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Does ICT Result in Dematerialization? The case of Europe, 2005-2017

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Abstract

Current levels of resource use are unsustainable, but there is a debate about the most feasible way to reduce them. One proposed mechanism is technological innovation: specifically, the implementation of information and communication technologies (ICTs) could result in significant reductions in material consumption by substituting virtual for material goods, increasing resource efficiency, and replacing more resource-intensive sectors. Critics of this view argue that dematerialization due to ICTs is unlikely: they consume large amounts of resources and encourage additional consumption. Additionally, increased efficiency resulting from ICT use could lead to rebound effects, reducing their environmentally beneficial impact. This paper uses a novel measure–material flows–to investigate the relationship between ICTs and material consumption. I use a Prais-Winsten regression model to examine this relationship in twenty-five European nations from 2005 to 2017. Despite both expectations that increased technological innovation will reduce materials use, as well as opposing expectations that it will increase material use, I find no relationship between ICT use and material consumption at the national level. This suggests both patterns are likely possible: increased material use and ICT consumption is balanced by the increased efficiency of ICTs and reduced materials requirements.

Keywords: Information and communication technology (ICT); Dematerialization; Material consumption; Environment; Sustainability; Material flows

Word Count: 6,916

Introduction

Dematerialization refers to a reduction in the material resources, including energy sources such as fossil fuels, required for a given level of economic production. Within the interdisciplinary community of environmental social science, some scholars (see Hilty and Ruddy 2010; Hilty et al. 2011; van den Bergh et al. 2009) argue the information and communication technology (ICT) sector has the potential to facilitate dematerialization. This possibility has been the focus of articles that propose, test, or disprove pathways through which dematerialization could occur.

The nation-level relationship between ICTs and material consumption could be either positive or negative. The dematerialization hypothesis suggests an expansion of the ICT sector would reduce the environmental impact of economies dependent on a cycle of production and consumption. There are two possible mechanisms through which increased ICT use can result in dematerialization: by reducing the environmental impact of the ICT sector itself even as it continues to grow, or by reducing the overall environmental impact of an entire economy by increasing efficiency across sectors. The second mechanism assumes ICTs are inherently more resource-efficient than analog technologies and their application to other sectors can reduce the environmental impact of those sectors. The first mechanism also assumes the ICT sector uses fewer resources than other sectors and the overall environmental impact of an economy will decline as this sector grows and displaces others. In either case, the beneficial outcomes of ICTs are assumed to be relevant for both the supply and demand sides of the economy: e.g., increasing efficiency in production as well as substituting virtual for material consumption. The alternative hypothesis suggests the expansion of the ICT sector would increase a nation's environmental impact. It is possible that, in contrast to the first mechanism's assumption, the ICT sector requires more resources than the sectors it displaces. It is also possible that, in comparison to the second mechanism's premise, the efficiency of the ICT sector results in increased resource consumption due to rebound effects.

In this article, I examine the relationship between the ICT sector and material consumption. Is an increase in the consumption of information and communication technologies associated with a decrease or an increase in material consumption in European nations? To address this question, I use ICT usage data from the World Bank (WB), and Organization for Economic Co-operation and Development (OECD), as well as material flows data from Eurostat. I focus on European nations because their use of ICTs is firmly established, and the penetration rate of the technologies in the general population is high. Europe also has high-quality material flows data available, as well as multiple years of data on ICT penetration. If ICT does encourage dematerialization, it is more likely to occur where the technologies have become integrated into everyday life. This article aims to contribute to our understanding of the potential and limitations of utilizing ICTs for the purpose of environmental sustainability.

Trends in ICT Use

The broadest definition of ICTs is "systems whose fundamental functions are anchored in the generation, processing, storage, communication, and/or presentation of digital information" (Masanet and Matthews 2010: 687). While all communication technologies facilitate the transfer of information, the specific technologies themselves included in the definition vary based on the discipline (Zuppo 2012). In this article, my definition of ICTs consists of the following technologies: telephones, both landline and cellular, broadband, and the internet. This definition is based on the World Bank's (2017) and covers the most common user-end applications of ICT.

Spending on ICT, including computers, radio, television, and communication equipment, telecommunication services, computer services, and office machinery, has increased in the European Union (EU) since 1995. However, the 2008 recession resulted in such a dramatic decrease in spending that the highest total expenditure has not been matched in subsequent years (Joyce et al. 2019). The absolute impact of ICT on the EU's total material footprint, GHG emissions, and energy consumption has remained in line with expenditures, showing no evidence of decoupling (Joyce et al. 2019).

Figures 1 through 4 show how ICT usage has increased in Europe. Telephone subscriptions, in Figure 1, are the only ICT that does not experience growth over the entire period from 1990-2017. This lack of consistent growth is most likely due to the dramatic rise in cell phone subscriptions, many of which have displaced fixed landlines. Mobile phone subscriptions, in Figure 2, increased dramatically from 1990-2008 but began to level off from 2008-2017. Broadband subscriptions, in Figure 3, and internet use, in Figure 4, are still experiencing growth: broadband data are available starting in 1999, and internet access data are available since 2005.

[Figures 1, 2, 3, and 4 near here]

ICTs require not only large amounts of resources for production and operation but also generate hazardous by-products. In 2007 the ICT sector accounted for only 1.3% of GHG emissions but consumed 3.9% of global electricity (Malmodin et al. 2010). The most recent analysis of the ICT sector's carbon and energy footprint found the sector's 2015 footprint is similar to its 2010 footprint, peaking in 2012-2013 (Malmodin and Lundén 2018). This finding lends some support to the hypothesis that ICT usage is decoupling from emissions. However, the increase in personal (rather than shared) devices, as well as the number of devices per person, and a shortened lifetime use of individual devices, has increased ICT consumption overall (Malmodin et al. 2010).

Material flows refer to the materials and energy extracted and consumed by economic systems (Krausmann et al. 2009). The Eurostat Material Flow Accounts dataset used in this analysis includes all solid, gaseous, and liquid materials imported into an economy or extracted domestically, measured in thousand tons per year. Trade is included in the measure, accounting for the domestic consumption of materials from other nations. Materials included in the measure include biomass, fossil fuels, metals, ores, minerals, and construction materials (Krausmann et al. 2009). Material flows data are often used in life cycle analysis and environmental accounting, but have been underutilized in sociological studies and infrequently examined using inferential statistics. These data are a good measure of material consumption, and so are well suited to a quantitative analysis of dematerialization. Figure 5 shows trends in total materials use within the EU.

[Figure 5 near here]

In this article, I first review the literature on ICT and dematerialization and visualize the possible pathways presented for ICT's impact on material consumption, including those that are positive, neutral, and negative. I then use a Prais-Winsten regression model to examine the relationship between ICT use and material consumption in European nations. I find that neither prediction—increased or decreased material consumption—is borne out at this level of aggregation. This suggests there are multiple pathways through which ICTs impact material consumption. These pathways are likely both increasing and decreasing consumption, ultimately resulting in a "draw" at the national level. Finally, I discuss the importance of the level of analysis and social context for understanding the impacts of ICT use on the environment.

Literature Review

Technology is commonly an essential component of theories aiming to find solutions to environmental problems. One such prominent theory is ecological modernization: proponents often argue technological innovation is needed to solve environmental problems, especially with regards to its purported ability to decouple economic growth from material consumption (Spaargaren 2000; Fisher and Freudenburg 2001). Increased efficiency, innovation, and changing practices are all pathways through which the increased implementation of technology could help make existing social and economic systems more environmentally friendly. Technology, in and of itself, is not expected to be enough to spur decoupling, but utilizing it in order to increase efficiency in both production and energy use is an essential component of sustainability (Spaargaren and Mol 1992: 339). Ultimately, ecological modernization theory suggests technology needs to be consciously designed for sustainability, and researchers and policymakers should remain aware of how technology itself can impact the environment (Mol and Spaargaren 2000). However, while technology plays a significant role in this theory in many applications it is treated as one element of a broader economic trend towards efficiency and sustainability rather than examined alone.

While increased efficiency can lead to sustainability, it can also lead to higher resource consumption. This possibility is often referred to as the Jevons Paradox. The paradox describes cases in which rebound effects exceed 100% resulting in a net increase in consumption, in contrast to cases where there is a net decrease in resource use despite an increase in consumption (York and McGee 2016). Rebounds can be further classified as either direct (e.g., when increased efficiency increases consumption of the same resource or product) or as indirect (e.g., when savings are used to increase consumption of other resources or products) (Grant et al. 2016). The size of a rebound—that is, whether it is large enough to result in a net increase in consumption—is dependent on context and level of analysis. For example, Grant et al. found that organizational factors, such as whether the plant relied on coal or utilized its full capacity, determined a power plant's susceptibility to rebound effects and that these effects were often not large enough to increase consumption overall (2016). While rebound effects do not usually "backfire" and lead to increased consumption, they do present the possibility that increases in efficiency are not as straightforward a path to conserving resources as they may first appear.

The promises and pitfalls of technology mean ICT's ability to increase or decrease material consumption is a question yet to be definitively answered. The literature on specific pathways for dematerialization still lack empirical examination, and existing studies use carbon dioxide emissions or energy use as an outcome, as opposed to a measure of material consumption. The literature is also split in terms of the level of analysis; articles either utilize a macro perspective (e.g., at the national level) or a micro perspective (e.g., at the individual level). The incorporation of ICTs into daily life can have important effects at both these levels: that of the individual consumer[1] as well as the sectoral level of economic production. The efficiency of individual ICT usage is mostly dependent on lifestyle, and so its cumulative effects on material consumption are difficult to quantify. This literature review will focus on the ICT sector and national domestic material consumption in order to examine the aggregate economic effects of ICT usage.

There are three ways in which ICTs have been theorized to lead to decreased resource use. First, widespread use and application of these technologies increase resource and energy efficiency. Second, the ICT sector has lower environmental impacts than other sectors and depending on which economic sectors it displaces its growth could lower total emissions for the economy as a whole. Third, ICTs lead to dematerialization by substituting for material goods. Figure 6 summarizes the proposed pathways leading to decreased material consumption, including a brief description of a possible mechanism for each case. Figure 7 begins with the same proposed pathways but includes mechanisms suggested by critics of the dematerialization hypothesis, who argue that levels of material consumption could increase or remain the same.

[Figures 6 and 7 near here]

While this paper focuses on material consumption, it is important to note the ICT sector has far-reaching environmental impacts. Large amounts of materials are required to produce ICT devices such as computers, including water, chemicals, energy (often from fossil fuels), and rare earths (Byster and Smith 2006). The pollution associated with the extraction of the materials themselves takes an additional toll on the environment. The production process enacts further damage, even when compared with products produced with fewer electronic components. For example, life cycle assessment comparing electric and conventional vehicles found the production of electric vehicles was more emissions intense than that of conventional vehicles, due mostly to battery production (Hawkins et al. 2012). The study found electric vehicles were more environmentally beneficial than conventional vehicles when they were powered using renewable electricity sources and used longer (250,000-lifetime kilometers) (Hawkins et

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[1] Some individual-level studies suggest pathways that would result in an increase in materials use: increased consumption due to ICT usage during what was previously "dead time," e.g., waiting for an appointment (Røpke and Christensen 2012); increased resource and energy use due to ICT-enabled multitasking and multiple device usage (Aro and Wilska 2013). Other studies suggest ICTs could allow for decreased material consumption: individual's use ICTs enables them to lead an environmentally-sustainable lifestyle (Lorenzen 2012); increased information available through ICTs allows for environmentally-conscious decision making (van den Bergh 2009); access to the internet encouraged participants interested in sustainability were engage in sustainable consumption practices (Wang and Hao 2018).

al. 2012). This suggests the increased environmental degradation associated with material extraction and production of ICTs is best offset when the technologies are in use longer.

Once ICT devices are discarded, the resulting electronic waste (or e-waste) creates additional environmental problems. The toxic chemicals and rare earths used in production either end up in landfills, where they can contaminate groundwater as well as the surrounding area or they are recycled (Byster and Smith 2006). However, recycling electronics is not as "environmentally friendly" as the term might suggest. In Europe, 60% of e-waste is exported, often to Asia, where workers often lack adequate protective equipment and means of disposal, resulting in harm to human health and the environment (Puckett 2006). While it is important to consider the entire life cycle of ICTs, this paper will focus on the impact of ICTs from use rather than from production or disposal.

In a comprehensive qualitative analysis of the existing ICT literature, van den Bergh et al. propose multiple mechanisms through which ICTs could lead to dematerialization—including production, increased efficiency, price effects, information effects, research and development, changing preferences, substitution, and sectoral growth—and found mixed results (2009). They suggest continued production of ICT and the growth of the sector would have negative consequences with regards to dematerialization, but the increased information available to consumers via information effects and substitution of virtual technologies for material goods would have positive results (van den Bergh et al. 2009). The majority of their proposed mechanisms have unclear impacts on dematerialization. Efficiency gains and price effects could lead to rebound effects as production and consumption become cheaper, but they could also reduce materials use; changing consumer preferences could reduce material consumption in some sectors, but an increase in ICT consumption could offset this reduction (van den Bergh et al. 2009). Research and development could likewise increase efficiency and reduce materials use, but could also introduce new products and continue the cycle (van den Bergh et al. 2009). Multiple empirical studies of ICT usage have found that it is associated with environmentally beneficial outcomes, such as decreased material footprints (Joyce et al. 2019), reduced GHG emissions (Joyce et al. 2019; Malmodin and Lundén 2018; Williams 2011; Moyer and Hughes 2012), increased efficiency in production (Gallegos and Narimatsu 2015), and substitution for energy and resource-intensive practices (Coroama et al. 2014).

Other studies propose particular pathways through which ICTs would decrease emissions as well as material consumption. The tendencies of ICTs to increase efficiency and accelerate production can encourage environmental sustainability when they are intentionally substituted on a large scale for older, less efficient, and more resource-intensive products: Townsend and Coroama refer to this process as "push impacts" (2018). Many technology-oriented start-ups utilize these push impacts; for example, some companies are "pushing" alternative forms of transportation (such as trains over airplanes, or dock-less bicycles over cars) and others are involved in the funding, manufacturing, and maintenance of solar panels to "push out" environmentally detrimental sources of electricity (Townsend and Coroama 2018). Ideally, push impacts not only utilize technology to decrease resource use, but also replace older industries with sustainable ones. Substituting virtual for physical products would allow for the dematerialization of demand rather than supply (van den Bergh et al. 2009). For example, the popularity of content sharing, where smartphone apps and social media facilitate participation, suggests information could substitute for some material assets by increasing access to intangible resources (Pouri and Hilty 2018).

Some scholars have found evidence that while using ICTs to increase efficiency has excellent potential to conserve resources; however, these technologies could also instigate rebound effects. Using fewer materials and energy could lower the cost of production, increasing access to other material goods (Plepys 2002). Additionally, ICT innovation introduces new devices that add to current consumption rather than replacing it (Galvin 2015). Increased technological efficiency can increase energy and material consumption by making technologies more accessible; the personal computer is an excellent example of this phenomenon (Galvin 2015). Galvin found a rebound in energy consumption of 128% in UK households from 2006-2012 as a result of increased daily computer usage (2015). Rebound effects alone are usually less than 100%, which would still result in a net decrease in energy usage; when coupled with cultural shifts in consumption and the creation of new “needs,” the overall rebound due to efficiency can be higher. Lange et al. found that digitalization, in particular, has increased energy consumption through direct effects and economic growth, which have outweighed the energy saved through increased efficiency and sectoral change (2020).

The ICT sector is responsible for a growing percentage of energy and resource consumption: it is projected to account for 14% of total greenhouse gas (GHG) emissions by the year 2040 (Belkhir and Elmeligi 2018). The two main culprits are the growth in data centers, which require large amounts of energy, and small devices such as cell phones, which require large amounts of resources and energy to produce but are often discarded after only a few years of use (Belkhir and Elmeligi 2018). A well-established indicator of ICT usage, number of phone lines, has been found to be positively correlated with multiple indicators of energy use, including per capita, production per capita, electricity consumption and production per capita, and cars per 1000 people (Longo and York 2015). Another study using fixed telephones as a measure of ICT found that the measure had a positive association with CO_2 emissions in less developed countries (Simpson et al. 2019). In developed nations, increased internet use was associated with increasing CO_2 emissions, in particular in the manufacturing and transportation sectors (Simpson et al. 2019). York and McGee examine the relationship between energy efficiency and changes in energy consumption and find that increased efficiency is significantly and positively associated with increased energy use, electricity consumption, and CO_2 emissions (2016). The authors suggest material resource consumption has a similar relationship to efficiency, but do not directly include such a variable in the model.

One explanation for the opposing dematerialization predictions is that the outcome depends on whether ICTs themselves are conceptualized as primarily material or immaterial (Roos et al. 2016). Those scholars who conceptualize ICTs as immaterial are more likely able to make the logical connection between technology and dematerialization. Focusing on the materiality of ICTs, from production to use and ultimately to disposal, reveals their resource intensiveness. Even the most materially nebulous technologies, such as cloud computing and the internet, produce emissions and require physical materials. For example, cloud computing relies on data centers that consume vast amounts of electricity: if the cloud were a nation, its energy use would make it the world’s fifth-largest energy consumer (Maxwell and Miller 2013).

The unclear results of the increased consumption of ICTs are due in part to the materiality paradox. The paradox states material goods are no longer valued as much for their materiality, but rather for non-material cultural meanings, which leads to the increased consumption of these goods and increasing the use of material resources (Schor 2010). The materiality paradox focuses on consumer dynamics to understand increasing material consumption. Even if technology changes the nature of consumption and increases the value of immaterial consumption, it could further this paradox and increase the consumption of material goods by changing consumer habits. As found in Galvin's study, innovation gives rise to new "needs," which are then met by increased consumption of technology (2015).

Overall, the literature on ICT usage and dematerialization is mixed; there are few empirical studies, as most articles discuss the possibility of dematerialization abstractly. Proponents of ICTs argue these technologies have the potential to facilitate economic dematerialization through increased efficiency and lower resource requirements for production, dematerialized consumer goods, and displacement of resource-intensive industries. Skeptics argue ICTs consume vast amounts of energy and material resources, the majority of which are hidden from public view in the production of devices and maintenance of data centers. Additionally, changes in ICT use due to the technologies' increasing ubiquity leads to increases in consumption, and reduced costs as a result of increased ICT efficiency could lead to rebound effects. This paper does not seek to test all of the proposed pathways empirically but instead focuses on investigating the national-level relationship between ICT and material consumption.

Methods

To test whether ICT usage has had an impact on material consumption, I estimated a Prais-Winsten regression model with panel-corrected standard errors (PSCE) and a correction for AR(1) disturbances[2]. I also include time- and nation-specific effects, so that the model is comparable to a two-way fixed-effect model. The nation-specific effects hold constant any characteristics of the nation that do not change over time, and the time-specific effects capture the influence of time series trends. This means differences across nations are held constant so that the model focuses on change within a nation over time rather than differences between nations, in effect using each nation as its own control, which ensures only variables that change over time need to be included in the model. The Prais-Winsten model helps account for issues that arise from a panel dataset with a relatively small sample size in relation to a relatively long time period. PCSE correct for understating actual coefficient variability by allowing for disturbances that are heteroskedastic and contemporaneously correlated across panels. This model is well suited to test the hypothesis that, at the macro-level of a national economy, consumption can be decoupled from material consumption because it examines whether a change in a nation's ICT use is associated with a change in the same nation's material consumption.

I used data from the World Bank and OECD on device subscriptions (cell phone, telephone, and broadband) and internet access to measure ICT use. I used material flows data from Eurostat to measure domestic material consumption. The time covered by the model is 2005 to 2017. While ICTs have been available for decades, widespread adoption by consumers, especially of technologies such as the internet and mobile phones, has occurred since the beginning of the 21st Century (see Figures 1-4). Thus,

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[2] The AR(1) correction takes into account first order correlation within the panels, which was present according to the Woolridge test for autocorrelation in panel data.

the time period under study captures the best conditions, thus far, for the outcomes of dematerialization to be realized.

Data

For these models, I chose to focus on countries belonging to the EU. A list of member nations, as of 1 January 2019, is in table three. I included two additional European countries that are not members of the EU to increase the sample size, and they are denoted in the table below. Europe is an area of the world where ICTs were adopted early and widely and has relied heavily on these technologies, often with the explicit aim to increase efficiency. ICTs are also easily accessible in these nations, and use is widespread among the general population. Additionally, the EU has the highest quality and longest period of material flows data currently available.

[Table 1 near here]

The dependent variable, material flow accounts, is from the Eurostat database, and measures total domestic material consumption in thousands of tons. It includes material inputs into an economy through domestic extraction and imports, as well as material flows out of an economy in the form of exports (Eurostat 2019). I focus on domestic extraction and imports, which includes most solids, gases, and liquids, except for water and air (Eurostat 2019). Using a measure of material consumption allows me to focus on the dematerialization aspect of the ICT decoupling hypothesis.

The independent variables measuring telephone, mobile phone, and broadband subscriptions are from the World Bank's World Development Indicators database. Telephone use is measured as the total number of active fixed analog telephone lines, public payphones, ISDN voice-channel equivalents, voice-over-IP, and fixed wireless local loop subscriptions (World Bank 2019). Mobile phone use is measured as the total number of public mobile telephone service subscriptions offering voice communication, which includes both post- and pre-paid accounts but excludes subscriptions via data services (World Bank 2019). Broadband use is measured as the total number of fixed subscriptions that enable access to high-speed public internet, which includes cable modems, DSL, fiber-to-residence, and other fixed-wired subscriptions, as well as satellite and terrestrial wireless broadband, for both residences and organizations, but excludes subscriptions via mobile networks (World Bank 2019). The final independent variable, internet access, was obtained from the OECD Telecommunications and Internet Statistics database. Internet access is measured as the percentage of households reporting access to the internet through dial-up, ADSL, or cable broadband (OECD 2019).

The WB variables have been used by other studies to measure ICT consumption (e.g., Longo and York 2015). While these measures are limited in scope by the focus on technology penetration rather than use, the subscription measures do not distinguish between individual, household, or corporate subscribers. However, they are a better match for the material flows variable, which measures overall domestic material consumption, as opposed to the household-level internet-access variable. The WB's Internet use variable was limited to a time frame of fewer than ten years, so a similar variable from the OECD covering a longer time frame was used.

The control variables are from the World Bank Development Indicators dataset and include GDP per capita and total population to control for national differences in wealth and size. Additionally, services as a percentage of GDP is included to control for a sector that, similarly to the ICT sector, is theorized to rely less on material resources (Gershuny 1978). All of the variables (independent, dependent, and control) were logged using log base ten so that the results are interpreted as elasticity models.

Results and Discussion

The results of this model, in table 2, indicate there is not a statistically significant relationship between ICT usage and material consumption in European nations.[3] None of the measures of ICT use (percentage of households with internet access, telephone, cell phone subscriptions, and broadband subscriptions) have a statistically significant relationship with material flows. Two of the three control variables have statistically significant associations with material consumption. A 1% increase in a nation's GDP per capita is associated with a 1.08% increase in material flows (p<0.001). Total population also has a statistically significant effect: a 1% increase in a nation's total population is associated with a 0.57% increase in material flows (p<0.05). The coefficient for the size of an economy's service sector as a percentage of GDP is negative and not statistically significant.

[Table 2 near here]

The model shows no signs of absolute or relative decoupling of increased ICT use from material consumption. This suggests dematerialization is not occurring. Other studies testing decoupling, such as economic growth from carbon dioxide emissions at the national level, found relative rather than absolute decoupling over time dependent on which measures were used and which nations were included in the sample (Jorgenson and Clark 2012). The lack of any form of decoupling, in this case, suggests the dematerializing effects of ICT are not strong enough to counter the positive relationship between GDP and material consumption. In the model, a 1% increase in GDP within a nation was associated with a 1% increase in material consumption. In comparison, a 1% increase in population leads to a 0.57% increase in material consumption. This suggests national wealth is a better indicator of high ICT usage than population.

It is not possible for there to be no relationship between material consumption and ICT use; as discussed in the literature review, ICTs rely on a plethora of materials as well as large amounts of energy (Byster and Smith 2006; Hawkins et al. 2012; Belkhir and Elmeligi 2018; Maxwell and Miller 2013). It is more likely that there are multiple pathways through which ICT and material consumption influence Some of these pathways increase consumption (York and McGee 2016; Galvin 2015; Longo and York

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[3] I estimated additional models, including two models using an ICT index—one from the OECD, one I compiled—which had substantively similar results in that the ICT measure did not have a statistically significant association with domestic material consumption. I also used the WB's internet measure, which further limited the time frame, again with similar results.

2015; Plepys 2002) and others decrease it (Joyce et al. 2019; Malmodin and Lundén 2018; Williams 2011; Moyer and Hughes 2012). At the level of a national economy, these different pathways are in effect negating one another.

While this study can only cover the first decade of the 21st Century, those years represent a period that saw a dramatic increase in ICT usage. While it is probable that dematerialization has occurred in specific sectors—the digitization of music, books, and movies are examples, as well as the rise of telecommuting and teleconferencing and the ubiquity of online shopping—the models I estimated suggest this limited change has not had an impact on consumption as a whole. It is still possible increased ICT development could lead to decoupling from particular resources. The energy efficiency of ICTs is also increasing rapidly; as mentioned previously, the energy and carbon footprint of the ICT sector in 2015 was almost the same as in 2010 (Malmodin and Lundén 2018) despite increasing ICT consumption. This indicates decoupling could be occurring with regards to ICT and energy use. Additionally, outside factors could be determining how successful dematerialization is: for example, there are currently few economic incentives to use ICTs to increase sustainability rather than decrease cost (Hilty and Ruddy 2010).

Limitations

The time frame of these models is limited; despite the fast pace of technology, dematerialization may be a slow process that will be better identifiable in the coming years. Another limitation of my models is that the sample includes only European nations, which currently have the best quality data on material flows. As material flows data of sufficient time and quality becomes available from other nations, it would be worth examining the possibility of dematerialization in different contexts, especially developing nations, where wireless technologies that require less infrastructure have become increasingly popular. The current measures of ICT consumption are also lacking; the number of devices or subscriptions indicates little about their use. Finally, at this level of aggregation, I found no relationship between ICT usage and material consumption. Still, at other levels, such as that of individual or corporate consumption, the results could differ.

Conclusion

The debate about dematerialization has been ongoing, but ICTs have been an established part of life in some parts of the world for long enough to test the theory. The estimated models used currently available, high-quality data on both ICTs and material consumption that spans over a decade, covering a time period when digital devices have become even more integrated into everyday life. Despite the best possible circumstances, a rigorous longitudinal model failed to find any sign that the promise of ICT-driven dematerialization has been fulfilled. However, the results also indicate the increased prevalence of ICTs is not associated with an increase in material consumption. This stalemate suggests there is a great deal of complexity in the relationship between ICTs and national economies: at the highest level of aggregation, the multitude of proposed pathways for both increased and decreased material consumption is, in effect, canceling each other out.

These findings highlight the importance of sociological insights, which would suggest dematerialization is not just a technological question with a technological solution. Longstanding findings from environmental sociology, such as rebounds and outsourcing, paint a more accurate but complicated picture of the relationship between technology and consumption. Overall, these insights cast doubt that one factor alone–even one as pervasive as ICTs–could have such a strong effect on material consumption at the national level. These models can only speak to the relationship ICTs and material consumption at the macro level within nations; future research could examine this relationship at the micro and meso levels as well as the differences between nations. The ICT sector is one in which there are near-constant innovations: developments in technology could yet change the balance between resource consuming and conserving effects.

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Appendix

Table 3. Summary Statistics

Variables	N	Mean	Std. Dev.	Min	Max
Material Flows, Thousand Tons	626	268,288.70	310,590.90	2,890.98	1,453,994
Telephone, Total Subscriptions	853	7,882,535	11,600,000	128,249	54,800,000
Broadband, Total Subscriptions	538	3,623,752	6,167,352	284	33,200,000
Internet Access, % Population	319	69.40	18.81	7.66	98.23
Cell Phone, Total Subscriptions	854	13,100,000	22,300,000	0	10,600,000
GDP, per Capita	835	29,485.19	20,888.11	3,150.46	111,968.30
Population, Total	868	18,600,000	23,100,000	354,170	82,700,000
Services, % of GDP	783	60.23	7.73	24.18	78.98

Table 4. Correlations

Variables	Material Flows	1.	2.	3.	4.	5.	6.
1. Telephone	0.91	1					
2. Broadband	0.68	0.77	1				
3. Internet	-0.08	0.05	0.23	1			
4. Cell Phone	0.85	0.72	0.85	0.004	1		
5. GDP per Capita	-0.008	0.12	0.12	0.53	0.08	1	
6. Population	0.95	0.92	0.74	-0.04	0.74	-0.02	1
Services	0.005	0.22	0.23	0.36	0.19	0.66	0.08

Tables and Figures

Table 1. European Nations in Sample

Austria	Finland	Ireland	Netherlands	Spain
Belgium	France	Italy	Poland	Sweden
Czechia	Germany	Latvia	Portugal	Switzerland*
Denmark	Greece	Lithuania	Slovakia	Turkey*
Estonia	Hungary	Luxembourg	Slovenia	United Kingdom

* denotes non-EU nation as of 01/2019

Table 2. Longitudinal Regression Models of the Effect of Information and Communication Technologies on Material Flows in European Nations, 2005-2017

	coefficient (SE)
Telephone Subscriptions	-0.09 (0.05)
Broadband Subscriptions	-0.01 (0.03)
% Households with Internet	-0.06 (0.05)
Cell Phone Subscriptions	0.16 (0.10)
GDP per Capita	1.08 (0.12) ***
Total Population	0.57 (0.26) *
Services % of GDP	-0.12 (0.35)
Overall R-Square	0.99
n (observations)	299
# of nations	25
Obs. per nation (min/avg./max)	9/12.6/13
Rho	0.53

Note. All variables are logged. Prais-Winsten model has panel-corrected standard errors, corrects for AR(1) disturbances, and includes unreported year- and unit-specific intercepts.

* $p<0.05$ ** $p<0.01$ *** $p<0.001$

Figure 1. Telephone subscriptions, 1990-2017

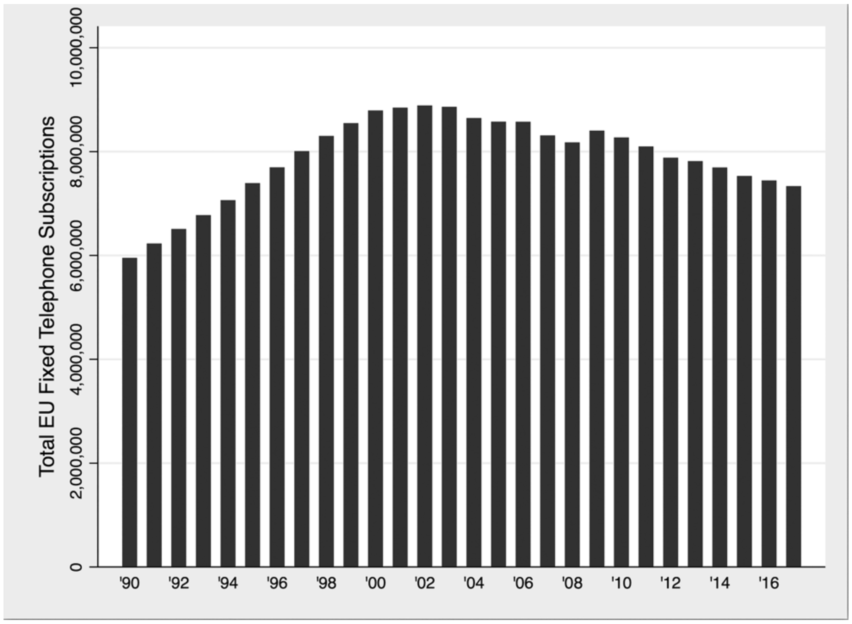

Figure 2. Mobile phone subscriptions, 1990-2017

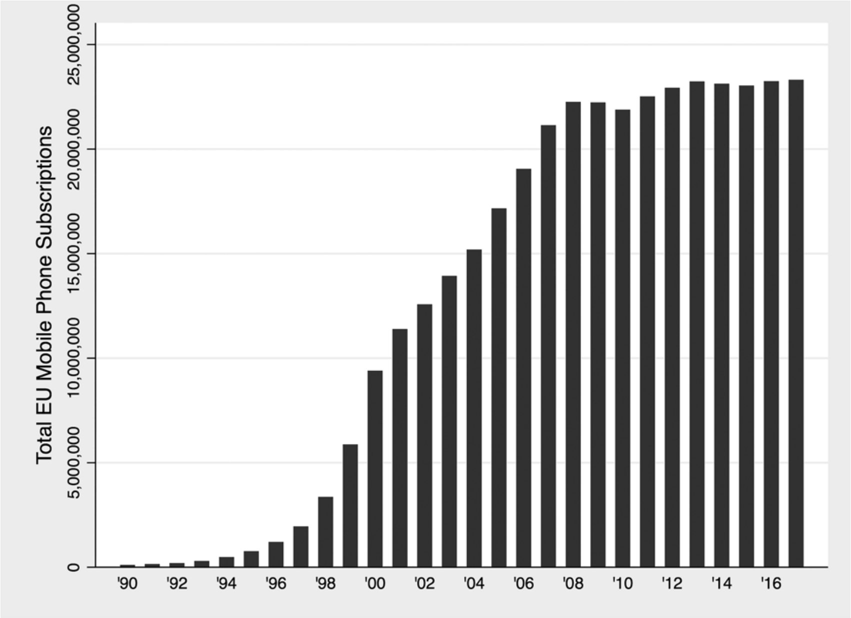

Figure 3. Broadband subscriptions, 1999-2017

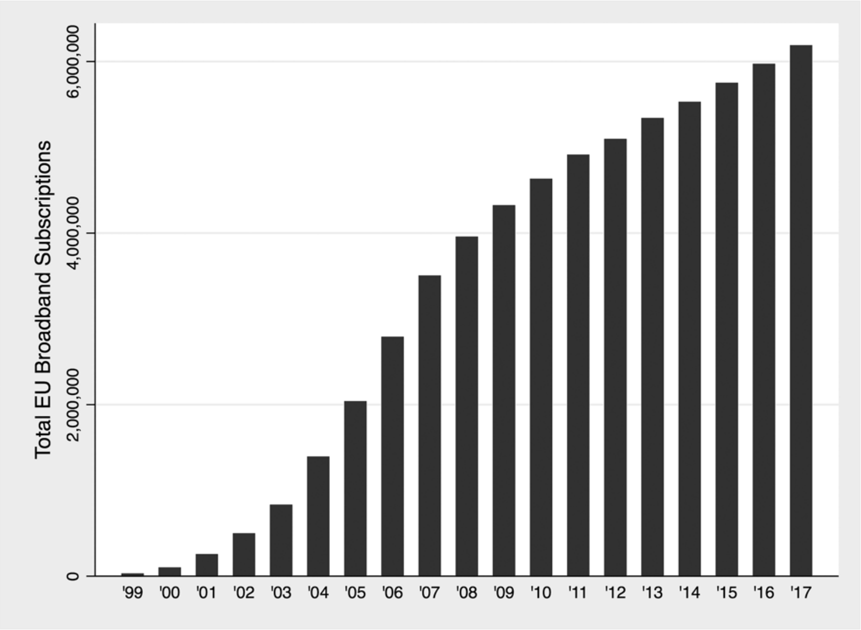

Figure 4. Household internet access, 2005-2017

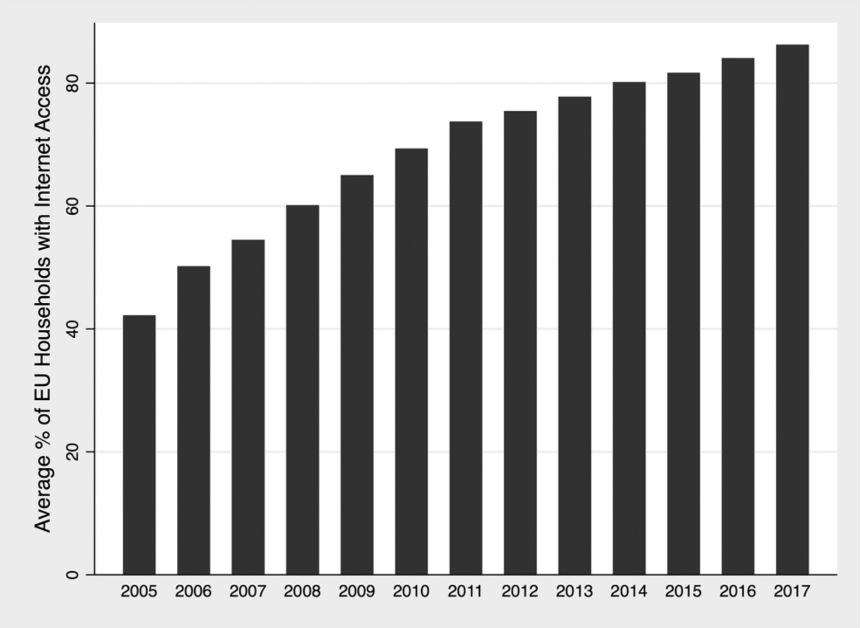

Figure 5. Total materials use in European nations, in thousand tons, 2000-2017

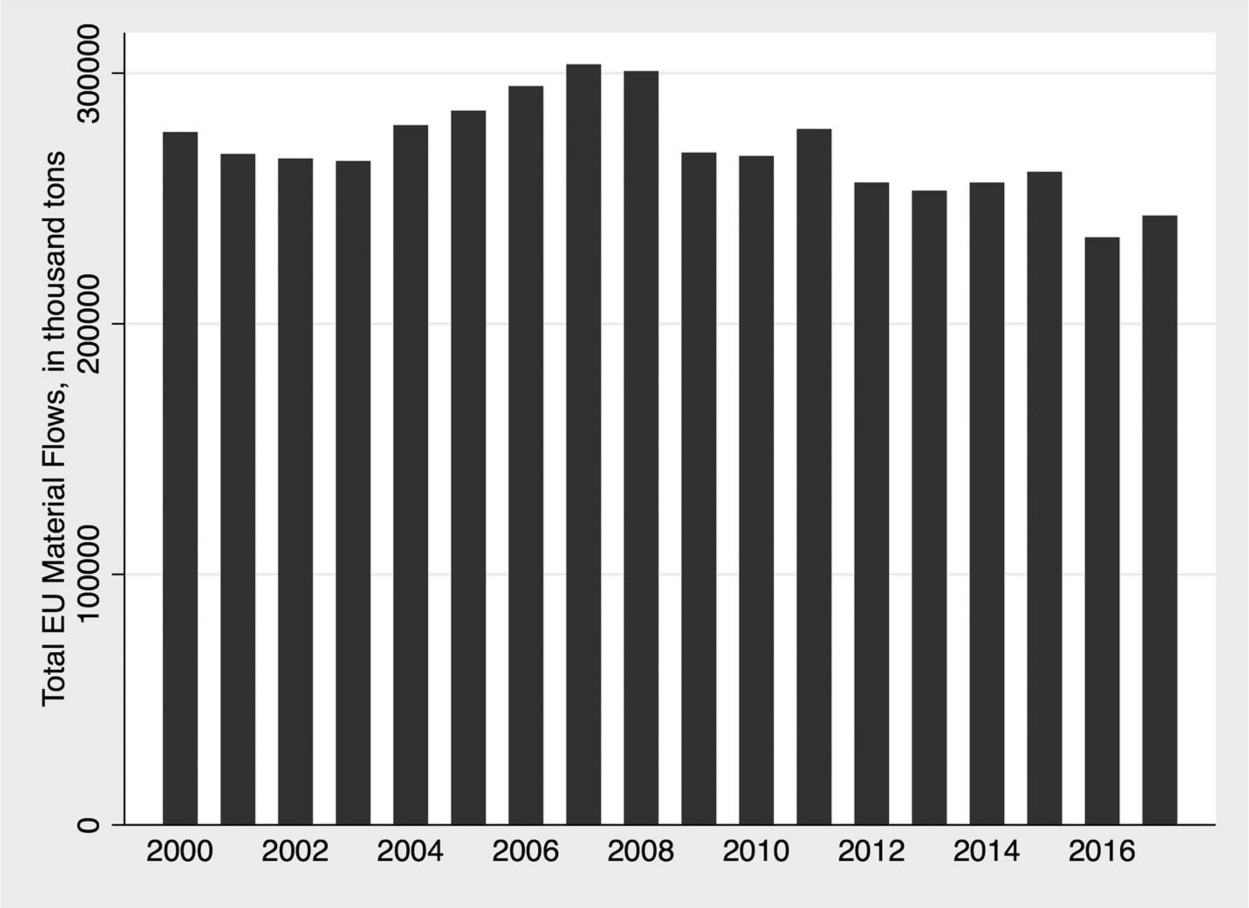

Figure 6. Proposed pathways through which ICTs could decrease material consumption

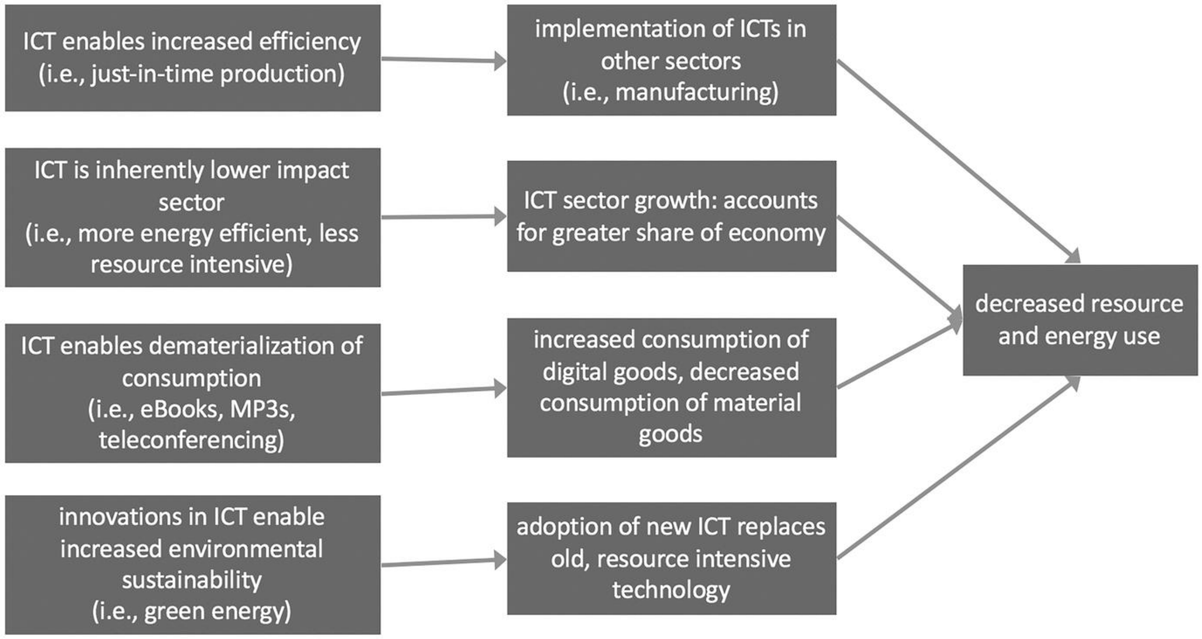

Figure 7. Proposed pathways through which ICTs could increase material consumption