BAS). When a building is first put into service, all its systems—heating, ventilation, and air conditioning (HVAC), lighting, elevators, security, and so on—are adjusted and tuned. If a BAS has control over these systems, it is programmed to operate the building in a way that lowers operational costs and optimizes occupant comfort, a process that initially saves energy. However, as new tenants with different floor plans, office equipment, and hours of operation move in over the years, expectations and demand for these initial systems also change. As a result, building performance often wanes as its systems are not optimized or re-tuned on a regular basis to keep up with changes in occupancy patterns. Maintenance staff who are not properly trained in performing routine checks of a building's mechanical systems and turnover in building management can exacerbate these issues. One study looking at advanced lighting controls, for example, found that "improperly maintained systems can lose 24–38% of expected energy" (cited in Srivastava, Awojobi, and Amann 2020).

In contrast, an advanced BAS using an intelligent efficiency approach will continuously collect building information and combine it with utility real-time pricing, weather forecasts,

[8] activeefficiency.org, www.iea.org/topics/digitalisation

and other data streams to design and implement optimal controls for the building's systems. With constant learning and continual refinements, these intelligent systems can drive down energy use and increase savings over time. Existing building commissioning (EBCx) or re-tuning of existing buildings has been found to provide energy savings in the range of 10–30%, with some buildings reporting up to 60% (Katipamula et al. 2021).

A system efficiency approach based on performance and behavior can target energy use where it is needed, with clear advantages over solely focusing on device-level upgrades. Upgrading incandescent lighting to LEDs improves device-level efficiency, but it does not prevent an LED luminaire from illuminating an empty room. The more comprehensive view of efficiency enables networked systems to outperform isolated upgrades at the device level: While LED retrofits can achieve 30% energy savings, implementing advanced lighting controls offers an additional 44% energy savings for the building's lighting with a payback of less than five years (Frank et al. 2015). Fully integrated smart lighting systems could achieve up to 90% energy savings, which includes installing LED luminaires and connecting sensors and controls to a centralized management system with data analytics and learning capability (Gartner 2015). A smart building with integrated systems, for example, can realize around 30–50% savings, whereas an upgrade to a single component or isolated system would result in energy savings of only 5–15% (King and Perry 2017). Achieving such high energy savings—a goal that is not only financially rewarding but would also help keep the United States on track to reach net-zero emissions by 2050—could be expedited if companies across the commercial and manufacturing sector designed their operations around networked and intelligent energy systems.

Experts interviewed in researching this report independently told us that both businesses and individuals are more likely to adopt ICT solutions for reasons other than energy savings or emissions reductions, even when these are nominally a priority (G. Hernandez, managing director, Ari Analytics; X. Jin, researcher, NREL; C. Nesler, chief executive officer (CEO), Nesler Group, pers. comm., June 2022). These non-energy benefits could include convenience. For instance, a user could schedule a meeting in a conference room using their work calendar, and the room settings would automatically adjust to accommodate the meeting. The room's HVAC controls could adjust the temperature 15 minutes before the meeting to bring the room from its vacant mode to a comfortable temperature; lights and motorized window blinds could be altered to provide natural light but prevent glare; ventilation rates could automatically modulate to the number of occupants detected by sensors after the meeting starts, and so on. After the meeting's conclusion, the room could revert to an unoccupied state. Thus, the amenities of natural light, fresh air, and comfort could be delivered along with energy savings with no additional effort from the person booking the room and arranging the meeting (Nesler 2019). Another example could be linking the building's safety systems with its occupancy and security systems so that in the event of a fire, pressure could be used to isolate the incident and data about occupancy could automatically be reported to the fire department, reducing the risk to firefighters (G. Hernandez, managing director, Ari Analytics; C. Nesler, CEO, Nesler Group, pers. comm., June 2022). Communication networks are the key to linking these disparate systems and realizing the benefits of coordination.

CARBON FOOTPRINT AND HANDPRINT

The concept of carbon handprints is grounded in the way companies and organizations report their greenhouse gas emissions. Methods for calculating handprints assume familiarity with life-cycle assessment and greenhouse gas emissions reporting methodologies. Companies have historically tracked their direct and indirect GHG emissions and environmental impacts in terms of a *carbon footprint*, which refers to emissions covered under Scopes 1, 2, and 3, described below and illustrated in figure 1.

Greenhouse Gas Emissions Reporting

According to the *GHG Protocol Corporate Accounting and Reporting Standard*, an international emissions protocol developed by the World Resources Institute and the World Business Council for Sustainable Development (2004), there are three main categories for emissions reporting: Scopes 1, 2, and 3. The protocol covers the accounting and reporting of seven greenhouse gases specified in the Kyoto Protocol.[9] These scopes are described as follows:

Scope 1

Scope 1 emissions are the direct GHG emissions from company-owned and controlled sources. These could include the greenhouse gases released by company facilities and vehicles.

Scope 2

Scope 2 emissions are indirect GHG emissions related to electricity, steam, heat, or cooling purchased from utility providers. While these upstream emissions are often not physically released on site, they are still included in an organization's inventory as part of their overall energy consumption.

Scope 3

Scope 3 emissions are all other indirect emissions not included in Scope 2 that occur up and down the value chain of the organization. Some of the main emissions from this category are associated with the upstream delivery and processing of capital goods and services, downstream use of sold products and services (including end of life treatment), business travel, and employee commuting. In practice, reported Scope 3 emissions are often limited: for instance, they may capture only upstream and downstream emissions to the point that products and services are delivered to the customer.

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[9] The seven gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3).

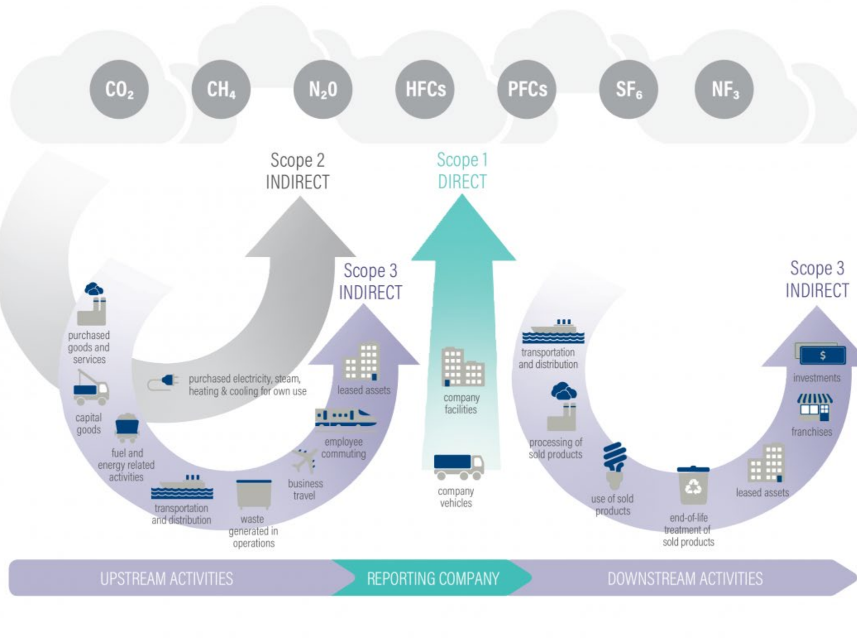

Figure 1. GHG Protocol scopes and emissions overview[10]

CDP (formerly known as the Carbon Disclosure Project) is an international nonprofit that runs the carbon disclosure system for companies, cities, and investors around the globe. This is the gold standard for environmental reporting, with more than 18,700 companies responsible for half of global market capitalization disclosing in 2022 (CDP 2022). While 9 out of 10 Fortune 500 companies reporting to CDP use the GHG Protocol, federal requirements in the United States on GHG reporting are limited to certain high-emitting sources.[11] The U.S. Securities and Exchange Commission (SEC) has recently proposed requiring the reporting of Scopes 1 and 2 emissions, and Scope 3 emissions "if material or if the company has set a GHG emissions reduction target or goal that includes its Scope 3 emissions" for all large publicly traded companies in the United States (Securities Exchange Commission 2022).

Both handprints and footprints demonstrate climate impacts by following international protocols for estimating material and energy use, lifetime performance, waste, and carbon capture and storage over a product or service's lifecycle. Functionally, many aspects of both calculations are the same. But a footprint attempts to capture the emissions impacts that are

[10] For more information, see https://www.wri.org/initiatives/greenhouse-gas-protocol.

[11] See https://www.epa.gov/ghgreporting for details.

inherent to an individual product, service, or organization, while a handprint is inherently a comparison, computed as the difference of two footprints. A carbon footprint calculation is useful in assessing ways to more efficiently manage resources and reduce Scopes 1, 2, and 3 emissions. But footprints offer investors and the public only a limited view of the risks and/or benefits posed by the products and services that firms provide.

Carbon Handprints

A carbon handprint is a means of estimating beneficial or detrimental impacts of a product, service, or actor that go beyond an individual company. Handprints can be computed for criteria other than greenhouse gas emissions, including social impacts, but while some of our discussion applies in those cases, we are restricting our attention to climate impacts and use the terms "handprint" and "carbon handprint" interchangeably. Other terms found in the literature to refer to this concept are "avoided emissions," "enablement effect" or "enabling effect," "indirect effect," "GHG abatement potential," "consequential accounting," and increasingly, "Scope 4 emissions." The World Resources Institute has used the term "comparative assessment" to encompass all these terms (Russell 2019). Regardless of the terminology, quantifying handprint data provides a path for companies to share with their customers and investors some of the ways in which they are working to combat climate change beyond their own direct operations. Handprint data may also be used internally by companies to assess new products and guide research and development.

Handprints have been developed to estimate the beneficial or detrimental impact a product, service, or organization can have on *society at large*. For example, since heating and cooling buildings is not part of the footprint of insulation makers, a footprint-only perspective might lead one to believe that producing less insulation is beneficial. However, when we consider a carbon handprint that includes reduced emissions from well-insulated buildings, then the benefits of insulation products to society become visible in a way that they do not with a footprint alone. Beneficial handprints can highlight how reducing resource consumption and emissions might be a business opportunity and drive economic growth.[12] But handprints need not be positive: for example, a ride-hailing app could have a detrimental handprint if its users would otherwise have walked or taken public transportation.[13] And producing a

[12] This idea is the impetus for Mission Innovation, a global initiative launched at the 2015 Paris climate accords, mission-innovation.net.

[13] Whether a handprint is positive or negative depends not just on the solution but also on the assumed baseline. According to the Union of Concerned Scientists, ride-hailing in an electric vehicle shared by other riders is substantially less polluting than ride-hailing alone in a gas-powered vehicle and could potentially be less polluting than riding a diesel-powered bus (Anair, Martin, and Pinto de Moura 2020). Assumptions are critical and could easily lead to biased results. For this reason, handprint methodologies emphasize a *consequential* approach that considers the impacts of a solution as broadly and holistically as possible. An agreed-upon framework is essential.

carbon handprint does not eliminate the need to perform greenhouse gas inventories and minimize carbon footprints.

A carbon handprint may be created either by helping a customer to reduce the footprint of their existing processes relative to business as usual, or by offering a completely new solution with a lower carbon footprint than the baseline solution. An example of the latter (a new solution) is using 5G unmanned aerial vehicles to inspect gas pipelines for leaks, reducing emissions compared to the service vehicles that would traditionally be required for field inspections. An example of the former (a reduced footprint of existing processes) is using more fuel-efficient service vehicles to transport workers to inspection sites. Note that the emissions reductions in the handprint may overlap with Scope 3 emissions of the solutions provider (as in the case of the fuel-efficient vehicles) or be external to the product footprint (as in the case of the drone). The Sustainability and Health Initiative for NetPositive Enterprise (SHINE) Institute (2021a) refers to these as internal and external handprints.

A variety of methodologies and frameworks have been proposed for estimating handprint effects (SHINE 2021a, SHINE 2021b, Pajula et al. 2021, Russell 2019, Stephens and Thieme 2020, and others). Several methodologies have been developed specifically for the ICT industry (ITU 2014; IEC 2014; GeSI and BCG 2010). These methodologies differ slightly, but all essentially boil down to the following:

1. Identify the operating environment: who the customers of the product or service are, what companies are potential contributors to the handprint, and a definition of the baseline.
2. Define life-cycle analysis (LCA) requirements similar to those for footprints (functional unit, system boundaries, data and sources).
3. Estimate the handprint by calculating the new footprint and subtracting it from the baseline footprint.
4. Critically review the handprint and communicate the findings.

The organizations that define methodologies and frameworks broadly agree that handprints are complementary to footprints. A handprint should be computed in addition to, not instead of, a footprint, and should be reported separately rather than combined with a footprint. Companies should also avoid focusing exclusively on products and services with beneficial impacts (cherry-picking): for example, the SHINE institute advocates for actor-based handprints that cover a company’s entire portfolio rather than product-specific handprints (SHINE 2021a). These practices, together with transparency about assumptions and methods, can help avoid the appearance of green washing.

Attribution

One question that arises when calculating a handprint is which parties are responsible for the implementation and should get credit for the emissions reduction. Similar issues come up for footprints: one company’s Scope 3 emissions are another company’s Scopes 1 or 2 emissions, or a fraction of them. Sorting out these overlaps and identifying primary responsibility for reductions can be problematic. Since handprints are computed by subtracting one footprint from another, this uncertainty in footprints gets passed along to handprints. ICT products and services in particular often come to market with many complex contributions along the value chain. For example, a building energy management system may rely on computers made by one company that use chips from another company and are enabled by networking equipment from a third and cloud computing services from a fourth, which in turn relies on networking equipment from the third and chips from the second. All these elements are required to enable the management of the building's energy system; attributing impacts to a single player is difficult when the boundaries between companies' contributions are blurred.

If a handprint is used for internal decision making (for example, to guide R&D spending), then precisely nailing down attribution may not be critical, but in some cases, handprints could be used as a carbon offset or to claim a monetary benefit, and in such cases, understanding attribution in detail is essential.

The Mission Innovation Framework outlines various approaches that have been proposed for attributing a carbon handprint among players (Stephens and Thieme 2020); Elliott, Srinivasan, and Hoffmeister (2022) have an overlapping discussion including the "shared responsibility, shared credit" approach of the SHINE institute. These sources more thoroughly discuss benefits and drawbacks of the various approaches; we briefly consider possible approaches here as they pertain to a handprint for communication networks:

1. **Allocate equally** among all players. In this approach, the emissions reduction is divided by the number of actors that are responsible for implementing the solution. Comprehensively assessing the contributions of different actors may be difficult, but, especially in the absence of better data, a simplified accounting may be "good enough."
2. **Attribute by the costs of production for each player, or the financial value of constituent products or services on the market.** This approach recognizes that different players make different contributions to reducing emissions through a given solution, but assumes the cost or value accurately reflects the contribution to reducing emissions. Counting the number of players is a prerequisite, with the added complexity of assessing the costs of production or value on the market of each contribution.
3. **Accept double counting.** In this case, each party involved would claim the full emissions reduction from implementing a solution. This approach is typical for carbon footprints, where Scope 3 emissions of one company are understood to overlap with those of other companies. If there is a similar shared understanding of the overlap for handprints, double counting may not be problematic, but it risks overstating emissions reductions, potentially leading to missed reduction targets or accusations of greenwashing.

4. **Allocate all avoided emissions to the solution's most obvious contributor.** In the case of a building energy management system (BEMS), this could be the provider of the BEMS service. This choice avoids double counting but neglects the contributions of the other players, and likely ignores essential components that enable the system to function, such as network communications.
5. **Allocate based on stakeholder consensus.** In this approach, stakeholders convene to share data and agree on methods to determine a "fair" contribution for each player that avoids double-counting. While this could be considered an optimal approach in some sense, it can be difficult and time consuming, and there is currently little incentive for companies to engage each other this way.[14]

It is unlikely that any of these approaches is best in all cases. For the applications in this report, we will explore how the outcomes may look using different attribution methodologies and how to better convey the outcomes to be clear, fair, and unbiased. The ultimate goal is to prioritize and incentivize technology and product development that can minimize overall societal carbon emissions. We discuss this issue further in the attribution section of our analysis.

Summary of Literature Review

The literature we found on carbon handprints of communication networks was so limited as to be virtually nonexistent.[15] For this reason, we expanded our literature review to include estimates of ICT handprints; many or most ICT solutions require communications networks, so these broader estimates could be considered network handprints. While we hoped to find a consensus about the impact of ICT in the literature, we did not. Estimates are generally difficult to compare because they may be based on very different assumptions. While these approaches may all be considered appropriate within their particular contexts, they underscore the importance of transparently stating assumptions and scopes in deriving such estimates.

[14] The SHINE Institute's approach is to attribute by costs or labor (i.e., approach 2) where possible, and where such accounting is not possible, to use *shared credit*, essentially double counting with an emphasis on joint ownership. If two actors are collectively responsible for reducing emissions by 1,000 kg, each actor can claim a 1,000 kg reduction but the handprint of the two actors together is also 1,000 kg (Norris 2013, SHINE 2023b). It is unclear how this might be interpreted from a practical perspective such as GHG reporting protocols.

[15] During the review process for this report, Bieser et al. (2023) published a review which summarized "enablement factors" reported by telecommunication network operators such as AT&T, Verizon, and Deutsche Telekom, in addition to scientific literature that we reviewed in writing this report. Their review generally aligns with the findings of our literature review.

Before investigating carbon handprints, it is useful to review some of the current approaches to and calculations of carbon footprints for the ICT sector.

CARBON FOOTPRINTS OF ICT AND NETWORKS

The ITU's 2015 baseline estimate of ICT's carbon footprint is 740 Mt CO2e which includes emissions from mobile networks, fixed networks, enterprise networks, user devices, and data center emissions. This is equivalent to the emissions from South Korea, the 13th most emitting country[16] (Climate Trace 2022). Excluding user devices and data centers, the footprint of networks is 198 Mt CO2e (ITU 2020). However, any estimate of carbon footprints comes with many uncertainties. We next discuss other ICT footprint estimates, both to illustrate the uncertainties and difficulties of comparing carbon footprints for ICT, including those of networks, and to provide context for the footprint of networks.

What Should Be Included in ICT?

One issue that complicates comparing footprints from different sources is what to include in the ICT sector. Some analyses focus exclusively on data centers. IEA (2022) reports that global data centers used 220–320 TWh of electricity in 2021 (which was about 1% of global final electricity consumption), with an additional 100–140 TWh for cryptocurrency mining. However, this is limited to a single (if arguably the most important) category of ICT equipment, and notably, does not include the impact of end-use devices. The question persists even when restricting attention to networks: GSMA calculated that the mobile sector had a global carbon footprint of 220 Mt CO2e in 2018, of which 98.4 Mt CO2e were attributed to mobile network operations. This does not include the impact of fixed (wired) networks.

For 2015, Malmodin and Lundin (2018) estimated that the ICT sector (including end-use devices) used 805 TWh of global electricity. This equates to about 3.6% of global electricity, with 730 Mt CO2e of associated greenhouse gas emissions—about as much as South Korea (Climate Trace 2022). An additional factor to consider is that with the growth of digital streaming, televisions and related equipment are converging with equipment that is more conventionally considered ICT, such as computers and monitors. If we were to include the 510 TWh of electricity from the entertainment and media (E&M) sector that TVs, TV networks, and other consumer devices use, the estimate would be 1,315 TWh or 6.0% of global electricity. The electricity impacts of these ICT categories are illustrated in figure 2.

Electricity versus Emissions

IEA (2021) estimates that communication networks used 260–340 TWh of electricity in 2021, about 1.1–1.4% of global electricity. Assessing energy used by global networks is already a

[16] The emissions of South Korea were 740 Mt CO2e in 2021, or 1.4% of global emissions.

complicated endeavor, but translating the electricity used into emissions requires additional information on where and how that electricity was produced. Emissions rates vary place to place and even minute to minute as the mix of generation sources changes; matching energy demand with its source and finding data at this level of granularity (even hourly or at 15-minute intervals) is difficult for today, let alone for a future scenario. Grid emissions are thus another major source of uncertainty in calculating footprints and handprints. If the future grid is powered by mostly renewables, then the emissions from using electricity will be less, and handprints and footprints will be smaller.

Where on Earth?

In 2017, Hilty and Bieser performed a detailed analysis of ICT emissions in Switzerland (2.08 Mt CO2e per year), but it is unclear if the use of ICT in Switzerland applies to other regions or can be scaled globally. Also, as mentioned above, the electricity mix affects the GHG emissions of devices in use. In Switzerland production of electricity mainly comes from hydropower and nuclear, which emits less compared to a region that relies on more carbon-intensive fuels to produce electricity.

Usage Patterns

Numerous factors related to the use of devices—such as whether they are used extensively or in a limited manner, if the device is on or off grid (such as a satellite phone), and if the connectivity is based on a fixed connection, Wi-Fi, or 4G—can impact the downstream emissions of ICT devices (Malmodin and Lundin 2018). Without a centralized or standardized evaluation of this information, a further layer of uncertainty is assumed when calculating these footprints.

Life-Cycle Stages

Emissions estimates are often restricted to the use phase of products and do not include embodied emissions. Even when embodied carbon is considered, estimates are often limited to upstream emissions from raw material extraction through manufacturing ("cradle-to-gate" emissions), and do not include downstream emissions from use, disposal, or recycling of products ("cradle-to-grave"). Hilty and Bieser (2017) state that a "throw-away mentality" for electronic devices could "substantially increase the footprint of the ICT sector," even with high rates of recycling. Malmodin and Lundin (2018) estimate that the cradle-to-gate carbon footprint of the ICT and E&M sectors is 196 Mt CO2e and 109 Mt CO2e, respectively.

Old Data And Rapid Change

Because ICT has evolved so rapidly, out-of-date estimates of the energy used by equipment have led to inaccurate estimates for the industry's footprint: Global data centers have improved the efficiency of their operations 20% every year since 2010, which is an order of magnitude higher than efficiency gains in other sectors with significant demand, such as aviation and industry (Masanet et al. 2020). Aslan et al. (2017) found that the energy intensity of networks has been cut in half every two years since 2000. Between 2010 and 2018, the number of internet users grew 185%, computing operations increased 600%, storage capacity increased 2,500%, and data center IP traffic increased 1,000% (ITU 2023; Masanet et al. 2020). Yet data centers used only 6% more energy over this period (Masanet et al. 2020).

As a result, estimates for the future footprint of ICT are subject to uncertainty. For example, ITU projects that in 2030 the footprint for networks will be 102 Mt CO2e and for ICT will be 388 Mt CO2e (ITU 2020). Peak data traffic is an important consideration for how the footprint of networks may evolve, because network infrastructure, like other infrastructure, is built with peak data traffic in mind. Video streaming is likely the most important activity for peak data traffic; it was expected to make up 82% of consumer internet traffic in 2022 and fits a “prime time” pattern that affects peak traffic (Carbon Trust 2021). Other large sources of increasing demand are blockchain, machine learning, and new technologies such as virtual reality.

Importantly, data traffic does not appear to significantly affect the energy used by networks; the energy required to run network equipment is essentially fixed, even when it is not being used much. This was demonstrated in 2020 in the response to the COVID-19 pandemic, when data traffic increased nearly 50% but energy use remained relatively constant (IEA 2021).

Traffic is expected to continue shifting to mobile device networks rather than wired or Wi-Fi only. Mobile devices are significantly more efficient than their larger, stationary counterparts, but wireless network equipment is less energy efficient. The impact of switching wireless networks to 5G is also uncertain, particularly the life-cycle emissions; producing equipment may account for over half of life-cycle emissions (Bieser et al. 2020).

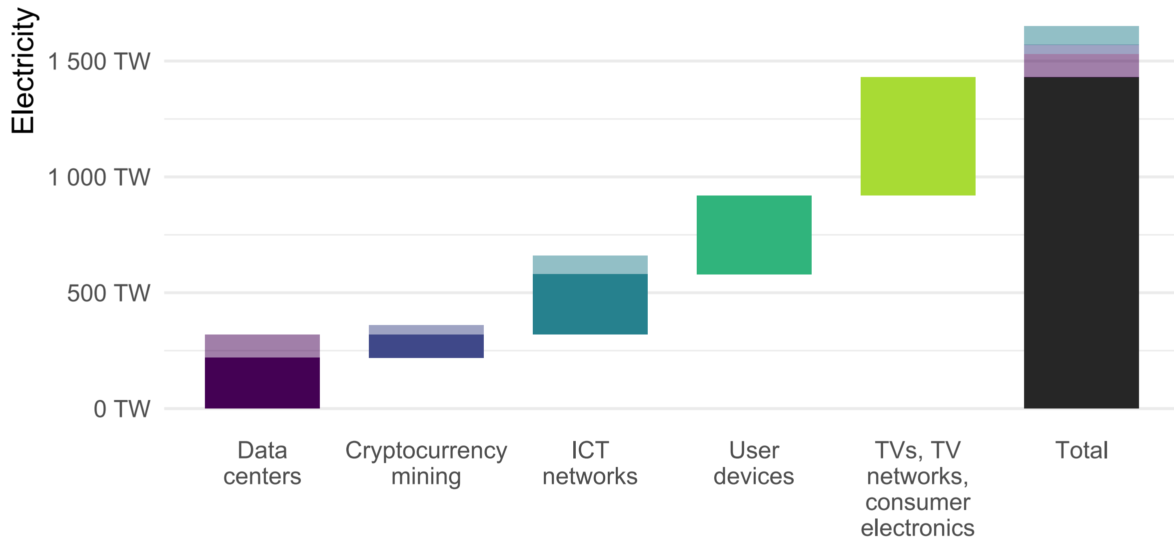

Figure 2. Global electricity use of ICT. Sources: IEA 2022 for data centers, cryptocurrency mining, and network electricity in 2021, Malmodin and Lundin 2018 for user devices and TVs in 2015. Where the data provided upper and lower bounds, we show upper bounds with transparent color.

CARBON HANDPRINT OF ICT AND OF NETWORKS

All the uncertainties that apply to carbon footprints, including geography, type of equipment, predictions, and emissions factors, also apply to carbon handprints. We now consider these and some additional uncertainties that apply to handprints.

Which Use Cases Are Being Considered?

The widespread deployment of 5G network infrastructure could provide companies and governments with pathways to significantly decrease GHG emissions. In 2020 the University of Zurich estimated the impact of 5G mobile networks on GHG emissions in Switzerland (Bieser et al. 2020). Assessing four specific 5G-supported use cases—flexible work, smart grid, automated driving, and precision farming—they determined an abatement of up to 2.1 Mt CO2e/year in 2030 in an optimistic scenario, 0.6 Mt CO2e/year in the expected scenario and 0.1 Mt CO2e/year in a pessimistic scenario. According to an Accenture study commissioned by CTIA (a U.S. trade association representing the wireless communications industry), "use cases on 5G networks are expected to enable the abatement of 330.8 million metric tons of carbon dioxide equivalents (Mt CO2e) across five industry verticals [in the United States] by 2025" (Kuroki et al. 2022). This would contribute approximately 20% in 2025 toward the U.S. 50–52% emissions reduction target by 2030. These estimates are not easily comparable since they use both different sets of use cases and different geographies.

How Much Can This Thing Actually Reduce Emissions?

Estimates of the handprint of individual ICT solutions vary wildly, ranging from slightly detrimental to over 100% energy or emissions savings. One source of uncertainty stems from the use cases to which the solution might apply, as discussed above; another is how widely solutions may be adopted. A further source of uncertainty is the potential for large rebound effects. While we recognize that the possibility of rebound effects has been used to attack energy efficiency for decades despite limited impacts in practice (Nadel 2012), two notable ICT solutions, ride hailing and online retail, may be increasing emissions. Online retail may be increasing emissions because the expectation of ever-shorter delivery times leads to freight that is less optimized for energy, and potentially because the convenience of online retail leads consumers to increase their consumption of goods. These increased emissions are an example of a "third-order disruption,"[17] difficult to discern when adoption remains limited (Wilson et al. 2020).

We can certainly imagine beneficial third-order disruption: for example, shared mobility, virtual mobility, autonomous vehicles, and usage-based mobility all could disrupt the conventional model of car ownership, and together could help satisfy mobility needs with many fewer vehicles. In turn, this could allow roads to be repurposed for housing or for other needs that could create "15-minute neighborhoods,"[18] further reducing emissions. While a scenario this rosy is far from guaranteed, we note the impact of ICT is generally thought to be beneficial in the literature (Wilson et al. 2020).

Ad Hoc versus Bottom-up Analysis

ICT sector-level emissions compound technology-level uncertainties. Many estimates are ad hoc back-of-envelope calculations rather than detailed, bottom-up analyses (Bieser and Hilty 2018). While these simplified calculations can be surprisingly accurate, more detailed assessments are needed to back them up and provide greater certainty about results. We have attempted to conduct a more detailed analysis in this report, but the trade-off in doing so was limiting our scope in geography, use cases, and time.

ICT and Network Handprints

Two of the most comprehensive studies exploring the global handprint of the ICT sector were conducted in 2015 by GeSI and Ericsson. Both studies provide impact potentials for the year 2030 and use the IPCC's global 2030 GHG emissions estimate of 63.5 Gt of CO2e as their analysis baselines. GeSI's *SMARTer2030* report examined ICT use in eight sectors: healthcare, education, building, agriculture, mobility, energy, e-business, and smart

[17] A "first-order" impact is part of the carbon footprint of a product, a "second-order" impact is a handprint effect that directly results from the product, and a "third-order" impact is a consequence of second-order impacts. (This terminology is not standard across sources we consulted; for instance, Wilson et al. (2020) use "second-order impact" to refer to what we have called "third order.")

[18] The 15-minute neighborhood is an idea in urban planning that residents can have improved sustainability and quality of life if they can access most daily needs such as work, groceries, childcare, and so on within a 15-minute walk or bike ride from home.

manufacturing. With slight differences in categorization, Ericsson generally looked at these same sectors. GeSI suggests that ICT solutions could avoid up to 20% of annual GHG emissions by 2030 on a global scale, equating to a cumulative 12 Gt of avoided global CO2e emissions. Given that GeSI and others project the carbon footprint of ICT sectors to be around 2% of global emissions in 2030, the emissions avoided through these ICT solutions could be 10 times greater than the emissions required to deploy, operate, and dispose of them. Ericsson presented two global GHG emissions reduction scenarios in 2030 as a result of implementing ICT-based solutions. The high reduction potential scenario projected 10 Gt CO2e of total GHG emissions reductions (or 15.3% of global GHG emissions in 2030), including in agriculture. In the medium reduction scenario, total GHG emissions were reduced by 5 Gt CO2e (or 7.4% of the global GHG emissions) (Malmodin and Bergmark 2015). Ericsson obtained their estimates on agriculture from GeSI's *SMARter2020* report. Using updated figures on agriculture from the *SMARTer2030* report, Ericsson's 2015 estimates would be 15.9% and 10% for the high and medium scenarios, respectively (GeSI 2015; Malmodin and Bergmark 2015).

Other analyses are less optimistic. In a 2017 University of Zurich paper, Hilty and Bieser find that by 2025, ICT applications could avoid around 3.37 times more GHG emissions than the amount of emissions caused by the deployment and operation of ICT devices and infrastructure in Switzerland. This equates to saving up to 6.99 Mt CO2-equivalents (CO2e) per year in Switzerland, compared to a carbon footprint of 2.08 Mt CO2e per year. Hilty and Bieser also calculated the handprint of ICT in Switzerland to be 0.43 of the footprint in 2015, so the application of solutions must become more widespread to realize the large potential.

The GSMA and Carbon Trust assessed the impact of mobile communications technology on carbon emissions at a global scale. Since mobile technologies rely on network communications, this could be considered a handprint for mobile networks. They concluded that in 2018 alone, global avoided carbon emissions were approximately 2,135.9 Mt CO2e. With the equivalent decrease in electricity, gas, and fuel, these abated emissions would be enough to power “more than 70 million houses for an entire year in the US, and enough fuel for all 32.5 million registered UK passenger cars to drive for 19 years” (GSMA 2019). We summarize ICT and network handprint estimates in table 1.

Table 1. Carbon handprints for the ICT sector[19]

Reference (handprint year)	Region	Potential handprint (Gt CO2e)	Projected footprint (Gt CO2e)	Handprint to footprint ratio
General ICT Estimates				
GeSI (2030)	Global	12	1.25	10x
Ericsson Research (2030)	Global	4–8		
University of Zurich (2025)	Switzerland	0.01	0.002	3.37x
Mobile Network Estimates				
GSMA (2018)	Global	2.1	0.22	10x
University of Zurich (2030)	Switzerland	0.0001 – 0.002		
CTIA (2025)	U.S.	0.33		

Analysis

Our aims for our analysis are twofold: first, to provide an illustrative example of a handprint calculation, and second, to demonstrate the need to account for potential side effects of adopting solutions, as well as the opportunities for ICT solutions to help avoid these detrimental side effects. We opted to use a hypothetical scenario for smart thermostats in Texas in 2028 to illustrate these points. The year 2028 was chosen because a good number of market projections were available to estimate how many smart thermostats will be adopted in the next five or so years, and because near-term climate action is increasingly vital.

[19] The "enablement factors" reported by telecommunication network operators for years between 2018 and 2020 given in Bieser et al. (2023) are mostly in the range of a handprint that is 2–7 times larger than the footprint. However, these estimates are not necessarily comparable for all the reasons we have discussed. Bieser et al. point out that reported enablement factors have increased over time at least in part because the number of use cases considered has increased, not necessarily because the handprint has truly increased or the footprint decreased. The consensus in the scholarly and GHG reporting communities has moved away from enablement factors or other metrics that combine handprints and footprints, and AT&T has changed their enablement goal from a factor of 10 to an absolute goal of 1 billion MT CO2e avoided by 2035 (Bieser et al. 2023).

EMISSIONS CALCULATION METHODOLOGY

We compare two scenarios. In the baseline scenario, we assume the current mix of manual, programmable, and smart thermostats applies in 2028. In the alternative, we assume higher rates of smart thermostat adoption. While smart thermostats may be more complex and resource intensive to produce, we assume that the difference in embodied emissions between smart thermostats and programmable or manual thermostats is relatively small. Thus, for our handprint, we only examine the difference in emissions from controlling heating equipment with the different thermostats.

We limit our attention to electric heating, which is how most Texas homes are heated (58%, most of which use electric resistance,[20] per EIA's 2020 Residential Energy Consumption Survey (RECS) (EIA 2023a)) and because our second aim of assessing potential side effects pertains to the impact on grid emissions. We assume that the proportion of homes that use electric heating will remain the same in Texas in 2028.

For our baseline, we use energy load profile data from the National Renewable Energy Laboratory's (NREL's) ResStock, a statistical model of the U.S. housing stock (NREL 2023b); for the comparison scenario, we use a load profile shape for homes using smart thermostats from an analysis of ecobee data by Lee and Zhang (2022) from midnight to noon including the morning peak, but keeping the baseline electricity demand for the remainder of the day.[21] Emissions data come from Cambium, an NREL model which projects electrical grid emissions for every hour up to 2050 (NREL 2023a).

We consider six scenarios: high/low adoption rates of smart thermostats (that is, 30% and 15% compound annual growth rates resulting in 70% and 42% of electric-heated Texas homes using smart thermostats in 2028), and high/medium/low energy savings from using smart thermostats (15%, 8%, and 3%, based on a variety of studies and considering uncertainty).

Further details about data, methods, and reasoning are in Appendix A.

[20] Of Texas homes heated with electricity in 2020, 36% used central heat pumps and about 1% used ductless mini-split heat pumps; 41% used a central electric furnace, with almost all the remainder using built-in or portable electric resistance units.

[21] We did not include the afternoon or evening peak because of a data problem while adapting Lee and Zhang's findings to the Texas housing stock model for 24 hours. Since the purpose of this report is to illustrate a method to quantify handprint, we focused our analysis on the first half of a 24-hour period, the data of which seem to be more comparable. The analysis using the full 24-hour curve from Lee and Zhang is documented in Appendix B for readers who are interested in further examination.

EMISSIONS CALCULATION RESULTS

An example of the electricity consumption in the high adoption, medium energy savings scenario is plotted with the baseline electricity consumption in figure 3, demonstrating the impact of smart thermostats in reducing the size of the morning peak.

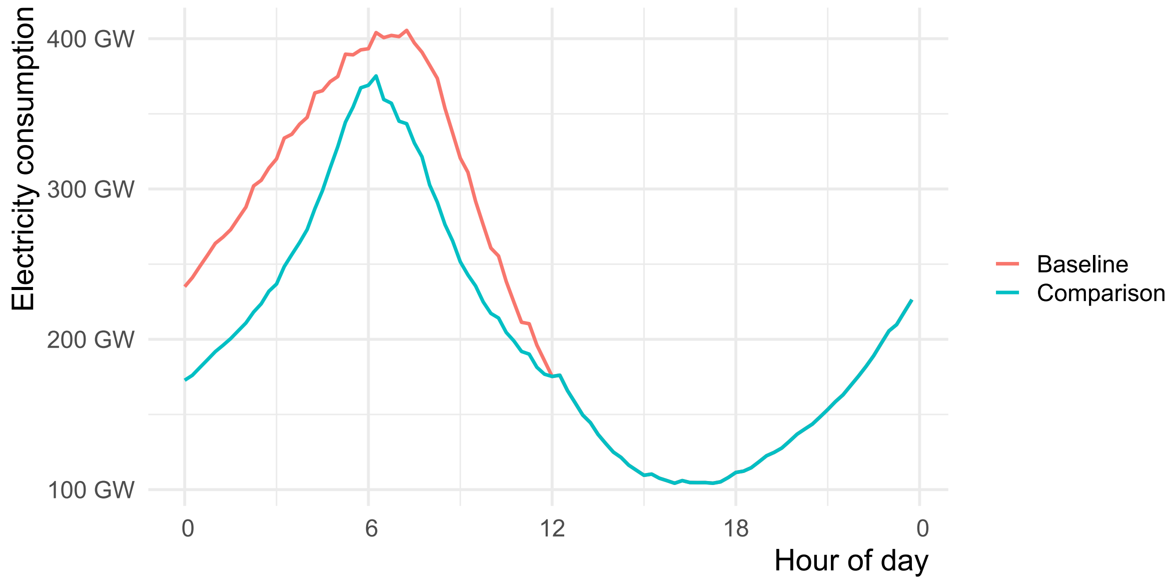

Figure 3. Electricity consumption in electric-heated homes in Texas in 2028 in the high adoption, medium energy savings scenario for smart thermostats compared to the baseline scenario

For the remainder of the figures, we show only the first 12 hours of the day since this is where our two curves differ.

Assumptions about Energy Savings

How much energy smart thermostats save is a matter of some debate, with estimates in the literature ranging from 0 to 50%. We discuss the estimates we reviewed in Appendix A. The highest savings numbers likely come from models that use a constant setpoint as a baseline, which may not always be the case in the real world. In addition, field studies generally report lower savings than engineering models because of real-world usage patterns. Noting the uncertainty caused by human behavior, we consider three reasonable scenarios (3%, 8%, and 15%), referred to by low, medium, and high energy savings. The impact on electric heating is shown in figure 4 for the high adoption case. Plots for the low adoption scenario are in Appendix B.

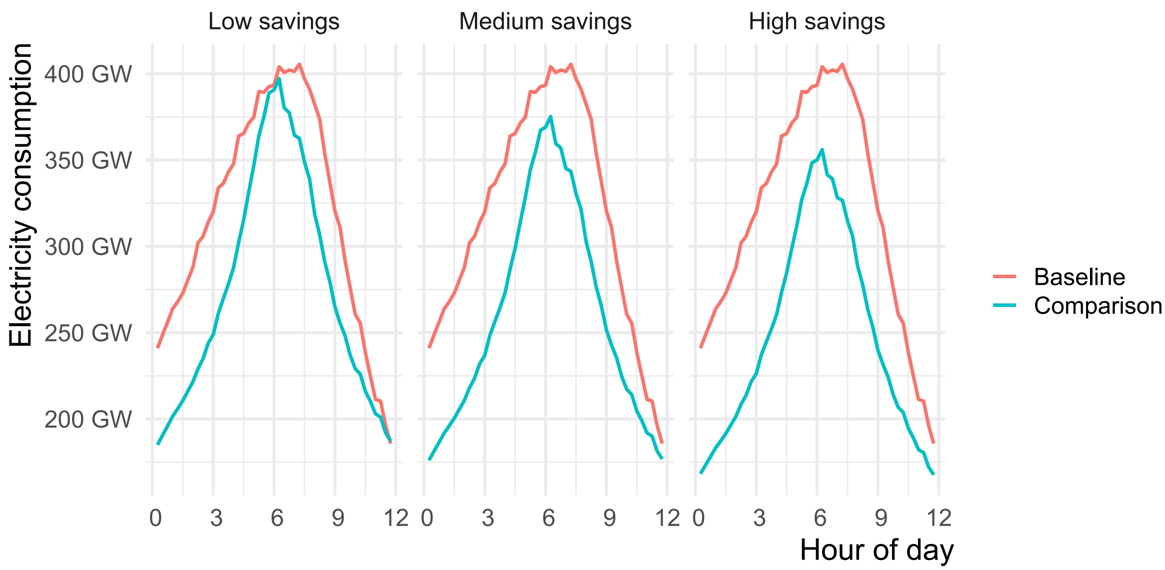

Figure 4. Electricity consumption in electric-heated homes in Texas in 2028 in the high adoption scenario for smart thermostats compared to the baseline scenario, with low, medium, and high energy savings assumed

The assumption of how much thermostats reduce energy use in a home dramatically impacts the total electricity consumption in our scenarios; the decrease in overall electricity consumption in the high savings scenario is nearly double that for the low savings scenario. In addition, peak electricity consumption is only slightly reduced in the low savings scenario but is reduced by about 50 GW in the high savings scenario, enough to power 100 million washing machines (Benningfield and Allen 2022). The plots for the low adoption case (not pictured) follow a similar pattern: the energy savings assumption has more of an impact than the adoption. The total annual electricity savings for electric heating in Texas in 2028 are summarized in table 2, with electricity savings ranging from 1.3–3.4 terawatt-hours, or 5.8–15.4% of the electricity needed for electric heating in the baseline scenario. Note the table contains some apparent discrepancies due to rounding.

Table 2. Electricity reductions from smart thermostats

Scenario		Electricity reduction (TWh/%)		Equivalent number of U.S. homes' annual electricity use[22]
High adoption	High savings	3.4	15.4%	320,000
	Medium savings	2.8	12.7%	260,000
	Low savings	2.1	9.6%	200,000
Low adoption	High savings	2.1	9.3%	190,000
	Medium savings	1.7	7.7%	160,000
	Low savings	1.3	5.8%	120,000

Emissions

Emissions produced in making electricity can vary even by the minute depending on the mix of resources used for generation (though data are rarely available at this granularity), which is one reason the timing or load profile of electricity consumption is important. We have used projected emissions factors for a given hour of the day averaged over the year 2028. In Texas, solar generation means emissions are often lower during the day than at night. For example, the emissions rate at 5 a.m. averages 372 kg CO2e/MWh, and at 8 a.m. averages 335 kg CO2e/MWh. The highest emissions occur 4–9 p.m. as evening activities take place and solar generation goes offline (NREL 2023a).

The emissions profiles for all adoption and energy savings scenarios are plotted in figure 5.

[22] Based on the average electricity use reported by EIA for U.S. residential customers, 10,632 kWh per year (EIA 2022c).

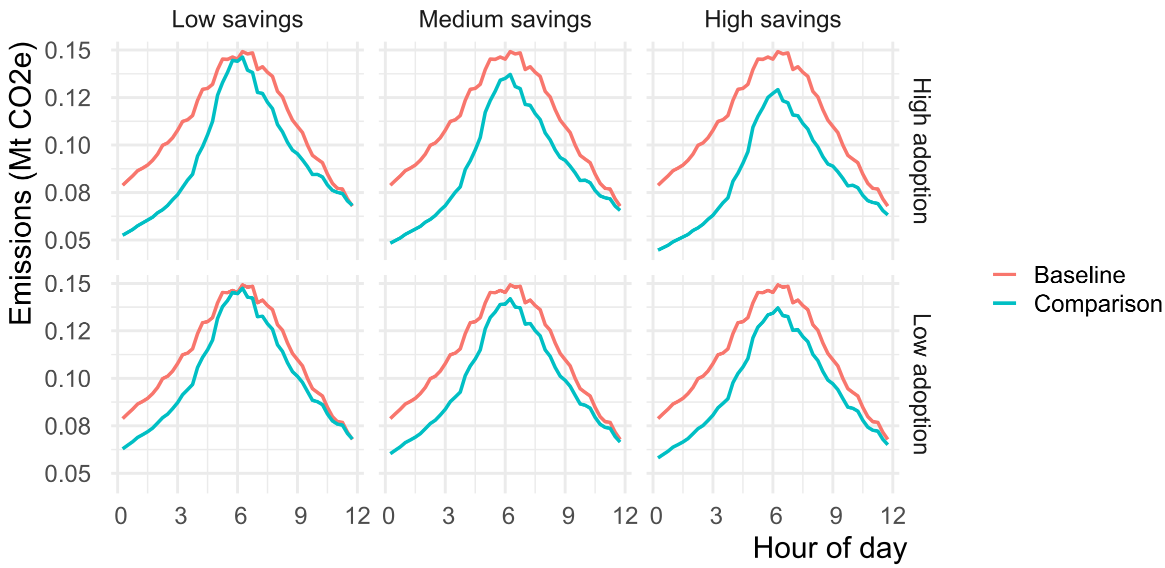

Figure 5. Emissions for all adoption and energy savings scenarios compared to the baseline scenario

Because of higher-emitting electricity generation during the night, smart thermostats have a significant impact, with noticeably lower emissions in the high adoption scenarios. The total emissions reductions for 2028 corresponding to the smart thermostat handprints in our model are given in table 3. In the high adoption, high energy savings scenario, smart thermostats in electric-heated Texas homes reduce emissions by 1.35 million metric tons in 2028. For comparison, the emissions from transportation in Washington, DC, in 2020 were 1.29 million metric tons (District of Columbia DOEE 2023). The emissions reduction was about a third as much in the low adoption, low savings scenario, with other scenarios falling in between. The high adoption scenario has approximately 165% more emissions reductions than the low adoption scenario (for equivalent savings) while the high savings reductions scenarios show approximately 180% more reductions than the low savings.

Table 3. Emissions reductions from smart thermostats

Scenario		Emissions reduction (handprint of smart thermostat) (Mt/%)		Equivalent number of U.S. homes' electricity emissions[23]
High adoption	High savings	1.35	17.0%	263,000
	Medium savings	1.12	14.1%	218,000
	Low savings	0.85	10.8%	165,000
Low adoption	High savings	0.82	10.3%	160,000
	Medium savings	0.68	8.6%	132,000
	Low savings	0.52	6.5%	101,000

ATTRIBUTING HANDPRINT SAVINGS

Having calculated possible emissions reductions for electric homes in Texas in 2028 from using more smart thermostats, we turn to the question of how and to whom to attribute or allocate these reductions. Figure 6 shows a simplified illustration for actors involved in the function of a home energy management system, which includes a smart thermostat.

[23] Using the EPA's Greenhouse Gas Equivalencies Calculator (EPA 2023).

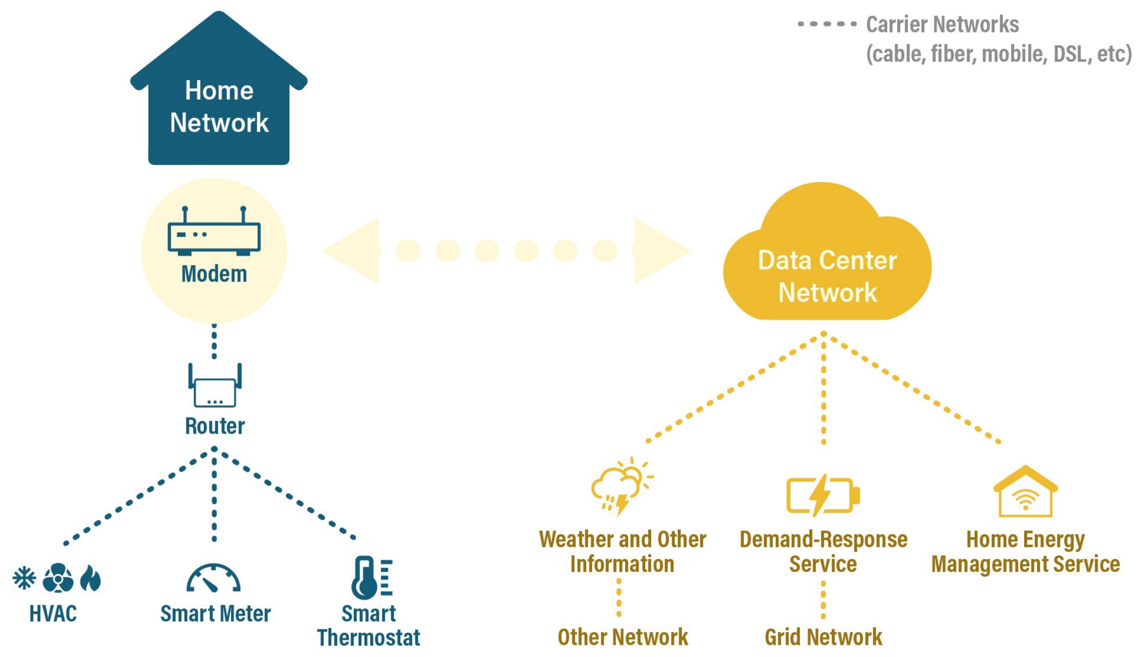

Figure 6. Contributors to home energy management system handprint

We limit our attention to the five major components illustrated in figure 6:

1. smart thermostat hardware
2. smart thermostat service (such as eco+) and utility demand response service via network
3. in-home network communications equipment (modem, router)
4. Internet service
5. data center that houses and supports cloud services and the extended networks that provide additional data, such as weather and grid emissions.

These components could be broken down further; for instance, data centers and other facilities have their own communication network services and equipment. We consider our approach a first-order approximation, with higher-order approximations possible in the future.

In the introduction, we considered five different ways to attribute handprints. Method 1 in the introduction, equal attribution, acknowledges the contributions of all players but avoids the complexity and need for additional data that some other approaches require. Using this method, we allocate the total handprint by dividing the emissions by 5, the number of major components, giving a range of 0.1–0.27metric tons of greenhouse gas reductions in Texas electric homes in 2028 to each major contributor. The results are summarized in table 4.

Method 1 can be modified to reflect that among the five major components of the smart thermostat solution—the smart thermostat hardware, the smart thermostat software/service, an in-home network, Internet service, and a data center—the last three all contain and rely on network infrastructure and solutions, namely an onsite network, internet infrastructure, and a data center network. These could all be considered part of the network contribution; therefore, we consider allocation among only three players as well as five.

Method 2, attributing by costs, would allocate more credit to networks, since constructing and operating extensive wide-area network infrastructure is likely more capital intensive than other parts of the smart thermostat solutions. While acknowledging the contributions from other players to these three components, we use 60% (3/5) for the network's contribution as a proxy for more detailed cost data.

Method 3, accepting double counting, attributes the full emissions reduction of implementing the solution to each party involved. Although the downside of this potentially less controversial solution is double counting (or quintuple counting in our example), it can be useful if the goal is to compare different technological solutions and prioritize development, investment, or deployment based on the potential handprints of these solutions. As long as carbon footprints and handprints are calculated and treated separately, double counting is less problematic.

Method 4, allocating all avoided emissions to the solution's most obvious contributor, can be interpreted several ways here. The network could arguably be considered the most obvious contributor, since three of five components could be considered network infrastructure and even the smart thermostat/demand response service rely heavily on network communication. One could counter that the smart thermostat hardware/software should get full credit since networks provide neutral infrastructure through which other, more fundamental solutions can be deployed. Ultimately, the consensus-based attribution of method 5 may offer a less controversial solution if all major players have an interest in jointly developing an attribution protocol. Method 4 allocates the total emissions reduction to networks (and is the same as allocating with double counting for networks, but not for other players). Method 5 is not shown in table 4.

Table 4. Handprint results with several attribution methods

Scenario		Total emissions reduction (overall handprint) (Mt)	Equal allocation among 5 (Mt)	Equal allocation among 3 (Mt)	Allocation by cost (60% to networks) (Mt)	Allocation with double counting (Mt)
High adoption	High savings	1.35	0.27	0.45	0.81	1.35
	Medium savings	1.12	0.22	0.37	0.67	1.12
	Low savings	0.85	0.17	0.28	0.51	0.85
Low adoption	High savings	0.82	0.16	0.27	0.49	0.82
	Medium savings	0.68	0.14	0.23	0.41	0.68
	Low savings	0.52	0.10	0.17	0.31	0.52

As more companies work to increase their beneficial handprints, more businesses will give to the environment more than they take. As handprints surpass footprints, decarbonization changes from a reductive process to one of healing.

LOAD SYNCHRONIZATION – A WARNING AND OPPORTUNITY

Lee and Zhang's analysis of heating in New York state found that while smart thermostats save energy overall, they synchronize loads and create a nearly 50% higher morning peak relative to the mean for homes using smart thermostats, as compared to the baseline peak relative to its mean (Lee and Zhang 2022). In other words, smart thermostats are optimized locally but not for the whole system. Networks could facilitate coordination to avoid this potential burden (through price signals and transactive controls, for example).

We evaluate the impact of several load shifting scenarios on peak emissions (i.e., assuming the electricity consumed is the same, only changing the timing), without attempting to evaluate the specific mechanisms for achieving these shifts. The shifts apply to homes using smart thermostats in our analysis and are illustrated in figure 7.

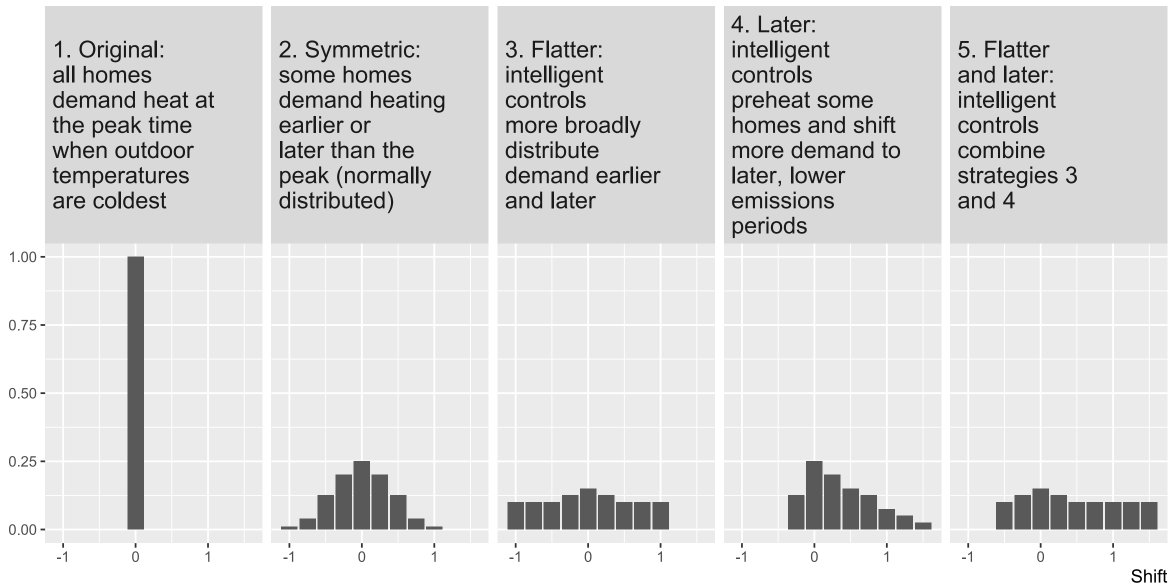

Figure 7. Load shifting distributions

We applied these shifts only between midnight and 12 p.m. since minimizing emissions in the afternoon and evening would involve shifting load earlier in the day rather than later. The impact on the overall electricity load between 3 a.m. and 10 a.m. is shown in figure 8 for the high adoption, medium savings scenario and is similar in other adoption and savings scenarios.

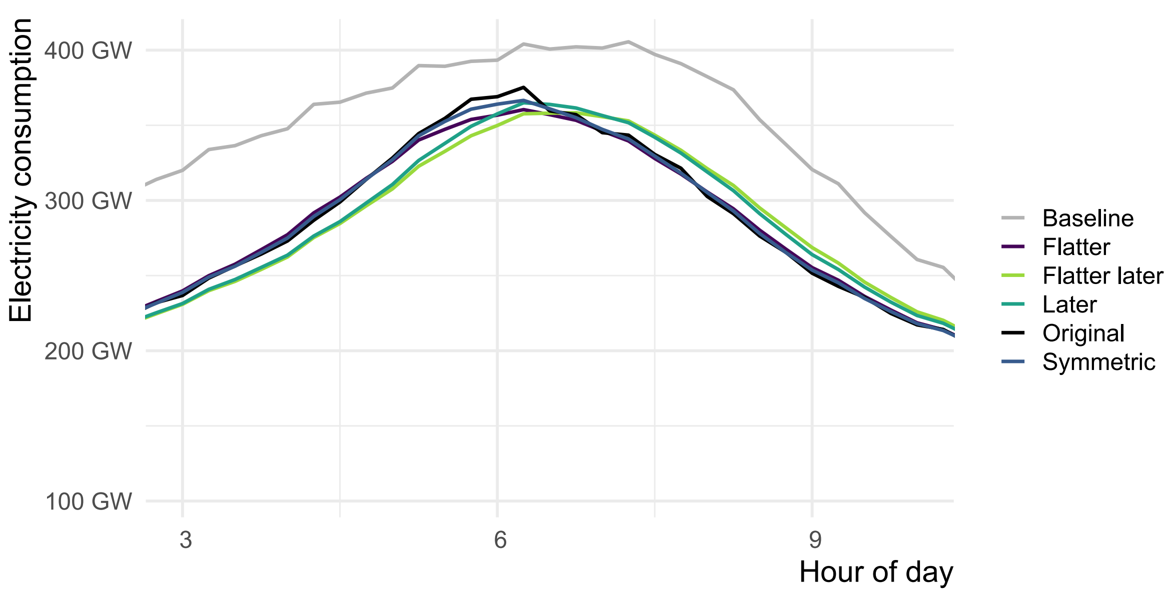

Figure 8. Impact of load shift on electricity consumption between 3 a.m. and 10 a.m. in the high adoption, medium savings scenario for smart thermostats. The baseline curve is shown in gray and the unshifted, (original) high adoption, medium savings scenario for smart thermostats is shown in black. This is the equivalent of figure 3.

Peak emissions are reduced about 2.5–5% from the original smart thermostat scenario (itself a reduction of about 6–15% from baseline), depending on the scenario and shifting strategy, illustrated in figure 9 for the high adoption, medium savings scenario.

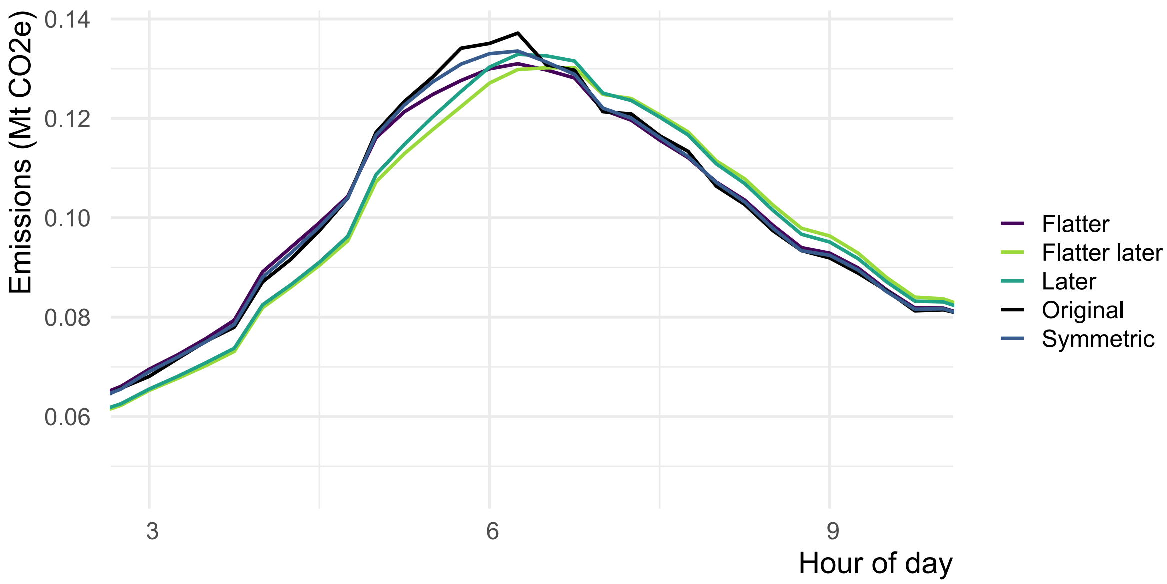

Figure 9. Impact of load shift on emissions between 3 a.m. and 10 a.m in the high adoption, medium savings scenario for smart thermostats. The baseline curve is not shown.

Generally, the impact of shifting later is more significant than the impact of making the distribution flatter. In all cases, emissions reductions over the course of a day were relatively small, less than 1%. Yet the distributions that involved shifting demand later reduced emissions by 26–58 ktons CO_2e, which equates to removing roughly 6,000–13,000 gas-powered vehicles from the road for a year, or replacing 1–2 million incandescent lightbulbs with LEDs (EPA 2023). We incorporate the average emissions reduction into our handprint calculation in table 5. For simplicity, we present only equal attribution among five players; but as we discussed in the previous section, we could attribute 20%, 60%, or 100% of the handprint to networks using different methodologies.

Table 5. Handprint results incorporating load shift

Scenario		Total emissions reduction (overall handprint) (Mt)	Equal attribution among 5 (Mt)	Equivalent number of gas-powered vehicles' emissions
High adoption	High savings	1.37	0.27	58,000
	Medium savings	1.14	0.23	50,000
	Low savings	0.88	0.18	39,000
Low adoption	High savings	0.83	0.17	37,000
	Medium savings	0.69	0.14	30,000
	Low savings	0.53	0.11	24,000

Thus, in a single limited application for electric heating in Texas, networks could avoid emissions equivalent to those of up to 58,000 gas-powered vehicles in one year (EPA 2023)

Discussion

As elaborated in the literature review, our handprint is subject to many forms of uncertainty. For smart thermostats, most estimates of energy savings are 25–30% on the high end, and 0–5% on the low end (Urban, Roth, and Harbor 2016; Lee and Zhang 2022; Brandon et al. 2022; Lusson 2020; Nest Labs 2015). Field studies have generally found lower savings than estimates based on engineering models. A major reason for the disparity is the way users interact with their thermostats. Users of smart thermostats may not program their thermostats initially or may frequently override the behavior of the thermostat designed to save energy. Just deploying technology is usually not enough to achieve energy savings.

Human behavior can also impact the baseline. Before getting a smart thermostat, homeowners may have been conscientious in turning thermostats up or down when leaving the house or at night, so smart thermostats do not provide much additional savings. The ease of adjusting temperatures could even lead to increased energy use, for example, if the homeowner used to adjust the thermostat manually after arriving at home but subsequently uses the smart thermostat to have the house reach the desired temperature at the time they expect to arrive home. Usage patterns (and adoption) may also vary with demographics; for example, lower-income people may be more likely to be at home during the day (BECC 2022).

Precise timing of these actions across homes can have a major impact on grid emissions. Our calculation uses yearly sums of energy use and average emissions for times of day, but this obscures significant variation: average emissions rates in Texas could be 200 kg CO2e/MWh one day at 3 a.m. and 500 kg CO2e/MWh the next, with marginal or peak emissions rates differing even more (NREL 2023a). ACEEE research has found that such differences average out in many places (Specian et al. 2022), but the value of smart technologies in adapting to these differences is hard to capture without more granular data. Various studies have investigated the impact of smart thermostats on peak demand and found them to be effective; for example, a study of Nest thermostats found users reduced energy use during a demand response event by 55% (Nest Labs 2014). Recently, California was able to reduce demand by 1.5 GW and avoid rolling blackouts on a day with a record-setting 52 GW of demand (Balaraman 2022). The benefits of demand flexibility in demand response events such as this are noteworthy, but we have not attempted to quantify responses to utility signals here, although they clearly require network communication. While we have attempted to quantify the influence of smart thermostats on more routine daily peak demand (about 6–20% reductions from baseline), research at National Labs has suggested peak demand reductions of 25–34% are possible when including other end uses besides heating, such as hot water (Brambley 2021; Buckberry et al. 2020).

In our calculation, levels of adoption are another significant, though perhaps secondary, uncertainty. A further, related source of uncertainty is rebound effects associated with large-scale adoption. The load synchronization observed by Lee and Zhang,[24] if not a true rebound, is a relevant example of the negative side effects that can occur with large-scale adoption of a technology. Although the peak emissions in our modeled scenarios were never larger than those in the baseline scenario, the peak is relatively larger than the average demand, nearly reaching the peak emissions of the baseline scenario if low savings are assumed. While seeking evidence of beneficial network effects (where 10 homes adopting smart thermostats is more beneficial than 10 times the benefit from 1 home), we found evidence that such network effects do not occur without active intervention. This illustrates the need to consider what could happen at a system level when smart technologies are widely adopted.

[24] Load synchronization has also been observed in timers for electric vehicle charging (Powell et al. 2022).

RECOMMENDATIONS FOR THE ICT INDUSTRY

PRIORITIZE USABILITY

Because human behavior has such significant effects on the impact of ICT solutions, companies should work to address the usability of their products. Making sure products and services work as intended will help realize the huge potential ICT solutions can have in reducing greenhouse gas emissions. Field studies and pilot projects are needed to assess how users interact with solutions in real-world contexts, including how users from diverse backgrounds may approach solutions differently. Field studies can also provide data to more robustly quantify the impact of ICT solutions.

MANAGE DISRUPTION, DO NOT REJECT IT

In conducting field studies and developing products, companies should try to assess possible rebound effects or other unintended consequences when solutions are adopted at large scale. The possibility of negative side effects should not deter companies from using the concept of handprint to influence business decisions. Companies should work with policymakers and other stakeholders to reap the benefits of potential disruptions while minimizing detrimental effects.

CONSIDER MOTIVATIONS FOR ADOPTING SOLUTIONS

Experts interviewed in researching this report agreed that both businesses and individuals are likely to adopt ICT solutions for reasons other than energy or emissions, such as convenience, even when emissions are nominally a priority. Relatedly, fears about privacy and cybersecurity risks are a real impediment to the adoption of ICT solutions, both among businesses and individual consumers. Some communities may be justifiably skeptical or distrustful of "tech" such as smart thermostats, for instance, because they have seen benefits go to the utility instead of their own community (BECC 2022). While the zeitgeist around cybersecurity may or may not match the (real) threats to cybersecurity and data privacy, companies must acknowledge customers' perceptions and motivations to increase the uptake of solutions.

INVEST IN BENEFICIAL SOLUTIONS

Most importantly, companies should continue working to address emissions not just through reducing footprints, but also by increasing focus on beneficial solutions in business decisions such as R&D priorities. Along with policy mechanisms such as carbon pricing, carbon handprints can help make the case to investors, customers, and others about the importance of prioritizing products and services with emissions benefits. Increasing the practice of carbon handprinting will also improve the available data and methods, leading to a virtuous cycle that continues to improve justification and better target solutions.

Conclusions

ICT solutions could reduce carbon emissions in wide-ranging applications across all economic sectors. While real-world usage patterns, levels of technology adoption, and rebound effects are important sources of uncertainty in assessing the potential impact of ICT, the literature generally supports the idea that these solutions can reduce carbon emissions.

Networks, including local networks, system level networks, and networks that link different parts of the economy, are key to allowing coordination and intelligent data processing to achieve system-level efficiency (as opposed to device-level efficiency) and target energy usage to where it is truly needed in buildings, industrial processes, transportation, or even entire economic sectors. Integrating systems may include substantial benefits beyond energy and emissions, such as user convenience, flexibility, and customization. These benefits require further research to be characterized and quantified. While integrating devices and systems could lead to beneficial network effects, these benefits are unlikely to occur on their own, without explicit policies or incentives.

Energy and emissions reductions enabled by ICT vary considerably by application and depend on multiple interconnected elements. Handprints represent a way to evaluate the beneficial or detrimental impact of products, services, and companies beyond what is encompassed in the company's footprint (Scopes 1, 2, and 3 emissions) and are essential for understanding the value (or cost) products and services provide to society. While several methods exist to evaluate handprints and the idea is gaining currency in the ESG investing community (often under other terms such as "Scope 4 emissions"), it remains largely theoretical. The existing methodologies broadly agree that handprints should be considered complementary to footprints rather than a substitute. A handprint also should not be considered to "cancel out" a footprint; rather, the handprint should be reported separately alongside a footprint. Companies should avoid focusing exclusively on products or services with a positive impact when computing handprints.

The important question of how to fairly allocate the handprint of a beneficial product or service to actors along the value chain remains largely unaddressed for various applications. Further adoption of handprints and data sharing will facilitate the development of improved methodologies and verification, both for attribution and for handprints in general.

While uncertainties remain about the impact of ICT solutions on emissions, the potential benefits are enormous. With proper policies and consideration, including use of carbon handprints, we can achieve the potential of ICT to help us realize a sustainable future.

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Appendix A. Methodology

Here we provide further details about our methodology. Recall that the aims for our analysis are twofold: first, to provide an illustrative example of a handprint calculation for communication networks, and second, to demonstrate the need to account for potential side effects of adopting solutions, as well as the ways ICT can help avoid these detrimental side effects. We have opted to use a hypothetical scenario for smart thermostats in Texas in 2028 to illustrate these points.

The year 2028 was chosen both because near-term actions are increasingly important for addressing climate change and because various market projections were available to estimate how many smart thermostats will be adopted in the next five or so years, ranging between 15–30% compound annual growth rates (CAGR).

EMISSIONS CALCULATION METHODOLOGY

We compare two scenarios. In the baseline scenario, we assume the current mix of manual, programmable, and smart thermostats applies in 2028, while in the alternative scenario, we assume higher rates of smart thermostat adoption. Although smart thermostats may be more complex and resource intensive to produce, we assume that the difference in embodied emissions between smart thermostats and programmable or manual thermostats is de minimis. Thus, for our handprint we only examine the difference in emissions from controlling heating equipment with the different thermostats.

We limit our attention to electric heating, which is how most Texas homes are heated (58% per EIA's 2020 Residential Energy Consumption Survey (RECS) (EIA 2023a), most of which use electric resistance[25]), and because our second aim (assessing potential side effects) pertains to the impact on grid emissions. We assume that the proportion of homes that use electric heating will remain the same in Texas in 2028.

BASELINE ELECTRICITY AND EMISSIONS

We use energy load profile data from NREL's ResStock, a statistical model of the U.S. housing stock (NREL 2023a). The energy load profiles are modeled energy use, but calibrated with real data; in our case, we use load curves calibrated to 2018. We do not adjust these curves for 2028 because according to EIA's Annual Energy Outlook 2022, residential energy consumption is expected to remain relatively flat through 2030 (EIA 2022a). ResStock's energy load profiles are available at the state level only (as load profiles can vary dramatically by region in magnitude, though the shape is often similar) (Wilson et

[25] Of Texas homes heated with electricity in 2020, 36% used central heat pumps and about 1% used ductless mini-split heat pumps; 41% used a central electric furnace, with almost all the remainder using built-in or portable electric resistance units.

al. 2022). We chose Texas since the Texas grid is somewhat isolated, both physically and in its regulatory structure. Moreover, Texas utilities have actively promoted smart thermostats, leading to somewhat higher adoption than the U.S. average. Furthermore, National Labs have cleaned ecobee data for California, New York, Texas, and Illinois, facilitating possible follow-up analysis (Building Bechmark Datasets n.d.). The ecobee dataset is described further in Appendix C.

Emissions data come from Cambium, an NREL model which projects grid emissions for every hour up to 2050 (NREL 2023a). We used time-of-day (tod) emissions factors for the "mid-case" scenario in 2028, which are the emissions rates at 1 a.m., 2 a.m., and so on, averaged over the entire year. For the baseline heating curve, we use the average CO2e emissions rate for loads, and use the long-term marginal CO2e emissions rate to calculate differences in emissions from the baseline (positive or negative).

REDUCED ENERGY USE FROM SMART THERMOSTATS

Using RECS 2020 microdata and weighting factors (EIA 2023b), we calculated that 11.9% of electrically heated homes in Texas had smart thermostats in 2020. S&P Global reported that 19.6 million U.S. homes had installed smart thermostats 2021 (Weinschenk 2022); we scaled the 2020 percentage of Texas electric homes with smart thermostats proportionally, assuming that 12.8 million U.S. homes had smart thermostats in 2020 (using RECS microdata) (EIA 2023b). We then applied compound annual growth rates for smart thermostat adoption up to 2028 (15% and 30% for the two scenarios) based on several market reports (Fortune Business Insights 2022, Straits Research 2022, Weinschenk 2022). This gave us 42.1% and 69.5% of electric-heated Texas homes using smart thermostats in 2028 in the low and high adoption scenarios, respectively.

We adopted a load profile shape for homes using smart thermostats from an analysis of ecobee data by Lee and Zhang (2022) for the morning peak (i.e., the hours before 12 p.m.), keeping the baseline electricity demand for the remainder of the day. We also conducted the analysis using the full 24-hour curve from Lee and Zhang (Appendix B). The Lee and Zhang curve is aggregated from homes using gas furnaces in New York state, but despite many potential differences between gas furnaces in New York and electric heating in Texas,[26] research from NREL suggests the shape (not the magnitude) of the load curve will be similar for electric heating in Texas (Wilson et al. 2022).

We multiply the normalized curve in Lee and Zhang by the mean of our baseline curve from ResStock and one of three different energy savings factors for smart thermostats (discussed

[26] For example, price incentives may include time-of-day pricing for electricity but not for gas; heating technologies differ; for example, heat pumps are more common in Texas than New York; heating techniques are different among different technologies such as radiant heating, heat pumps, and forced air furnaces.

below), then scale this by the proportion of homes using smart thermostats. The remaining proportion of homes is assumed to follow the baseline curve from ResStock.

As with other ICT products, estimates of savings from smart thermostats differ substantially. Some research suggests that compared to a constant thermostat setpoint, savings over 50% are possible (Oh 2017). Ecobee says their products provide cost savings "up to 26%" on heating and cooling (ecobee 2022), compared to a constant setpoint of 72°F. Constant thermostat setpoints are a common point of comparison for smart thermostats but may not be the best baseline. Nest studies found that Nest users had 20% savings compared to a constant setpoint, but that in practice, most Nest users had a baseline (before acquiring a Nest thermostat) of 8–10% more efficient thermostat settings than a constant setpoint (e.g., by setting back the temperature during the day and/or at night, or by using lower setpoints for heating). Nest analysis has found their thermostats save 10–12% of heating energy and 15% of cooling energy on average (Nest Labs 2015). Past ACEEE research has reported 6–10% savings (King 2018) and some recent publications suggest 5–8% savings (Lee and Zhang 2022) or even no benefit (Brandon et al. 2022; Lusson 2020). Other field studies continue to suggest there is a benefit. Urban, Roth, and Harbor (2016) conclude that the potential savings from smart thermostats are 15% from assessing a variety of field studies (including the Nest studies) and incorporating a small boost from expected improvements in technology. Noting the uncertainty caused by human behavior, we consider three reasonable scenarios: 3%, 8%, and 15% (referred to by low, medium, and high energy savings, respectively).

Appendix B. 24-Hour Analysis

Originally we conducted our smart thermostat analysis using the Lee and Zhang curve for the full 24-hour period. However, while the impact of smart thermostats in reducing demand is clear in the morning, the baseline curve is surprisingly lower than the comparison scenario in the afternoon, as shown in figure B-1 for the high adoption, medium savings scenario for smart thermostats.

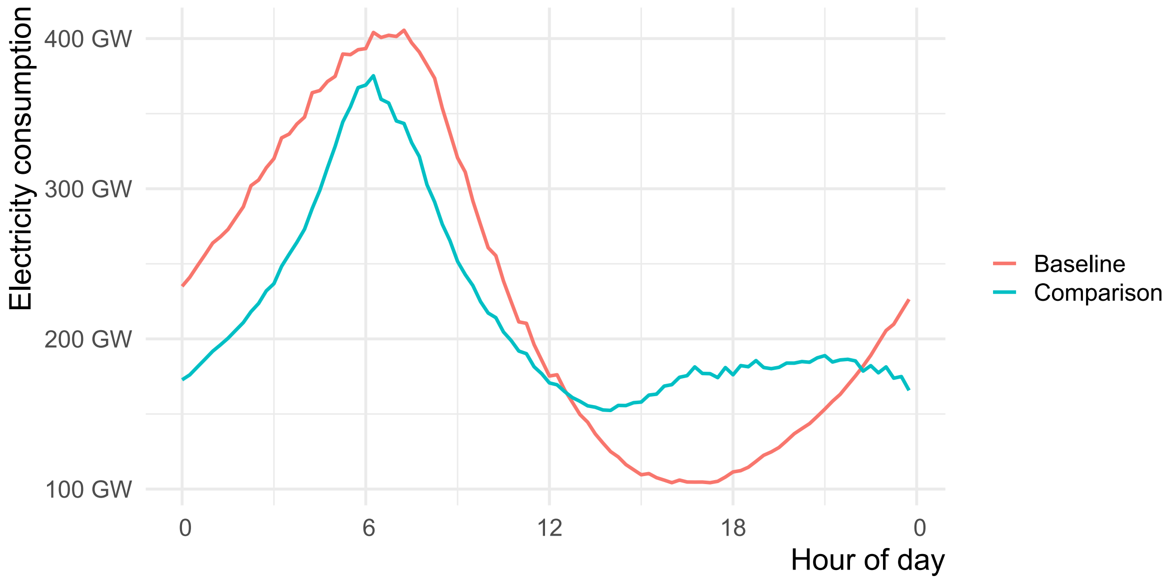

Figure B-1. Electricity consumption in electric-heated homes in Texas in 2028 in the high adoption, medium energy savings scenario with 24-hour comparison

We suspect this is at least partially an underestimate of savings from using smart thermostats arising from our methods and data sources. Firstly, ResStock and the related end-use load profiles are complex models of housing stock that include many different types of equipment and assumptions for homes. Some homes in ResStock use thermostat setbacks, where the heating temperature set on the thermostat is reduced for some time, such as at night or during the workday, and some homes do not have such a setback. Rather than applying the smart thermostat savings specifically to homes that do not have such setbacks, we have applied them to the aggregate curve, and thus may be saving relatively less than expected. Furthermore, homes with setbacks vary in scheduling by as much as 10 hours, which may be unrealistic (e.g., while the typical daytime setback may begin at 9 a.m. and end at 5 p.m., some homes in ResStock have setbacks that begin at 4 a.m. and end at 12 p.m. or that begin at 2 p.m. and end at 10 p.m.). The effect of this could overly smooth the curve and make it less peaky than it should be. Homes with setbacks in ResStock have a heating load profile more similar to our smart thermostat curve in shape (note this could be because ecobee data were used as a consistency check for the load curves). The overall shape of the baseline curve is dominated by homes with no thermostat setback. Finally, while the overall load curves have been calibrated to utility datasets, it is possible the ResStock end-use load profile curve has slightly less of an evening peak than it should. See the ResStock end-use load profile documentation for further details (Wilson et al. 2022).

While these factors may offer a partial explanation, given the high likelihood of distracting readers from the focus of our report (as evidenced by our internal review), we elected to use an analysis assuming usage is the same in the later 12 hours of the day for the main body of the report and retain the 24-hour curve in the appendix. Other data sources, described in Appendix C, may provide a better source for comparison, but pursuing these was beyond the scope of this report.

The remainder of this appendix parallels the main text and contains all equivalent figures.

Energy Savings and Adoption

The impact of assumptions about energy savings on electricity for heating is shown in figure B-2a for the high adoption scenario and for all scenarios in figure B-2b. Note that the first 12 hours of the day are the same shape as those in the main analysis.

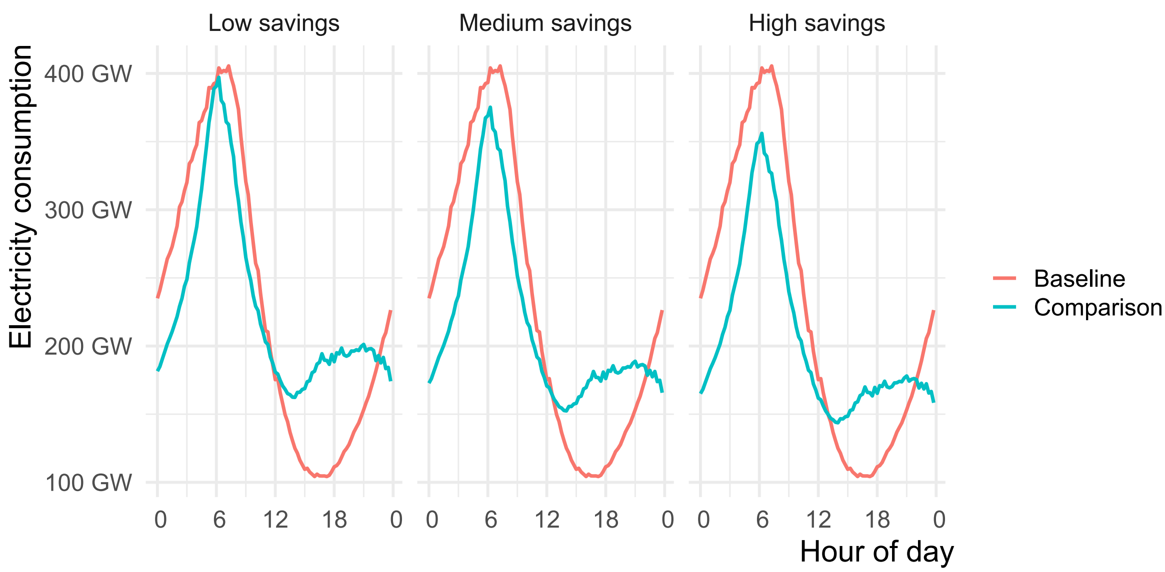

Figure B2a. Electricity consumption in electric-heated homes in Texas in 2028, high adoption 24-hour scenario with low, medium, and high energy savings

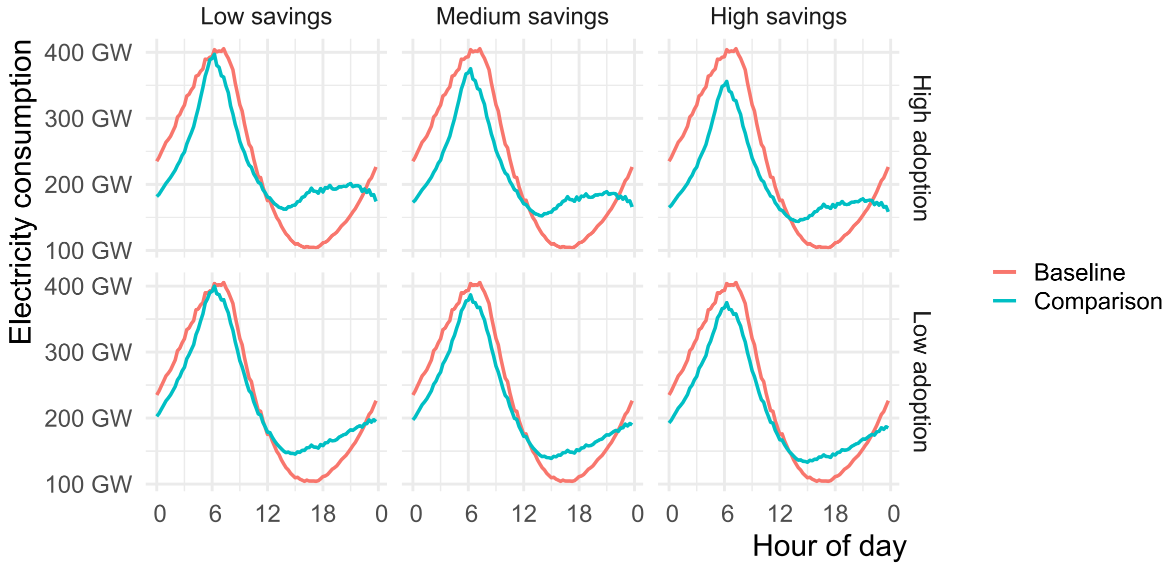

Figure B-2b. Electricity consumption in electric-heated homes in Texas in 2028 across all 24-hour scenarios for smart thermostats

The assumption of how much smart thermostats reduce energy use in a home has a dramatic impact on the projected electricity consumption: high savings scenarios show a significant decrease in overall electricity consumption, whereas with low savings, modestly lower electricity demand in the morning is essentially cancelled out by the evening peak (though again, this may underestimate the savings). The plots for the high and low adoption cases follow a similar pattern; the energy savings assumption has more of an impact than adoption rates. The total annual electricity savings for electric heating in Texas are summarized in table B-1, with reductions in electricity ranging from 0.01–2.30 terawatt-hours, or 0.0–10.5% of the electricity needed for electric heating in the baseline scenario. Note there are some apparent discrepancies due to rounding.

Table B-1. Electricity reductions in 2028 from smart thermostats (24-hour scenarios)

Scenario		Electricity reduction (TWh/%)		Equivalent number of U.S. homes' annual electricity use[27]
High adoption	High savings	2.30	10.5%	220,000
	Medium savings	1.23	5.6%	120,000
	Low savings	0.01	0.1%	1,000
Low adoption	High savings	1.40	6.3%	130,000
	Medium savings	0.75	3.4%	70,000
	Low savings	0.01	0.0%	0

Emissions

The emissions profiles for all adoption and energy savings scenarios are plotted in figure B-3. All show the same general pattern of lowered emissions in the morning and at night, and somewhat higher emissions in the afternoon and evening corresponding to the increased electricity use for smart thermostat homes relative to the baseline. As in the case of electricity above, these changes largely offset each other when we assume energy savings are low (though to a lesser extent than with electricity due to the reduction in high emissions periods), and result in significantly lower emissions when we assume savings are high.

[27] Based on the average electricity use reported by EIA for U.S. residential customers, 10,632 kWh per year (EIA 2022c).

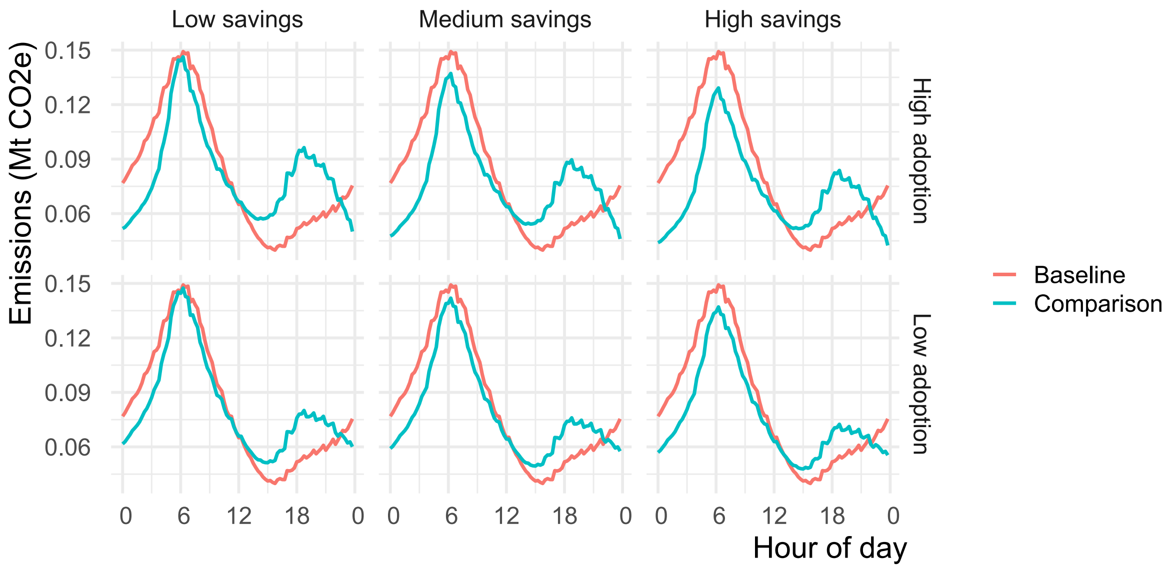

Figure B-3. Emissions for all 24-hour adoption and energy savings scenarios

The total emissions reductions for 2028 corresponding to the smart thermostat handprints in our model are given in table B-2. In the high adoption, high energy savings scenario, smart thermostats reduce emissions by 0.92 million metric tons. For comparison, the emissions from transportation in Washington, DC in 2020 were 1.3 million metric tons (District of Columbia DOEE 2023). There was no emissions reduction in the low adoption, low savings scenario, with other scenarios falling in between. The high adoption scenario has emissions reductions approximately 160% as much as low adoption, while the high savings scenarios are approximately 180% of those with medium savings, and much larger than those with low savings.

Table B-2. Emissions reductions from smart thermostats (24-hour scenarios)

Scenario		Emissions reduction (handprint of smart thermostat) (Mt/%)		Equivalent number of U.S. homes' electricity emissions[28]
High adoption	High savings	0.92	11.6%	179,000
	Medium savings	0.49	6.2%	95,000
	Low savings	0.01	0.1%	2,000
Low adoption	High savings	0.56	7.0%	109,000
	Medium savings	0.30	3.8%	58,000
	Low savings	0.00	0.0%	0

ATTRIBUTING HANDPRINT SAVINGS

We allocate the smart thermostat handprint as described in the main text, with results summarized in table B-3.

[28]Using EPA's Greenhous Gas Equivalencies calculator (EPA 2023).

Table B-3. Network handprint results (24-hour scenarios)

Scenario		Total emissions reduction (overall handprint) (Mt)	Equal allocation among 5 (Mt)	Equal allocation among 3 (Mt)	Allocation by cost (60% to networks) (Mt)	Allocation with double counting (Mt)
High adoption	High savings	0.92	0.18	0.31	0.55	0.92
	Medium savings	0.49	0.10	0.16	0.30	0.49
	Low savings	0.01	0.00	0.00	0.00	0.01
Low adoption	High savings	0.56	0.11	0.19	0.33	0.56
	Medium savings	0.30	0.06	0.10	0.18	0.30
	Low savings	0.00	0.00	0.00	0.00	0.00

LOAD SYNCHRONIZATION

Our load shifting analysis is essentially the same since, as in the main analysis, we applied shifts in the increased smart thermostat scenarios only in the first half of the day, between midnight and 12 p.m. The emissions reductions for the 24-hour analysis including the contribution of load shifting are summarized in table B-4.

Table B-4. Network handprint results incorporating load shift for 24-hour analysis

Scenario		Total emissions reduction (overall handprint) (Mt)	Equal allocation among 5 (Mt)	Equivalent number of gas-powered vehicles' emissions
High adoption	High savings	0.94	0.19	41,000
	Medium savings	0.52	0.10	22,000
	Low savings	0.03	0.01	2,000
Low adoption	High savings	0.57	0.11	24,000
	Medium savings	0.31	0.06	13,000
	Low savings	0.02	0.00	0

Thus, in a single, limited application for electric heating in Texas, networks could avoid emissions up to those of about 41,000 gas-powered vehicles in one year (EPA 2023).

Appendix C. Potential Data Sources

In researching this report, we asked a variety of experts for applications of ICT that we could use to calculate a network handprint. While there are many potential examples in transportation, utilities, and industry, the available data is limited, and particularly in industry, include many bespoke applications that are difficult to generalize. One of the most promising sources of data our experts mentioned is ecobee's Donate Your Data program (ecobee 2023). While we decided not to use this dataset for our analysis, we include a description here to highlight its potential.

Ecobee's dataset consists of thousands of files for individual homes, organized by month and year. These files contain information about the status of various temperature, humidity, and motion sensors (not all of which may be present in a home), as well as thermostat settings, reported in five-minute intervals. The data also include user-reported information on the home and its occupants, leading to some data quality issues (e.g., location reported as "United States" versus "U.S."). Aside from the user-reported metadata, the data are likely of high quality since it is automatically reported by the thermostat, but there can be significant data gaps for individual homes: One file we consulted included only outside temperatures; all fields about the home's heating and cooling systems were blank. Lawrence Berkeley National Laboratory (LBNL) has produced a curated set of 1,000 U.S. homes with heating and cooling data (including a small percentage of imputed values) for the entire year 2017. These homes are all in four states: California, Texas, Illinois, and New York (DOE 2023).

In principle, smart thermostats could offer a natural experiment that helps illustrate the role of communication networks. Products such as the ecobee learning thermostats can operate autonomously, essentially functioning as a programmable thermostat, or with a variety of features that require network communications. Ecobee's dataset includes a field for whether a thermostat participates in the eco+ program, which includes the following five features:

1. Optimizing for humidity as well as temperature
2. Suggesting changes to programmed schedules using machine learning
3. Adjusting thermostat settings based on occupancy, as detected by the presence of smart phones (geofencing)
4. Precooling/preheating at times when energy is cheaper and/or less emissions-intensive
5. Participating in utility demand response programs[29]

[29] www.ecobee.com/en-us/eco-plus/#Features

The last four of these features require communication networks to operate; thus, comparing homes enrolled in the eco+ program with those not enrolled could give an indication of the role of the network in saving energy, emissions, and money. This would have the clear merit of a large dataset, and, conveniently for calculating a handprint, the equipment is the same in both scenarios. Thus, we could reasonably assume that life-cycle emissions are the same, aside from those produced in heating and cooling the two groups of homes.

However, it would not be perfect experiment: We do not know how comparable individual homes are to each other (though the size of the dataset makes this less of a concern), and more significantly, we do not know which eco+ features are active, even when the eco+ field is filled. In particular, it seems unlikely that users share information with the Donate Your Data program via network communications when they are not using network communications to optimize their heating and cooling systems. For LBNL's cleaned dataset, homes are either marked as participating in the eco+ program or the field is blank; larger versions of the ecobee dataset are available but likely have the same issue.

The ecobee dataset is large and allows a remarkably granular look at heating patterns in homes. It provides strong evidence for how smart thermostats can potentially save energy. If the data were more complete about eco+ participation, it could enable a rigorous comparison of the energy savings of smart thermostats compare to programmable thermostats (which is how the ecobee thermostat functions if it is not connected to Wi-Fi). More extensive data about the types of functions used (geofencing, demand response events, etc.) could help pinpoint the role of particular features in saving energy, as well as the involvement of external equipment such as that required for networking. Utility "bring your own thermostat" programs could potentially offer better data in this regard.