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Review

"Quantifying the implications of behavioral changes induced by digitalization on energy transition: A systematic review of methodological approaches"

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ABSTRACT

Digitalization is expected to play an important role in mitigating environmental issues and supporting the energy transition to meet future energy and climate targets. To understand the role of Information and Communication Technology (ICT) applications in the energy transition, a prior understanding of their implications on user behavior and energy consumption is essential to identify and prevent potential rebound effects. With a systematic literature review, this paper investigates approaches to quantify behavioral changes and energy impacts for different ICT applications. The review highlights a gap in linking the effects of ICT on users' behavior and impacts on energy consumption over a long time horizon and beyond the specific regional case study. We find that the difficulty in expanding the temporal and spatial resolution is related to the type of approach used to assess user effects. The review highlights and describes the problem of selecting the appropriate approach to perform an analysis that is robust in assessing both changes in user behavior on the one hand, and future energy implications related to ICT applications on the other hand.

1. Introduction

Information and Communication Technology (ICT) is characterized as a General Purpose Technology [1], adopted in different sectors of an economy and able to induce a broad spectrum of innovations [2]. ICT affects everyday lives, impacts macroeconomic growth, and affects society by enabling infrastructure and standard of living improvements [3].

Digitalization and ICTs are expected to play a relevant role in mitigating environmental issues [4] and supporting the energy transition to achieve the energy and climate goals identified by the Paris Climate Agreement [5]. Digital technologies affect the energy consumption of different economic sectors through their ability to optimize energy production and operation processes [6]. They enable innovation and foster the virtualization of activities [7], creating "e-substitutes" for physical products [8], shifting the economy to more service-based and information-intensive activities [9], which is expected to result in a reduction of resources and energy used [10]. On the other hand, the diversification of ICT uses [11] and their penetration into everyday activities have increased the demand for products and services [12] with a related impact on energy demand [13].

It is controversially discussed whether ICTs will contribute to reducing energy demand or whether their potential rebound effect will cause an additional burden [14] on the energy system. Furthermore, due to the cross-sectoral application of ICTs, isolating the impact on energy patterns of a specific ICT application is complicated [15], increasing the difficulties of promoting targeted policies to strength their beneficial contribution and reduce their negative implications [16].

This paper aims to provide state of the art on the implications of ICT adoption on user behavior and, consequently, on energy consumption. Specifically, it focuses on the approaches used to quantify the energy impacts of ICTs, accounting for rebound effects induced by the penetration of ICTs into everyday activities. However, these effects are complicated to quantify, as they are connected to the socio-economic change induced by the type of ICT end-uses [17].

While the literature focuses on the direct energy impact [17] related

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to the production and use of ICT devices [18], the energy impacts related to the socio-economic changes induced by the application of ICT are only partially assessed, with impacts such as the rebound impacts [17] and systemic impacts d [18] often neglected. Direct impacts are widely analyzed in the literature, and they refer to the energy impacts of the production, use, recycling and disposal of ICTs [19]. The attention to the quantitative assessment of the direct impacts gained relevance in the past years due to the increasing worldwide ICT electricity demand. Including data centers, data networks and connected devices, it accounted for almost 6 % of the global final electricity demand in 2020 [20], with the electricity demand for data centers alone accounting for 1 % of the global final electricity demand in 2020 [21].

By contrast, when analyzing ICT-induced changes in the energy consumption patterns of individuals, several problems arise. First, there is a lack of empirical data on how human users interact with ICT systems [8]. Most studies assessing the indirect impacts of ICTs have either treated changes in consumption behavior as exogenous variables, neglecting how ICTs change collective consumption patterns [22], or have relied on optimistic assumptions and tended to neglect the rebound effects of ICTs, resulting in an overestimation of potential energy savings [7]. Reviewing LCA case studies, Pohl et al. [17] concluded that user-related ICT effects and many behavioral effects were often not integrated into the assessment.

It is evident that the implication between changes in users' behavior induced by ICT applications and the impact on energy consumption patterns has not yet been fully investigated. Furthermore, while several taxonomies exist in the literature to analyze the energy impacts of ICT [8,17,18], only a few studies classify the effects induced by ICT on consumers' behavior (user-related effects[1] [17]. An attempt to systematically asses these effects was made by Börjesson et al. [23] using e-commerce as an example, although a taxonomy linking the user-related effects with their energy impacts is still missing.

To answer the overarching question of how the implications of behavioral changes induced by the introduction of ICTs on energy transition are quantified, we formulated further sub-questions to understand better the connections between ICT applications, behavioral changes and energy impacts:

R.a): Which user-related effects are analyzed for different ICT applications?

R.b): What are the existing approaches to quantify these changes in user behavior?

R.c): Which energy impacts related to these changes are analyzed and how?

The paper is organized as follows: Section 2 describes the method used to conduct the systematic review, while Section 3 analyses the systematic review results. Then, in Section 4, the results and limitations of the research are discussed, along with our suggestions for future research, concluding with a summary of the main findings in Section 5.

2. Methodology

2.1. Queries and filtering method

To assess the energy impacts of ICT connected to changes in user behavior, we conducted a systematic literature review (SLR), starting with identifying the main search keywords based on our research questions (R.a, R.b, R.c), "*ICT; higher-order impact; behavior; energy*".

Synonyms have been used for all of the main search keywords to broaden the search results, separated by the OR operator. We selected common scientific literature databases and platforms, such as Web of Science, Scopus, Google Scholar, and for all libraries, we used the same search query [18]. The search for keywords is performed through all fields of the papers.

The resulting query that was used in this SLR is:

ALL = (("ICT" OR "communication technology" OR "digitalization") AND (" higher order impact" OR "rebound effect" OR "indirect impact") AND ("behavior" OR "preference")).

Peer-reviewed journal articles and conference proceedings were included, while books, book chapters, technical reports, thesis, and all studies not accessible at the time of the review (e.g. behind a paywall) were excluded. Furthermore, only studies in English were considered. The results from the different libraries were merged and duplicates removed, obtaining the "initial sample". In the screening phase, reviews were removed and additional inclusion/exclusion criteria (Table 1) were applied to select relevant publications for our research questions. To be included, a study must directly address the effect of ICTs on users' behavior and provide a quantification of this effect. Therefore, studies that provided only a conceptual framework or qualitative assumptions on users-related effects were excluded. After the systematic search, relevant publications that were referenced by reviews identified in the search query were added, leading to the final sample.

In the following paragraph, we introduced an alternate taxonomy intending to provide a guideline to classify studies according to the user-related effects and the energy impact.

2.2. A taxonomy to connect user-related effects and energy impacts

To standardize the connection between behavioral effects and energy implications, we first subdivide the effects of ICTs into micro-level effects and macro-level effects. While the micro-level includes all the effects related to user behavior choices and are independent of a country's economic growth and evolution, the macro-level encapsulates effects that affect and depend on the transformation of the whole society (including industry, business and government). Building upon the classification identified by Börjesson et al. [24], an overview of the user-related effects is presented.

- Micro-level effect:
- *Usage effect*: refers to the variation in the intensity of usage of digital technology to perform an activity
- *Substitution effect*: occurs when new technologies become available or when a change in users' activity patterns allows them to choose a technology that was not suitable before for their purpose.

Table 1
Inclusion and exclusion criteria applied in the selection phase of our systematic review. Reviews are excluded from the final sample but are used to assess state of the art and to compare our findings (cf. Section 4).

Inclusion criteria	
IC1	The study refers to an analysis of ICT impacts on user behavior
IC2	The study quantifies changes in user behavior
IC3	The study is in English

Exclusion criteria	
EC1	The study does not assess an impact on consumers behavior
EC2	The studies introduce a framework or a methodology without quantifying the behavioral change
EC3	The study is not accessible at the time of review (e.g. behind a paywall)
EC4	The study is a book, doctoral thesis, and technical report (only peer-reviewed academic journals and conference proceedings are included)
EC5	The study is a review
EC6	The study was published before 2010
EC7	The study focuses only on the direct impacts of ICTs, neglecting the higher-order impacts

[1] In the following paragraphs, the term "effect" is used to analyze the ICT-induced change in consumer behavior, while the term "impact" refers to the energy implications of this change.

- *Changed practice effect*: the introduction of ICT into users' daily life transforms their everyday practice and the related consumption patterns.
- *Time rebound effect*: ICT application impacts the time used to perform an activity, allowing for reallocating time to other activities
- *Induction rebound effect*: the adoption of an ICT application induces behavioral changes in another activity not connected to it
- Macro-level effect:
- *Space effect:* a change in a daily activity allows users to change where they live, influencing the demographic and urban evolution of a country
- *Transformational effect:* reflects changes in society due to the spread of new technologies, practices and economic growth
- *Learning effect*: increases in efficiency in performing an activity due to easier solutions for consumers
- *Spending effect*: occurs when ICT applications result in monetary savings that are then spent using that product more or purchasing other goods or services.

  This effect also encapsulates the increase in the consumption of goods allowed by lower prices due to ICT applications.

The eight identified categories of user-related effects are then linked to energy impacts. Based on the studies of Horner et al. [13], Court et al. [12], Pohl et al. [17], we grouped energy impacts into four categories: Direct impact, Indirect impact, Rebound impact and Systemic impact on technology and society, as shown in Table 2.

Although rebound impacts, used in the literature to describe an unexpected increase in energy demand, can be further divided into direct and indirect impacts [25] [26], the author of this paper decided to aggregate them under the general category "rebound impact", while keeping a detailed characterization of possible rebound effects under the classification of user-related effect. An example of the connection between users effects and energy impacts is shown in Table 2 using the activity of teleworking.

Relying on the proposed taxonomy, we classified papers in the final sample according to four criteria: (i) the user-related effect, (ii) the approach used to analyze the user-related effect of the ICT application, (iii) the approach to quantify energy implication, (iv) energy impact.

2.3. Estimating the scalability of results

A "scaling-up" index is developed to classify papers according to their ability to generalize their results and provide suggestions to policymakers about the role ICTs can play in the energy transition. The index is calculated as a linear combination of the following indicators: a) Spatial scale, b) Time horizon, c) Environmental implications, d) Energy impact. The time horizon of the papers is classified into "yearly" horizon (papers dealing with a time horizon shorter than one year), "short" horizon (time horizon shorter than ten years) and "long" horizon (time horizon longer than ten years). Similarly, the spatial scale is classified into "Regional scale", "Country scale", and "Global scale". The environmental implications are classified into "Policy needed" (policies are needed to enhance the positive environmental impact of ICTs), "Positive/Negative", "Uncertain" (environmental impact can be either positive or negative, depending on the assumptions, but policies are not suggested). Each indicator can take a value from 0 (minimum contribution to scaling-up) to 1 (maximum contribution to scaling-up), as shown in Table 3. For example, it is recognized that the time horizon selected plays a relevant role when performing an analysis concerning emissions from energy consumption [108] affecting, for example, the selection of an appropriate discount rate to adjust the present value of future decisions [109]. A long time horizon analysis is considered important to judge the effectiveness of an energy policy and understand its implication after the end of the support schemes [27]. For this reason, a paper covering a period longer than 10 years is given a value of 1 for the time horizon indicator. The higher value for the energy impact indicator is given to studies analyzing a large number of energy impacts, as they are assumed to reduce the risk of overestimating potential energy savings [7] compared to studies analyzing only one impact. A paper with a scaling-up index greater than or equal to 3 is considered "Strong" when applying its results to provide policy recommendations, as explained in Table 4. A scaling-up index in the range [2,3) is considered "Medium", while below 2 is considered "Weak" (see Section 3.4).

3. Results

3.1. Screening phase

The search identified a sample of 882 studies from Scopus, 980 studies from Google Scholar, and 24 from Web of Science. After removing duplicates, an initial sample of 1886 studies was identified. Next, 1770 articles were removed as considered not relevant to the topic after screening the abstracts. A complete test screening additionally excluded 71 studies as not pertinent to our inclusion criteria, leading to a sample of 44 studies. Finally, three additional papers considered relevant by authors and cited by the excluded reviews were added to this

Table 2
Taxonomy to connect user-related effects of ICT with their energy impacts. In column 4, an example of user-related effects for teleworking practice is shown, while in column 5, the energy impacts connected with teleworking practice are summarized.

Alternate taxonomy	Taxonomy described in this paper*		Example: Teleworking		
[7,8,17]	User-related effect	Energy impact	User-related effect		Energy impact
Direct impact	ICT usage	Direct	Increase usage of ICT technology	→	Laptop energy consumption Internet data consumption
Higher-order impact	Changed practices Substitution	Indirect	Reduce commuting to the workplace Increase time at home	→	Reduction of travel demand Increase energy demand for home space Energy used and saved in industry and services
	Time rebound Induction rebound	Rebound	More free time due to the saved time from less commuting	→	Increase travel demand for leisure activities or trips previously linked to commuting trips such as shopping. Reduction of traffic jams.
	Space effect Transformational effect Learning effect Spending effect	Systemic impact on technology and society	Move to the rural area due to less commuting to the workplace Economy growth Change in job and society Change in industrial and organizational structure Increase of available income due to saving for fuels	→	Energy used and saved in industry and services Increase in the commuting distance

* Based on Horner et al. [8], Court et al. [7], Pohl et al. [17]

Table 3
The four indicators used to evaluate the scaling-up indicator are defined as Spatial scale (Regional, Country, Global), time horizon (Year=" < 1 year", Short=" < 10 years", Long = "> 10 years"), energy impact (following the taxonomy in Section 2), environmental implications (Policy, Uncertain, Positive/Negative). Each indicator can take a value from 1 to 0, with the highest value given to the sub-categories that best contribute to scaling up the results. A long time horizon, a global scale, more than two energy impacts analyzed and positive environmental implications are considered the best contributor to scaling up the results to provide policy recommendations. On the other hand, studies covering an annual time horizon, a regional scale, a small number of energy impacts and uncertain environmental implications are assumed to be unable to provide results that can be generalized to make policy recommendations, so they have the lowest scaling-up index.

	Time horizon			Spatial scale			No. of energy impact			Environmental implications	
Definition	Long	Short	Yearly	Global	National	Regional	3,4	2	1	Policy/Pos/Neg	Uncert.
Numerical value	1	0.5	0	1	0.5	0	1	0.5	0	1	0

Table 4
The three values that the scalability indicator can assume are described, with the corresponding interval range.

Scaling-up criteria	Definition	Range
Strong	Results can be easily scaled up and used to provide policy recommendation	[3;4]
Medium	Results can be scaled up, but policy recommendations cannot be extrapolated without further assumptions	[2,3)
Weak	Results cannot be scaled up, and policy recommendations cannot be extrapolated	[0;2)

sample, providing a final sample of 47 studies (Fig. 1).

Fig. 2 Summarizes the publication year of the studies in the final sample, showing an increase in publications in recent years: 50 % of the identified studies were published between 2020 and 2022, reflecting the growing interest in digitalization and ICT applications.

Four different ICT applications were identified by analyzing the studies in the final sample: mobility, residency, ICT services, ICT use. The articles in the final sample were grouped by ICT applications and classified according to the four criteria identified in Section 2.2. Details of the classification of each paper are given in Tables 5-8, including a brief summary of the study's main findings.

3.2. Overview of the identified approaches

A general overview of the identified approaches used to quantify user-related effects and energy impacts is provided to help the reader familiarize themselves with the terminology used in the following sections.

Following the identification of user-related effects in Table 2, six effects were identified in the final sample: usage, substitution, changed

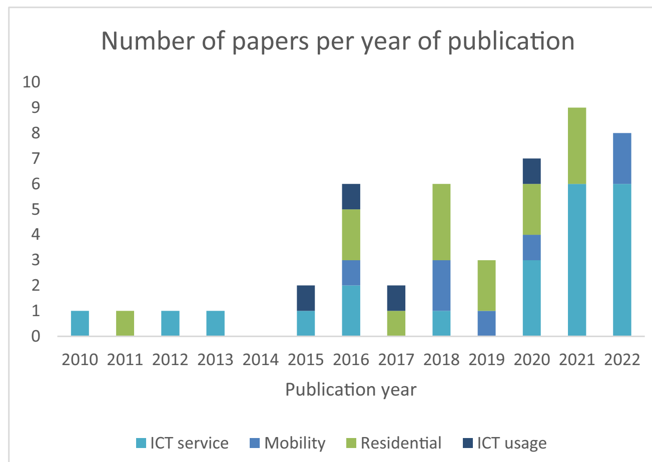

Fig. 2. Papers in the final sample are grouped by year of publication and type of ICT application.

practice, time rebound, spending, and induction rebound. A summary of the results is presented in Table 9. As some studies analyze more than one effect, the number of papers differs from the final sample size.

Six approaches were mainly used in the reviewed studies to quantify the identified user-related effects:

- *Empirical data/Scenario assumption*: 10 studies relied on scenario assumptions based on empirical data. In this case, authors utilized secondary data such as reviews, articles, open sources statistics and public databases as sources for their assumptions. "*A scenario is a coherent, internally consistent, and plausible description of a possible*

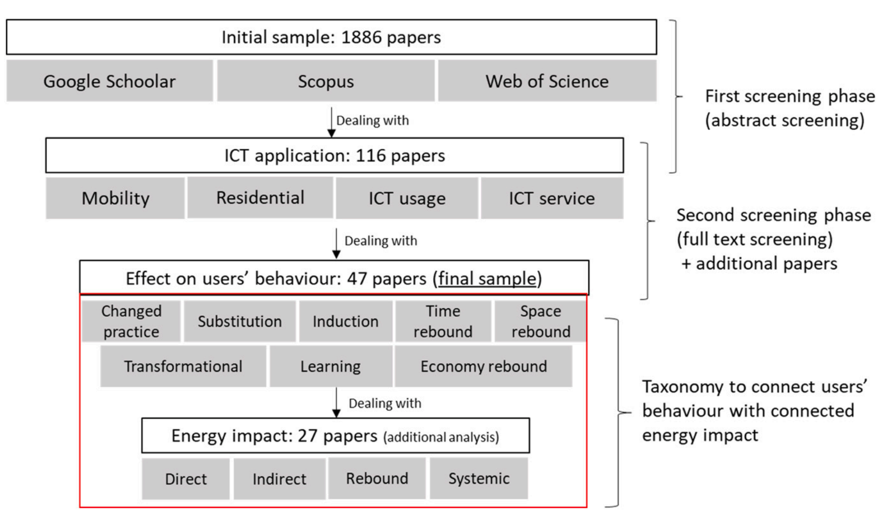

Fig. 1. The number of publications included and dropped in each step of the literature search is represented.

Table 5
Classification of studies in the final sample dealing with mobility applications. Column 3 shows the user-related effects analyzed in the paper, following the taxonomy introduced in Section 2. Papers are then subdivided by the approach used to quantify user-related effects, Energy analysis and energy impact. An "x" indicates that the paper does not perform an energy analysis and that all the parameters used to evaluate the scaling-up index (columns 7,8,9,10) are not analyzed. Papers dealing with energy analysis are then subdivided into spatial scale, time horizon, environmental implication and scalability of the results calculated according to Tables 3 and 4. The last column provides a summary of the analysis performed with the main conclusions.

Paper	Authors and year	User-related effect	ICT application	Approach	Energy analysis	Energy impact	Spatial scale	Time horizon	Environmental implication	Scaling-up	Summary
[34]	Noussan et al. 2020	Substitution Changed practice	Mobility ICT service (teleworking)	Scenario analysis	Simulation model	Indirect	Global/ EU	Long	Policy	Strong	Potential effects of digitalization on mobility demand energy consumption and CO2 emission (including mobility as service, shared mobility and autonomous vehicles).
[35]	Harb et al. 2018	Changed practice	Mobility	Naturalistic experiment	x	x	Regional	x	x	x	Impact of automated driving technologies on travel behaviors. Increase in vehicle miles traveled and the number of trips per week.
[36]	Pakusch et al. 2018	Substitution	Mobility	survey	x	x	Regional	x	x	x	Influence of autonomous driving on mobility behavior. Car sharing will benefit from automation, but the growth of car-sharing will reduce the use of public transport, while private cars will remain the preferred travel mode.
[37]	Mostofi 2022	Substitution	Mobility	Survey	x	x	Regional	x	x	x	Modal shift induced by ridesourcing. Ride sourcing can replace trips done with taxis, private cars and public transport
[38]	Tarnovetckaia et al. 2022	Substitution	Mobility	Survey	x	x	Regional	x	x	x	66 % of ride sourcing users shifted from public transport to these new mobility services in Moscow.
[39]	Paloheimo et al. 2016	Changed practice	Mobility	Survey	Analytical model	Indirect	Country	Year	Uncertain	Weak	Crowdsourced delivery reduces an average of 1.6 km driven by car in Finland.
[40]	Cellina et al., 2019	Substitution	Mobility	Real data (app based)	Extrapolation of real data	Indirect	Regional	Year	Uncertain	Weak	App-based experiment to persuade sustainable mobility patterns in Switzerland produced a decrease in CO2 emissions and energy consumption per kilometer.

future state of the world. [..] A set of scenarios often is adopted to reflect, as well as possible, the range of uncertainty in projections." [28]

- *Survey/Questionnaire*: 17 studies used survey data to analyze behavioral changes. In particular, these studies utilized and analyzed their own designed surveys or regional/national surveys. This approach allows researchers to collect data from a selected sample of individuals and then use the information to make inferences about the wider population. Most surveys were conducted as online surveys or questionnaires sent by email, allowing researchers to contact many people in a short amount of time, avoiding problems connected to geographic distances and reducing the cost [29]. In addition, the survey approach has been used to analyze different types of user-related effects, thanks to the flexibility to create an ad hoc survey for the specific topic of interest.
- *Living lab/ Field experiment/ Real-time experiment*: 7 studies applied the living lab or field experiment approach, where participants' lifestyles and decisions are monitored on a daily basis for a fixed period. This user-centered approach is a combined lab−/household system [30], relevant to test the acceptance of sustainable technologies and practices among users, focusing on the social needs of people and including technical and socioeconomic influences.
- *Agent-Based Modelling*: 4 studies used the Agent-Based Model (ABM) approach to analyze different user-related effects. The ABM approach [31] allows for investigating the spread of a specific behavior over time and society, accounting for social parameters to explain how human interactions influence general trends and how personal beliefs impact the adoption and spread of technologies. The ABM is recognized as an appropriate tool to target people with specific social-economic characteristics that are more willing to adopt environmentally friendly behavior and for whom it is possible to create ad-hoc environmental policies.
- *Time use diary*: 3 studies relied on the time-use diary approach, which requires attenders to compile a diary to take track of their daily routine, connecting everyday activity with the time of the day when the activity is performed. The approach is used to understand if ICT usage changes when users perform their activities and if a change in time also changes how and where the practice is performed.
- *Social practice*: 1 study used the social practice approach to understand how the usage of ICT changes the lifestyle of users. The social practice approach puts at the center of the study the evolution of everyday practices performed by individuals over time and space, analyzing how new practices arise from the utilization of new technologies (such as ICTs [32] while old ones are phased out. Furthermore, considering that energy is needed and used to accomplish a social practice [30], understanding how social practices develop and change over time and space also means understanding the evolution of trends in energy demands [31].

Out of 47 papers in the final sample, 27 assessed energy impacts related to behavioral changes. Five methods were identified to perform the energy analysis:

- *Simulation model*: 2 papers adopted a simulation model to analyze energy impacts. This category includes models that are too complex to be solved analytically and requires the use of a computer [32]
- *LCA*: 7 studies combined their findings on user-related effect of ICT with a Life Cycle Assessment (LCA) approach by modelling cause-effect relationships throughout the entire value chain of ICT production, use and disposal phase [28].
- *Extrapolation of real-time data*: 6 papers relied on real-time data to extrapolate the energy demand related to the ICT application. Real-time data are provided via smart metering, web-based applications or energy bills.
- *Environmentally extended input-output analysis (EEIO):* 2 papers integrated the economic rebound effect of ICT applications into environmental consideration, performing an environmentally extended

Table 6
Classification of residential application studies. Classification of studies in the final sample dealing with mobility applications. Column 3 shows the user-related effects analyzed in the paper, following the taxonomy introduced in Section 2. Papers are then subdivided by the approach used to quantify user-related effects, Energy analysis and energy impact. An "x" indicates that the paper does not perform an energy analysis and that all the parameters used to evaluate the scaling-up index (columns 7,8,9,10) are not analyzed. Papers dealing with energy analysis are then subdivided into spatial scale, time horizon, environmental implication and scalability of the results calculated according to Tables 3 and 4. The last column provides a summary of the analysis performed with the main conclusions.

Paper	Authors and year	User-related effect	ICT application	Approach	Energy analysis	Energy impact	Spatial scale	Time horizon	Environmental implication	Scaling-up	Summary
[41–43]	Walzberg et al. 2018, Walzberg et al. 2019, Walzberg et al. 2020	Changed practice Spending	Residential	ABM	LCA + environmentally extended input-output	Direct Indirect Systemic	Regional	Year	Policy	Medium	2018: engaging pro-environmental behavior following energy feedback from energy management system in smart houses 2019: several behavior changes considered 2020: spending effect
[44]	Pohl et al. 2021	Induction	Residential	survey	LCA	Rebound Direct	Country	Short	Policy	Medium	Smart home with smart heating, change in users behavior
[45]	Tuomela et al. 2021	Changed practice	Residential	Real life experiment	Real time data	Indirect	Regional	Year	Uncertain	Weak	Home energy management system reduced by 30 % the electricity consumption of 10 Finnish houses.
[46]	Bastida et al. 2019	Changed practice	Residential	Empirical data	Simulation model	Indirect	Global (EU)	Long	Positive	Strong	ICT-based application in households decreases electricity usage, improves energy efficiency, and contributes to GHG reduction. ICT based effect on consumers' behavior to reduce electricity consumption.
[47]	Renz et al. 2016	Changed practice	Residential	Survey	Extrapolation real data	Indirect	Global (EU)	Short	Uncertain	Weak	ICT feedback instruments affected behaviors and achieved saving in electricity and heating demand.
[48]	Eon et al. 2018	Changed practice	Residential	Social practice	x	x	Regional	x	x	x	System practice approaches showed that automation affects households practice and can be considered an effective solution to influence resource use in the home.
[49]	Cominola et al. 2021	Changed practice	Residential	Real time data	x	x	Regional	x	x	x	Consumption-based feedback achieved an 8 % reduction of volumetric water consumption in Spain.
[50]			Residential	survey	x	x	Regional	x	x	x	

(continued on next page)

Table 6 (*continued*)

Paper	Authors and year	User-related effect	ICT application	Approach	Energy analysis	Energy impact	Spatial scale	Time horizon	Environmental implication	Scaling-up	Summary
	Alharbi et al. 2016	Changed practice									ICT artefact that provides direct and indirect persuasion to deliver messages about energy conservation behavior.
[51]	Loock et al. 2011	Changed practice	Residential	Field experiment	x	x	Regional	x	x	x	Online applications aiming at motivating energy conservation should incorporate bonus points to reward desirable action immediately.
[52]	Hedin et al. 2018	Changed practice	Residential	survey	x	x	Regional	x	x	x	A serious game is developed to help people learn about their own energy consumption and to support their changes toward sustainable habits. A positive correlation is found between future behavioral changes and the perceived usefulness of the application.
[53]	Baedeker et al. 2020	Changed practice	Residential	Living lab	Living lab/ estimation	Indirect	Regional	Year	Positive	Weak	User-centered building management system as a prototype for office buildings to enhance energy efficiency.
[54]	Ro et al. 2017	Changed practice	Residential	Real data experiment	Real data	Indirect	Regional	Year	Positive	Weak	New sustainability game reduced people's household electricity consumption.

input-output analysis (EEIO). EEIO is a consumption-based approach used to understand the energy requirements or the environmental burden associated with specific sectors or the components of final demand [28].

- *Econometric analysis:* 2 papers applied regression analysis, multivariate analysis, factor analysis or structural equation modelling to understand the relationships among observed variables [33].
- *Analytical model:* 7 papers adopted analytical calculation to analyze energy impacts.

In the following sections, the results of the systematic search are discussed in detail for each ICT application, providing examples of users' behavior analyzed and details on the approaches used to estimate them. Where applicable, the type of energy impacts considered and the approaches used to quantify them are also described.

3.3. Mobility application

Seven studies analyzed the innovation introduced in the field of mobility by ICTs, with two studies analyzing the impact of automated vehicles on user behavior, five studies dealing with the lifestyle changes introduced by car sharing and crowdsourcing, one paper focusing on the impact of a persuasive app to induce behavioral change in travel patterns (Table 5).

To estimate user-related effects, one paper used empirical data [34], four papers used a survey [36–39], and two papers used a field experiment [36,40]. The changed practice effect is analyzed in three studies [34,35] [39], while five studies concentrated on the substitution effect [34,36–38,40].

Focusing on the changed practice effect, Paloheimo et al. [39] discovered from a survey conducted after a real-life experiment that crowdsourced deliveries adopted by public service libraries can save 1.5 km per car.

Table 7
Classification of ICT service application studies. Classification of studies in the final sample dealing with mobility applications. Column 3 shows the user-related effects analyzed in the paper, following the taxonomy introduced in Section 2. Papers are then subdivided by the approach used to quantify user-related effects, Energy analysis and energy impact. An "x" indicates that the paper does not perform an energy analysis and that all the parameters used to evaluate the scaling-up index (columns 7,8,9,10) are not analyzed. Papers dealing with energy analysis are then subdivided into spatial scale, time horizon, environmental implication and scalability of the results calculated according to Tables 3 and 4. The last column provides a summary of the analysis performed with the main conclusions.

Paper	Authors and year	User-related effect	ICT application	Approach	Energy analysis	Energy impact	Spatial scale	Time horizon	Environmental implication	Scaling-up	Summary
[55]	Borggren et al. 2013	Changed practice Usage	ICT service	survey	LCA	Direct Indirect	Regional	Year	Uncertain	Weak	Mediated meetings using a personal computer can reduce GHG and energy demand, but the energy savings' potential changes considering the frequency of use and the transport mode involved in the analysis.
[56]	Seidel et al. 2021	Changed practice Usage	ICT service	Scenario assumption	Analytical model	Direct Indirect	Country	Short	Positive	Medium	Virtual conference could contribute between 0.3 % and 2.8 % to the German mitigation effort.
[57]	Patwary et al. 2022	Changed practice	ICT service	Survey	x	x	Country	x	x	x	Online shopping reduces trips for grocery shopping
[58]	Motte-Baumvole et al. 2022	Changed practice	ICT service	Survey	Econometric analysis	Indirect	Country	Year	Uncertain	Weak	Online shopping can reduce the number of trips for grocery shopping, resulting in a 37 % reduction in households CO2 emissions.
[59]	Frick and Matthies 2020	Spending	ICT service	survey	x	x	Regional	x	x	x	The study examines whether perceived behavioral efficiency gains of online shopping are associated with a higher consumption level of good or services. Perceived behavioral gains of online shopping were linked to higher consumption levels of digital devices and travels.
[60]	Tabata and Wang 2021	Changed practice Usage	ICT service	Empirical data	LCA	Direct Indirect	Country	Short	Negative	Medium	CO_2 emissions of online music and video streaming devices
[61]	O'Keefe et al. 2016	Changed practice Time rebound	ICT service	Survey	Analytical model	Indirect	Regional	Year	Positive	Weak	Environmental effect of telecommuting. There are carbon emission savings from individuals adopting telecommuting
[62]	Shah et al. 2022	Changed practice Time rebound	ICT service	Survey	x	x	Regional	x	x	x	Telework reduces mandatory and maintenance tours while increasing online shopping.
[63]	Kim et al. 2015	Changed practice	ICT service	Survey	x	x	Country	x	x	x	Telecommuters travel more than

(continued on next page)

Table 7 (*continued*)

Paper	Authors and year	User-related effect	ICT application	Approach	Energy analysis	Energy impact	Spatial scale	Time horizon	Environmental implication	Scaling-up	Summary
		Time rebound									non-telecommuters.
[64]	Kim 2016	Changed practice Time rebound	ICT service	Survey	x	x	Country	x	x	x	Telecommuters' non work trips are greater than those who do not telecommute.
[65]	Wöhner 2022	Changed practice Time rebound	ICT service	Survey	x	x	Country	x	x	x	Teleworkers commute less but their non-work travel increase in Switzerland.
[66]	McArthur et al. 2022	Changed practice Time rebound	ICT service	Survey	x	x	Regional	x	x	x	Teleworkers reduce the number of trips for work purpose, but no evidence of rebound effects is observed.
[67]	Cerqueira et al. 2020	Changed practice Time rebound	ICT service	Survey	Econometric analysis	Indirect Rebound	Country	Short	Policy	Medium	Trade-off effects between work and non-work trips is observed for teleworkers, which increase CO2 emission levels.
[68]	Villeneuve et al. 2021	Changed practice Time rebound Induction	ICT service	Survey	x	x	Country	x	x	x	Teleworking impacts energy-related behaviors and attitudes, including the energy behavior at home and in the office.
[69]	Bieser et al. 2021	Changed practice Time rebound Substitution	ICT service	Time use diary, living lab	Living lab/ estimation	Indirect Rebound	Regional	Year	Policy	Weak	Telecommuters use less time traveling and more time on chores and leisure activities. The substitution toward a more energy-efficient transport modes depends if they work from home or from a co-office.
[70]	Vaddadi et al. 2020	Time rebound Substitution Changed practice	ICT service	Time use diary, living lab	Living lab/ estimation	Indirect Rebound	Regional	Year	Policy	Weak	Energy requirements associated with co-working can counterbalance commuted related energy savings. Co-working should be accompanied by additional energy savings measures
[71]	Sekar et al. 2018	Time rebound Changed practice	ICT service	Time use survey	Econometric analysis (Time use model)	Indirect Rebound	Country	Short	Positive	Medium	More time at home and less time traveling is observed, with a positive reduction of 1.8 % of the US national demand in 2021
[72]	Tenailleau et al. 2021	Changed practice Time rebound Substitution	ICT service	ABM	Analytical model	Indirect Rebound	Regional	Year	Uncertain	Weak	An agent based model analyzes the impact of teleworking on trips, showing an average reduction in emission of 0.42 % for an increase of 1 % in teleworking.

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Table 7 (*continued*)

Paper	Authors and year	User-related effect	ICT application	Approach	Energy analysis	Energy impact	Spatial scale	Time horizon	Environmental implication	Scaling-up	Summary
[73]	Scheck 2010	Changed practice Spending	ICT service	Empirical data	Analytical model	Direct Indirect Rebound Systemic	Regional	Year	Uncertain	Weak	CO_2 emission from mobile networks and environmental impact of ICTs resulting from different user behavior.
[74]	Fu et al. 2012	Changed practice	ICT service	Empirical data/ scenario	Analytical model	Indirect	Country	Year	Policy	Weak	Home working allows an average net savings of 9.33 Kwh per day after deducing the energy associated from home working in the residential sector.
[75]	Guerin 2021	Changed practice Time rebound	ICT service	Empirical data/ scenario	LCA	Indirect rebound	Country	Year	Policy	Medium	Teleworking is prove to reduce environmental impacts only if the worker travels >30 km. The increase in the residential energy demand related to teleworking can offset the reduction obtained by less commuting.
[76]	Navaratnam et al. 2022	Changed practice	ICT service	Empirical data/ scenario	Analytical model	Indirect	Regional	Year	Policy	Weak	Effect of teleworking on transport, residential and commercial sector. Teleworking from 1.5 to 4 days per week can reduce by 1.21 to 5.76 MT CO2 eq per year in Australia.

Introducing two different scenarios to analyze the impact of autonomous vehicles and car-sharing diffusion on the transport demand in Europe, Noussan et al. [34] analyzed two users' effects. Based on empirical data, one of the scenarios assumed an increase in the miles traveled due to the use of autonomous vehicles. At the same time, a substitution effect is observed between car sharing and public transport. In line with these assumptions, an increase in the number of trips and the miles traveled related to the usage of autonomous vehicles emerged from a realistic experiment designed by Harb et al. [35].

The substitution effect of car-sharing is analyzed in different papers. Utilizing an online survey to understand the impact of automated vehicles on users 'preference for transport mode, Pakusch et al. [36] discovered that automated vehicles for car sharing could substitute the demand for public transport. Similarly, the survey's results analyzed by Mostofi [37] showed a substitution effect of ride-sourcing of 30 % for private cars and 24 % for public transport, while Tarnovetckaia et al. [38] concluded that the combination of ride-sourcing and car sharing would shift 66 % of the public transport demand in Moscow.

An app-based experiment was performed by Cellina et al. [40] to analyze the impact that persuading information provided via an app can have on travel behavior in two cantons of Switzerland. They observed a substitution effect from private cars to lower CO_2 emission transport mode for the regular routes of app users.

Three papers deal with the energy implications of the identified behavioral change in transport patterns. Extrapolating real-time data, the substitution effect observed by Cellina et al. [40] reduced by 0.136 Kwh per km the energy consumption related to the transport demand. Combining their real-time data with assumptions to extrapolate their results to Finland, Paloheimo et al. [39] calculated that a reduction of 10 % of the trip traveled by car due to crowdsourcing delivery can reduce 4 % of the carbon footprint per person due to a reduction in the consumption of crude oil. Noussan et al. [34] performed an energy analysis using a deterministic model with a linear calculation of the indirect impact and rebound impact of the identified behavioral changes. With the exploitation of digital technologies to maximize the population's benefit, Europe's energy consumption can increase by 20.1 % in 2050 compared to the baseline scenario.

3.4. Residential application

The residential application of ICT is analyzed in 14 papers in the final sample (Table 6). Smart homes and smart building management systems are analyzed in 6 papers [41–43] [44] [45] [53], while to provide information on energy consumption and incentivize positive behaviors, four studies analyzed the role of feedback devices [48] [46] [49] [47], two studies developed a web application [51] [50] and 2 used serious game [52] [54].

Three studies developed an ad-hoc ABM [41–43] to estimate user-related effects, while one paper used empirical data [46], four papers used a survey [44] [47] [50] [52], five papers used a field experiment or a living lab approach [45] [49] [51] [53] [54], one paper used a social practice approach [48]. The changed practice effect is analyzed in all the studies, while one paper deal with the spending effect [43] and 1 with the induced effect. [44].

In their studies, Walzberg et al. [41–43] quantified the changed practice effect induced by green feedback (e.g. switching off lighting

Table 8
Classification of ICT usage application studies. Classification of studies in the final sample dealing with mobility applications. Column 3 shows the user-related effects analyzed in the paper, following the taxonomy introduced in Section 2. Papers are then subdivided by the approach used to quantify user-related effects, Energy analysis and energy impact. An "x" indicates that the paper does not perform an energy analysis and that all the parameters used to evaluate the scaling-up index (columns 7,8,9,10) are not analyzed. Papers dealing with energy analysis are then subdivided into spatial scale, time horizon, environmental implication and scalability of the results calculated according to Tables 3 and 4. The last column provides a summary of the analysis performed with the main conclusions.

Paper	Authors and year	User-related effect	ICT application	Approach	Energy analysis	Energy impact	Spatial scale	Time horizon	Environmental implication	Scaling-up	Summary
[77]	Le Vine et al. 2016	Time rebound	ICT usage	Time use diary	x	x	Country	x	x	x	Relationship between internet usage and time use with a positive correlation of internet usage with time spent traveling and time spent at out-of-home activities
[78]	Bris et al. 2017	Spending	ICT usage	dataset	x	x	Global (Several countries)	x	x	x	Households transport expenditure is negatively correlated with internet penetration
[79]	Santarius and Bergener 2020	Time rebound	ICT usage	survey	x	x	Regional	x	x	x	Correlation between ICT usage and filling breaks and downtimes with activities and with performing activities in parallel. ICT was correlated with performing activities faster and performing time-saving activities instead of time-consuming activities
[80]	Håkansson et al. 2015	Spending	ICT usage	Scenario, empirical data	Environmentally extended input-output analysis (EEIO)	Direct Systemic	Country	Short	Policy	Medium	Efficiency improvement in ICT equipment will produce a rebound effect that reduces potential emissions savings. Increasing spending for ICT products will reduce the consumption of other products and services, leading to an overall reduction of emissions.

more often, reducing thermostat temperature) and load shifting on households' behavior using an agent-based model approach. These energy conservation behavior lead to different economic savings that can be reallocated to buy additional products and services (the savings rebound effect was quantified via scenario assumptions). Pohl et al. [44] proposed an online survey to quantify the induction rebound effect of smart houses on households' behavior in terms of temperature setting, concluding that no significant difference was identified between the smart home sample and the control group. In a real-life experiment, Tuomela et al. [45] discovered that a home energy management system can induce behavioral changes due to increased awareness. However, the changed practice effect depends on the adaptability of the households, as a family with small children cannot easily adapt its temperature settings. Baedeker et al. [53] tested a user-centered building management system in Germany. By adopting a living lab approach, they demonstrate the usefulness of the device in inducing changes in the offices' ventilation practices.

Feedback on the energy consumption of the building or providing energy savings tips can convince households to modify their behavior, resulting in a changed practice effect. Bastida et al. [46] estimated this

Table 9
Summary of the reviewed papers classified according to ICT applications, user-related effect, approach for users' behavior, approach for energy analysis, energy impact.

ICT application	No. of studies	Specific studies
Mobility	7	[34,35–40]
Residential	14	[41–43,44–50,51,52–54]
ICT Service	22	[55–73,75,76,77]
ICT usage	3	[78,79,80]
User-related effect		
Usage effect	2	[55,56]
Substitution	9	[34,36,37,38,40,69,70,72]
Changed practice	33	[34,35,39,41–43,45,46,47,48,52,53,54,55,56,57,58,60,61,62,63,64,65,66,67,68,69,70,71,72,73,74,75,76]
Time rebound	14	[61,62,63,64,65,66,67,68,69,70,71,72,75,77,79]
Spending	5	[41–43,59,73,78,80]
Induction rebound	2	[44,68]
Approach to quantify users related effect		
Empirical data/scenario assumption	10	[34,46,56,60,73,74,75,76,78,80]
Survey/questionnaire	17	[36–39,44,47,52,55,57,58,59,61,62,63,64,65,66,67,68,71,79]
Living lab/ field experiment	7	[35,40,45,53,54,69,70]
ABM	4	[41–43,72]
Time use diary	3	[69,70,77]
Social practice	1	[48]
Approach for Energy analysis		
Simulation model	2	[34,46]
LCA	7	[41–43,44,55,60,75]
Extrapolation of real time data	6	[40,45,47,53,54,69]
Environmentally extended input-output analysis (EEIO)	2	[41–43,80]
Econometric analysis	2	[67,71]
Analytical model	7	[39,56,61,72,73,74,76]
Energy impact		
Direct	8	[41–44,55,56,60,73,80]
Indirect	23	[34,39,40,41–43,45,47,46,53,54,55,56,58,60,61,67,69,70,71,72,73,74,75,76]
Rebound	10	[34,41–43,44,67,69,70,71,72,73,75]
Systemic	4	[41–43,73,80]

effect via scenario assumption, while Renz et al. [47], analyzing survey panel data, discover that ICT feedbacks are useful for inducing changes in users' behavior as reducing the indoor temperature, shortening the showers, and switching off TV or other equipment when not used. A social practice approach by Eon et al. [48] confirmed that ICT feedback could influence water savings, changing how people use water. Similar conclusions are reached by the real-time data analyzed by Cominola et al. [49]. In line with the feedback device results, web-based applications also encourage people to change habits such as turning off appliances in standby mode, unplugging unnecessary cables and reducing indoor temperature settings [50–52,54].

Nine papers quantified the energy impact of these user-related effect, with four papers using LCA analysis [41–43] [44], four papers extrapolating real-time data [45] [47] [53] [54], one paper applying a simulation model [46].

Combining LCA analysis with ABM, Walzberg et al. [42] concluded that 2 % of electricity could be saved due to energy feedback in smart homes (indirect energy impact). However, if households' economic savings from load shifting programs are spent on polluting commodities such as gas or diesel oil (systemic impact), the potential environmental benefit of smart houses is dimmer by 5 % [43]. The LCA study of Phol et al. [44] concluded that a 6 % of annual heating savings needs to be reached by smart houses in Germany to compensate for the energy used in the production and operation phase of the system. Analyzing real-time data, Tuomela et al. [45] concluded that a home energy management system can reduce by 30 % the electricity consumption of Finnish households.

Renz et al. [47] extrapolated real-time data to understand the indirect energy impact of behavioral changes induced by feedback technology. They concluded that behavioral changes such as reducing the indoor temperature, shortening the showers, and switching off TV or other equipment could lead to a savings of 10 % in electricity. Ro et al. [54] showed a potential energy reduction of 26 kWh per month as a consequence of the participation in a serious game of American households. Real-time data analysis proved that by combining a reduction of temperature settings with changes in ventilation practices, a 20 % reduction in the energy demand of offices in Germany can be achieved [53].

A simulation model is applied by Bastida et al. [46] to analyze the potential energy impact of ICT's induced behavioral changes on Europe's energy sector, concluding that they could contribute to a total electricity savings of 80 TWh per year [46].

3.5. *ICT services*

Twenty-one studies (Table 7) analyzed the virtualization of services through the applications of ICT, which allows users to partially (or totally) substitute a material service with a virtual one, such as teleworking (17 papers), online business meetings(2 papers), online music (1 paper) and online shopping (3 papers).

The adoption of mediated meetings can replace the need to travel by car, train or airplane (change practice effect) while increasing the usage of ICT technology (usage effect). Borggren et al. [55] organized meetings and interviews with different companies to analyze these changes in users' behavior. They performed an LCA analysis to discover that an average savings of 1900 TJ per year can be achieved. Similar changes in users' behavior and related energy impacts are analyzed by Seidel et al. [56] using scenario assumptions and analytical mode, concluding that videoconferencing can contribute up to 2.8 % to the German mitigation effort in 2030.

The analysis of a travel survey confirmed that online shopping reduces the number of shopping trips (changed practice effect) [57,58], but it does not increase the number of non-shopping trips (no rebound effect) [58]. Although online shopping can foster the consumption of digital services and travel (induction rebound effect), as discovered by the analysis of an online-survey by Frick and Matthies [59]. Only Motte-

Baumvol et al. [58], applying a structural equation modelling, estimated that the indirect and rebound energy impact of online shopping can lead to a 37 % reduction of household CO2 emissions in England.

Tabata and Wang [60] analyzed how the evolution of online music and video streaming adoption in Japan in four years produced lifestyle changes in society, increasing the amount of music streamed and listened to. An LCA analysis assessed that 1545 kt CO_2 emissions are related to the direct and indirect energy impact of increased online music and video streaming use.

3.5.1. The case of teleworking

ICT technology allows people to relocate their work activities to different places than the offices (working from home, co-working in a different location). Surveys' results [61–67] indicated that teleworking allows households to reduce the number of trips and miles traveled compared to those who do not perform teleworking (changed practice effect). Additionally, time saved due to a reduction in commuting can be reused by households (time rebound effect) to perform other activities (working, leisure time, shopping, and household tasks) [61,68]. Increasing the time spent at home can induce additional behavioral change, such as increasing the apartment's indoor temperature [68].

The time rebound effect is evident from the results of different travel surveys [62–67] [71], where teleworking is proven to increase the number of non-commuting trips, as teleworkers cannot concatenate other activities (e.g. shopping) with the commuting trips.

Similar conclusions are reached by Bieser et al. [69], analyzing how the co-working practice impacted the time use of employees in Stockholm via the time use diary approach. Together with Vaddadi et al. [70], they discovered that it could lead to a substitution effect concerning the transport mode, as co-working spaces are usually located in the neighborhood of the households, providing an incentive to use bikes, public transport or walking instead of traveling by private cars.

Applying an Agent-Based model (ABM) approach, Tenailleau et al. [72] investigated the combination of different users' effects induced by teleworking, such as the changed practice effect, the time rebound effect and the substitution effect.

Several papers relied on empirical data to quantify user-related effects of teleworking, such as the number of kilometers saved [74] [75] [34] [76] [73], the time rebound effects related to increasing traveling activities for shopping [75], the substitution effect to more efficient transport mode [34] and the spending effect [73].

Twelve papers analyzed the energy implications of behavioral changes due to teleworking, with eight studies adopting analytical models to quantify them [61], [34,73], [69,70,72,74,76]. The energy savings obtained by less commuting are considered in all of them. Additionally, three of them corrected these savings by including the increase in the residential energy demand [70,74,76], two included the change in the energy demand of offices spaces [70,76], two addressed the rebound impact arising from the increase in non-working related trips and the substitution effect on transport mode [69,72].

A structural equation model allowed Cerqueira et al. [67] to estimate the rebound energy impact of the increase in non-working related trips. It led to an increase in transport demand and fuel consumption, resulting in an increase of 20 kg CO_2 emissions level compared to the CO_2 emissions of a person that does not telework.

A Time use model was developed by Sekar et al. [71] to analyze the indirect energy impact of teleworking on transport and residential demand in the United States, concluding that savings in commuting offset the increase in the residential energy demand, leading to a savings of 1.8 % of the national energy demand.

LCA analysis is performed by Guerin [75] to analyze the environmental impact of teleworking, including assumptions of the change in commuting demand, offices and residential energy demand. For example, if the residential energy demand overcomes 1212 KWh per year, the savings obtained by less commuting are offset.

3.6. ICT usage

The category ICT usage aggregates papers dealing with the usage of ICT devices such as laptop, computer, mobile phone and their effects on users' behavior (Table 8).

Santarius and Bergener [79] used a survey to verify that ICT use allows performing activities faster, allowing users to re-spend the time saved on other activities (time rebound effect). Le Vine et al. [77] analyzed a travel diary survey to confirm that ICT technology usage correlates with increased time spent on out-of-home activities. A cross-sectoral dataset analysis revealed that households' transport expenditure is negatively correlated with Internet penetration, underling the changed practice effect of ICT on physical mobility and strengthening the assumption that ICT can help overcome the cost of spatial separation [78].

The efficiency increase of ICT technology can save energy and increase households' available income. Håkansson and Finnveden [80] relied on scenario assumption to estimate how this spending effect can change the spending pattern of Swedish households. Performing an EEIO for Sweden, they discovered that the change in spending patterns (e.g. relocating the spending to products from sectors with high CO_2 emissions) could reduce the environmental benefit related to the efficiency increase in the ICT sector [80].

3.7. Quantify the implications of behavioral changes induced by digitalization on energy transition

The previous sections show that of the 47 studies in the final sample, only 27 address the energy implications of ICT applications. The 27 studies were further categorized according to the time horizon, the spatial scale and the energy impacts they investigated. The scaling-up index, discussed in Section 2.3, is then calculated for these studies to assess their ability to evaluate the role of ICT applications in the energy transition (Table 10).

Two out of 27 papers are classified as "Strong" in providing information on the role of ICT in the energy transition by the scaling-up index. Ten are classified as "Medium" while 15 are estimated as "Weak. Table 11 reports the two "strong" papers, characterized by a long time horizon, a global spatial scale, and a high number of analyzed energy impacts. One analyzes the implication of ICT for the transport sector, while the other analyzes the residential sector. Noussan et al. [34] compared two scenarios to assess the positive or negative potential of digitalization for the European transport sector. One scenario, called "Responsible Digitalization", assumed the use of digital technology to optimize the collective benefits, leading to a 25 % energy demand reduction in 2050. The other scenario, which assumes the use of digital technologies to optimize individual benefits, so-called "Selfish digitalization", will increase final energy consumption by up to 20 % in 2050. Policies were suggested to benefit from using ICT applications, such as promoting the digitalization of services, efficient transport technologies, and adoption of public transport.

Bastida et al. [46] quantified the CO_2 mitigation impact of ICT-based intervention in European households for electricity use, recognizing that feedbacks provided by ICT solutions, as well as dynamic prices and tariffs to incentivize load shifting and demand response strategies, are essential to contribute to the 1.5 °C target. The combination of these ICT-based interventions can contribute to the European target of reducing CO_2 eq. emissions by up to 3.3 % per year.

Regarding the approaches used to quantify the changes in users' behavior, these two papers relied on empirical data to support their scenario assumptions. They adopted deterministic models to quantify the impact of ICT application over a long time horizon for European countries.

Other approaches identified to analyze user-related effects, such as surveys, living labs, and time use diaries, are mainly applied to case studies with a small spatial scale and for a short time horizon, which

Table 10
The scalability indicator is evaluated as explained is Section 2.3. The table provides information about the time horizon, spatial scale, energy impact and environmental implication of each study. To better visualize the results, a color scale is applied, from green (Strong) to red (Weak).

		Time horizon			Spatial scale			Energy impact	Environmental implications			Scalability	
Paper	Authors	Long	short	year	Global	national	regional		Policy	Uncert.	pos/neg	Value	
[34]	Noussan et al. 2020	1			1			Indirect	1			3	Strong
[39]	Paloheimo et al. 2016			0		0,5		Indirect		0		0,5	Weak
[40]	Cellina et al., 2019			0			0	Indirect		0		0	Weak
[43]	Walzberg et al. 2020			0			0	Direct Indirect Systemic	1			2	Medium
[44]	Pohl et al. 2021		0,5			0,5		Direct Rebound	1			2.5	Medium
[45]	Tuomela et al. 2021			0			0	Indirect		0		0	Weak
[46]	Bastida et al. 2019	1			1			Indirect			1	3	Strong
[47]	Renz et al. 2016		0,5		1			Indirect		0		1,5	Weak
[53]	Baedeker et al. 2020			0			0	Indirect			1	1	Weak
[54]	Ro et al. 2017			0			0	Indirect			1	1	Weak
[55]	Borggren et al. 2013			0			0	Direct Indirect		0		0,5	Weak
[56]	Seidel et al. 2021		0,5			0,5		Direct Indirect			1	2,5	Medium
[58]	Motte-Baumvole et al. 2022			0		0,5		Indirect Rebound		0		1	Weak
[60]	Tabata and Wang 2021		0,5			0,5		Indirect			1	2	Medium
[61]	O'Keefe et al. 2016			0			0	Indirect Rebound			1	1,5	Weak
[67]	Cerqueira et al. 2020		0,5			0,5		Indirect Rebound			1	2,5	Medium
[69]	Bieser et al. 2021			0			0	Indirect Rebound			1	1,5	Weak
[70]	Vaddadi et al. 2020			0			0	Indirect Rebound			1	1,5	Weak
[71]	Sekar et al. 2018			0		0,5		Indirect Rebound			1	2	Medium
[72]	Tenailleau et al. 2021			0			0	Indirect Rebound		0		0,5	Weak
[73]	Scheck 2010			0			0	Direct Indirect Rebound Systemic		0		1	Weak
[74]	Fu et al. 2012			0		0,5		Indirect	1			1,5	Weak
[75, 76]	Guerin 2021			0		0,5		Indirect rebound	1			2	Medium
[76]	Navaratnam et al. 2022			0			0	Indirect	1			1	Weak
[80]	Håkansson et al. 2015		0,5			0,5		Direct Systemic	1			2,5	Medium

Table 11
Papers dealing with energy implications and identified as Strong by the scalability indicator.

Paper	Authors and year	User-related effect	ICT application	Approach	Energy analysis	Energy impact	Spatial scale	Time horizon	Environmental implication
[34]	Noussan et al. 2020	Substitution Changed practice	Mobility ICT service	Scenario analysis	Simulation model	Indirect Rebound	Global/ EU	Long	Policy
[46]	Bastida et al. 2019	Changed practice	Residential	Empirical data	Simulation model	Indirect	Global (EU)	Long	Positive

reduces the possibility of scaling-up their results. For example, Pohl et al. [44] concluded that smart home systems in Germany could provide environmental benefits if at least 6 % of annual heating energy is saved. However, long-term measurements of household energy consumption are needed to validate their results.

The studies categorized as Medium (Table 12) due to a limited number of energy impacts, a small spatial scale, or a short time horizon that weakened the robustness of their results showed a variety of approaches used to quantify changes in users' behavior. For example, three studies utilized surveys, four relied on empirical data and scenario assumptions and one on ABM. Similarly, different approaches are used to estimate energy impacts: four studies used LCA, one relied on an analytical model, three developed an econometric analysis and one used the EEIO approach. While the EEIO approach is connected to the quantification of the spending effect, different approaches have been used to analyze the same users' behavior effect for the same ICT application. For example, concerning teleworking, the time rebound effect was quantified via surveys [67,71], time use diaries [69,70] and empirical data [75].

Similarly, in the remaining studies [39] [40] [45] [47] [53] [54] [55] [58] [61] [69] [70,72] [73] [74] [76], different approaches were found to quantify users' behavior effects and energy implications. These studies are rated as Weak due to the combination of a small spatial scale, a short time horizon and a limited number of energy impacts analyzed, leading to uncertain results. For example, after analyzing the case study of a living lab in Stockholm for a few months, Bieser et al. [69] concluded that to provide reliable results on the impact of the adoption of co-working on a large scale, systemic effects and transformation of the transport system need to be addressed. Similarly, O'Keefe et al. [61] concluded that telecommuting can be a sustainable policy, but their results are restricted to the Greater Dublin Area or to similar regions.

4. Discussion and future research agenda

The studies examined differ in the type of ICT applications, the type of user effect analyzed, the approach used and the energy impacts considered, which does not allow for a straightforward comparison of the results. However, this was not the article's intent, which aimed to focus on the gaps identified in relation to the user effects analyzed and the approach used to carry out the analysis. Specifically, three main gaps were identified.

4.1. A non-inclusive analysis of behavioral changes

Despite the general understanding of the broad impact that ICT applications have on different aspects of user activities and behaviors [81], the reviewed studies do not include all the possible effects in their study. The consequences on energy demand of a non-inclusive analysis of behavioral changes can be analyzed by considering the residential application and the teleworking application, which cover almost 70 % of the reviewed studies.

The residential application mainly focused on feedback to provide users with information on their energy consumption and possible suggestions to improve their behavior to achieve energy savings. Since this application aims to change household practices toward more sustainable behavior, it is not surprising that the changed practice effect was analyzed in all studies. Given this effect, when analyzing Table 6, the lack of analysis of other users' effects is evident.

Only two papers analyzed additional user-related effects and energy impacts in a smart house application. Walzberg et al. [42] identified that a smart house can provide a 2 % reduction in environmental impact, although the spending r effect induced by monetary savings [43] can reduce it. By linking an EEIO analysis with an LCA analysis, they conclude that the systemic impact induced by the spending effects can reduce a smart house's environmental benefit by 5 %. This impact is not included in the study of Pohl et al. [44], who instead include rebound and direct impacts in their user-perspective LCA model, concluding that smart homes must achieve energy savings of 6 % to provide an environmental benefit. The differences between the two studies make comparison difficult, although it is clear that the missing users' effects and related energy impacts could change the results of both studies.

Although the variety of users' effects is known in the literature, and it is recognized that increasing the number of effects analyzed increases the quality of the results [82], none of the studies analyze all of them together. A similar conclusion can be observed when analyzing the teleworking case, which is characterized by the most significant number of users' effects analyzed. As discussed in Section 3.5.1, working from home reduces the travel demand for commuting, opening up the

Table 12
papers dealing with energy implications and identified as Medium by the scalability indicator.

Paper	Authors and year	User-related effect	ICT application	Approach	Energy analysis	Energy impact	Spatial scale	Time horizon	Environmental implication
[41–43]	Walzberg et al. 2018,. 2019, 2020	Changed practice Spending	Residential	ABM	LCA + environmentally extended input-output	Indirect Rebound	Regional	Year	Policy
[44]	Pohl et al. 2021	Changed practice Unintended	Residential	survey	LCA	Indirect Direct Rebound	Country	Short	Policy
[56]	Seidel et al. 2021	Changed practice Direct	ICT service	Scenario assumption	Analytical model	Direct Indirect	Country	Short	Positive
[60]	Tabata and Wang 2021	Changed practice	ICT service	Empirical data	LCA	Indirect	Country	Short	Negative
[67]	Cerqueira et al. 2020	Changed practice Time rebound	ICT service	Survey	Econometric analysis	Indirect Rebound	Country	Short	Policy
[71]	Sekar et al. 2018	Time rebound Changed practice	ICT service	Time use survey	Econometric analysis	Indirect Rebound	Country	Short	Positive
[75]	Guerin 2021	Changed practice Time rebound	ICT service	Empirical data/scenario	LCA	Indirect rebound	Country	Year	Policy
[80]	Håkansson et al. 2015	Spending	ICT usage	Scenario, empirical data	Environmentally extended input-output analysis (EEIO)	Direct Systemic	Country	Short	Policy

opportunity to substitute the transport mode. However, it could increase the number of trips for non-working related activities due to additional time. Additionally, the money saved through fewer trips can be reinvested in supplementary services. Table 7 shows that out of 17 studies dealing with teleworking, only three include three users' effects, while 11 includes two users' effect and three only one effect.

4.2. Exploiting the synergies between ICT applications and different energy sectors

Focusing on a specific ICT application, the reviewed studies do not exploit the interrelationships between different applications.

The teleworking case is a good example to show how limiting the analysis to one specific application affects the robustness of the results. The practice of teleworking affects transport demand, residential demand and office demand simultaneously. However, only five studies on teleworking have extended their analysis to the impact teleworking will have on residential and office energy demand. As Guarin et al. [75] pointed out, the energy demand saved by reduced commuting may be overestimated if it is not corrected by the increase in residential energy demand. Furthermore, as discovered in the study by Villeneuve et al. [68], the induction and time rebound effects of working from home can significantly impact residential energy demand. In their study, telecommuters increased their indoor temperature to increase their comfort while working from home. In addition, they did laundry during working hours instead of in the evening, potentially affecting their electrical load profile. Vaddadi et al. [70] were able to quantify the energy demand consumed by offices and homes for people teleworking in their living lab study. However, they confirm the need for a more in-depth analysis regarding different practices, such as cooking and laundry, to provide a complete overview of the potential energy impact of teleworking.

To understand whether ICT applications provide positive implications to support the energy transition, an interdisciplinary study should be conducted to assess the various synergies between ICT applications and different energy sectors. For example, a study on teleworking can be linked to a study on feedback applications for the residential sector to assess how combining these ICT applications can avoid negative user behavior to maximize energy savings.

4.3. Changes in user behavior vs. future energy implications: the appropriate approach

Finally, the review highlights a gap in the ability of the studies to provide recommendations on the role ICTs could play in reaching energy and climate goals. The scalability index identified only two papers as Strong [34,46] due to their long time horizon analysis applied to a global scale. The remaining studies focus mainly on a regional scale for a short time horizon. The difficulty of expanding the temporal and spatial scale is related to the approaches used to assess the user-related effects.

The two papers covering a long time horizon at the global level used empirical data to validate scenario assumptions on the energy impacts of ICT. However, regarding the quality of the results, this approach presents some issues. According to Hook et al. [82], the use of empirical data or scenario assumptions to analyze behavioral changes can lead to "weak scenarios", while "strongest results" tend to be connected with studies analyzing surveys.

Surveys can account for the heterogeneity of households, allowing inferences to be made about socio-demographic conditions that may lead to behavioral changes or the adoption of a specific technology or application. Therefore, it is evident that approaches such as the survey or Living Lab are preferred to provide solid results regarding the quality of the analyzed behavioral changes. For example, the ability of Living Lab approaches to observe complex user behavior is advocated by J. Buhl et al. [83]. However, most of the reviewed studies using surveys or living lab approaches are classified as Weak or Medium by the scalability index due to the difficulty of extrapolating results over a long period of time or generalizing them to a broader scope. The reason for this can be identified in the ability of surveys to provide an assessment of the current situation, a "snapshot of the current time", but they present some limitations when their results are used to infer changes over a long time period, as overtime events might occur that change an individual's intentions [84], so the estimation of the percentage of people who will engage in the behavior can be biased [85].

A long time horizon is required to understand how behavioral change and technology acceptance will spread among individuals and society and how these changes will affect energy consumption and emissions. Analysis covering a short period risks underestimation of the future impact of a digital society and, therefore, cannot be used to inform stakeholders and policymakers about the potential benefit of these technologies in achieving energy goals.

The adoption of the scalability index to compare Strong and Medium papers highlights the issue of selecting the appropriate approach to perform an analysis that is robust in assessing both changes in user behavior and future energy implications connected to ICT applications.

4.4. Suggestions for future research

Future research should develop a framework to analyze the adoption of several ICT applications and the variety of user-related effects over time and space to quantify the effect this digital transition will have on future energy targets. Furthermore, difficulties related to the implication of ICT applications for a long time horizon need to be addressed, as the lack of historical data [86], the challenge of capturing new emergent behavior [87], the uncertainty related to the lack of trust of consumers in internet-based services, related for example to insufficient market transparency for the case of online purchasing or lack of confidence in government and enabling technologies for e-government services [88].

A solution to include the heterogeneity of behavioral changes among a population while analyzing a long time period could be using in-depth surveys to inform an ABM. The use of ABM to analyze how user behavior will spread into society over a long time horizon is well known in the literature. For example, ABM is used to analyze the adoption of new technologies such as solar PV panels or renewable technologies [89–92], but there are few examples of models assessing the impact of ICT (see [93]). The limitations of this approach are identified in the large amounts of data required for the initialization and calibration of the model and in the difficulties of interpreting the outputs due to the high number of parameters involved [94], which tend to make the model case-study-specific and limit the opportunity to extract general recommendations [95].

The social practice approach could also be a solution, being able to assess the spread of new technologies and change behaviors over a long time horizon. However, studies applying this approach to analyze the impact on energy consumption are mainly restricted to qualitative analysis or theoretical frameworks (see [96–98]). The study of Corsini et al. [99] revealed that social practice theory has been applied to the energy research field since 2015, explaining why quantitative frameworks using this approach are still lacking. Only one paper [48] among the reviewed studies applied a social practice approach to understand changes in water consumption practices related to feedback applications.

Of the papers in the final sample, only one attempted to implement a hybrid model linking an ABM with an LCA analysis to analyze the energy and environmental implication of ICTs application. Although their analysis is limited to a short period of time, the paper of Walzberg et al. [43] is an example of a multidisciplinary framework concerning ICT applications that can bring together techno-economic details and a strong representation of actor heterogeneity [100]. Several examples of hybrid models in the literature use different coupling methods to integrate economic or societal considerations into energy analysis. Still, most of them are designed to investigate a single sector [100]. One of the reasons why a single sector is considered lies in the difficulties connected to selecting appropriate interfaces between models [101] and the appropriate linkage method that deals with their different sets of assumptions and methodologies [102].

As discussed for teleworking, due to their cross-sectoral interdependencies, ICT applications can play a relevant role in providing flexibility to couple energy vectors through cross-sectoral technologies, which is recognized as a prerequisite to achieving cost-efficient pathways toward carbon neutrality [103]. To benefit from this cross-sectoral application, future frameworks aiming to include the energy impact of ICTs should also include the interactions between different economic sectors in their design.

4.5. Discussion on the limitation of our findings

This section discusses the limitations of the methodology applied in this paper.

First, the keywords selected for our analysis had to be generic in order to cover the wide range of ICT-related applications and user effects. Consequently, studies focusing mainly on a specific application might have been excluded. However, this approach made it possible to identify current trends in the ICT sector. It revealed a particular scoping on ICT services such as teleworking, online shopping and videoconferencing from 2020 onwards, probably motivated by the COVID-19 pandemic (out of twelve articles published between 2021 and 2022, eight recognized the impact of COVID-19 on user behavior).

Second, by focusing on users' effects and the approaches used to quantify them, the search query applied can explain the limited number of papers estimating the energy impacts of ICTs. Expanding our review to a broader literature, based on the well-cited reviews of Horner et al. [8] and Court and Sorrell [7], we discovered that most of their cited studies rely on scenario assumptions to quantify the user-related effect of interest. In line with our finding, Court and Sorrell [7] concluded that user-related effects and rebound effects were mainly excluded by the analysis's assumptions when dealing with an energy assessment of ICT.

Third, the scaling-up index has been calculated by assuming that each indicator has the same weighting. This assumption may risk overestimating or underestimating the scaling-up impact of the studies. However, to the authors' knowledge, the literature does not provide indications that would help estimate each indicator's weight differently, considering our topic of application (e.g. whether the time horizon has greater relevance than the spatial scale or vice versa).

Fourth, studies dealing exclusively with the direct impact of ICT use and infrastructure were excluded from our review, as the analysis focused on the higher-order impacts of ICT on user behavior. The direct impact was considered along with other impacts by only a few studies (e.g. [44]), probably due to the difficulties of assessing the energy demand and related emission of data centers, network infrastructures and the energy requirement of internet data [104].

Fifth, the paper mainly evaluates the energy impacts of ICT without addressing sustainability issues or environmental implications. By focusing on user-related effects, our analysis provides an understanding of possible rebound effects and unsustainable practices among ICT users, which can help identify areas where sustainable ICT use needs to be promoted. This can benefit the field of ICT sustainability, which research has focused "[..] *more on developing techniques and standards for reducing the ICT carbon footprint without giving much attention to the adoption process in-depth*" [105].

Finally, the systemic impact on society and the economy is partially covered in our reviewed papers due to the research focus on users' behavior. The transformation of the manufacturing and services sectors related to the current trend of dematerializing processes and the implementation of digital business is expected to provide environmental benefits [106]. However, this transformation needs to be sustained by a digital readiness of individuals and government efforts to incentivize the adoption of ICT-based solutions [107], which were not addressed in this review. To fully understand this systemic impact of ICTs, a framework to connect the main dimensions of society, technology, business and policy is needed [3].

5. Conclusions

The systematic literature review focusing on the approaches used to quantify the implications between behavioral changes and energy impacts revealed several gaps.

Referring to our first research question R.a, six user-related effects are identified in the reviewed studies, with a maximum of three user-related effects analyzed per study. The studies are grouped by the ICT application they analyzed, identifying four main ICT applications (Residential, Mobility, ICT services, ICT usage). Besides the general understanding of the broad impact of ICT applications on different aspects of user activities and behaviors, the reviewed studies do not include all the possible effects in their study, risking underestimating or overestimating the energy impacts related to the analyzed ICT applications. Furthermore, focusing mainly on one ICT application, the reviewed studies do not exploit the interrelationships between different applications. Using teleworking as an example, we demonstrate the need to consider the synergies between ICT applications and different energy sectors to avoid disruptive behavior that could inhibit energy-saving potential.

Answering research questions R.b and R.c, empirical data and surveys are identified as the common approaches utilized to quantify changes in user behavior, while energy impacts are mainly quantified by LCA approaches and analytical models. The scalability index is adopted to rank the reviewed papers by their ability to quantify the implications of behavioral changes induced by the introduction of ICTs on energy transition.

Comparing the studies based on their scalability index, the issue of selecting the appropriate approach to perform an analysis that is robust in assessing changes in user behavior and future energy implications related to ICT applications emerged. In the literature reviewed, the approaches used to ensure high-quality results in terms of identified behavioral changes hinder the ability to scale the results to the broader spatial scale and long time horizon, which is required to provide robust insights into the role ICT applications can play in the energy transition.

These identified gaps lead to the conclusion that further research is needed to better understand the energy impacts of ICT applications. Specifically, a framework able to analyze the adoption and systemic interdependencies of several ICT applications and the variety of user-related effects over time and space would be highly demanded.

CRediT authorship contribution statement

Lidia Stermieri: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Writing - Revision, Visualization. **Tom Kober**: Writing – Review & Editing, Supervision, Funding acquisition. **Thomas J. Schmidt**: Writing – Review & Editing, Supervision. **Russell McKenna**: Writing – Review & Editing. **Evangelos Panos**: Conceptualization, Writing – Review & Editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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