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The Environmental Effects of Investing in ICT

Evidence from Sweden

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Abstract

The potential of Information and Communication Technology (ICT) to reduce greenhouse gas emissions has been increasingly acknowledged as relevant in intergovernmental policy documents. However, the positive and negative environmental effects of ICTs are widely debated and there is a lack of systematic analysis regarding causal links between ICT and the environment. This paper attempts to bring clarity and to provide empirical evidence to the debate on technologies' environmental effects, by examining the relationship between ICT investments and carbon dioxide (CO_2) emissions using annual industry level data for Sweden in the period 1995 to 2016. The baseline model is a standard two-way fixed effects model. Taking the timing as the source of identification seriously, the model is also extended to include linear time trends for each industry as well as quadratic trends. Finally, this paper also acknowledges the latest developments in how to construct event studies in order to graphically judge placebo and dynamic effects. The results confirm that investments in ICT have a negative effect on emissions. The most credible estimate shows that an increase of a standard deviation of investment in ICT annually in an industry lowers the emissions by 7.5 percentages on average. The events study graphs are also consistent with a causal interpretation, although estimated with a low precision.

Key words: environment, emission, ICT, technology, distributed-lag and event study.

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1 Introduction

Information and Communication Technology (ICT) is often viewed as the solution to sustainability issues, due to its potential to decarbonise the global economy and energy supply, and to dematerialise production and consumption (Cologna *et al.*, 2020). It is thought to substitute for, or at least improve, the use of energy and materials. In agreement with this, the potential of ICT to reduce greenhouse gas emissions has been increasingly acknowledged as relevant in intergovernmental policy documents (e.g. OECD, 2009; European Commission, nd a).

However, systematic analysis regarding the links between ICT and environmental sustainability is limited, partly due to lack of reliable data (Berkhout & Hertin (2001). Therefore, it remains unclear if ICT actually has a significant positive effect on the environment. Berkhout and Hertin (2001, p. 4) write in their report to the OECD that "at first sight, the environmental effects of ICT appear to be exclusively positive because information is generally considered to be quick distinct from the material aspects of the natural environment". However, Berkhout and Hertin (2001) add that ICT does not always contribute to dematerialization and could even have negative environmental effects.

This paper aims to bring clarity and to provide empirical evidence to the debate on technologies' environmental effects, by examining the relationship between ICT investments and carbon dioxide (CO_2) emissions. To estimate the environmental effect of ICT the paper will use i) annual data on investments in ICT, including computers, telecommunication and software, and ii) annual data on CO_2 emissions, both at the industry level and in Sweden. Sweden is a great testing ground for a number of reasons. First, Sweden is among the leading countries across all OECD countries in the diffusion and use of digital technologies (OECD, 2018). Second, Swedish industries have played an essential part in the ICT development in Sweden, with support from the government. It is not only the ICT sector that has seen an increase in ICT investments, but also sectors where the potential of ICT for environmental improvements is deemed greatest, such as the construction and transportation sector (Ministry of Enterprise and Innovation, 2010; Statistics Sweden 2020a). Third, the Swedish setting also offers advantages when it comes to both data availability and empirical identification, relative to previous literature studying the relationship between ICT and environmental quality. Data on both ICT investments and emissions is available at an annual basis across multiple industries for the period 1995 to 2016. Although it is not a considerably large data set, this paper tries to implement an arguably better identification of the environmental effect of ICT investments compared to other studies by implementing the latest improvements in design-based evaluation.

The classical non-design based approach has been regression and control, relying on the assumption of conditional mean independence. However, all firm decisions, (although aggregated into industry data) are potentially jointly set and hence cannot solve the issue of omitted variable bias (so called bad controls). This route of doing empirical analyses is thus strongly recommended against (Angrist & Pischke, 2009, pp. 64-68). A design-based approach would be to find a valid instrument. However in this setting it as notoriously difficult to find an instrument that fulfils both the “as good as random” assignment and the exclusion restriction.

Instead, the paper takes a different approach and tries to solve the causality issue by relying on the timing of changes in ICT investments. The baseline model is a standard two-way fixed effects model. Taking the timing as the source of identification seriously, the model is also extended to include linear time trends for each industry. Hence, identification is then based on annual deviations from a linear trend. Moreover, quadratic trends are included and hence identification is then also based on annual deviations from that trend. Finally, this paper also acknowledges the latest developments in how to construct event studies in order to graphically judge placebo and dynamic effects. Although this may seem counterintuitive when having a continuous treatment with no distinct events, Schmidheiny and Siegloch (2019), show that a standard event study model is a re-parametrization of the distributed-lag model and is equivalent to a standard event study under some assumptions also in the case of continuous treatment.

The paper is related to a number of studies. It is related to the fundamental literature and debate, especially during the 1970s, on economic growth versus the environment (e.g. Mishan, 1967; Meadows *et al.*, 1972; Georgescu-Roegen, 1971; Daly, 1977), which fuelled the discussion on the role of technological development. It further relates to the growing amount of literature on the environmental impact of ICT in particular (e.g. Hilty, 2008; Börjesson Rivera *et al.*, 2014; Berkhout & Hertin, 2001; Erdmann & Hilty, 2010). Existing literature in this area has provided two major findings, 1) the characteristics of ICT - such as exceptional dynamics of innovation and diffusion, social embedment and cross-sector application - are a challenge to deal with in macroeconomic studies, which is a reason to why mainly microeconomic studies have been conducted (Erdmann & Hilty, 2010), and 2) the environmental effects of ICT can be distinguished into three levels, which all have different implications; first order, second order and third order impacts. These effects will be discussed in chapter 3. In summary, the environmental effects of ICT have been characterised and described by a number of authors in the past but have only recently become the subject of systematic research. Existing research has shown that ICT can have both negative and positive impacts, depending on the effects included in the analysis. This paper adds to the existing literature since it examines more than 30 industries as well as it studies ICT in its wider definition using all three components of ICT (computers, telecommunication and software)[1]. Most importantly, the paper adds to the literature since it is using a credible research design that allows for variation in treatment timing, which no previous literature in the area has considered.

The results of this study confirm that investments in ICT have a negative effect on emissions and hence a positive effect on the environment. The most credible estimate shows that an increase of a standard deviation of investment in ICT annually in an industry lowers the emissions by 7.5 percentages on average. The events study graphs are also consistent with a causal interpretation, although estimated with a low precision.

The paper is structured as follows. Chapter 2 portrays the ICT development in Europe and in Sweden respectively, as well as important policy changes and initiatives. Chapter three describes the environmental effects of ICT, both from a theoretical perspective and from empirical evidence. Chapter 4 describes the data and data sources used. The empirical approach is presented and discussed in chapter 5. Lastly, the results are presented in chapter 6 and chapter 7 concludes the study.

2 ICT as a Tool in Today's Increasingly Digital Global Economy

In recent years ICT has been recognized as an important tool to not only improve the environment, but also people's lives. For example, ICT is directly embedded in two of the seventeen UN Sustainable Development Goals; in target 9c which is "significantly increase access to information and communication technology and strive to provide affordable access to the Internet in least developed countries by 2020" and in target 5b

[1] Most systematic research in the area studies a single industry and focuses on a narrower perspective, such as e-commerce (see Reijnders and Hoogeveen, 2001; Hesse, 2002; Matthews *et al.* 2002).

which is “enhance the use of enabling technology, particular information and communication technology, to promote the empowerment of women” (UN, nd). ICT is also integrated in the European Union’s climate targets, and has been a major focus in recent years in Sweden. This chapter will describe the ICT development in Europe and in Sweden respectively.

2.1 Shaping Europe’s Digital Future

In 2007, European Union leaders set three climate and energy targets as part of the 2020 climate and energy package, which is a set of binding legislation with the purpose to ensure that the union meets its climate and energy targets for the year 2020. The three key targets entail a 20-percentage cut in greenhouse gas emissions (from 1990 levels); 20 percentages of EU’s energy should come from renewables; and a 20-percentage improvement in energy efficiency. These are also headline targets of the Europe 2020 strategy for smart, sustainable and inclusive growth (European Commission, nd a). Early in 2009, the European Commission presented a second communication, with the aim to mobilise information and communication technologies in order to facilitate the transition to an energy-efficient, low-carbon economy. The communication states that ICTs have the potential to both improve energy efficiency in all sectors of society, as well as enable a more effective measure and evaluation of energy efficiency initiatives, at both the system and the individual level (Ministry of Enterprise and Innovation, 2010).

The European Commission argues that ICT is vital for Europe’s competitiveness. Their ambition is to move from a classic ICT sector approach to a comprehensive local/regional/national “digital agenda”. In accordance, improving access, use and quality of ICTs was one of the 11 thematic objectives for the Cohesion Policy in 2014 to 2020[2]. Over €20 billion from the European Regional Development Fund (ERDF) were made available for ICT investments during the 2014 to 2020 funding period. The funding was built upon the achievements during the previous funding period in 2007 to 2013, where more than 20,700 ICT projects received ERDF support. 5.8 percentages of the total €20 billion funds for further development of ICTs were allocated to Sweden (European Commission, nd c).

[2] The EU's cohesion policy aims to strengthen economic and social cohesion by reducing disparities in the level of development between regions. The policy focuses on key areas that will help the EU face up to the challenges of the 21st century and remain globally competitive (European Commission, nd b).

2.2 ICT Investments in Sweden

As a response to the European Commission's communication and recommendation from 2009, Sweden has implemented a number of ICT initiatives. However, already in the beginning of the 2000s the Swedish Government appointed a *forum for ICT and the environment*, under the previous Minister for the Environment with a mandate until December 2003. The forum was initiated to create a natural platform for ICT and ecologically sustainable development. In addition, the government implemented a working group consisting of representatives from industry, research, the Swedish Environmental Protection Agency (EPA), ministries and environmental organisations. One of the main responsibilities of the working group was to study the potential of ICT use in the development of emerging infrastructure and goods that are resource-efficient and less environmental damaging. The work thereafter continued under the Government's *Strategy Group on IT Policy*. In April 2010, the Swedish EPA finalised its proposal for an action plan to the Government, which set the ground for the *ICT for a greener administration – ICT agenda for the environment 2010-2015*, that the Government adopted in July 2010. The agenda includes objectives and recommendations in three action areas – 1) acquisition, 2) operation and use and 3) travel and meetings. The objectives for these three areas are to increase the number of acquisitions with environmental requirements in the ICT area; to reduce energy consumption in ICT activities; and to increase the number of travel-free meetings. Several initiatives have been made, especially in the public sector and in sectors where the potential of ICT for environmental improvements is considered greatest, such as building and construction, transport and logistics, and the ICT sector itself (Ministry of Enterprise and Innovation, 2010).

According to Statistics Sweden (2020b), companies' expenses and investments in computers, telecommunication products and software have increased steadily since 2009. The latest figures from 2019 show that companies' expenses and investments in ICT amount to 72.4 billion Swedish krona (SEK), which is an increase of about 40 billion Swedish krona (SEK) compared to 2009. 70 percentages of the total ICT expenses and investments in 2019 were accounted by large companies, with 250 employees or more. Software is the group that stands for the highest share of total IT related expenses and investments. In the past eleven years software expenses and investments have increased with 76 percentages for small companies (10 to 49 employees) and 72 percentages for medium sized companies (50 to 249 employees). Expenses and investments in computers and telecommunication products have increased with 28 percentages respectively 7 percentages for small and medium sized companies since 2009. The great increase in ICT investments is also notable for a longer time period. According to Statistics Sweden (2017), ICT investments has steadily increased since 1993 and is the subgroup of machine investments that has seen the greatest increase in terms of volume since 1993, with the exception of the economic downturn of 2008 to 2009.

3 The Environmental Effect of ICT

This section will first describe the different indirect and direct effects of which ICT often is categorized into and how they are implemented in this study. Thereafter, a discussion on ICT's potential effects, based on previous literature, will follow.

3.1 Different Types of ICT Effects

In general, there are three levels of ICT effects on the environment that should be considered when examined the relationship between ICT and the environment. These have been discussed in papers such as Hilty (2008), Erdmann and Hilty (2010) and Berkhout and Hertin (2001; 2004):

i. *First order impacts*: direct effects of ICT stem from the production, use and disposal of hardware. They are not very different from the environmental effects of other products, but create a number of specific problems in terms of resource use, emissions and waste management. These direct effects are predominantly negative, but there are also positive direct impacts such as the use of ICT for environmental protection purposes (e.g. monitoring of toxic emissions).

ii. *Second order impacts*: indirect effects of ICT are expected to be mainly positive. ICT is expected to contribute to increasing the efficiency of production processes, higher production speed and scale, and greater control. It is also expected that a number of products and services, such as insurance and access to information, are likely to become fully de-materialised. However, many of these digital goods may not replace existing goods, but rather come in addition, which will create added environmental pressure.

iii. *Third order impacts*: Structural and behavioural effects of ICT relate to broader processes of change, and are believed to have both negative and positive impacts. On the positive side, the spread of ICT contribute to a shift from an industrial economy to a service economy, which will tend to have lower levels of resource and energy use at the point of use. It can also support behavioural changes in favour of a 'greening' of products and services. On the negative side, efficiency gains could be offset by a so-called 'rebound effect', mostly observed in the transport and energy sector. This happens when efficiency gains, directly or indirectly, stimulate growing demand that balances or over-compensate for positive environmental effects. In other words, these appear when a resource is used more efficiently and the prices of the goods or services produced from this resource go down, which induces an increase in the consumption of other resources.

The treatment variable in this study, ICT investments as a share of total investments, ought to capture all these three effects. It should capture the direct effect, since the ICT investments included in this study are intended for use in processes of production only (Stehrer *et al.*, 2019). The indirect effects should also be captured since outcomes such as efficiency gains and a larger-scale production are likely some of the reasons behind investing in ICT in the first place. Due to the push both from the Swedish government and the rest of Europe to invest in ICT because of its great potential, it is further likely that the treatment variable also capture some of the structural and behavioural effects of ICT. Although it is likely that ICT investments ought to capture all three effects, it is difficult to prove and to further know exactly how much of the environmental effect is due to each of the three different categories respectively.

3.2 Previous Literature

Berkhout and Hertin (2001; 2004) conclude in both their reports that the environmental impacts can be both positive and negative. Börjesson Rivera *et al.* (2014) come to a similar conclusion. Supporters of ICT seem to focus on the positive second order impacts, such as efficiencies from intelligent production processes and intelligent logistics and distribution. Supporters mean that the economy can grow, not through the addition of more resources, but by the intelligent use of resources to produce greater value. Börjesson Rivera *et al.* (2014) and Kuhndt *et al.* (2003) imply that these scale effects will occur when large-scale production has a lower environmental impact than small-scale production, so that increased production lowers the environmental impacts per unit. Kuhndt *et al.* (2003) further argues that new markets for dematerialised goods and services will arise, leading to a new economy, which is less resource intensive and can even replace material goods. The authors also mean that ICT can improve resource efficiency of manufacturing processes and energy transformation processes, leading to reduced resource requirements per unit value added. This in turn, enables the transport infrastructure to become smarter and hence reduces the environmental pressure per transport unit. De Bruyn (2012) also means that although more output growth can have negative environmental effects, it raises the funds from which one can invest in the environment. Thus, if ICT allows for resources to be extracted more efficiently, which in turn leads to increases in production and profits, it is possible to liberate the excess capital to more sustainable investments. However, Berkhout and Hertin (2001) mean that empirical evidence of these effects is sparse.

In summary, the relationship between information technologies and the environment can be described as rather complex and uncertain. The relationship further depends on the effects of ICT included. It remains difficult to draw any definite conclusions on the environmental effects of ICT, since the literature provides mixed results.

4 Data

To conduct empirical research on the environmental effects of ICT investments, the paper utilises data from two highly reliable sources. The ICT data is extracted from EU KLEMS (2019) - an industry level, growth and productivity research project financed by the European Commission. The latest EU KLEMS release provides a database with capital input data at the industry level for all European Union member states. It covers variables on different assets and equipment, including ICT equipment, both in terms of volume and value. These have been calculated based on data from Eurostat. The dataset is built upon the industry classification NACE Rev. 2, and covers the period 1993 to 2016.

The data on air emissions is extracted from Statistics Sweden's Environmental Accounts (2020a), which is built upon the Swedish Standard Industrial Classification

(SNI). The Swedish Industrial Classification is based on the EU's recommended standards, NACE Rev. 2. Hence the two datasets are compatible.

Both datasets are at the industry level, either at letter level or in some cases at two-digit level[3]. This does not provide a large set of observations, but since the twenty-year time period is still relatively long, the total number of observations of this study should be enough. However there are two issues that need to be solved. First, for the years 1993 to 2008, the air emission data was based on an older version of the Swedish Industrial Classification, namely SNI 92, whereas the emission data in the period 2008 to 2018 is based on SNI 2007. In order to make these two datasets comparable, the Statistics Sweden's correspondence keys have been used to the greatest effort. To control for any differences in the two datasets all data in the year 2008 has been reviewed by industry, which is available in both datasets. A second issue with the datasets is that the industry lists differ slightly between the two databases because industries have been aggregated differently across the two lists. Statistics Sweden has an industry list containing 55 respectively 53 industries for the time periods 1993 to 2008 and 2008 to 2018. EU KLEMS has an industry list with 49 industries. To make the data sets' industry lists comparable, some industries had to be aggregated to a less detailed level. Given this, the sample in this study contains 31 industries. These are presented in table A1 in Appendix. Furthermore, the time period had to be shortened to 1995 to 2016 due to missing values in the years 1993 to 1994 and 2017 to 2018.

[3] Letter level is the highest level, which entails different sections, for example section C (Total manufacturing). Two-digit level is the second highest level, which entails divisions. Section C covers division 10-33, where for example division 10 covers manufacture of food products.

Table 1. Summary Statistics of the Sample

	Observations	Mean	Standard Deviation	Minimum	Maximum
CO_2 Emissions	682	1,789	2,612	11	14,419
log(CO_2 Emissions)	682	6.269	1.762	2.398	9.576
ICT Share of Total Investments	668	0.175	0.168	0.004	0.862
Investments in					
Communication Technology	682	672	968	0	6,736
Information Technology	681	541	973	0	6,984
Software	682	2,305	4,967	11	64,257
ICT	681	3,522	6,019	42	70,150
All assets	682	22,495	32,527	0	258,557

Note: The sample includes 31 industries for the period 1995-2016. The investment data comes from EU KLEMS and data on emissions comes from Statistics Sweden. CO_2 emissions are measured in kiloton. 'Software' is short for Computer Software and Databases. 'ICT' is the sum of investments in communication technology, information technology and software. 'All assets' include computing equipment, communications equipment, computer software and databases, transport equipment, other machinery equipment, total non-residential investment, residential structures, cultivated assets, research and development and other IPP assets. Investments are measured in volume as Gross Fixed Capital Formation.

4.1 ICT data

'Information and communication technologies', or digitalisation technologies, usually consists of two or three product groups. While both Statistics Sweden and EU KLEMS separate ICT equipment into the two main groups (computers and telecommunication) OECD (2020) includes a third component in the definition of ICT, namely software. In the EU KLEMS database, the corresponding group is Computer Software and Databases, which is a part of Intellectual Property products along with Research and Development. Software includes pre-packaged software, customized software and software developed in-house.

The predominant definition of ICT in previous literature includes all three components. In accordance, the analysis here will focus on the somewhat wider definition of ICT.

The EU KLEMS data is measured as Gross Fixed Capital Formation (GFCF), more commonly known as investments. These investments are intended for use in processes of production only. The investment data is calculated as chain-linked volumes, meaning data at previous year's prices, linked over the years via appropriate growth rates[4]. The latest EU KLEMS release uses 2010 reference prices. The ICT investments will be calculated in two steps. First, ICT investments are calculated as the sum of investments in i) computing equipment, ii) communication equipment and iii) computer software and databases. Second, to get a measure of ICT investments as a share of total investments, ICT investments will simply be divided by EU KLEMS' variable for total assets. The procedure of which GFCF is calculated is not without problems, according to the report on methodologies and data construction for the EU KLEMS Release 2019 (Stehrer *et al.*, 2019). The reason is that investment can become negative in the database. In the case of Sweden, twelve observations were negative, resulting in negative ICT shares. Another observation took a value greater than one, implying that ICT investments were greater than all investments, which is probably a mistake in the database. These thirteen observations were changed to zero in order for the ICT share to be bounded between zero and one.

Figure 1 shows the development of the mean ICT investments as a share of total investments during the period 1995 to 2016.

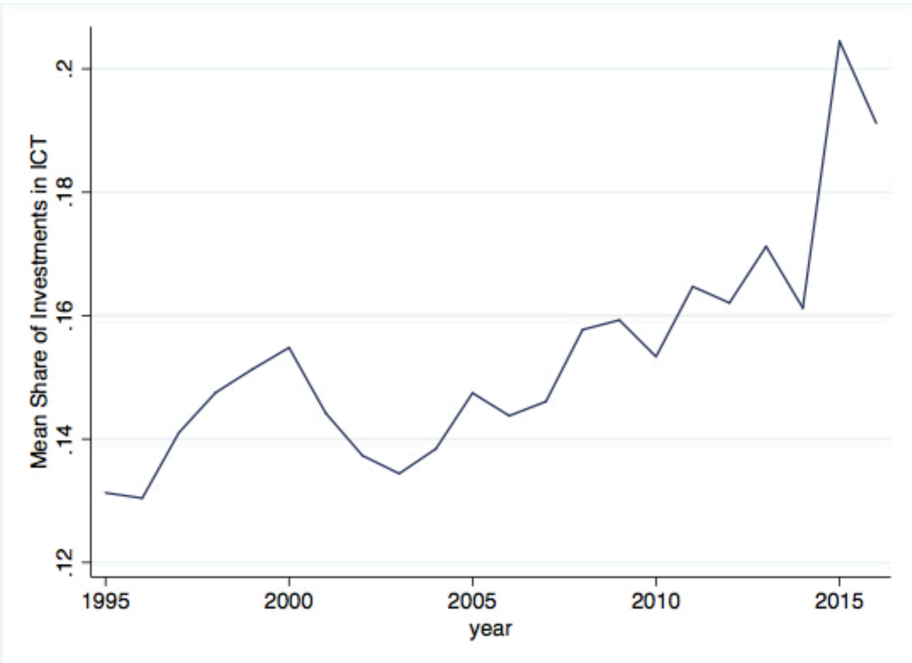


Figure 1. Mean Share of Investments in ICT

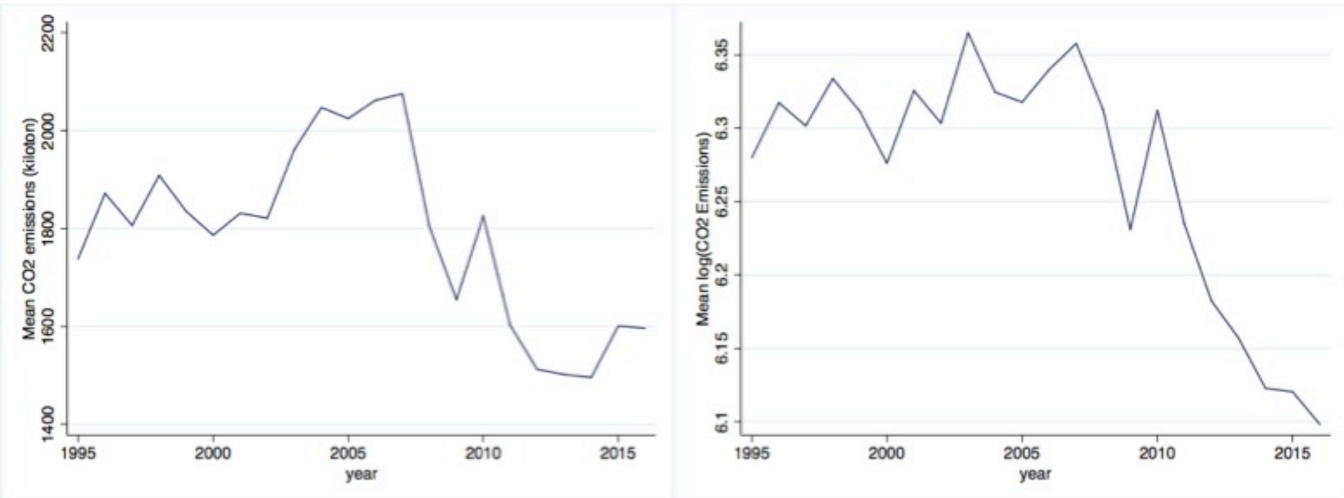
Note: The sample includes 31 industries for the period 1995-2016. The data comes from EU KLEMS.

[4] A more detailed description of how chain-linked volumes are calculated can be found in EU KLEMS' methodology report (see Stehrer *et al.,* 2019, p. 10).

4.2 Air Emission Data

Various indicators can be used for environmental pressure, either atmospheric emissions (e.g. sulphur dioxide, nitric oxide, carbon dioxide and heavy metals) or some types of environmentally relevant material flows. The indicator used in this paper is kiloton carbon dioxide emissions. It is the same indicator that is used in earlier empirical studies.

In the early period, 1993 to 2008, Statistics Sweden only accounts for carbon dioxide stemming from burning fossil fuel, whereas in the later period, 2008 to 2018, Statistics Sweden separates carbon dioxide stemming from burning either fossil fuel or biogenic. The paper will only study effect on carbon dioxide arising from burning fossil fuel due to consistency, but also due to the fact that while fossil fuel use increases the total amount of carbon in the biosphere-atmosphere system, bioenergy systems operates within the system. Hence, burning biomass emits carbon that is already part of the biogenic carbon cycle (International Energy Agency Bioenergy, nd). Figure 2 shows the development of mean CO_2 emissions during the period 1995 to 2016.



Panel A. Mean CO_2 Emissions **Panel B.** Mean log(CO_2 Emissions)

Figure 2. Mean CO_2 Emissions

Note: The sample includes 31 industries for the period 1995-2016. CO_2 emissions are measured in kiloton. The 2007 dip is likely caused by the financial crisis. The data comes from Statistics Sweden.

As depicted in figure 1 and in table 1, the share of ICT investments shows a positive trend, with a mean value of 17.5 percentages across time and industries. There is a large variation in ICT share within industries and time, where the minimum is the value of 0.4 percentages belonging to the industry of *Real Estate Activities* in 2007. This is also the industry that account for the lowest values of ICT share across all industries. The maximum of 86.2 percentages belongs to the industry of *Financial and Insurance Activities* in 2000, the same industry that account for the highest values of ICT share across the group of industries. In terms of CO_2 emissions, both graphs in figure 2 show a relatively stable trend in the first years of the period, whereas there is a downward trend in the end of the period. The mean emission value across all observations is 1,789 kiloton, respectively 6.27 in its logarithmic form. The industries of *Transport and Storage* and *Electricity, Gas, Steam and Air Conditioning Supply* accounts for the highest values of emissions whereas the ICT intensive *Manufacturing Industry of Computer, Electronic and Optical Products* account for the lowest values of emissions. By only observing the data and figures, it can be concluded that there is no obvious relationship between CO_2 emissions and ICT investments. Hence, it is necessary to use an empirical approach to examine if there is a causal relationship.

5 Empirical Strategy

This section will first introduce and discuss the empirical approach of this study, with features and pitfalls. It will especially explain why a distributed-lag model equivalent to an event study works as a specification check to the standard two-way fixed effect model where treatment effects are heterogeneous. Thereafter follows a description on how the two models are set up in this paper.

5.1 Methodology

Since investing in ICT is not a random choice, the paper will first use a two-way fixed effect approach to estimate the causal environmental effects of investing in ICT. The model is often used to examine the impact of natural experiments (typically with distinct events, denoted difference-in-differences or DID), where events are assigned to certain units due to some development beyond the control of the researcher, such as changes in policies or the environment, and as such, the setting does not assume that assignment is random (Clarke & Tapia Schythe, 2020). The approach is also often used to estimate the impacts of policies that are implemented at different times in different groups. In such settings, the regression includes controls for both group and time fixed effects, a two-way fixed effects regression.

There is a recent debate on the pitfalls of standard two-way fixed effects models. First, assuming parallel trends in a standard DID may not be innocuous as discussed by for example Roth (2020). It is proposed to relax this assumption by adding linear or even higher order time trends interacted with the unit of observation. Thus, identification is no longer assuming parallel trends but rests on variation of deviation from linear or higher order time trends. Since this study has no clear control grounds due to continuous treatment, this approach seems even further sensible.

Second, when the treatment effect is constant across groups and over time, thus groups adopt the treatment at a particular point in time and then remain exposed to this treatment at all time afterwards, the regression estimates the effect under the standard parallel trends assumption. However, it is often unlikely that the treatment effect is constant. Recent papers, such as Athey and Imbens (2018), Borusyak and Jaravel (2018), de Chaisemartin and D'Haultfœuille (2020) and Goodman-Bacon (2019), have interpreted the coefficient on the treatment status when there is variation in treatment timing. Goodman-Bacon (2019) for example looks at the DID application with variation in treatment timing, hence where there is variation across groups of units that receive treatment at different times. He shows that any two-way fixed effects estimates of DID relying on variation in treatment timing can be decomposed into a weighted average of all possible two-by-two DID estimators that can be constructed from the panel data set. The decomposition has two very important implications. First, two-way fixed effects estimates of DID that rely on variation in treatment timing only recover the average treatment effect when treatment effects are homogenous. Second, the DID estimates are biased when treatment effects change over time within units. This happens because already treated units serve as controls. When treatment effects are not constant over time, using already treated units as controls necessarily biases the estimates of the treatment effect, by introducing a term representing the change in the treatment effect on the already treated units. In such situations, Goodman-Bacon (2019) shows that the two-way fixed effects estimators are not appropriate and alternative approaches, such as event study estimation, should be used. This is further in line with what other papers have proposed.

As the implementation of estimating heterogeneous effects in a two-way fixed effects setting are rather at the edge of the scientific frontier (de Chaisemartin and D'Haultfœuille (2020), there is to my knowledge no available estimator for this setting with a continuous treatment and I will therefore follow Schmidheiny and Siegloch (2019) which is valid under the assumption of homogenous treatment effects.

Schmidheiny and Siegloch (2019), show that a standard event study model is a re-parametrization of the distributed-lag model if the effect window, in which the treatment effect is allowed to change, is limited to a finite number of leads and lags. Chapter 5.3 describes this assumption and its implications more in detail. Schmidheiny and Siegloch (2019) further show that the rationale of the equivalence between the standard event study design and distributed-lag model can be generalized and adapted to institutional environments, such as multiple events and events of different sign and intensity of the treatment. The model is therefore very suitable to use in this paper, since the treatment variable in this paper measures the *intensity* of ICT investments as a share of total investments. This is important to stress, as this paper does not study an event per se (e.g. a policy change), but events where the intensity of ICT investments as a share changes both across time and space. Since the equivalence principle is somewhat counterintuitive, this paper will interpret the effects before the "event" as placebo effects. The event study design is very appealing since i) coefficients can be graphed, ii) both post-event effects and the identifying assumption of no pre-event trends (the placebos) are immediately visible and iii) the underlying econometrics are intuitive as they can be reduced to a simple panel event data model where the independent variables of interest are a set of non-parametric event indicators which are defined relative to the "event" (Schmidheiny & Siegloch, 2019).

5.2 Two-Way Fixed Effect Model

To measure the environmental impact of ICT investments, the paper relies on industry-level, annual data of ICT investments and total investments. With this data it is possible to define ICT investments as a share of total investments made in each industry *i* at time *t*.

(1) $$\frac{I_{it}^{ICT}}{I_{it}^{Tot}} \epsilon [0,1]$$

The variable in equation (1) is a measure of treatment *intensity*. Most of the literature on causal effects is concerned with estimating the effect of a binary treatment, where units adopt a treatment at a particular time. However, in this study, similarly to studies in medicine examining drug dosage, the interest lies in the variation in treatment intensity. In this setting, industries are always "treated", but the intensity of treatment varies across industries and time. Since the variable is a share, it can take values between zero and one, where zero means that the industry did not make any ICT investments and one means that ICT investments accounted for all investments made. The following regression model further measures the relationship between ICT investments and CO_2 emissions:

$$(2) \qquad log\ (CO2_{it}) = \beta \left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right) + \nu_{it}$$

The parameter ß in equation (2) measures the strength of this relationship. The extreme interpretation of the coefficient is that if the ICT share goes from zero to one, hence an industry goes from not investing anything in ICT to only investing in ICT, CO_2 emissions either decrease or increase by the ß coefficient's value in percentages. If the coefficient value is -0.10 it simply means that if the ICT share goes from zero to one, emissions decrease by ten percentages. Similarly, a one-percentage point increase in ICT investments will lead to a 0.1 percentage decrease in CO_2 emissions.

The standard errors, ν_{it}, are clustered at the industry level to control for serial correlation. The number of clusters (31) is on the border of being too small to fulfil the asymptotic validity of clustered standards errors. A possible outcome is overestimation of the significance of the results.

Taking equation (2) seriously would raise concerns about potential omitted variable bias. Since the regression model only includes one independent variable, it is possible that the model leaves out confounding variables. This can bias the coefficient estimates since it forces the model to attribute the effects of omitted variables to the variable that is in the model. A solution to this potential bias is to include other variables, confounders, which correlate both with the other independent variable and the outcome variable. Given that the literature on the relationship between ICT investments and emissions is scarce, there is no empirical suggestion on confounders. Moreover, as discussed thoroughly by Angrist and Pischke (2009), the problematic confounders are at the same level as treatment, the industry level. Most thinkable variables at this level will all be a function of firm decisions which invalidates inclusion since they are endogenous ("bad controls") which will do even more harm. Thus, omitted variable bias may exist because the confounding variables are unknown or because there is a lack of data. Therefore, the paper will instead exploit changes across both time and space, which corresponds to a two-way fixed effects design. Hence, both industry fixed effects, α_i, and time fixed effects, λ_t, will be added to the equation.

(3) $$log(CO2_{it}) = \alpha_i + \lambda_t + \beta\left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right) + \upsilon_{it}$$

Thus, all time invariant effects by industry specific factors are controlled for by α_i. Moreover λ_t controls for all annual time shocks that hit all industries equally, such as macro shocks.

Finally, industry-specific linear and quadratic time trends, δ_{it} and θ_{it} will be added, in accordance to a recent discussion on the problems associated with tests for parallel trends (see Roth, 2020; Bilinski & Hatfield, 2019). By adding industry-specific time trends, divergent trends between the industries are accounted for as long as they follow the functional form. This has the effect of moving the underlying assumption from parallel trends to parallel growth, which is a less stringent assumption. As a result, the identifying variation comes from deviations from these time trends. The panel data regression will then take the form:

(4) $$log(CO2_{it}) = \alpha_i + \lambda_t + \delta_{it} + \theta_{it} + \beta\left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right) + \upsilon_{it}$$

5.3 Distributed-lag Model

To further ensure the validity of the specification, the paper will also estimate a distributed lag model. As shown by Schmidheiny and Siegloch (2019) the standard event study design is equivalent to a distributed-lag model if the effect window, in which the treatment effect is allowed to change, is limited to a finite number of leads and lags. This requires binning the endpoints of the window. This subchapter will describe this set-up more specifically.

Recall that the ICT share is a measure of treatment intensity, which implies that industries are always treated, but the intensity of treatment varies across industries and time. Hence, the effect of the treatment intensity can be observed at different time periods $t = \underline{t},\ldots,\overline{t}$. $[\underline{t},\ldots,\overline{t}]$ is the observation window for the dependent variable, CO_2 emissions, which in this setting runs from $\underline{t} = 1995$ to $\overline{t} = 2016$. As the treatment effect is allowed to vary over time, it is possible to study its dynamics over a window ranging from $\underline{j} < 0$

periods prior to the "event" to $\bar{j} \geq 0$ after the "event". This window is referred to as the effect window. By binning the endpoints of the effect window, the effect window will be restricted at a certain lag and lead. By limiting the effect window to $\underline{j} < 0$ periods prior to the "event" to $\bar{j} \geq 0$ after the "event", the effect is assumed to stay constant before and after this effect window. This implies that the treatment effect at time j is equal to the treatment effect at time $\underline{j}$ for all $j < \underline{j}$. Similarly, the treatment effect at time j is equal to the treatment effect at time $\bar{j}$ for all $j > \bar{j}$.

To see how the treatment effect changes with leads and lags, the model will first add one lag and one lead of the variable $\frac{I_{it}^{ICT}}{I_{it}^{Tot}}$ to equation (4). Thereafter, two lags and two leads will be added, and so on up until four lags and four leads have been added. A regression with four lags and four leads is shown in equation (5).

(5)
$$log(CO2_{it}) = \alpha_i + \lambda_t + \delta_{it} + \beta_4 \left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right)_{t+4} + \beta_3 \left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right)_{t+3} + \beta_2 \left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right)_{t+2} + \beta_1 \left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right)_{t+1} + \beta_0 \left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right)_{t} + \beta_{-1} \left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right)_{t-1} + \beta_{-2} \left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right)_{t-2} + \beta_{-3} \left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right)_{t-3} + \beta_{-4} \left(\frac{I_{it}^{ICT}}{I_{it}^{Tot}}\right)_{t-4} + \upsilon_{it}$$

This specification allows for testing whether there are pre-treatment and dynamic effects of the share of ICT investments on CO_2 emissions. The coefficients on the lags, i.e. β_0, β_{-1}, β_{-2}, β_{-3} and β_{-4}, show if there are any dynamic causal effects whereas the coefficients on the leads, β_4, β_3, β_2 and β_1, show if there are any pre-treatment effects. If the methodological approach is credible, there should be no pre-treatment effects. Meaning that the coefficients on the leads should be both individually and jointly statistically equal to zero. In practice this means that a future treatment, e.g. in time t+1, should not have any effects on the outcome today. In addition, the immediate effect, β_0, should ideally also be statistically and significantly different from zero to show that the treatment has a large and immediate impact on emissions.

Important to add is that the distributed lag model in equation (5) is numerically identical to an event study design with binned endpoints, leading to the same parameter estimates after correct re-parametrization (Schmidheiny & Siegloch, 2020). Thus, if δ_j denotes the event study parameter at time j, then the following equivalence between the parameters in the event study design with 5 leads and 4 lags in equation (5) holds:

(6) $\delta_5 = -(\beta_4 + \beta_3 + \beta_2 + \beta_1), \delta_4 = -(\beta_3 + \beta_2 + \beta_1), \delta_3 = -(\beta_2 + \beta_1), \delta_2 = -\beta_1, \delta_1 = 0, \delta_0 = \beta_0, \delta_{-1} = \beta_0 + \beta_{-1}, \delta_{-2} = \beta_0 + \beta_{-1} + \beta_{-2}, \delta_{-3} = \beta_0 + \beta_{-1} + \beta_{-2} + \beta_{-3}, \delta_{-4} = \beta_0 + \beta_{-1} + \beta_{-2} + \beta_{-3} + \beta_{-4}$

Note that an event study with $\bar{j}$ = 4 years and $|\underline{j}|$ = 5 years corresponds to a distributed lag model with $\bar{j}$ = 4 lags and to $|\underline{j}|$ - 1 = 4 leads.

6 Results

6.1 Results of the Two-Way Fixed Effects Model

This section presents the results of the effect of investing in ICT on CO_2 emissions in its logarithmic form.

Table 2. Two-Way Fixed Effects Specification

	(1) log(CO_2 Emissions)	(2) log(CO_2 Emissions)	(3) log(CO_2 Emissions)
Share of ICT Investments	-0.902**	-0.436***	-0.436***
	(0.343)	(0.146)	(0.150)
Time and Industry Fixed Effects	Yes	Yes	Yes
Linear Industry Specific Time Trend	No	Yes	Yes
Quadratic Industry Specific Time Trend	No	No	Yes
Observations	668	668	668

Note: Each column displays a two-way fixed effects regression of the impact of investing in ICT on CO_2 emissions. Standard errors are presented in the parentheses and are clustered at the industry level. *** p<0.01, ** p<0.05, * p<0.1

Table 2 shows the results derived from the standard two-way fixed effects specification. Column 1 shows the specification without any industry specific time trends, whereas the regression in column 2 includes a linear industry trend. Column 3 presents a regression with additional quadratic industry specific time trends. The results indicate that ICT investments have a significantly negative effect on emissions, hence a significantly positive effect on the environment. This is true for both the case where industry specific linear time trends are excluded and the case where they are included. However, as can be seen in column 2 the effect is approximately 50 percentage points smaller and significant to a greater level when industry specific time trends are added to the specification. Thus it is reassuring that the point estimate is not further decreased when adding a quadratic time trend. The preferred estimate is thus around 0.43. When accounting for divergent trends between the industries, the results demonstrate that going from having no ICT investments to only having ICT investments will decrease the industry's CO_2 emissions by 43.6 percentages. In other words, a one percentage point increase in ICT investments will lead to a 0.4 percentages decrease in CO_2 emissions. Or using a standard deviation of ICT (0.17) from table 1, the interpretation is that if ICT investment increases by one standard deviation, then emissions go down by 7.5 percentages. Overall it is a non-trivial effect.

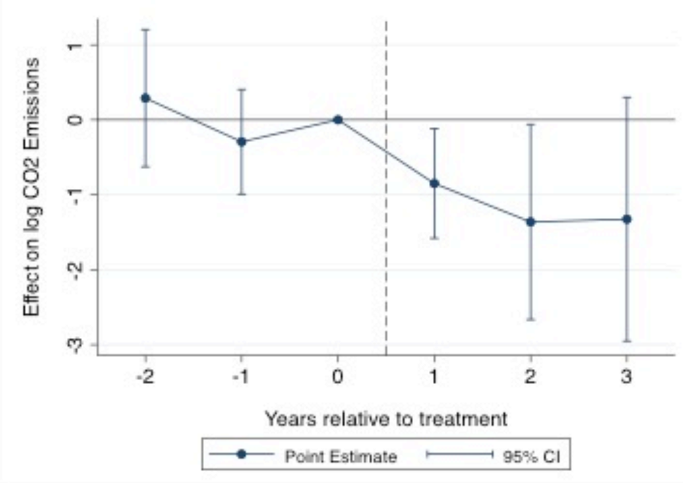
6.2 Results of the Distributed-lag Model[5]

When implementing an event study in this setting, it naturally does not use data at the endpoints of the sample as a year of data is consumed for every lag and lead introduced. If the figure varies a lot, then the set up is sensitive for data in the endpoints. As this study does not have a very long time span, the paper will display event graphs for two lags and leads up until five lags and lags for completeness. The year before the "event" is the normalized baseline according to the transformation in equation (6). 95 percentage confidence intervals are also depicted.

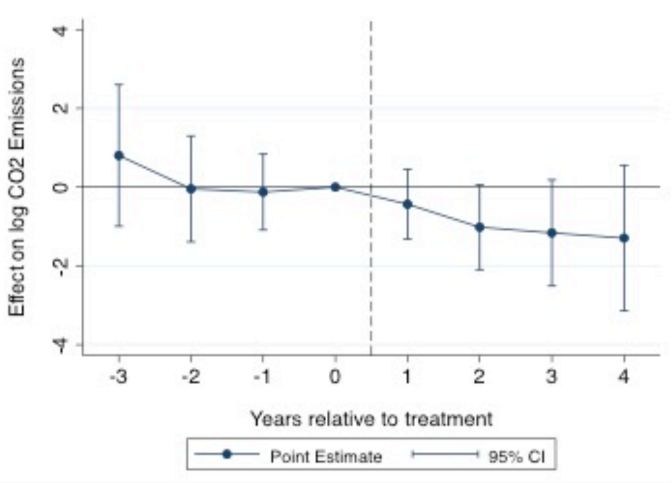
Starting with the results using two lags and leads shown in Figure 3, panel A, there is no evidence of placebo effects. The point estimates are close to zero and change in sign. Most importantly, the immediate impact effect, β_0, shows that the treatment has a large and immediate impact on the outcome. Reassuringly, the point estimate is also significant and around 0.8. The effect stabilizes at around one. Thus, the magnitude lines up well with the estimate from Table 2, column 1. Adding more leads and lags to the regression as shown in Panel B, C and D does not dramatically changes the interpretation. As such, there is no evidence of placebo effects.[6] There is some evidence of increasing effects over time. However, naturally when adding more leads and lags the effects are more and more imprecisely estimated. The overall conclusion is that the patterns in the event graphs give support for a causal interpretation, although an even longer panel in the time dimension would have been preferred.

[5] Unfortunately, the study has too few observations to estimate annual treatments effects combined with industry time trends as that will consume even more degrees of freedom in addition to adding lags and leads. Thus, this exercise is based on expanding the equation estimated in Table 2, column 1.

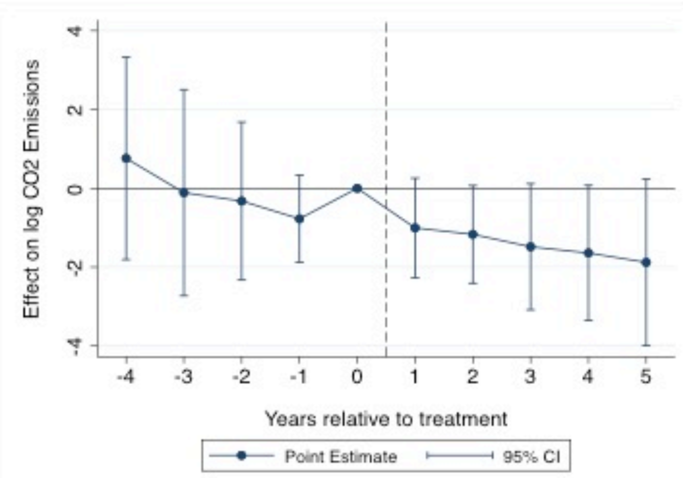
[6] Formally, the F tests, which show if the coefficients on the lags are different from zero, are never rejected.



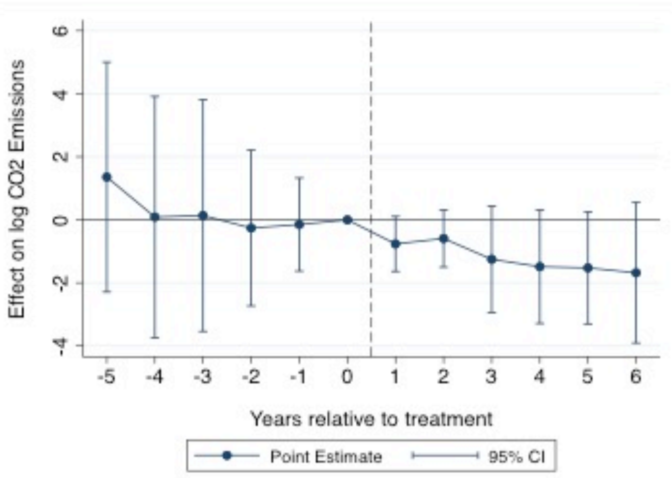
Panel A. Two lags and leads



Panel B. Three lags and leads



Panel C. Four lags and leads



Panel D. Five lags and leads

Figure 3. Event Study Graphs

Note: The year before the “event” is the normalized baseline according to the transformation in equation (6). 95 percentage confidence intervals are presented for each point estimate. A full set of time-varying industry-level controls is included.

7 Discussion

ICT is increasingly integrated in both households and firms. Increasing access to this type of technology is also embedded in the UN Sustainable Development Goals, as ICT is argued to be an essential tool for achieving the goals and improve people's lives (UN, 2015). However, as ICT is dynamic it has aspects that can both worsen and improve the environment, and it is therefore important to establish if the relationship between ICT and the environment is causal, if the effect is negative or positive, and its magnitude. The most credible estimate in this study shows that an increase of a standard deviation of investment in ICT annually in an industry lowers the emissions by 7.5 percentages on average. The events study graphs are also consistent with a causal interpretation, although estimated with a low precision. Overall, this study shows that ICT investments have a significantly positive effect on the environment. Thus, ICT investments coupled with appropriate policy actions have an important role in tackling climate change and environmental issues. With the world needing to halve overall carbon emissions every decade to limit global warming to well below 2, preferably 1.5 degrees, according to the Paris Agreement, ICT have the potential to be an enabler in this goal. The manufacture, use and disposal of ICT equipment (often referred to as the ICT sector) are known to contribute around 2 percentages of global emissions of carbon dioxide in 2020 (McKinsey & Company, 2008). However, as ICT can be used to reduce emissions in other sectors, which this study also shows, the ICT can reduce far more emissions than they generate. In this sense, an annual decrease in emissions by 7.5 percentages is quite promising, and the paper can conclude that policy makes should extend their policies to enable firms to invest even more in ICT. For example, ICT has great potential to reduce the environmental impact in the building and property sector. According to the Ministry of Enterprise and Innovation (2010), the construction sector is responsible for about 40 percentages of society's energy consumption. They further argue that ICT can help reduce its environmental impact by creating what is known as "smart buildings". These come with smart systems that provide residents with information regarding their own energy consumption and how they can influence it, which have the potential to also incentivise and bring about a shift in behaviour at the individual level. With the growing amount of people living in cities, ICT has also been recognised to reduce the environmental pressure by introducing the concept "smart cities". This paper advocates support to more initiatives such as the *Smart City*

Sweden, a national state-funded export and investment platform for smart and sustainable city solutions, focusing on environmental technology and which involves a large group of authorities, regional organisations and private firms (Smart City Sweden, nd). It is a great example of how ICT can enable reductions in emissions, not only by ICT investments in production processes but also with knowledge sharing.

8 Conclusion

This paper aimed to provide empirical evidence to the debate on the environmental effects of Information and Communication Technology, since very little systematic analysis exists within the field. To estimate the environmental effect of ICT the paper used reliable panel data from EU KLEMS and Statistics Sweden, covering 31 Swedish industries across the time period 1995 to 2016. The paper is an extension to the current literature since it implements an arguably better identification of the environmental effect of ICT investments compared to other studies since it implements the latest improvements in design-based evaluation. The paper uses two empirical approaches. First, a standard two-way fixed effects model with linear and quadratic time trends, and then a distributed-lag model equivalent to an event study to graphically judge placebo and dynamic effects. The results confirm that investments in ICT have a negative effect on emissions. The most credible estimate shows that an increase of a standard deviation of investment in ICT annually in an industry lowers the emissions by 7.5 percentages on average. The events study graphs are also consistent with a causal interpretation, although estimated with a low precision. The study concludes that ICT investments coupled with appropriate policy actions can have an important role in tackling climate change and environmental issues.

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Appendix

Table A1. List of Industries Included in the Sample

Divisions	Section	Description
1-3	A	Agriculture, forestry and fishing
5-9	B	Mining and quarrying
10-12	C10-C12	Manufacturing: food products, beverages and tobacco
13-15	C13-C15	Manufacturing: textiles, wearing apparel, leather and related products
16-18	C16-C18	Manufacturing: wood and paper products; printing and reproduction of recorded media
19	C19	Manufacturing: coke and refined petroleum products
20-21	C20_C21	Manufacturing: chemicals; basic pharmaceutical products
22-23	C22_C23	Manufacturing: rubber and plastics products, and other non-metallic mineral products
24-25	C24_C25	Manufacturing: basic metals and fabricated metal products, except machinery and equipment
26	C26	Manufacturing: computer, electronic and optical products
27	C27	Manufacturing: electrical equipment
28	C28	Manufacturing: machinery and equipment n.e.c.
29-30	C29_C30	Manufacturing: transport equipment
31-33	C31-C33	Manufacturing: other manufacturing; repair and installation of machinery and equipment
35	D	Electricity, gas, steam and air conditioning supply
36-39	E	Water supply; sewerage; waste management and remediation activities
41-43	F	Construction
45-47	G	Wholesale and retail trade; repair of motor vehicles and motorcycles
49-53	H	Transportation and storage
49	H49	Transportation and storage: land transport and transport via pipelines
50	H50	Transportation and storage: water transport
51	H51	Transportation and storage: air transport
55-56	I	Accommodation and food service activities
58-63	J	Information and communication
64-66	K	Financial and insurance activities
68	L	Real estate activities
69-82	M_N	Professional, scientific, technical, administrative and support service activities
85	P	Education
86-88	Q	Health and social work
90-93	R	Arts, entertainment and recreation
94-96	S	Other service activities