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Mapping and Quantifying the Impacts of Digital Applications on Energy Use

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Abstract

The impacts of digitalisation on energy use are potentially large but uncertain. In this paper, we map, visualise, and quantify the impact mechanisms linking digital applications in buildings to outcomes that explain estimated reductions or increases in energy use.

Digital applications provide functionality through different mechanisms. As examples, they coordinate supply and demand and so better integrate energy use into networks or systems of provision (e.g. demand response). They substitute for energy-intensive activity (e.g. teleworking). They control or optimise performance (e.g. building energy management systems). They reduce friction or effort (e.g., smart heating).

Which mechanisms have the largest impacts on energy use?

We synthesise evidence from the literature to compile a dataset of 40 quantitative impact estimates for seven different digital use cases in buildings ranging from energy management systems and smart lighting to disaggregated energy feedback and peer-to-peer platforms for trading goods.

First, we propose a set of seven mechanisms and five outcomes that explain the variety of ways digital applications impact energy use. We then develop impact pathways linking specific mechanisms to outcomes for each digital application. For example, smart heating provides control (mechanism) that helps avoid energy waste (outcome), but also reduces effort (mechanism) that rebounds in the form of more heating (outcome).

Second, we visualise the impact pathways in wire diagrams that demonstrate the complexity of linkages, and the dominance of certain mechanisms such as the integration of building energy use into networks which is a distinctive feature of digitalisation.

Third, using a larger more diverse sample of impact estimates for 23 digital applications not just in buildings but also in transport and food domains, we use meta-analysis to quantify which mechanisms have the largest impact on energy use, controlling for differences between types of digital application and variation in study design. Across all digital applications, we find the substitute mechanism results in the largest reductions in energy use (median of -45%) and the optimise mechanism leads to the largest increases in energy use (median of +2%).

Understanding the mechanisms through which digitalisation impacts energy use in buildings helps guide innovation activity towards functionality linked to energy savings, and emphasises the need to tackle rebound outcomes for certain types of digital application.

Introduction

The impacts of digitalisation on energy use and greenhouse gas (GHG) emissions are direct, indirect, and systemic (Horner, Shehabi et al. 2016). Impacts increase in both magnitude and uncertainty up through this hierarchy.

Direct impacts are from the manufacturing and use of the physical information & communication technologies (ICTs) themselves. These are the most obvious elements of digitalisation: smartphones, fibre-optic cables, and server farms at scales from individual users up to global network infrastructures. Direct impacts of ICTs combining both embodied emissions (manufacturing stage) and operational emissions (use stage) are currently around 1.5 - 4% of total global greenhouse gas emissions (Freitag, Berners-Lee et al. 2022, Bieser, Hintemann et al. 2023) or, for use stage only, about 4% of total global electricity (Malmodin, Lövehagen et al. 2024). This is expected to rise as more and more ICT infrastructure is built (Malmodin and Bergmark 2015).

In addition to these direct energy and emission impacts, the material footprint of ICTs throughout their lifecycle from the mining of minerals to end-of-life disposal imposes further environmental burdens (Malmodin and Bergmark 2015). For example, electronic waste (e-waste) is the fastest growing waste stream in the world (WEF 2019).

However, the indirect impacts of digitalisation resulting from what these ICTs are used for are larger than the direct impacts but also much harder to reliably estimate. This is for a variety of reasons. First, there are a large and diffuse number of digital applications and services throughout energy-using sectors and the economy. Second, there is a lack of standardisation in how different indirect impacts are assessed (Lange, Pohl et al. 2020, Bremer, Kamiya et al. 2023). Third, the system boundaries in each impact study may vary in scope, time horizon, and scale. Fourth, studies estimating indirect impacts of discrete digital applications use different designs and methodologies (e.g., field trials, controlled experiments, simulation modelling) that vary in robustness and generalisability. Fifth, the counterfactual or 'without digitalisation' reference case may be hard to identify in cases where digitalisation is already pervasive. Despite these difficulties, there are a large number of studies that estimate the indirect impacts of specific digital applications on energy use (see Wilson, Kerr et al. (2020) for a synthesis) using empirical data from use cases or case studies in specific deployment contexts, or modelling simulations for emerging or prospective applications for which sufficient observational data are not yet available (Noussan and Tagliapietra 2020). Bieser, Hintemann et al. (2023) synthesise indirect impact estimates from multiple use cases across sectors, drawing particularly on studies by GeSI, the Global e-Sustainability Initiative (GESI & Accenture Strategy 2015, GESI & Deloitte 2019, GESI 2022).

On the one hand, digital applications help optimise, control, manage, substitute, balance supply-demand, and improve the efficiency with which energy is used for a wide range of activities. But on the other hand, by reducing the cost, time, friction or effort of these activities, digitalisation can lead to growth in demand either through a ‘rebound’ of more demand for the same activity or from an induced demand for new activities. This basic trade-off between efficiency and growth determines the net indirect impact of digitalisation on energy use and GHG emissions (Lange, Pohl et al. 2020, Briglauer, Köppl-Turyna et al. 2023).

In buildings, smart meters, sensors, IoT devices, heating, lighting, and control systems collect and analyse information in real-time to help optimise energy management and enable buildings to flexibly contribute to balancing demand with supply on electricity networks. As buildings increasingly become sites for distributed energy generation and storage assets (e.g., solar panels, batteries, and electric vehicles (dis)charging), digitalisation allows for pricing or network signals to incentivise or automate reductions in electricity demand during peak periods. This demand responsiveness or flexibility to shift loads helps electricity suppliers avoid the need for costly infrastructure upgrades and GHG-intensive generators to help meet demand peaks. Algorithms that disaggregate smart meter data to specific appliances or activities provide actionable information to building users motivated to reduce or shift demand. Digital platforms and peer-to-peer networks enable sharing economies for users to trade or exchange surplus goods, space, and even electricity.

These various digital use cases in buildings impact energy consumption indirectly through different mechanisms. Analysing these indirect impact mechanisms is the focus of this paper. (Note we do not consider the direct impacts or energy footprints of digital devices themselves which are small relative to the indirect impacts).

Impact mechanisms can have both energy-saving outcomes (e.g., the 'optimise' mechanism) and energy-increasing outcomes(e.g., the 'reduce friction' mechanism). These impact mechanisms connect these outcomes back up to the distinctive features of digitalisation for the application in question (e.g., platforms connecting supply with demand in real time, or data-rich analysis & control feedback). The linkages from application through impact mechanism to outcome form an impact pathway.

In this paper, we ask: *what are the impact mechanisms and pathways through which digital applications in buildings impact energy use? And which impact mechanisms have the largest energy-saving benefits?*

We use a unique dataset of 40 quantitative impact estimates for seven different digital applications in buildings, taken from a larger dataset of 23 digital applications also in transport and retail) (Wilson, Kerr et al. 2020).

First, we develop a taxonomy of seven impact mechanisms and five outcomes in order to map the impact pathways that link digital applications in buildings to changes in energy use. For example, smart heating provides control (mechanism) that helps avoid energy waste (outcome), but also reduces effort (mechanism) that rebounds in the form of more heating (outcome).

Second, we visualise the impact pathways in wire diagrams that demonstrate the complexity of linkages, and the dominance of certain mechanisms including data-driven control functionality which is a distinctive feature of smart or grid-responsive technologies deployed in buildings.

Third, we use meta-analysis techniques to quantify which mechanisms have the largest impact on energy use, controlling for differences between types of digital application as well as differences in study design. In this final step we pool data on digital applications in buildings with other digital applications related to transport, food, and consumer goods.

Data

We draw on prior studies to identify seven use cases of digitalisation in buildings for which there is clear evidence of energy saving or load shifting potential to support system integration, but also risks of rebound or induced demand (Beaudin and Zareipour 2015, Jacobs, Leidelmeijer et al. 2015, Hsu and Lin 2016, BIT 2017, Fremstad 2017, IEA 2017, Laidi, Djenouri et al. 2019, Creutzig, Roy et al. 2022). The digital use cases are shown in Table 1. In some cases these are fully digital applications: e.g., peer-to-peer platforms for exchanging goods (Koide, Murakami et al. 2022) or non-intrusive load monitoring algorithms that disaggregate building smart meter data. In other cases, digitalisation adds functionality to physical hardware: e.g., smart heating controls that learn user preferences (Duman, Hamza Salih et al. 2021).

We then compile quantitative data from the literature on how these digital use cases impact energy-related outcomes. We normalise impact estimates as % changes (%Δ) relative to reference cases (without the digital application). Normalisation into %Δ estimates allows more direct comparability of relative effect sizes between applications; however, the absolute magnitude of impact in energy (GJ) or emission (tCO2) terms depends on the activity affected (see right column in Table 1).

We focus on activity and energy metrics where possible as the most direct measures of impact without confounding factors such as the emission intensity of electricity. This method follows the precedent set in the recent IPCC Sixth Assessment Report (see Fig 5.12 in (Creutzig, Roy et al. 2022); also (Wilson, Kerr et al. 2020)) which synthesised evidence on a wide range of demand-side digital applications.

A summary of the min – median – max range of impact estimates is shown in Table 1. Impact estimates for smart home appliances (e.g., fridges, washing machines) were found in one study but considered insufficiently robust so were excluded.

Heat pumps were included in the initial literature search as they can be configured with digital control systems that enable demand response to signals from the grid (Gaur, Fitiwi et al. 2021). However they are not included in Table 1 as their principal impact on energy use and carbon emissions is through the electrification of heat.

Table 1. Change (%Δ) in activity, energy or emissions associated with seven digital applications used in buildings.

Digital Application	**n studies**	**min %Δ**	**median %Δ**	**max %Δ**	**share of building energy use impacted**
smart heating systems	5	-36.0%	-18.7%	2.0%	high
smart lighting	5	-73.2%	-39.3%	-3.0%	medium
smart home appliances & internet of things	1				low

(IoT)					
home energy management systems (HEMS) *[1]	14	-90.0%	-24.1%	9.1%	high
pre-fabricated retrofit solutions *[2]	2		-77.0%		high
disaggregated energy feedback	10	-24.0%	-12.6%	-3.5%	medium
peer-to-peer exchange of goods	1	-12.6%	-6.1%	0.4%	low

*[1] HEMS can also enable load shifting

*[2] Digitalisation elements include 3d scanning, imaging & use of design software (including building information models) for offsite fabrication of high energy performance retrofit components or integrated whole building retrofits (Jacobs, Leidelmeijer et al. 2015).

Distinguishing Mechanisms and Outcomes in Digitalisation Impact Pathways

Various studies have proposed taxonomies for the mechanisms through which digitalisation impacts energy use (Table 2). The taxonomies take different perspectives. From a computer science perspective, Coroamă (2020) identifies computing action mechanisms linking computing advances & trends to positive & negative outcomes called ‘bright’ and ‘dark’ outcomes respectively. From a consumer behaviour perspective, Wilson, Kerr et al. (2020) identify mechanisms linking specific digital applications to potential emission reduction benefits as a result of changes in how energy services like heating or mobility are provided or consumed. From an ICT industry perspective, GESI & Deloitte (2019) identify 'impact functions' that link digital technologies with broad ways in which they interact with the world and shape behaviour and processes. In all cases, the impact mechanisms emphasise the unique capabilities of digital applications to collect, store, analyse, and exchange data in real-time.

Table 2. Alternative taxonomies of digitalisation impact mechanisms.

	Coroama (2020)	**Wilson et al (2020)**	**GESI (2022)**
mechanisms	- coordination & control - simulation & modelling - feedback - virtualisation - proof-of-work	- access - coordinate - optimise - virtualise - substitute - control - avoid waste	- connect & communicate - monitor & track - analyse, optimise & predict - augment & autonomate *
outcomes	good & bad (bright & dark patterns)	good (energy-saving)	not specified, but assumed mainly good
applications	wide range, illustrative	focused set in homes as well as mobility and food domains with quantitative impact estimates	not specified

* 'autonomate' as in to make autonomous (as opposed to 'automate' as in to make automatic)

These taxonomies in Various studies have proposed taxonomies for the mechanisms through which digitalisation impacts energy use (Table 2). The taxonomies take different perspectives. From a computer science perspective, Coroamă (2020) identifies computing action mechanisms linking computing advances & trends to positive & negative outcomes called ‘bright’ and ‘dark’ outcomes respectively. From a consumer behaviour perspective, Wilson, Kerr et al. (2020) identify mechanisms linking specific digital applications to potential emission reduction benefits as a result of changes in how energy services like heating or mobility are provided or consumed. From an ICT industry perspective, GESI & Deloitte (2019) identify 'impact functions' that link digital technologies with broad ways in which they interact with the world and shape behaviour and processes. In all cases, the impact mechanisms emphasise the unique capabilities of digital applications to collect, store, analyse, and exchange data in real-time. were proposed for specific reasons which do not correspond perfectly with our aim in this study to characterise the different mechanisms through which digital applications in buildings can help reduce energy use. Some mechanisms are not relevant to buildings applications (e.g., proof-of-work, augment & autonomate). Other mechanisms important for buildings applications are missing (e.g., reducing friction and cost). Consequently, we combine elements of the different taxonomies to provide a parsimonious but complete picture of the impact mechanisms for the digital applications used in our study (We draw on prior studies to identify seven use cases of digitalisation in buildings for which there is clear evidence of energy saving or load shifting potential to support system integration, but also risks of rebound or induced demand (Beaudin and Zareipour 2015, Jacobs, Leidelmeijer et al. 2015, Hsu and Lin 2016, BIT 2017, Fremstad 2017, IEA 2017, Laidi, Djenouri et al. 2019, Creutzig, Roy et al. 2022) . The digital use cases are shown in Table 1. In some cases these are fully digital applications: e.g., peer-to-peer platforms for exchanging goods (Koide, Murakami et al. 2022) or non-intrusive load monitoring algorithms that disaggregate building smart meter data. In other cases, digitalisation adds functionality to physical hardware: e.g., smart heating controls that learn user preferences (Duman, Hamza Salih et al. 2021) .).

Specifically, we characterise seven different mechanisms that lead to a set of five different outcomes related to energy use. These are taken directly from Various studies have proposed taxonomies for the mechanisms through which digitalisation impacts energy use (Table 2). The taxonomies take different perspectives. From a computer science perspective, Coroamă (2020) identifies computing action mechanisms linking computing advances & trends to positive & negative outcomes called 'bright' and 'dark' outcomes respectively. From a consumer behaviour perspective, Wilson, Kerr et al. (2020) identify mechanisms linking specific digital applications to potential emission reduction benefits as a result of changes in how energy services like heating or mobility are provided or consumed. From an ICT industry perspective, GESI & Deloitte (2019) identify 'impact functions' that link digital technologies with broad ways in which they interact with the world and shape behaviour and processes. In all cases, the impact mechanisms emphasise the unique capabilities of digital applications to collect, store, analyse, and exchange data in real-time., with the addition of reducing friction and cost that are important to specify as mechanisms explaining rebound effects (Coroamă and Mattern 2019, Lange, Frick et al. 2023).

The seven impact mechanisms of digitalisation used in this study are:

- to substitute with a less energy-intensive technology or form of service provision
- to exchange or trade goods peer-to-peer (cf. reuse)
- to control or manage how a service is provided, including for resource efficiency
- to integrate into a system to optimise or enable efficient design & functioning
- to communicate or signal information in real-time to enable adaptive response and/or gamification
- to reduce friction or effort in providing or using a service
- to reduce cost of providing or using a service

The control and communicate mechanisms are often supported by monitoring, sensing or tracking functionality that provides real-time data on energy-related activity.

Each impact mechanism associates with specific outcomes that explain whether digital applications have net energy-saving or energy-increasing impacts.

Of the five outcomes, three are typically associated with energy savings:

- *higher utilisation rates* of physical goods or infrastructure
- *higher service efficiency* or lower energy needs to provide a useful service
- *less waste* of energy and other resources in providing a useful service

In Wilson, Kerr et al. (2020)'s original taxonomy, avoiding waste was included as a mechanism, but is reassigned here as an outcome of certain impact mechanisms, such as control or exchange.

Two outcomes are typically associated with energy increases due to rebound effects:

- *more demand (same service)*, i.e., direct rebound from cost, time savings
- *more demand (other services)*, i.e., indirect rebound from cost, time savings

Whether digitally-enabled improvements in the efficiency with which an energy service like heating or lighting is provided lead to absolute reductions in energy use depends on whether the amount of service consumed remains constant, or - for example - increases due to rebound effects. Similarly, whether increases in the utilisation rate of physical goods or space enabled by digital platforms lead to absolute reductions in energy use depends on - for example - whether the total stock of physical infrastructure in use is reduced.

Note that we do not consider the direct energy footprint of the digital devices themselves in this study.

Mapping Digitalisation Impact Pathways from Application through Mechanism to Outcome

With these building blocks of impact mechanisms and outcomes, we can then map the impact pathways for each digital application (Table 3). Explanations for each impact pathway are given in the final column of Table 3. A single application can have multiple impact pathways, with outcomes both energy-saving and energy-increasing. The relative strength of each pathway determines the net effect on energy use.

Table 3. Digitalisation impact pathways.

Application	**Mechanism**	***Outcome***	**explanation of impact pathway**
smart heating systems	control	*higher service efficiency*	smart heating adaptively responds to external conditions and learns about users' needs and preferences
	control	*less waste*	smart heating avoids heating unoccupied rooms or homes
	reduce friction	*more demand (same service)*	smart heating makes it easier to control heating (including by remote) so is used more
smart lighting	control	*higher service efficiency*	smart lighting adaptively responds to external conditions and users' needs
	control	*less waste*	smart lighting avoids lighting unoccupied rooms or homes (e.g., through motion sensing)
	reduce friction	*more demand (same service)*	smart lighting makes it easier to switch lighting on by remote (e.g., as a burglar deterrent) so is used more
smart home appliances & IoT [*1]	control	*higher service efficiency*	smart home appliances are controllable to reduce energy demand
	integrate	*higher system efficiency*	smart home appliances reduce peak demand on electricity networks
home energy management systems (HEMS)	control	*higher system efficiency*	HEMS control energy flows to improve system performance
	integrate	*more avoided supply*	HEMS maximise use of own energy generation & storage and reduce peak demand
pre-fabricated retrofit solutions	integrate	*higher service efficiency*	pre-fab retrofits deliver high specification building envelopes that improve thermal comfort provision
	reduce friction	*more demand (other services)*	pre-fab retrofits reduce disruption & time spent on whole home renovations freeing up time for other activities
disaggregated energy feedback	communicate	*less waste*	disaggregated real-time energy feedback informs appliance-level energy-saving opportunities
peer-to-peer (P2P) exchange of goods	exchange	*less waste*	P2P exchange of goods increases recirculation and avoids or delays product end-of-life waste
	reduce friction	*higher utilisation*	P2P exchange of goods increases product reuse and extends in-use lifetimes, avoiding new supply
	reduce cost	*more demand (same service)* [*2]	P2P exchange of goods reduces cost and friction of acquiring (used) products so more are acquired

[*1] Heat pumps configured for demand flexibility or load shifting in response to grid signals also impact energy outcomes though the integrate mechanism with the outcome of *higher system efficiency*.

[*2] *More demand (other services)* is also possible, i.e., indirect rebound.

Visualising Digitalisation Impact Pathways

The impact pathways summarised in Table 3 linking digital applications via mechanisms to outcomes help emphasise the many different ways in which digitalisation impacts energy use. These are shown in a visual form in Figure 1 for a single application, and in Figure 2 for multiple applications overlain on the same set of mechanisms and outcomes.

The impact pathways in Figure 1 & Figure 2 include the final linkage from outcomes to quantitative impacts on activity, energy, or emissions, drawing on the data shown in We draw on prior studies to identify seven use cases of digitalisation in buildings for which there is clear evidence of energy saving or load shifting potential to support system integration, but also risks of rebound or induced demand (Beaudin and Zareipour 2015, Jacobs, Leidelmeijer et al. 2015, Hsu and Lin 2016, BIT 2017, Fremstad 2017, IEA 2017, Laidi, Djenouri et al. 2019, Creutzig, Roy et al. 2022) . The digital use cases are shown in Table 1. In some cases these are fully digital applications: e.g., peer-to-peer platforms for exchanging goods (Koide, Murakami et al. 2022) or non-intrusive load monitoring algorithms that disaggregate building smart meter data. In other cases, digitalisation adds functionality to physical hardware: e.g., smart heating controls that learn user preferences (Duman, Hamza Salih et al. 2021) . (shown as min-max bars on the right of the Figures).

Visualising the pathways in this holistic way helps: (1) to communicate the complexity of digitalisation impact mechanisms; (2) to identify similarities and differences in impact mechanisms across applications; (3) to make explicit that a single digital application can have impact mechanisms that are both ‘bright’ (energy saving) and ‘dark’ (energy increasing).

Indeed, most digital applications have more than one impact pathway with outcomes that affect energy use. The relative strength of these different impact pathways determines the overall quantitative impact. For example, smart heating systems enable control (mechanism) of the building environment leading to *higher service efficiency* and *less waste* (outcomes). As examples, *higher service efficiency* is achieved through automatic adjustments of temperature set points to compensate for changes in outdoor air temperature, whereas *less waste* can be achieved using occupancy sensors in smart systems to avoid heating unoccupied rooms. Smart heating systems also reduce friction (mechanism) through learning, automation, and remote access that makes it easier and more convenient to control the building environment which in turn can induce *more demand* (outcome) for heating or other energy-using activities. As examples, app-based controls allow households to pre-heat homes while out (direct rebound) (Hargreaves and Wilson 2017).

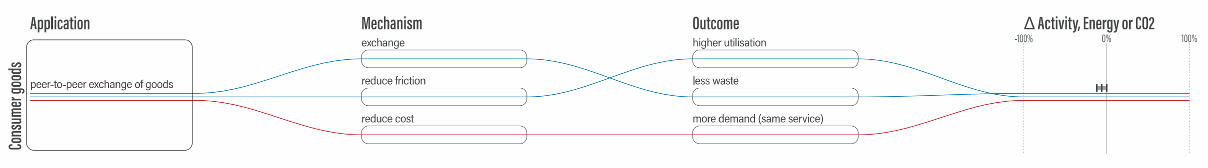

Figure 1. Digitalisation impact pathways for a single application. Blue lines denote energy-saving pathways; red lines denote energy-increasing pathways.

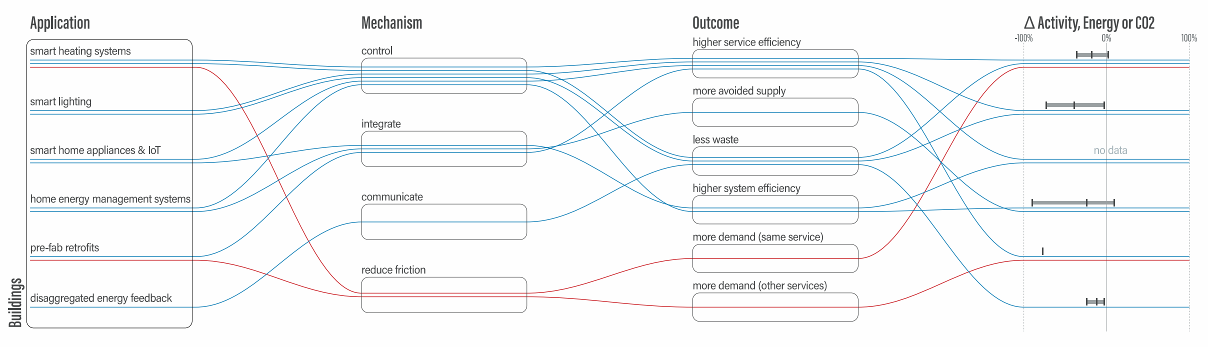

Figure 2. Digitalisation impact pathways for multiple applications. Blue lines denote energy-saving pathways; red lines denote energy-increasing pathways.

Meta-Analysis of Quantitative Impacts per Digital Mechanism

The impact pathways shown in Figure 2 link applications through mechanisms to outcomes. The different outcomes combine to explain the impact of the digital application, estimated as a % change in activity or energy. These changes are uncertain, so are shown as min – median – max ranges on the right side of Figure 2 (using data from We draw on prior studies to identify seven use cases of digitalisation in buildings for which there is clear evidence of energy saving or load shifting potential to support system integration, but also risks of rebound or induced demand (Beaudin and Zareipour 2015, Jacobs, Leidelmeijer et al. 2015, Hsu and Lin 2016, BIT 2017, Fremstad 2017, IEA 2017, Laidi, Djenouri et al. 2019, Creutzig, Roy et al. 2022) . The digital use cases are shown in Table 1. In some cases these are fully digital applications: e.g., peer-to-peer platforms for exchanging goods (Koide, Murakami et al. 2022) or non-intrusive load monitoring algorithms that disaggregate building smart meter data. In other cases, digitalisation adds functionality to physical hardware: e.g., smart heating controls that learn user preferences (Duman, Hamza Salih et al. 2021) .).

It is not possible to isolate the discrete effect of each impact pathway on energy use for a given application. However, using meta-analysis techniques, it is possible to estimate the relative effect size of each impact mechanism across all applications by exploiting variation across a large number of quantitative estimates.

However, the sample size of 40 impact estimates for seven digital use cases in buildings (We draw on prior studies to identify seven use cases of digitalisation in buildings for which there is clear evidence of energy saving or load shifting potential to support system integration, but also risks of rebound or induced demand (Beaudin and Zareipour 2015, Jacobs, Leidelmeijer et al. 2015, Hsu and Lin 2016, BIT 2017, Fremstad 2017, IEA 2017, Laidi, Djenouri et al. 2019, Creutzig, Roy et al. 2022) . The digital use cases are shown in Table 1. In some cases these are fully digital applications: e.g., peer-to-peer platforms for exchanging goods (Koide, Murakami et al. 2022) or non-intrusive load monitoring algorithms that disaggregate building smart meter data. In other cases, digitalisation adds functionality to physical hardware: e.g., smart heating controls that learn user preferences (Duman, Hamza Salih et al. 2021) .) is too small and with insufficient variation for our meta-analysis, so we pool these into a larger sample of 141 impact estimates for 23 digital applications not just in the buildings domain but also in the food and transport domain. This sample is compiled from two sources: (Wilson, Kerr et al. 2020, Creutzig, Roy et al. 2022). Example digital applications in the food domain include online hubs for local food (also called digital farmers' markets), 11th hour food apps, foodpairing apps, diet shift gamification apps. Examples in the transport domain include car- and ride-sharing platforms, ridehailing, mobility-as-a-service, shared e-bikes, videoconferencing. All the applications are consumer-facing, i.e., they provide services to or are interacted with by end-users (e.g., building occupants or device users in the case of digital applications in the buildings domain).

For our meta-analysis we use the set of impact mechanisms from Wilson, Kerr et al. (2020) shown in Various studies have proposed taxonomies for the mechanisms through which digitalisation impacts energy use (Table 2). The taxonomies take different perspectives. From a computer science perspective, Coroamă (2020) identifies computing action mechanisms linking computing advances & trends to positive & negative outcomes called 'bright' and 'dark' outcomes respectively. From a consumer behaviour perspective, Wilson, Kerr et al. (2020) identify mechanisms linking specific digital applications to potential emission reduction benefits as a result of changes in how energy services like heating or mobility are provided or consumed. From an ICT industry perspective, GESI & Deloitte (2019) identify 'impact functions' that link digital technologies with broad ways in which they interact with the world and shape behaviour and processes. In all cases, the impact mechanisms emphasise the unique capabilities of digital applications to collect, store, analyse, and exchange data in real-time.. These differ slightly from the mechanisms used in the mapping and visualisation of impact pathways specific to the subset of digital application in buildings (Figure 2). For the meta-analysis of impact mechanisms across buildings, food, and mobility domains, we include an access mechanism (accessing a service rather than owning a good) which is particularly important for mobility, e.g., car clubs, ride-sharing, mobility-as-a-service business models which can supress the need for car ownership and use (Baptista, Melo et al. 2014, Namazu and Dowlatabadi 2015, Hoerler, Stünzi et al. 2020). We do not include reduction in fiction, cost or effort as these were not included by Wilson, Kerr et al. (2020)'s impact taxonomy which focused on energy-saving impacts (see Various studies have proposed taxonomies for the mechanisms through which digitalisation impacts energy use (Table 2). The taxonomies take different perspectives. From a computer science perspective, Coroamă (2020) identifies computing action mechanisms linking computing advances & trends to positive & negative outcomes called 'bright' and 'dark' outcomes respectively. From a consumer behaviour perspective, Wilson, Kerr et al. (2020) identify mechanisms linking specific digital applications to potential emission reduction benefits as a result of changes in how energy services like heating or mobility are provided or consumed. From an ICT industry perspective, GESI & Deloitte (2019) identify 'impact functions' that link digital technologies with broad ways in which they interact with the world and shape behaviour and processes. In all cases, the impact mechanisms emphasise the unique capabilities of digital applications to collect, store, analyse, and exchange data in real-time.).

The impact mechanisms we test in our meta-analysis are: access; coordinate (or exchange in Table 3); optimise (or integrate in Table 3); substitute; control.

Our expectation is that of the impact mechanisms, substitute will have the largest consistent net-energy saving benefit if digital or digitally-enabled alternatives are used instead of more energy-intensive activity (e.g., teleworking instead of physical commuting, car-sharing instead of sole occupancy driving). The energy-saving benefits of other mechanisms are more contingent on use context. This includes access (to services), coordinate (between surplus supply and demand, enabling exchange or trade), and control (improved functionality for users).

We test this expectation by first measuring bivariate associations between each mechanism and the estimated quantitative impacts (shown in We draw on prior studies to identify seven use cases of digitalisation in buildings for which there is clear evidence of energy saving or load shifting potential to support system integration, but also risks of rebound or induced demand (Beaudin and Zareipour 2015, Jacobs, Leidelmeijer et al. 2015, Hsu and Lin 2016, BIT 2017, Fremstad 2017, IEA 2017, Laidi, Djenouri et al. 2019, Creutzig, Roy et al. 2022) . The digital use cases are shown in Table 1. In some cases these are fully digital applications: e.g., peer-to-peer platforms for exchanging goods (Koide, Murakami et al. 2022) or non-intrusive load monitoring algorithms that disaggregate building smart meter data. In other cases, digitalisation adds functionality to physical hardware: e.g., smart heating controls that learn user preferences (Duman, Hamza Salih et al. 2021) . for the digital applications in buildings, and in Wilson, Kerr et al. (2020) for the digital applications in food and mobility). As noted earlier, these impact estimates are expressed as % changes in activity, energy or emissions relative to a without digitalisation reference case.

For these bivariate associations we control for variation in the contexts in which digital applications are deployed. Descriptive results are shown in Figure 3 (left panel). We use the term 'emissions-related outcomes' to describe the impacts. Our controls for contextual variation are: domains of application, user behavioural response, dependence on physical infrastructure. Domain of application (transport, food, buildings) characterises the functional conditions and settings that influence the use of digital applications (Aall and Hille 2010, Creutzig, Roy et al. 2018, Moberg, Aall et al. 2019, Ivanova, Barrett et al. 2020). User behavioural response (avoid, shift, improve) characterises the implications for user behaviour of a digital application distinguishing doing less (avoid), doing differently (shift), and doing more efficiently (improve) (Creutzig, Jochem et al. 2015, Creutzig, Niamir et al. 2021). Dependence on physical infrastructure (high, medium, low) characterises the additional reliance of digital applications on enabling physical infrastructure (e.g., renewable generation and battery storage, roads, docking stations, logistics warehouses) (Sochor, Karlsson et al. 2016, Gnann, Funke et al. 2018, Jones and Leibowicz 2019).

We then introduce further controls for variation in study designs across the 141 impact estimates in our sample. Descriptive results are shown in Figure 3 (right panel). Study design characteristics generate differences in methodological approach that can affect both the magnitude and direction of estimated changes in activity, energy, or emissions. Our controls for study design variation are: internal validity or robustness (e.g., use of control groups), external validity or generalisability (e.g., real-world contexts), and analytical method used (e.g., simple estimation or simulation model). We also control for differences in the metric of impact used: activity, energy, or emissions.

From these results, we test whether differences between impact mechanism are statistically significant using meta-regression. First, we use bivariate quantile regression to test for differences between impact mechanism controlling for application characteristics but not variation in study design. This is a non-parametric linear regression approach which predicts median impact values as a linear function of the distribution of the independent variable. Second, we use multivariate quantile regression to introduce additional controls for study design characteristics. Differences between impact mechanism within each of these models are deemed to be significant if $|p|<=0.05$.

Table 4 shows the results. In line with expectations, we find that the substitute mechanism has the largest energy-saving benefit (mean = -43.9%) compared to all other mechanisms, with the coordinate, access, and control mechanisms also consistently showing net energy-saving outcomes.

When introducing controls for variation in study design, explained variance (R^2) increases from 8.31% to 11.7%. Study design characteristics do moderate the relationship between digital application and impact estimates. In line with expectations we found that studies with lower internal validity (robustness) or lower external validity (generalisability) tended to report larger impacts. Controlling for these effects, the substitute mechanism further strengthens in energy-saving benefit, but now also with the access and control mechanisms showing improved net energy-saving outcomes (Figure 3 right panel).

We note again that these results are not just for digital applications in buildings, but also for digital applications in the food and transport domains. These are described in full in Wilson, Kerr et al. (2020). This more diverse set of applications was necessary to boost variation in our sample of impact estimates as a basis for difference testing.

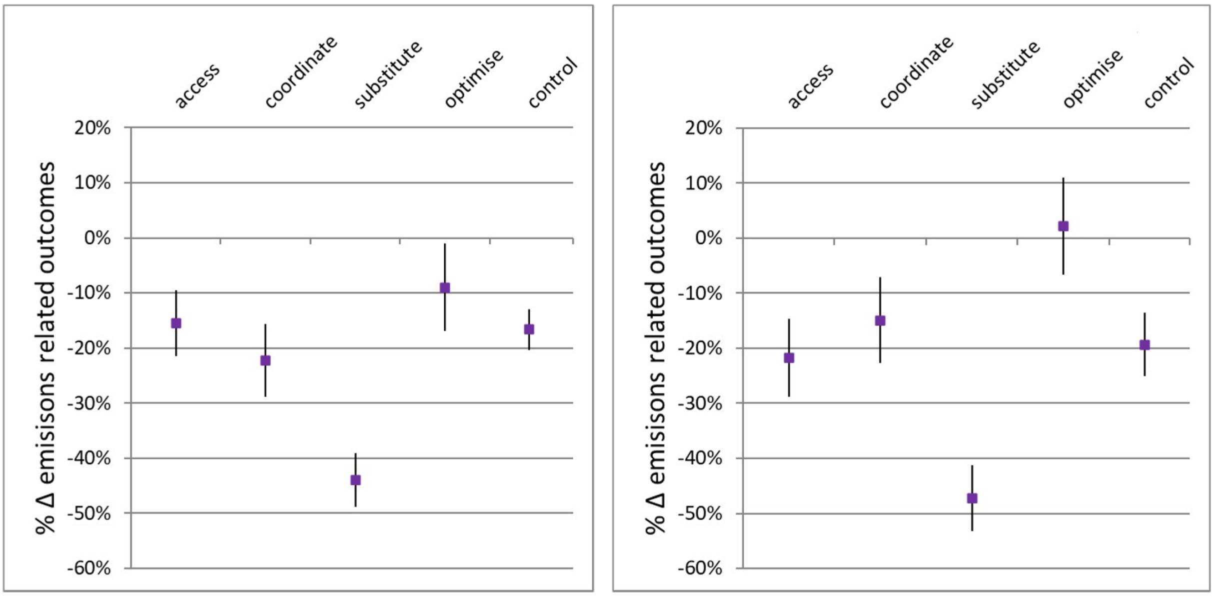

Figure 3. Impact of digital applications on activity, energy use, or emissions, grouped by impact mechanism. Digital applications span buildings, transport and food domains. Left panel shows mean changes in impact for each mechanism, controlling for variation in deployment context (domain of application, user behavioural response, and dependence on physical infrastructure). Right panel shows the same data but with additional controls for variation in study design (internal validity, external validity, analytical method, metric of impact)..

Table 4. Digitalisation impacts on activity, energy or emissions, grouped by impact mechanism, using meta-regression. See text for details.

Impact mechanism	**Estimated % change in impact metric (activity, energy or emissions)**	
	with controls for use context without controls for study design	with controls for use context with controls for study design
access	-15.5	-21.7**
coordinate	-22.3	-14.9
substitute	-43.9**	-47.2**
optimise	-9.0	2.21
control	-16.6	-19.3**

explained variance (R^2)	*8.31%*	*11.70%*

** |p|<=0.05

Discussion & Conclusion

Understanding the mechanisms through which digitalisation impacts energy use in buildings helps guide innovation activity towards functionality linked to energy savings, and emphasises the need to tackle rebound effects for certain types of digital application that can increase energy use.

For an illustrative set of seven digital applications in buildings, we show the relevance, complexity, and explanatory power of different impact mechanisms linking application to outcomes. We represent these impact mechanisms visually to show how different applications share similar mechanisms, and how digitalisation in a single application can have confounding effects on energy use in both beneficial and adverse directions.

To disentangle the relative strength of these different impact mechanisms, we pool our impact estimates for the digital applications in buildings with an additional set of digital applications used in food and mobility-related services. We show that the substitute mechanism consistently has the largest net energy-saving benefit within this diverse sample of digital applications.

We also demonstrate that study design characteristics affect the magnitude of impacts estimated for digital applications. In other words, to properly understand the impacts of digitalisation, we need to account for variation between individual studies: the ‘known un-knowns’ described by Horner, Shehabi et al. (2016).

There are inherent challenges to comparing the effects of different impact mechanisms that rely on the availability and validity of established empirical evidence. Further work in this area would be improved by the creation of standardised methodological approaches that produce greater consistency in how quantitative impacts are estimated (Bremer, Kamiya et al. 2023). Recent proposals in this direction by the International Telecommunications Union are a welcome advance (ITU 2022). The proposed standards explicitly cover system boundary definition and the desirability of including rebound or induced demand effects. Drawing on lifecycle inventories, they also extend in scope to include material as well as direct and indirect energy impacts.

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