What is the impact of ICT on CO_2 emissions?
A macro perspective

by

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Abstract

This paper uses macroeconomic methods to investigate the link between information and communication technologies (ICT) and carbon dioxide emissions at a global level. Previous literature reveals that such technologies have negative as well as positive effects on the environment. Negative direct effects through its direct use and production through the energy and materials it consumes. Positive indirect effects which creates a potential to mitigate human activity's impact on the environment through creating more efficient production and distribution processes, and negative rebound effects, that offset efficiency gains with increased consumption. Although these effects have been investigated extensively, there is no consensus on the net effect of ICT on the environment on a global level. To this end, this study uses macroeconomic methods to investigate ICT's net impact on CO_2 emissions on a global level, through a panel analysis of 130 countries for the years 2000-2016 with two different measures of ICT: mobile usage and ICT capital. The mobile usage is measured with number of unique subscribers as share of population, and the ICT capital is measured through an index composed by the ICT capital stock and ICT capital services. Findings suggest that ICT usage is associated with increased CO_2 emissions at time of implementation, but that it has potential to lower the emissions from three years after reaching high levels of use of ICT. No significant impact of the ICT capital on CO_2 emissions is found.

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Keywords: ICT, CO_2, emissions, sustainability, mobile, enablement effect.

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1. Introduction

The threat of climate change is one of the greatest challenges of our time. To reach the targets of the Paris agreements, it has been estimated that the world economy must reduce its carbon dioxide emissions per dollar of income by 6.3 % per year until year 2100 (PWC, 2018). This raises questions on what the structure of tomorrow's economy will be, and how the world can enjoy growth and prosperity in the future without shattering the hope of a habitable planet. Simultaneously, information and communication technologies (ICT) has drastically changed the way we lead our lives, as well as how societies and economies function. The development has raised hopes that ICT can be part of the solution to reach the environmental targets (GeSI, 2015; European e-Business Report, 2010; Añón Higón, et al., 2017).

The European Commission has acknowledged ICT's crucial role in reaching lower emissions and a sustainable development (European Commission, 2008). Estimates have shown that ICT can help mitigate the human activity's effect on the environment, lowering emissions by 6-20 % by 2030 (GeSI, 2015; Malmodin & Bergmark, 2015). However, as greenhouse gas emissions have been rising at a higher pace in the 21st century than in the three previous decades[1] (JRC, 2017), as have the use ICT of the world economies, there is a question if the hopes of ICT's potential have yet been materialised. Although there are hopes for the ICT's potential to reduce human activity's impact on the environment, there are also clear implications on the technologies' strain on the environment; their impact on electricity and energy consumption, amounting to an estimated contribution of ICT to around 1.4 – 2 % of global carbon dioxide equivalent emissions (Malmodin & Lundén, 2018; GeSI, 2015).

Although significant interest has been addressed to the issue in recent years, the net impact of ICT on the environment has yet to provide conclusive results. The literature emphasizes

- the direct effects of the ICT industry, often negative and defined as the impacts of the lifecycle of ICT hardware and software, usually assessed through lifecycle analyses (Erdmann & Hilty, 2010; Malmodin & Lundén, 2016),
- the indirect effects, i.e. which potential ICT has to lower emissions through greater energy efficiency, smart applications, dematerialization and reduced demand for transport (Malmodin & Bergmark, 2015; GeSI, 2015; Houghton, 2009), and

[1] Although 2016 made the third consecutive year for which the emissions where flat (JRC, 2017).

- rebound effects, which comprise the negative effects that efficiency gains may provoke through increased consumption, and thus mitigating or completely nullyfying the environmental gains that they could have posed. The effects are often attributed to the decrease in price which follows a efficiency gain, and thus increased demand (Binswanger, 2001; Gossart, 2015).

Since the different effects have different impacts (direct and rebound effects are usually shown to have a negative effect on the environment, whereas the indirect effects are often positive), there has been a call for evaluating the net impact of such technologies, to understand which potential ICT has to mitigate GHG emissions in the future (Malmodin & Bergmark, 2015; GeSI, 2015), as well as to evaluate the until-now impact empirically (Añón Higón, et al., 2017; Asongu, 2018), to understand to what extent the proposed mititgation effect has been leveraged. It is the until-now net impact that is of interest in this study. Although the topic has been adressed on a regional scale, such as on Chinese regions (Zhang & Liu, 2015), Sub-Saharan Africa (Asongu, 2018) or OECD countries (Alam, et al., 2016), the globality of today's economies and spillover effects make it worth exploring the relationship on a global level. Few studies have had the aim to evaluate the net impact that ICT has had on the GHG emissions on a global level. Añón Higón, et al. (2017) had this aim, but with data only until 2010. The rapid development and ICT penetration that has happened since then, not least in developing countries, calls for a study on more recent data. Thus, the aim of this study is to find an answer to what the net effect of ICT on CO_2 emissions on a global scale is, with recent data.

The question is analysed through panel analysis with data from 130 countries from the first 17 years of the 21st century, using two different measures of ICT: mobile usage and ICT capital. The findings show that mobile usage is associated with an increase in CO_2 emissions upon implementation, but that it has the potential to reduce the emissions a few years after reaching high levels. The results show no significant impact of ICT capital on CO_2 emissions.

The rest of the paper is structured as follows; section 2 provides a theoretical background, section 3 a review of the previous literature, section 4 describes the methodology and data, section 5 presents the results, and discussion and conclusive remarks are found in section 6.

2. Theory

There are two main streams of thought through which the question of interest for this study can be attacked. The relationship is explained either by the Environmental Kuznets Curve, which usually used to explain the relationship between environmental degradation and economic growth, that can also be applied on ICT and its effect on the emissions. Or, the direct – indirect – rebound effect approach, which most empirical studies use.

2.1 The Environmental Kuznets Curve

The Environmental Kuznets Curve (EKC) normally describes the relationship between environmental degradation and income level, but has also been used to describe the relationship between ICT and the environment (see Grossman & Kreuger, 1991) [2]. In this line of thought, greenhouse gas emissions are expected to grow at low levels of ICT, where initial investments in heavy ICT equipment cause greater emissions (in the EKC framework referred to as the scale effect). However, when the ICT equipment is in place, it can be used to optimise production and distribution processes and increase energy efficiency (in EKC lingo, referred to as the technology effect). The relationship is thus expected to take the form of an inverted U-shape (Añón Higón, et al., 2017; European e-Business Report, 2010). This view can be tested through a polynomial panel regression.

2.2 Direct, indirect and rebound effects

The EKC fails to address the changes in behaviour or consumption that technological development and increases in energy efficiency may bring. When energy efficiency increases the prices are likely to fall, which in turn would increase demand. To take these effects into account, one can divide the effects into direct, indirect and rebound effects. In this framework, the direct effects are those that the production and use of ICT equipment have on emissions, mainly caused by its effect of electricity, energy and materials consumption in production and use. The indirect effects are the enabling effects of ICT that through energy efficiency gains in

[2] Criticism towards the Environmental Kuznets Curve has been put forward by among others Arrow, et al. (1995), Stern (2004) and Laestadius (2013). They argue that the empirical evidence for such relationship weak, that it may exist on local level but that the global effects are ignored, as well as that the relationship has only been observed for some pollutants of which CO_2 is not one. Laestadius (2013) argues that even if the emissions-intense investments decrease when an emerging economy reaches high levels of income, the infrastructure that they were invested to build will keep contributing to environmental degradation. However, the criticism is aimed towards the traditional EKC, and not the ICT-related one. Ideally, investing in ICT could enable emissions reductions instead after equipment is put in place.

production and use, optimisation in production and distribution processes as well as dematerialisation and transport substitution can have positive impact on the environment (Houghton, 2009). There are also examples of negative indirect effects. A negative indirect effect arises when an ICT application enables more emitting activities. One example is more efficient system for booking of air travels. The rebound effects are the changes in demand induced by the indirect effects' efficiency gains. The phenomenon is referred to as the "Jevon's paradox"; where greater energy efficiency is contra productive in efforts to save energy, since increased efficiency will reduce the price of energy and thus increase demand (Jevons, 1866). For example, if data can be stored with lesser consumption of energy, firms will not consume less energy but rather store more data (Gossart, 2015). With this framework, the net impact of the ICT industry is ambiguous, even at high levels of ICT matureness in an economy. Whereas the EKC predicts an inverted U-shape, the direct – indirect – rebound view has conflicting forces that can generate negative as well as positive net impact of ICT on the environment at all levels of ICT matureness, depending on which effect dominates.

3. Literature review

3.1 Direct – indirect – rebound effects

The direct effects of ICT refer to what is also called the carbon footprint; the carbon dioxide equivalent emissions that an ICT product or service causes through production or use during its lifecycle, including raw material acquisition, production, use and end-of-life-treatment phases (Malmodin & Lundén, 2018). These studies typically combine lifecycle assessment with market forecasts to estimate current and future footprint of ICT. Malmodin & Lundén (2018) suggested that the ICT footprint for 2015 was 1.4 % of total global carbon dioxide emissions. In terms of electricity consumption, the above mentioned study estimates that ICT uses 3.6 % of overall electricity production for its global operation. In this sector, data centres is a main contributor: Rong, et al. (2016) estimated that it amounts to up to 1.5 % of the world's electricity consumption, while Malmodin & Lundén (2018) estimate it to 1.1 %. The estimates of the development of the footprint differ; but local estimations have shown that ICT related emissions have reached peak in 2010 in Sweden, after which it has decreased (Malmodin & Lundén, 2016). The decrease of the direct footprint can be traced to greater energy efficiency in modern ICT products such as smartphones and tablets rather than PC's and TV's. The emissions caused by use of ICT equipment is also related to the source of electricity for a country, (i.e. Sweden has low-carbon electricity mix and thus the operation of ICT devices in Sweden causes lower levels of emissions) (Malmodin & Lundén, 2016). As for global tendencies, it is suggested that the peak occurred in 2012/2013 (Malmodin & Lundén, 2018).

The indirect effects of ICT were influentially described by Romm (2002), where the decoupling of the relationship between energy consumption and economic growth was attributed to the "new internet economy". He explained the phenomenon with that the ICT sector is less energy intensive than the traditional manufacturing sector, as well as that it provokes technological change that increases energy efficiency. It is the latter explanation that has gained most attention in the later research. Erdmann & Hilty (2010) summarised the ways in which ICT solutions can help mitigate the impact of human activity on the environment in i) the impact of ICT in the production sector though process automation and smart motors, ii) ICT application in the energy sector, iii) smart buildings (controlled heating, ventilation, and air conditioning systems), iv) smart transport systems, v) fuel efficiency of vehicles, vi) e-commerce, vii) dematerialisation. Horvath & Toffel (2004) show that video conferencing and reading newspaper online creates lower environmental impact than do the traditional alternatives. Coroama, et al. (2015) argue that many ICT solutions have the potential to substitute more energy intesive alternatives, however, if the substitution is not done but both used simultaneously, the net effect may be an increase. Malmodin & Lundén (2018) show that the consumption of graphical paper and prints has decreased since 2008, and sees this to be due to digitalisation of information. Paired with the energy efficiency gains in screens, the digitalisation of information decreases the impact of entertainment and media sector. Altogether the estimates on the total enablement effect of ICT are optimistic, with the GeSI's report: #SMARTer2030 (2015) estimating that whereas the ICT carbon footprint will ammount to around 2 % of global carbon dioxide emissions in 2030, the enablement effect[3] will be up to 10 times greater. Estimates by Malmodin & Bergmark (2015), who partly oppose the method applied by the former, show more modest estimates for the enablement potential; ranging from 6 – 15 % in 2030 depending on different scenarios for the reduction potential of ICT.

What is referred to as the rebound effect was first described by William S. Jevons in 1866, when he noted that increasing efficiency in industries led to increased consumption of coal rather than as one would expect: that increasing efficiency would save energy (Jevons, 1866).

[3] Meaning that the emissions avoided by employing ICT solutions are 10 times bigger than the emissions that itself produces.

The explanation is simple: greater energy efficiency lowers energy price and thus increases demand. The rebound effect is often used to investigate the effects of efficiency gains in terms of energy use (Gillingham, et al., 2016), but can also be evaluated from an ICT perspective. If ICT investments that are aimed to increase energy efficiency or to have a positive impact on the environment are subject to rebound effects, then their benefits of using such technology is reduced. The rebound effects of ICT have yet to be thoroughly investigated, but some interesting findings can be pointed out. The rebound effect is further divided into direct, indirect and economy-wide rebound effects.

The direct rebound effects are those that when energy efficiency gains impose lower price of a good, the demand increases for the same good. Hilty et al. (2011) illustrates the direct rebound effect's impact on the Swiss market for mobile phones, where the average physical mass of a mobile phone was 4.4 times smaller in 2005 than in 1990, but the total mass of mobile phones in Switzerland had grown eight times of the same period. The fact is explained by how that greater and cheaper technology made prices drop and consequently, demand exploded. Similar patterns can be shown for computer screens, where the lower price as well as the smaller size of computer screens make it possible to have two screens per person in the workplace (Girod, et al., 2010). There is also evidence that the technology to more efficiently store data does not decrease the energy used but rather more data to be stored (Gossart, 2015). The list can be made long in how the availability and readiness of ICT changes behaviour into more energy consuming activities; Galvin (2015) exemplifies this with how family activities has gone from gather around a radio or TV in the evening, to having the family members busying with one device each. However, evidence shows that these rebound effects do not lead to net increases in energy consumption. Malmodin & Lundén (2018) instead mean that the smaller screens are more effiecient, as well as that the increased storage of data due to efficiency gains has not led to more emissions.

The indirect rebound effects are similar to the direct rebound effects but will increase the demand for *other goods* when the energy efficiency of a specific good increases (Gossart, 2015). The time and money saved from faster and more available technology can be spent on other activities, which can be either more or less energy intensive. For example, when motor vehicles can use fuel more efficiently, consumers may use to money saved on petrol for the car into traveling by aeroplane more frequently. As for ICT, it has been shown that although e-shopping has the potential to save energy through less demand for driving from the consumer as well as more efficient distribution processes, consumers do not tend to drive less to reach traditional shopping centres (Falch, 2012). Another example is teleworking, that is often held as a positive impact of ICT on the environment, but may actually have a negative effect. The negative effect would come from employees deciding to live further away from the workplace – so that when they eventually go to the office, their transportation is longer. Moreover, more intensive use of ICT products with teleworking would have a negative impact on the environment (Gossart, 2015).

The economy-wide rebound effects are those that occur when ICT provokes a structural change in production and distribution processes as well as consumption habits throughout the economy. The new technologies might change production processes through for example efficiency gains in energy, materials, the use capital and labour, causing a price drop in final or intermediate goods that then have effect on the entire economy (Plepys, 2002). Though these effects are hard to estimate and attribute to solely the development of ICT, Plepys (2002) make a convincing case of ICT that the effects that ICT has in changing our lifestyles and creating more productive economies creates productivity gains that reduces production costs and prices of all kinds of commodities.

Total estimations of the rebound effects are inconclusive, but according to a study done on 8 European countries, including firm level data, showed that ICT increased the electricity consumption on the aggregate level, but increased the energy efficiency at the micro level (Alam, et al., 2016).

3.2 Macro/net effect

The different effects of the ICT industry on global emissions spurs a curiosity on the net effect on a global level. Out of the direct, indirect and rebound effects, which dominates? The question has been tackled by either a bottom-up approach: by aggregating the micro-level impact of ICT applications to a macro-level; or a top-down approach: isolating the effect of ICT through macroeconomic indicators (Erdmann & Hilty, 2010). Often, studies assess the *future* impact of the ICT on GHG emissions, using dynamic modelling to evaluate the impact of different ICT applications to different environmental indicators. For example, Hilty et. al (2004) models the effect from the energy, transport, production and waste sectors and then aggregate the effects to estimate the macro-effect of ICT on emissions. The method differs from the lifecycle assessment (that is often used to study the direct effects) in that it can take account for more long-term effects of ICT applications considered. However, the method of aggregating the impact of different sectors demands that an exhaustive list of sectors is considered, and if not all sectors are considered, the whole environmental effect of ICT may not be captured. For example, Erdmann & Hilty (2010) do not consider the emissions of the production of ICT products, which is sometimes and especially for some product categories stated to be one of the largest sources of the direct effect emissions that ICT causes (Malmodin, et al., 2013).

For the macroeconomic top-down approach, few studies have been done with recent data on a global level. Most relevant with this approach is Añón Higón, et al. (2017), that through evaluating the in-country CO_2 emissions, ICT usage and other macroeconomic indicators isolate the ICT's impact through panel analysis on a global level, with data until 2010. They find a relationship in the form of an inverted U-shape, as suggested by the EKC, such that the CO_2 emissions increase with ICT usage until a certain level of usage is reached, and then the emissions start decreasing with further usage. They separate developing and developed countries and find that most developed countries seem to have reached the peak after which CO_2 emissions start decreasing, whereas most developing countries have not. Alam et. al (2016) provides a study with a similar aim, but including OECD countries only and investigating solely internet usage and not the effect of ICT as a whole. They find no short-term impact of internet usage on CO_2 emissions, but that it has an emissions-increasing effect, though small, in the long run (using a 1991-2012-year panel). Brahmasrene & Lee (2014) investigates the relationship on a panel of ASEAN[4] countries, and find that the use of ICT increases the carbon dioxide emissions within the countries examined. Zhang & Liu (2015) find that ICT decreases the CO_2 emissions in China through a panel analysis on Chinese regions, and attributes the findings to three phenomena; firstly, the energy efficiency that ICT brings, secondly, the transition to a more environmentally friendly lifestyle through demateralisation, and thirdly, to the structural transformation from manufacturing to a higher service-intense economy.

The regional results are interesting, however, in an increasingly globalised world, there is reason to investigate the relationship on a bigger set of countries. Moreover, recent years' rapid development and penetration of ICT usage in developing countries call for a global study on

[4] Association of Southeast Asian Nations

more recent data than that of Añón Higón, et al., (2017). Furthermore, previous studies have not considered that the effect of ICT on carbon dioxide emissions may come with a lag. Lastly, this study suggests other proxies for measuring ICT matureness than the above mentioned studies.

4. The model and the data

4.1 The model

The model for the analysis is specified below. The ICT variable is squared to consider the U-shaped relationship that the Environmental Kuznets Curve predicts. GDP per capita is included and squared for the same reason. To avoid omitted variable bias, control variables that is expected to affect CO_2 emissions and covary with ICT matureness are included: industry[5] value added to GDP (Zhang & Liu, 2015) and share of electricity production from oil, gas and coal sources (Malmodin & Lundén, 2016). Regressions on subsamples divided by income will detect if ICT's impact differs between different levels of GDP, and robustness of those results will be checked with a Chow test.

The model will be constructed as follows:

$$CO2_{it} = \beta_1 ICT_{it} + \beta_2 ICT_{it}^2 + \beta_3 GDP_{it} + \beta_4 GDP_{it}^2 + X'_{it}\theta + \alpha_i + \gamma_t + \varepsilon_{it}$$

Where $CO2_{it}$ is the CO2 emissions from country i in time t, ICT_{it} is the measure of ICT, with unique mobile subscriptions and the ICT capital index respectively. GDP_{it} is the gross domestic product per capita of country i in time t, X'_{it} is the vector of control variables for country i in time t, these are the variables that are expected to vary within countries over time. Variables that differ between countries but remain the same within countries over time are captured in the country fixed effects, α_i. γ_t captures the time fixed effects and ε_{it} is the error term.

If the explanatory variables are correlated with the error term, the estimates will be biased. With panel data, it is likely that there is unobserved heterogeneity between the countries. If so, i.e. if countries have characteristics that affect the carbon dioxide emissions but are not taken account for in the model, estimates will be biased. If these characteristics are correlated with the other explanatory variables, fixed effects should be used. If they are uncorrelated with the other

[5] Industry, value added (% of GDP). It comprises value added in mining, manufacturing, construction, electricity, water, and gas.

explanatory variables, random effects should be used. (Random effects assume that the country specific effects are drawn from an independent and identically distributed population (random), and fixed effects take account for that they are correlated with the other explanatory variables). The question is then whether the country specific effects can be considered as drawn from an independent and identically distributed variable distribution (Hausman, 1978). Whether the fixed or random effects estimator should be used or not is determined with a Hausman test. [6]

In econometric models like this one there is always a question of whether the findings represent causal relationships or spurious correlation. Instrumental variable regression can be used to correct for simultaneity, reverse causality and omitted variable bias. In this case the simultaneity and reverse causality problems are unlikely to be present as the level of per capita emissions are unlikely to affect the level of ICT. Omitted variable bias are controlled for through including control variables. Robustness checks are performed to confirm that the relationship holds for different specifications and different ways of measuring ICT. Fixed effects will control for unobserved heterogeneity across the countries. These measures are taken to make as adequate estimations as possible, and then the results are discussed with the theory and findings from previous literature.

4.2 How to measure ICT?

There are multiple ways to measure ICT. Most macroeconomic studies are interested in the usage of ICT. It is often measured with proxies such as mobile subscriptions and/or internet usage, using number of subscriptions per 100 people (Añón Higón, et al., 2017; Brahmasrene & Lee, 2014; Alam et al., 2016; Asongu, 2018). When measuring the number of subscriptions, it is every subscription that counts, resulting in that people with multiple subscriptions will be counted multiple times. Another alternative is to measure the number of unique subscribers as a share of population. The unique subscribers measure is defined as the share of population that has at least one mobile connection, and can be a more accurate measure of the market penetration of ICT. The higher accuracy is illustrated by that in Sub-Saharan Africa, it is not unusal to have many connections per person to achieve the best connection in different locations, since the quality of connection varies between operators and locations. The number of mobile subscriptions per 100 people is therefore not a particurlarly good proxy for the ICT penetration and matureness of an economy, but would in this case indicate that the quality of

[6] Hausman test confirmed that fixed effects should be used.

connections and thus dependency of ICT is lower[7]. Furthermore, there are probably diminishing returns to number of connections per person; meaning that the first connection will create greater behavioural or organisational changes than the second or third one. Therefore, this study will use the share of unique mobile subscribers of population as the appropriate proxy for ICT matureness (GSMA Intelligence, 2018).

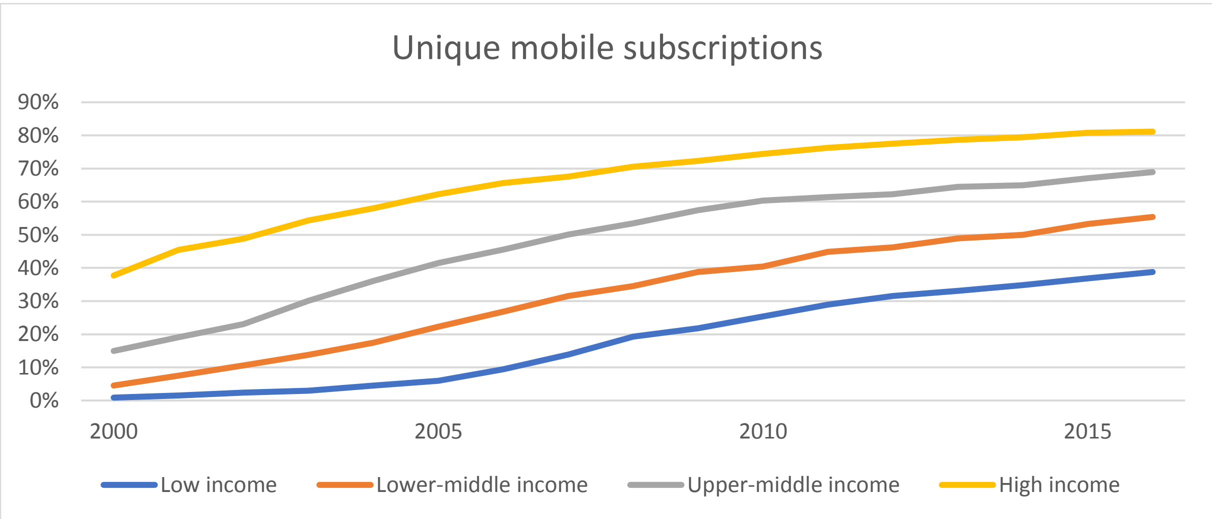
However, there is reason to argue that the sole use or market penetration of mobile subscription does not mean that countries have had the chance to implement and take part of the enablement effects ICT that could bring, such as smart technology and greater energy efficiency in production. Take for example Angola, where share of unique subscribers in the population has increased with a factor of 283 over the past decade, compared to 1.73 in Sweden (GSMA Intelligence, 2018). The strong increase in mobile subscriptions does not ensure that Angola enjoys the enabling effect that ICT can bring, albeit the fast growth of cellular subscriptions. This could give a misleading picture in a panel regression, even when controlling for GDP. Therefore, in addition to a model with the ICT usage, this study will use a measure of ICT capital as complementary measure of the ICT importance in the economy. The ICT capital estimate is based on data on the ICT capital stock from The Conference Board Total Economy Database (2017). Jorgenson & Griliches (1967) argued that estimates of a capital stock and its productivity will be biased if data on annual utilisation and user costs are not taken into account. To this end, a new index is constructed based on the ICT capital stock and growth rates of ICT capital services. Capital services, unlike the raw capital stock measure, account for the differences in amount of services provided per unit of stock between short and long-lived assets (U.S. Bureau of Labor Statistics, 2016). The result is a new estimation of the ICT capital that is comparable over time and take the user cost into account. Further description on how the estimate is calculated can be found in appendix. This measure gives an image of to which extent the economy can enjoy the effects of ICT and will complement the measure of usage.

The two graphs below show the averages of unique mobile subscriptions and ICT capital in the countries, divided into income groups. Figure 1 shows that the unique mobile subscriptions have grown at similar pace across the income groups, although starting from different levels. The ICT capital estimate show more diverse trends in figure 2. Here, the difference in level as

[7] Countries that lie in top in terms of mobile subscriptions per 100 people in 2016 are Macao, Hong Kong, Maldives, Bahrain, United Arab Emirates, and Jordan, whereas Norway, Finland, Hong Kong, Taiwan and Sweden top the league for share of unique subscribers.

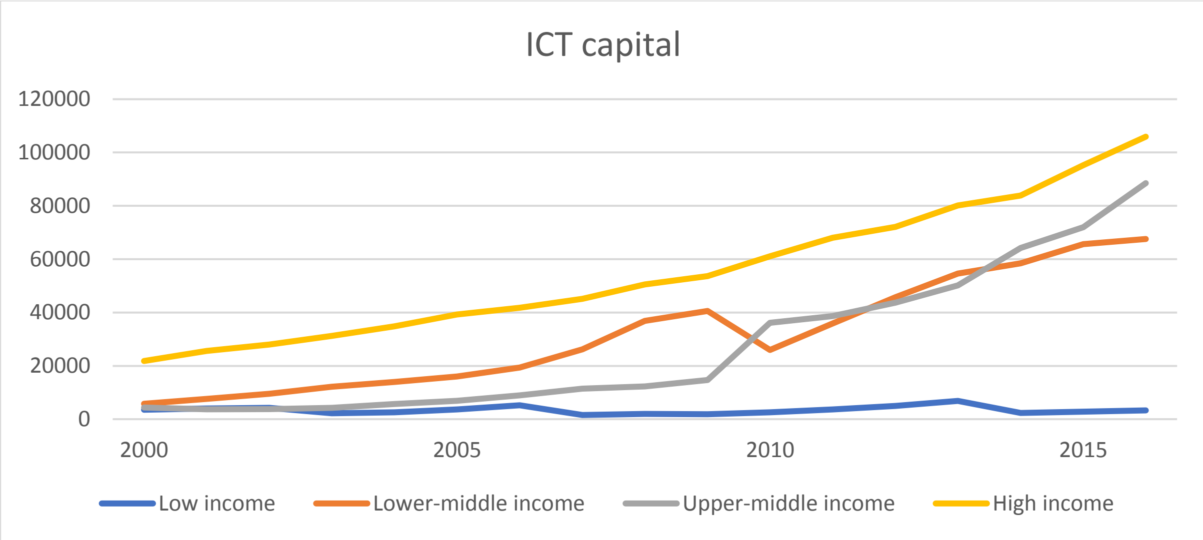
well as in trend between high and low-income countries is much larger than for unique mobile subscriptions. The ICT capital is the result from investments and thus sensitive to economic conditions. A few points are worth noting. Firstly, contrastingly to the high, upper-middle and lower-middle countries that have had ICT capital growing by a factor of 5, 20 and 12 respectively since the beginning of the period, the ICT capital is 6,5 % smaller in the low-income countries in 2016 than in the beginning of the period. Secondly, the lower middle-income countries have a larger capital stock than the upper middle-income countries up until the years around the financial crisis. Whereas the financial crisis seems to have caused a reduction in the ICT investments in lower middle-income countries, the opposite is true for upper-middle income countries. It could be that firms used the financial crisis as an opportunity for "creative destruction", where old technologies are replaced by new ones (see Hershbein & Kahn, 2017). It might be so that upper-middle income countries before the crisis were more dependent on a traditional manufacturing sector, whereas they took the opportunity to invest in new technology when recovering from the crisis, when interest rates were exceptionally low. Lower income countries were possibly not able to take the opportunity since capital tend to drain quicker in high risk environments in case of financial stress (Kose, et al., 2017).

Figure 1. Unique mobile subscriptions as share of population.



Source: ICT: GSMA Intelligence (2018), Income classification: World Bank (2016).

Figure 2. ICT capital, average per income group



Source: ICT: The Conference Board Total Economy Database (2017), Income classification: World Bank (2016)

4.3 How to measure CO_2 emissions?

Macroeconomic studies with the top-down approach tend to use ICT usage (such as mobile subscriptions or internet usage) as proxies for the ICT penetration in the countries (Añón Higón, et al., 2017; Brahmasrene & Lee, 2014; Alam et al., 2016). They then pair this with data on CO_2 emissions that are emitted within the boundaries of that country. However, there is reason to believe that the usage of ICT and other products impacts not only the emissions within that country but in other countries. This "export of emissions" occurs since the production of ICT hardware gives significant contributions to the environmental impact of ICT (Malmodin, et al., 2013), and thus the usage of ICT may cause the direct, negative effects on the CO_2 emissions in the country of production, whereas the indirect, enablement effect is reserved for the country where the technology is used. Furthermore, it is not only the production of ICT hardware, but also other CO_2 intensive production that can be moved to other countries with help of ICT. Therefore, data on consumption-based emissions would be desired for this study. Although estimates have been made on consumption on regional level, there is not yet, to the knowledge of the author, any global data on consumption-based emissions. Therefore, also this study will be restricted to use the production-related emissions. Future research should aim to produce data on consumption-based emissions to complement the results and get further insight in how ICT impacts carbon dioxide emissions.

Global carbon dioxide emissions increased at a higher pace from the first decade of the 21st century than in the preceding decades. However, from 2014 through 2016, emission levels have been flat (European Commission, 2017). Since population have kept increasing, the emissions per capita have actually decreased during this period (World Bank, 2017). The BRIC[8] countries has been strongly contributing to the rise of emissions in the first decade of the 21st century. The recent flattening of China's emissions as well as those of Brazil, paired with steady decrease of EU28's emissions since the 1990's has been contributing factors to the flattening of CO_2 emissions between 2014 and 2016 (European Commission, 2017). Though it may be too early to conclude a trend break, it will be interesting to see if ICT's enabling effects could have played a role in this development.

4.4 Variable description and descriptive statistics

Table 1. displays the variables used for this study and their sources.

Table 1. Variable description

Variable	Description	Source
CO_2 per capita	Carbon dioxide emissions in metric tons per capita.	European Commission (2017)
ICT subscriptions	ICT market penetration, measured as the total number of unique users who have subscribed to mobile services, expressed as a percentage share of the total population.	GSMA Intelligence (2018)
ICT capital	ICT capital consists of hardware, software and communications equipment. Further description on how the stock is estimated can be found in the appendix. Values are per capita.	The Conference Board Total Economy Database™ (2017) World Bank (2017)
GDP per capita	Gross domestic product per capita, constant 2010 $US.	World Bank (2017)
Industry	Industry, value added (% of GDP). It comprises value added in mining, manufacturing, construction, electricity, water, and gas.	World Bank (2017)
Electricity mix	Electricity production of coal, oil and gas as share of total electricity production.	World Bank (2017)
Governance	An index measuring the governance through six indicators.[9] Values range between -2.5 and 2.5, where 2.5 is strong governance.	World Bank (2018)
Oil reserves	Proven crude oil reserves, billion barrels.	US Energy Information Administration (2018)

[8] Brazil, Russia, India and China.

[9] The indicators are: Voice and Accountability, Political Stability and Absence of Violence, Government Effectiveness, Regulatory Quality, Rule of Law and Control of Corruption.

Descriptive statistics of the included variables are provided in table 2., and divided by income group in table 3. The descriptive statistics are pooled over all years included. The high-income countries have as expected higher average values in all variables except from the electricity mix and industry variable. High income countries have an on average per capita emissions of 10.86 metric tons per capita, compared to 2.75 for low and middle-income countries.

Table 2. Descriptive statistics

Variable	All countries N= 2062				
	Mean	Median	Std. Dev	Min.	Max
CO_2 per capita	5.64	3.91	6.38	.04	55.45
ICT subscriptions	.47	.51	.27	.0002	.92
ICT capital[10]	.001	.0005	.0014	7.18e-07	.01
GDP per capita	15424	6416	19782	193.87	111968
Industry	31.92	29.29	14.35	6.84	213.69
Electricity mix	59.73	64.78	33.86	0	100
Oil reserves	7.67	.05	32.36	0	297.74
Governance	.20	.01	.96	-1.82	2.44

Table 3. Descriptive statistics divided by income group

Variable	High income countries N=736				Low income countries N=1326			
	Mean	Std.dev	Min	Max	Mean	Std.dev	Min	Max
CO_2 pc	10.86	7.63	1.37	55.45	2.75	2.77	.04	16.11
ICT sub.	.68	.17	.06	.92	.36	.24	.0002	.88
ICT cap.	.002	.001	.0001	.01	.0003	.0005	7.18e-07	.0035
GDP pc	35908	20671	6933	111968	4088	3280	193	14778
Industry	31.98	19.13	6.84	213.69	31.89	10.85	9.69	78.52
Elmix	62.32	33.37	.01	100	58.28	34.06	0	100
Oil	10.32	44.01	0	266.6	6.19	23.33	0	297.7
Gov.	1.25	.60	-.37	2.43	-.39	.53	-1.82	1.27

[10] The number of observations for the ICT capital stock data is 1452, since the capital stock is available for a lower number of countries than the ICT usage measure.

5. Empirical results

5.1 Unique mobile subscriptions

The empirical results of the effect of ICT usage on carbon dioxide emissions are shown in table 4. In specification 1., we can observe the inverted U-shape[11] predicted by the Environmental Kuznets Curve between mobile subscriptions and CO_2 emissions. That is, the CO_2 emissions first increase when mobile usage increases, but the effect diminishes and reaches a turning point after which an increase in the share of population with a mobile connection leads to a decrease in CO_2 emissions. The turning point is estimated to 80 % market penetration, which is found in the 92nd percentile in the data distribution. The same relationship holds for the relationship between GDP and CO_2 emissions.

Table 4. Benchmark regression.

CO_2 per capita	1.	2.
ICT subscriptions	5.610***	3.862***
	(1.012)	(1.026)
ICT subscriptions^2	-3.471***	-0.568
	(1.237)	(1.187)
GDP per capita	.0003***	.0002**
	(.0001)	(.0001)
GDP per capita^2	-2.77e-09***	-2.38e-09**
	(1.16e-09)	(1.07e-09)
Industry share		.079***
		(.015)
Electricity mix		.020***
		(.006)
Number of countries	185	130
Number of obs.	3067	2062
Avg. obs. / country	16.6	15.9
ICT turning point (percentile)	0.8083 (92)	Linear rel.
R^2 (within)	0.1709	0.4351

Note: Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Country fixed effects are used.[12] Time fixed effects are controlled for using year dummies in all regressions. Years examined are 2000-2016.

[11] The both ICT variables are significant, with opposing signs, implying a U-shaped relationship.
[12] Hausman test confirmed that fixed effects should be used.

However, when controlling for to which extent electricity is produced by gas, coal and oil in the countries, and energy intensive industries,[13] the results change. Both control variables have expected signs, affecting emissions positively, but the squared term of ICT is no longer significant. Instead there is a linear relationship at which CO_2 emissions will increase with increasing mobile usage. The relationship between GDP and CO_2 emissions is robust.

Excluding the two control variables one by one shows that it is the industry variable that causes the insignificance in the squared ICT term. It implies that countries with higher levels of mobile usage also have lower share of energy intensive industries, and that is what drove the observed decrease in emissions after 80 % market penetration in specification 1.

The ambiguity of the first two specifications makes it worth considering another specification. Even if there is no actual turning point at which ICT starts having a reducing effect on emissions, the effect may be diminishing. That is, even if higher levels of ICT are associated with higher levels of carbon dioxide emissions, the relationship may be less than linear so that the relationship becomes flatter at high levels. To this end, the ICT and GDP variables were logarithmically transformed, and results are presented in table 5. The results confirm that the ICT market penetration is associated with increasing levels of CO_2 emissions, though at a diminishing rate. The magnitude of the coefficients shows that a one percent increase in the share of population having a mobile connection is associated with an average of 0.05 percent increase in the per capita emissions. The results are robust when including control variables, coefficient change slightly.

[13] Industry share of GDP comprises the value added in mining, manufacturing, construction, electricity, water, and gas.

Table 5. Logarithmic regression.

ln CO_2 per capita	3.	4.
lnICT subscriptions	.0499***	.0391**
	(.0101)	(.0180)
lnGDP per capita	.3995***	.4746 ***
	(.0719)	(.1208)
Industry share		.0019**
		(.0020)
Electricity mix		.0043***
		(.0155)
Number of countries	185	130
Number of obs.	3067	2062
Avg. obs. / country	16.6	15.9
ICT turning point	Log rel.	Log rel.
F-value	15.42	12.83
R^2 (within)	0.3064	0.3637

Note: Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Country fixed effects are used. Time fixed effects are controlled for using year dummies in all regressions. Years included are 2000-2016.

5.1.1 High vs. low and middle-income countries

To detect whether the effect differs between countries with different levels of income, regressions were run on subsamples, where countries is divided into one group of high income countries, and one of low and middle-income countries.[14] Results are presented in table 6.

Results show that the impact of ICT on CO_2 emissions differs between the two subsets of countries. It seems like an inverted U-shape is driven by the low and middle-income countries. The turning point at which higher levels of ICT is associated with lower levels of CO_2 emissions is at 0.49 market penetration, which is well above the average of ICT market penetration for low and middle-income countries (0.24). The turning point coincides with the 25th percentile in 2016 in the low and middle-income sample, meaning that 75 % of the low and middle-income countries have reach a point at which ICT start having a decreasing effect on CO_2 emissions in 2016. Note however that the low and middle-income group's regression is significant only on

[14] The income classifications are those of the World Bank, 2016. High income countries are those with GNI per capita of $12,476 or more in 2015, and low and middle-income countries are those with GNI per capita of $12,475 or less. GNI per capita is calculated using the World Bank Atlas method (World Bank, 2016b).

the 10 % level (the lowest level of significance), and that the difference between the groups is not robust for a Chow test (see robustness section).

Table 6. Regressions on subgroups of countries separated by income level.

CO_2 per capita	5. High income countries	6. Low and middle-income countries
ICT subscriptions	5.6202	1.7785*
	(5.3524)	(1.011)
ICT subscriptions^2	1.0554	-1.8262*
	(4.3878)	(1.0222)
GDP per capita	.0001	.0007**
	(.0001)	(.0003)
GDP per capita^2	-1.35e-09	-1.64e-08
	(8.31e-10)	(1.15e-08)
Industry share	.1035***	-.0081
	(.0055)	(.0081)
Electricity mix	.0329**	.0031
	(.0138)	(.0033)
Number of countries	47	83
Number of obs.	736	1326
Avg. obs. / country	15.7	16.0
ICT turning point (percentile)	.	0.4869 (25)
F-value	.	6.33
R^2 (within)	0.5858	0.3590

Note: Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Country fixed effects are used. Time fixed effects are controlled for using year dummies in all regressions. Years included are 2000-2016.

In the high-income regression in table 6., neither ICT nor GDP are significant determinants of CO_2 emissions. This suggests that the specification is problematic, since as we would expect that GDP affects the CO_2 emissions (Sharma, 2011). The sample of only high-income countries might be too small to detect a relationship, or the variation in the variables is not large enough to establish a relationship. Also, the classification of countries may have an impact: here, the income status from 2016 is used, which is only the last year for observation. Also, there might be a higher level of path-dependency in high income countries, where previous investments affect emissions more so that they are less sensitive to ICT development. The logarithmic regressions are displayed in table 7.

Table 7. Logarithmic regression on subsamples.

lnCO2pc	7. High income countries	8. Low and middle-income countries
lnICT subscriptions	.1923***	.0104
	(.0474)	(.0213)
lnGDP per capita	.2874**	.4145***
	(.1441)	(.1443)
Industry share	.0024***	-.0001
	(.0004)	(.0036)
Electricity mix	.0053***	.0023
	(.0014)	(.0020)
Number of countries	47	83
Number of obs.	736	1326
Avg. obs. / country	15.7	16.0
F-value	42.55	7.50
R^2 (within)	0.6243	0.3664

Note: Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Country fixed effects are used. Time fixed effects are controlled for using year dummies in all regressions. Years included are 2000-2016.

The results for high-income countries in this regression show an increasing effect on CO_2 emissions, though at a diminishing rate. Results suggest that the logarithmic regression is a better fit for the high-income country data. From the two tables we can conclude that it is the high-income countries driving the emissions-increasing relationship, and that the low and middle-income countries eventually reaches a turning point after which ICT has a reducing effect on CO_2 emissions. The lack of turning point in the high-income regressions could be explained by a higher incidence of rebound effect (see also discussion in section 6).

5.1.2 What about a lagged effect?

In exploring computerisation’s effect on productivity, Brynjolfsson and Hitt (2003) find that it takes 5 years for the investments to materialise in increased productivity due the necessity of complementary inputs, such as organisational capital. If the effect of computarisation on productivity comes with a lag, it is likely that also the indirect and rebound effects on CO_2 emissions come with a lag. This is because the indirect effect requires behavioural, organisational and technological changes. The rebound effect is the induced by the indirect effects and should thus also come with a lag. To explore this, lagged values of the mobile subscriptions were included in the regressions.

Table 8. Polynomial regression including time lags.

CO_2 pc	1 lag	2 lags	3 lags	4 lags	5 lags
ICT, current	.9866	1.4774	1.7587	1.9056*	2.1645*
	(1.4185)	(1.1366)	(1.080)	(1.1086)	(1.0768)
ICT, lagged	3.2816**	3.1273***	3.3268***	3.3583***	3.2001***
	(1.6320)	(1.1043)	(.8827)	(.7900)	(.7274)
ICT^2, lagged	-1.1387	-1.6264	-2.5368**	-3.3167***	-3.850***
	(1.2091)	(1.1233)	(.9854)	(.8691)	(.7960)
GDP pc	.0003**	.0003***	.0003***	.0004***	.0004***
	(.0001)	(.0001)	(.0001)	(.0001)	(.0001)
GDP pc^2	-2.67e-09***	-3.01e-09***	-3.31e-09***	-3.61e-09***	-3.46e-09***
	(1.02e-09)	(9.47e-10)	(9.14e-10)	(8.69e-10)	(1.02e-09)
Electricity mix	.0185***	.0186***	.0192***	.0179***	.0157***
	(.0057)	(.0054)	(.0054)	(.0054)	(.0047)
Industry share	.0801***	.0859***	.0822***	.0704*	.0451
	(.0174)	(.0230)	(.0308)	(.0362)	(.0300)
Number of countries	130	129	129	129	129
Number of obs.	1944	1824	1704	1584	1463
Avg. obs. / country	15.0	14.1	13.2	12.3	11.3
ICT turning point	Linear rel.	Linear rel.	0.6557	0.5063	0.4160
R^2 (within)	0.4460	0.4635	0.4423	0.4112	0.3849

Note: Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Country fixed effects are used. Time fixed effects are controlled for using year dummies in all regressions. Years included are 2000-2016.

The results confirm that there is a positive (emissions-increasing) relationship between ICT and carbon dioxide emissions. However, the significance of the squared term for ICT in the third lag and onwards show that after a certain level of market penetration, further increase of ICT will be associated with lower levels of CO_2 emissions. The implementation of ICT applications as well as the behavioural and organisational changes they provoke do not have an instant effect on CO_2 emissions but come with a lag. The result shows that higher levels of mobile usage are associated with a decrease in emissions three years later. The turning point is estimated to 0.66, meaning that during the examined period, share of unique subscribers of 66 % is associated with that emissions starts decreasing three years later. 66 % ICT market penetration is below the average value of the sample in 2016, which has an average market penetration of 70 %. The median country reaches the turning point at which further market penetration could have a decreasing effect on CO_2 emissions in 2013. According to this estimation, half of the countries have reached such levels of mobile usage that they should start seeing a decreasing effect of ICT on CO_2 emissions in 2016 (three years after the turning point has been reached). This implies that part of the flattening of the carbon dioxide emissions could be attributed the use of ICT.

Table 9. Logarithmic regressions including time lags.

lnCO2 per capita	1 lag	2 lags	3 lags	4 lags	5 lags
lnICT, current	.0327	.0318	.0250	.0335	.0470
	(.0585)	(.0402)	(.0343)	(.0311)	(.0308)
lnICT, lagged	.0130	.0200	.0313	.0343	.0333*
	(.0590)	(.0365)	(.0273)	(.0214)	(.0184)
lnGDPpc	.4978***	.5081***	.5231***	.5356***	.5560***
	(.1209)	(.1196)	(.1139)	(.1039)	(.0905)
Electricity mix	.0042***	.0042***	.0038**	.0033**	.0029**
	(.0015)	(.0015)	(.0015)	(.0015)	(.0014)
Industry share	.0012**	.0017*	.0018	.0018	.0017
	(.0008)	(.0009)	(.0011)	(.0013)	(.0015)
Number of countries	130	129	129	129	129
Number of obs.	1944	1824	1704	1584	1463
Avg. obs. / country	15.0	14.1	13.2	12.3	11.3
F-value	12.04	12.90	12.19	13.83	15.20
R^2 (within)	0.3704	0.3755	0.3680	0.3770	0.3837

Note: Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Country fixed effects are used. Time fixed effects are controlled for using year dummies in all regressions.

Including lags in the logarithmic regression gives insignificant results for the current value and the lags until the fifth lag. This model is unable to detect the U-shape found in table 8. The fact that the logged regressions provide insignificant results then implies that the relationship found in table 8 better describes the data. We can conclude from these two tables that there is an inverted U-shaped relationship between CO_2 emissions and lagged values of unique mobile subscriptions.

5.2 ICT capital estimates

Regressions on ICT capital's effect on carbon dioxide emissions are presented in table 10. The relationship between ICT capital and carbon dioxide emissions first appears to be negatively correlated. However, when including the control variables, the effect on emissions are completely contributed to the industry share of GDP as well as to the electricity mix. This implies that there is no significant relationship between the size of the ICT capital of a country and the size of the carbon dioxide emissions of that country, on average. Note that these regressions may be subject to a small measuring error. It derives from the fact that in the regression, we include GDP as a control variable. As ICT investments is included in the measure for GDP as well, they are counted twice in the regression. This could give rise to a bias, but it should be small since the ICT investments are share of GDP is on average small.

Table 10. Regressions with the ICT capital

CO_2 per capita	9.	10.
ÌCT capital estimate	-902.6408**	-354.3889
	(446.1476)	(349.6449)
ICT capital estimate^2	30291.6	9638.579
	(29598.46)	(22988.33)
GDP per capita	.0005***	.0003***
	(.0001)	(.0001)
GDP per capita^2	-3.75e-09**	-2.96e-09***
	(1.48e-09)	(1.12e-09)
Industry share		.0806***
		(.0082)
Electricity mix		.0273***
		(.0093)
Number of countries	92	92
Number of obs.	1452	1452
Avg. obs. / country	15.8	15.8
R^2 (within)	0.2857	0.4807

Note: Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Country fixed effects are used. Time fixed effects are controlled for using year dummies in all regressions. Years included are 2000-2016.

The results from the logarithmic regression is displayed in table 11. Neither in this specification does the level ICT capital of a country seem to have a significant impact on the level of CO_2 emissions. Note that the estimates for GDP's effect on carbon dioxide emissions are significant, but magnitudes have changed compared to the regressions with unique mobile subscriptions.

The difference may have to do with the fact that the sample are considerably smaller for the ICT capital data, and biased towards higher income countries compared to the data on mobile subscriptions. Countries with higher income have larger spread on the level of carbon dioxide emissions, so a one unit change in GDP may have a greater impact on emissions if only the high-income countries are considered than on average in a sample where more low-income countries are included.

Table 11. Logarithmic regression with the ICT capital.

ln CO_2 per capita	11.	12.
lnICT capital	.0438	.0417
	(.0301)	(.0307)
lnGDP per capita	.7697***	.6882***
	(.1046)	(.1052)
Industry share		.0021***
		(.0006)
Electricity mix		.0051***
		(.0017)
Number of countries	92	92
Number of obs.	1452	1452
Avg. obs. / country	15.8	15.8
R^2: Within	0.4265	0.4948

Note: Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Country fixed effects are used. Time fixed effects are controlled for using year dummies in all regressions. Years included are 2000-2016.

5.2.1 High vs. low and middle-income countries

To further explore the impact of the ICT capital, sample is divided into two subsamples of high versus low and middle-income countries, respectively. These regressions also provide non-significant results for the ICT capital's effect on the CO_2 emissions.

5.2.2 What about a lagged effect?

The lagged effect of the stock on the CO_2 emissions appears after 4 years, and then with the opposite relationship to the relationship found in the regressions with ICT usage. All the other variables have expected signs. Neither a regression where CO_2 per capita were kept raw but the lags of ICT were logarithmic provided significant results.

5.3 Robustness

Results are robust for including other control variables, such as the proven crude oil reserves and the governance indicator (Añón Higón, et al., 2017). This means that the results do not change including other factors that may affect the carbon dioxide emissions.

Table 12. Polynomial and logarithmic regression including other control variables.

$lnCO_2$ per capita	13.
lnICT subscriptions	.0422**
	(.0183)
lnGDP per capita	.4784*
	(.1322)
Governance	.0610
	(.0503)
Oil	.0003
	(.0005)
Number of countries	127
Number of obs.	2011
Avg. obs. / country	15.8
R^2 (within)	0.3253

Note: Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Country fixed effects are used. Time fixed effects are controlled for using year dummies in all regressions. Years included are 2000-2016.

Moreover, Qatar has exceptionally high emissions per capita, with average per capita emissions 7 standard deviations higher than the mean of the rest of the countries included throughout the examined period. Therefore, Qatar is considered an outlier and were excluded from the regressions. The results were not significantly impacted by excluding Qatar and could thus be considered robust.

To further elaborate on the difference between the income groups, a structural break was performed through a Chow test[15] the regressions of the full sample. The test provided a non-significant interaction variable between ICT market penetration and income group, implying that there is no difference in the effect of ICT on CO_2 emissions in the two income groups. Thus, the difference between the groups is not robust.

[15] In a Chow test, a dummy for the income groups is interacted with the explanatory variable of interest (ICT market penetration). If the interaction variable provides significant results, there is sign of a structural break in the regressions. A structural break means that the effect of ICT on CO2 emissions differs between the two groups (Woolridge, 2009).

The lack of significance with the ICT capital data is of course problematic for providing convincing results on the relationship of interest. The discussion section elaborates on the misalignment in the results of the two ways to measure ICT readiness.

6. Discussion and conclusive remarks

6.1 Mobile usage

Starting with the instant effect of mobile usage, an CO_2 emission-increasing effect was found, though at a diminishing rate. The fact that the mobile market penetration seems to be associated with increasing emissions at a diminishing rate, can be evaluated in two ways in relation to the frameworks described in the theory section. When looking through the glasses of the Environmental Kuznets Curve, the lack of turning point can be a result of that the carbon dioxide reducing effects of ICT, also referred to as the technology effects, have simply not yet been implemented to a large enough scale, on average in the countries examined. It could be so, that the technology effects have created energy efficiency that mitigates the impact of ICT and of other sectors on the environment, but not to an extent at which it compensates for the negative impacts of use and production. Thus, it seems that more enabling technologies have yet to be implemented for the environment to benefit on a larger scale.

However, the above explanation does not take the behavioural changes that the ICT revolution provokes into account. If we instead look at the results through the direct – indirect – rebound framework, the increasing effect at a diminishing rate that we found can be viewed in another way. Here, the increasing effect of the ICT market penetration on CO_2 emissions at low levels of ICT usage emerges for the same reason as before – higher energy consumption from consumption and use of ICT products without being ICT mature enough for the enabling effects that mitigates emissions to have been put in place. However, when ICT reaches higher levels, the economy can enjoy energy efficiency in use and production, optimisation in production and distribution processes, dematerialisation and transport substitution. These factors reduce the direct effect of ICT on emissions and enables emissions reductions in other industries and sectors as well. At these levels of ICT, the efficiency gains in energy could impose behavioural changes and price reductions that make people and industries to consume more CO_2-intensive way and thus cause larger emissions to a lower price - the rebound effect. These two effects, the enabling and the rebound effect, are in conflict and would push the emissions in different directions, and we cannot disentangle the size of each effect. What we can see though, is that the direct effect of production and use plus the rebound effect dominates over the enabling effect at all levels of ICT market penetration.

The difference between the high versus low and middle-income countries is that the model detects a turning point after which higher levels of ICT is associated with decreasing emissions in the lower income group, but not in the richer countries. It could be explained by that the rebound effect is larger in high income countries. The behavioural changes that ICT evokes, such as using multiple screens per person or simply adding new technologies to already existing ones is more likely to be a phenomenon in richer countries. The drop in prices for ICT products when technology develop may have been what has spread the wider use of cell phones and ICT in developing countries, whereas in richer countries, it provokes a behaviour that has negative impact on carbon dioxide emissions. Although this explanation gives interesting insights, one should note that the difference in trends between the income groups is not robust. In the lagged regressions described below, the countries are again pooled in the same sample.

The lagged regressions give interesting implications. They imply that there is a point at which ICT starts having decreasing effects on carbon dioxide emissions. The implication of this is that under the period included, growths in the ICT mobile penetration has caused increasing emissions, but also reached a point after which the enabling potential of ICT dominates. 97 % of the high-income countries and 28 % of the low and middle-income countries reach such ICT penetration in 2013 that they should according to the model have started reducing the carbon dioxide emissions three years later. It gives hopeful implications for the future of further ICT penetration and reduction of CO_2 emissions. However, caution should be taken when interpreting the result. It might be so that these high-income countries have exported CO_2 intensive production to countries where the cost of labour is cheaper. If so, the decreasing potential might not have the same pattern for the country to which more energy intensive industries have moved. However, there is hope for the technological progress of the ICT sector to further increase efficiency to such extent that also the production can be less emission intensive, which would dampen the effect. Thus, the next years will provide interesting results in whether also the low and middle-income countries can acquire the potential to start reducing emissions. To this end, data on consumption-based emission would complement the picture on how ICT usage contributes to carbon dioxide emissions.

6.2 ICT capital

The study shows that ICT capital is of lesser importance than the use of ICT when it comes to carbon dioxide emissions. One possible explanation could be that ICT usage may give a better picture of the ICT readiness of an economy. Even if ICT investments are high, they may be isolated into a specific sector that carries only a marginal part of the overall economy and/or share of emissions.

Moreover, Malmodin & Lundén (2018) argue that it is not increased data traffic, but increased number of subscriptions, that is correlated to the development of the ICT carbon footprint. This is in line with the earlier argument that the major behavioural and organisational changes come with the first connection rather than additional increases in the ICT, such as further data-driving investments in ICT. The results imply that countries can keep investing in ICT without affecting the carbon dioxide emissions.

6.3 Conclusive remarks

This study contributes to the literature through examining the net effect of ICT on CO_2 emissions from a macroeconomic perspective, on a global level. Results give interesting implications on the potential of ICT to mitigate human activity's impact on the environment. They show that although ICT usage is associated with increasing CO_2 emissions upon implementation, it has the potential to lower emissions just a few years after implementation. According to the findings, countries had in 2013 on average reached such levels that the usage of ICT should have a decreasing effect on carbon dioxide emissions. It seems like the relationship is driven by unique subscribers rather than the ICT capital. The implications are encouraging for further spread of ICT solutions to foster a sustainable development. Future research should address consumption-based emissions as well as reassess to confirm that results are lasting.

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Appendix

A.1 List of countries

High income countries[16]

Australia
Austria
Bahrain
Belgium
Brunei Darussalam
Chile
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hong Kong SAR, China
Hungary
Iceland
Ireland
Israel
Italy
Japan
Korea, Rep.
Kuwait
Latvia
Lithuania
Luxembourg
Malta
Netherlands
New Zealand
Norway
Oman
Poland
Portugal
Qatar
Saudi Arabia
Singapore
Slovak Republic
Slovenia
Spain
Sweden
Switzerland
Trinidad and Tobago
United Arab Emirates
United Kingdom
United States
Uruguay

Low and middle-income countries

Albania
Algeria
Angola
Argentina
Armenia
Azerbaijan
Bangladesh
Belarus
Benin
Bolivia
Bosnia and Herzegovina
Botswana
Brazil
Bulgaria
Cambodia
Cameroon
China
Colombia
Congo, Dem. Rep.
Congo, Rep.
Costa Rica
Cote d'Ivoire
Croatia
Cuba
Dominican Republic
Ecuador
Egypt, Arab Rep.
El Salvador
Eritrea
Ethiopia
Gabon
Georgia
Ghana
Guatemala
Honduras
India
Indonesia
Iran, Islamic Rep.
Jamaica
Jordan
Kazakhstan
Kenya
Kyrgyz Republic
Lebanon
Macedonia, FYR
Malaysia
Mauritius
Mexico
Moldova
Mongolia
Morocco
Mozambique
Myanmar
Namibia
Nepal
Nicaragua
Nigeria
Panama
Paraguay
Peru
Philippines
Romania
Russian Federation
Senegal
Serbia
South Africa
Sri Lanka
Suriname
Tajikistan
Tanzania
Thailand
Togo
Tunisia
Turkey
Turkmenistan
Ukraine
Uzbekistan
Venezuela, RB
Vietnam
Yemen, Rep.
Zambia
Zimbabwe

[16] Income status from 2016

A.2 Construction of the ICT capital index.

The ICT capital stock data is collected from The Conference Board and is constructed with the perpetual inventory method. It consists of hardware, software and communications equipment.

$$ICT_{i,t} = ICT_{i,t-1}(1 - \partial_i) + I_{i,t}$$

Where $ICT_{i,t}$ is the ICT capital stock for country I in year t, ∂_i is the depreciation rate and $I_{i,t}$ is the real investment in ICT. The depreciation rate is constant over countries and time, but different for the assets included in the in ICT. The starting year is:

$$ICT_0 = \frac{I_0}{gI} + \partial$$

Where gI is the average investment growth over the first 10 years of data.

Jorgenson & Griliches (1967) argued that estimates of a capital stock and its productivity will be biased if data on annual utilisation, user costs and depreciation is not taken into account. To this end, a new index is constructed based on the ICT capital stock. It is done through starting from a base year[17]and then multiplying with the growth rates of ICT capital services. Capital services, unlike the raw capital stock measure, account for the differences in amount of services provided per unit of stock between short and long-lived assets (U.S. Bureau of Labor Statistics, 2016). The result is a new estimation of the ICT capital that is comparable over time and take the user cost into account. Data for growth of ICT capital servcies is extracted from The Conference Board Total Economy Database (2017). Lastly, the estimations of the capital estimates are divided by the population to attain per capita values that are comparable across countries.

A.3 Data manipulation

Electricity mix

For electricity mix, data was missing for 2015 and 2016. Data was inputted using the average from the 5 previous years.

Government effectiveness

The index was estimated biannually until 2002, from when new estimations are provided every year. Therefore, data for 2001 was inputted with the average of the value of year 2000 and year 2002 for each country.

[17] 2011 is picked as base year since variables are measured in constant prices with 2011 US dollars.

CO_2 emissions

The data on carbon dioxide emissions were extracted from the EDGAR database. Data for a few small countries with low emissions are included in the aggregate of a larger country. Therefore, these countries were recoded to only represent the bigger country in each pair. Although this could introduce an upward bias for the bigger countries, the effect is expected to be negligible. The countries in questions are: France and Monaco (recoded to France), Italy and San Marino (Italy), Israel and Palestine (Israel), Serbia and Montenegro (Serbia), Spain and Andorra (Spain), Switzerland and Lichtenstein (Switzerland). As for China, the official statistic was used, chosen before the alternative measure.

A.4 Chow test

Table 12. Chow test on ICT mobile subscriptions data set.

CO2pc	13.	lnCO2pc	14.
ICT	3.9326***	lnICTmarket	.0389**
	(1.4535)		(.0193)
ICT^2	-.6578		
	(1.3796)		
GDP per capita	.0002**	lnGDPpc	.4863***
	(.0001)		(.1207)
GDP per $capita^2$	-2.38e-09**		
	(1.07e-09)		
Industry share	.0790***	lnIndustry share	.0799
	(.0160)		(.0988)
Electricity mix	.0208***	lnElectricity mix	.0368**
	(.0062)		(.0151)
Rich*ICTmarket	.1007	Rich*lnICTmarket	-.0224
	(1.5220)		(.0444)
Number of countries	130	Number of countries	130
Number of obs.	2062	Number of obs.	2045
Avg. obs. / country	15.9	Avg. obs. / country	15.7
R^2: Within	0.4351	R^2: Within	0.3364

Note: Cluster robust standard errors are presented in parenthesis. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Country fixed effects are used. Time fixed effects are controlled for using year dummies in all regressions. Years included are 2000-2016.