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INFORMATION COMMUNICATION TECHNOLOGIES AND ENVIRONMENTAL INNOVATIONS IN FIRMS: JOINT ADOPTIONS AND PRODUCTIVITY EFFECTS

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Abstract

Information communication technology (ICT) and environmental innovation (EI) are relevant waves of the ongoing technological revolution. We study the complementarity in innovation adoption to test the research hypothesis that the higher the diffusion and intensity of usage of ICT and EI, the higher a firm's productivity performance might be. However, it is not certain that the use of different innovations stemming from different innovation paths generates higher productivity. To test our hypothesis we use original survey data concerning manufacturing firms in Northeast Italy including detailed information on both ICT and EI. Empirical evidence shows that there are still wide margins to improve the integration between EI and ICT in order to exploit their potential benefits on productivity. The awareness of specific synergies seems to mainly characterize the heavy polluting firms that are subject to more stringent environmental constraints, while some trade-offs tend to emerge for the remaining firms.

Keywords: ICT, environmental innovations, polluting sectors, complementarity, labour productivity

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1. Introduction

The role of innovation as a driver of long-term productivity goes back to the pillars of growth theory in economics, revitalised by the advent of sustainable policy-oriented thinking that tries to integrate the economy and the environment with synergy. Environmental innovation (EI) (Kemp, 1997; Kemp, 2010; Brunnermeier and Cohen, 2003) is crucial for creating synergies between sustainability and competitiveness towards the green economy (EEA, 2013, 2014, Gilli et al., 2013; Lanoie et al., 2011;). EIs (Rennings, 2000, 1998) are a key factor among the innovation capabilities of firms, as it is well known that sustainable economic growth depends upon a constant investment in technological and organisational changes addressed to manage the production process more efficiently (Mazzanti and Gilli, 2017).

Nevertheless, technologies per se, and specifically EIs, are not self-sufficient to ensure sustainability. The potential of EI must be enriched and embedded within a very broad set of innovation and knowledge related factors, as well as economic, social and environmental effects (Horbach, 2008; Diaz-Lopez, 2011; Kemp and Pontoglio, 2011; De Marchi, 2012; Kesidou and Demirel, 2012)[1]. On the side of EI 'effects', namely, productivity, employment and other economic outcomes, research has progressed more slowly than for 'drivers', largely due to greater difficulties in bringing together innovation survey data and real balance account sheets. Among the most recent and relevant examples of the emerging literature on the effects of EI are Martin et al. (2014), who analyse the carbon tax effects on revenue, employment, energy intensity for UK manufacturing plants; Ghisetti and Rennings (2014) investigated the link between eco-innovation adoption and profitability for Germany; Lotti and Marin (2017) and Franco and Marin (2017) analysed the productivity effects of EIs respectively on Italian and EU firms testing Porter hypotheses; productivity effects following from the joint adoption of organisational changes and environmental innovations are also scrutinised by Hottenrott et al. (2016); Gagliardi et al. (2017) studied the effect of green patents on employment for Italy; and Cecere and Mazzanti (2017) analysed the correlation between eco innovation adoptions and green jobs creation for the EU.

The present paper aims to fill a gap in the aforementioned EI-related literature by studying whether the joint adoption of two main radical innovation patterns (Mazzanti and Rizzo, 2017; Perez, 2010) such as Information and Communication Technologies (ICT) and EI generate positive or negative economic performances: (i) ICTs might be a driver of economic productivity (empirical evidence is always necessary on this point) and of dematerialisation patterns (saving material resources); (ii) EIs might increase both environmental and economic productivities, the latter by

[1] For recent surveys of the literature and a methodological analysis of drivers and effects of EI, we refer to Mazzanti et al. (2016) and Barbieri et al. (2016).

product innovations that increase value, and process innovations that save costs (Harrison et al. 2014; Cecere and Mazzanti, 2017). Positive effects can be generated if the higher costs of ‘organisational complexity’, namely linking strategies for two innovation paths at firm level, are lower than the benefits of this complementarity (e.g. increasing returns to scale). It is worth noting that Egli et al. (2015) begin by stating that “In the past, a number of technologies (e.g. information and communication technologies and nanotechnologies) have had far reaching consequences on important economic variables (e.g. productivity) and/or our capacity to meet social and environmental challenges at relatively low cost” (Egli et al. 2015). They recognise the breakthrough feature of some innovation/inventions, such as ICT/green technologies, and the way ICT might influence both economic and environmental performances.

It is also noticeable that ICT can help achieving Sustainable Development Goals (SDGs) more effectively and faster. As The Earth Institute and Ericsson (2016) note: “each country can and should speed its own learning curves and shorten the time of each technology generation, especially for ICT-based solutions that necessarily have strong local content (e.g. for education, healthcare, agriculture, and environmental management)”[2].

This paper provides new micro evidence by bringing together the streams of literature that have scrutinized the effects of ICT[3] (e.g., Daveri, 2002; Bloom et al., 2014) and EIs (e.g., Cainelli et al., 2011; Ghisetti and Rennings, 2014) on productivity.

As for other technological breakthroughs (e.g., robotisation) that might bring about positive or negative environmental effects and heterogeneous impacts on employment by sector (Arntz et al. 2016), innovation breakthroughs generate outcomes that are not fully predictable ex ante. As Mazzanti and Rizzo (2017), noted: “Radical innovations require assessments of both the economic feasibility of a blockbuster, i.e., very costly technologies such as carbon capture and storage (CCS), and the enhancement of *complementary* technological and organisational innovations. These are related to human capital/skills and may represent a more feasible route, even in the short and medium term”. Thus, the complementarities between different innovations are key elements in order to create the pre-conditions for achieving and integrating social, economic and environmental goals by 2020 (e.g., the EU 2020 strategy on energy efficiency, climate change, renewables, resource efficiency, etc.; EEA, 2014) and in the longer run (EEA, 2013). Still, though the literature on EI and complementarity has evolved (Gilli et al., 2014; Antonioli et al., 2013), there is currently space for additional original research, especially in the field of EI. In fact, while it is possible that

[2] Ioannidis (2017) recently emphasized the interconnections between ICT, SDGs and sustainable development.
[3] See the special issue in Oxford Review of Economic Policy, vol. 18, 2002, which empirically addressed the well-known ‘Solow Paradox’. In 1987 Nobel prize winner Solow stated “you can see the computer age everywhere but in the productivity statistics” (Solow, 1987). This stimulated empirical research at macroeconomic and microeconomic levels.

firms may exploit incremental innovations and separate the adoption of innovations to achieve less stringent targets in the short run (e.g., -20% CO_2 by 2020 in the EU), more radical aims (e.g., the existing -40% CO_2 binding targets by 2030 and proposed -89/90% cuts by 2050 to limit temperatures rises at approximately 2 degrees) will eventually require radical innovations and new ways to integrate innovation realms (Grubb et al. 2017).

On this basis, we developed the present work, which intends to fill the gap concerning firm level analysis on the presence of complementarities among ICT and EI that influence a firm's productivity[4].

The article is organised as follows. Section 2 provides the conceptual setting, and section 3 sets the macro-framework and describes the data. Section 4 provides a description of the methodology and complementarity theory, followed by the empirical analysis. Conclusions and discussions are provided at the end.

2. Background literature and research hypotheses

This study originally focuses on the role of complementarity/substitutability (namely, synergies or trade-offs) between two sources of innovations, namely, ICT and EI, as a way to improve economic performance[5]. These two breakthrough innovation waves might provide positive effects on economic and environmental performance. Therefore, it is relevant to study whether they also synergistically operate given the lack of evidence in this respect.

Indeed, the economic literature shows that ICTs are a key enabler of green growth in different sectors of the economy (Ropke, 2012, Faucheux and Nicolaï, 2011, Cecere et al. 2014). More generally, the digitalization of the economy has transformed business and society, and the widespread use of ICT represents an important engine of economic growth. The impact of ICT in different sectors has increased the attention towards their direct and indirect environmental impacts (Mansell, 2012). Thus, looking at additional and potentially complementary innovation realms, the important role of ICT as an engine of growth in both developed and developing countries has increasingly been noticed, as shown by the commitments related to the European Digital Agenda (Cardona et al., 2013). The development of ICT can be associated with the reduction of the environmental footprint of economic activities, while also having an important role in improving the productivity of labour, capital and natural resources (Berkhout and Hertin, 2004, Brynjolfsson

[4] Along similar lines of analysis, Hottenrott et al. (2016) investigate the effects on productivity of complement organisational and environmental innovations using survey data.

[5] To address the complementarity/substitutability between EIs and ICT, we focus on the analysis of productivity and its firm-level productivity determinants by previous works (Arvanitis, 2005; Giuri et al., 2008; Hall et al., 2013; Antonioli et al., 2010, 2016).

and Hitt, 2000). As EIs are concerned, their role as determinants of increased competitive advantages has been put under scrutiny. A considerable stream of seminal empirical works (Jaffe and Stavins, 1997; Jaffe et al. 1995, 2002; Aghion et al. 2016) stem from the Porter hypothesis realm (Porter and van der Linde, 1995; Porter 2010), that focuses on green technology oriented and environmental policy driven competitive advantages[6] (Costantini and Mazzanti, 2012; Albrizio et al. 2017).

The Porter hypothesis (Ambec at al, 2013) can be disaggregated into two components: (i) the 'weak' version, which, going back to Hicks and the notion of induced innovation, states that environmental regulation may spur EIs (Jaffe and Stavins, 1997)[7] and (ii) the 'strong' version, stating that the introduction of EIs and the accrued efficiency gains offsets the additional regulatory costs, eventually leading to sustained competitive advantages (Costantini and Mazzanti, 2012). The emphasis on the economic performances of EI is then consistent to the 'strong' version of the Porter hypothesis, but it is also consistent with the structure and aims of the green economy and circular economy strategies and policies (EEA, 2014, 2016). Although extended, the empirical literature fails in providing convincing and unambiguous evidence on the positive role of environmental innovations on firm economic performance, partly because of the environmental innovation proxy used (e.g. green patents), which fails in accounting for not patentable innovation activities. On this point, a recent OECD work also focuses on the links between environmental policy, innovation and productivity (Albrizio et al. 2017), pointing out the limited evidence of the empirical literature in supporting the strong Porter hypothesis. They claim that environmental policies may be transmitted to the firms through different channels, partly determining the firms heterogeneity and the diverse effect of environmental regulation on their performance. One of these channels is innovation, which needs to be captured and proxied not only through patent data, which represent a very limited share of innovations, mostly of them not patentable. The importance of firm level survey data is then pointed out by the authors, since they complement more macroeconomic-wide studies that often exploit patents/inventions for comparative analysis aims.

The choice of the firm as unit of analysis may also be functional to re-conduce the study of ICTs and EIs, mainly belonging to two separate streams of analysis, within a single framework. Indeed, firms heterogeneity passes also through the different kind of innovation bundles they decide

[6] We focus on the strong version of the Porter hypothesis, namely the (positive) innovation effects on economic performances. See also Dangelico (2015) for a survey on the drivers and effects, including the productivity of 'green product' innovations.

[7] It connects to the 'dynamic efficiency' property of Environmental economic instruments (e.g. emission trading, carbon taxes; Mazzanti and Rizzo, 2017; Costantini and Mazzanti, 2013).

to adopt. They search for assets that may assure competitive advantages, and one of this assets is given by a consistent strategy of ICT and EIs joint implementation.

It is worth noting that the green economy transition, as other radical changes, is “a vast innovation opportunity space and [provide] a new set of associated generic technologies, infrastructures and organisational principles that can significantly increase the efficiency and effectiveness of all industries and activities” (Perez, 2010, p. 6). The diffusion of innovation is crucial to make radical changes real, so it is important to understand how innovations are *idiosyncratically* and *complementary* adopted by firms in different sectors and subsequently spread through those sectors. The ICT as EIs enablers play an important role in shaping complementary types of innovation couples. Complementarity can be considered as a radical asset that can strongly enhance performance through innovation and that redesign corporate strategies; it is a non-codified source of competitive advantage as Spinozzi and Mazzanti (2017) note, that can make the firms capable of offsetting the disadvantages induced by environmental regulation.

The latter is a leading factor in determining the propensity for the adoption of EIs (Horbach et al., 2012, Veugelers, 2012, Barbieri et al, 2016). As reported in the model of Kriechel and Ziesemer (2009) the timing of adoption of EIs may be crucial in determining competitive advantages, and environmental regulation may induce firms to adopt EIs sooner in time than their counterparts not subject to environmental policy. One of the main environmental economic policy that the EU set out to achieve climate change targets is the European Emission trading scheme (ETS). It covers more than 10,000 establishments and more than 50% of the EU’s CO2 emissions (Borghesi, 2011). We refer to Borghesi et al. (2015) for a recent study that investigates the specific innovation effects of ETS in the EU, with discussions on the ETS policy framework and evolutions. We argue that ETS in EU has been an instrument that induced subject firms to adopt EIs as leader and to exploit the productivity gains originated by the complementary adoption of EIs and ICT.

We propose two main hypotheses that follow from the analysis of the various streams of literature we touched upon, where the main issue revolves around the effects of innovation streams on economic performances in a realm where EIs are driven by internal (R&D) and external (e.g., sector, policy) factors:

[H1] *The joint adoption of ICT and EI can be a sustainability-oriented innovation strategy to generate economic gains*[8].

[8] In the two hypotheses, the null is the presence of complementarity. The non-rejection of the null points to complementary (synergic) factors; rejection of the null signals substitutability (trade off).

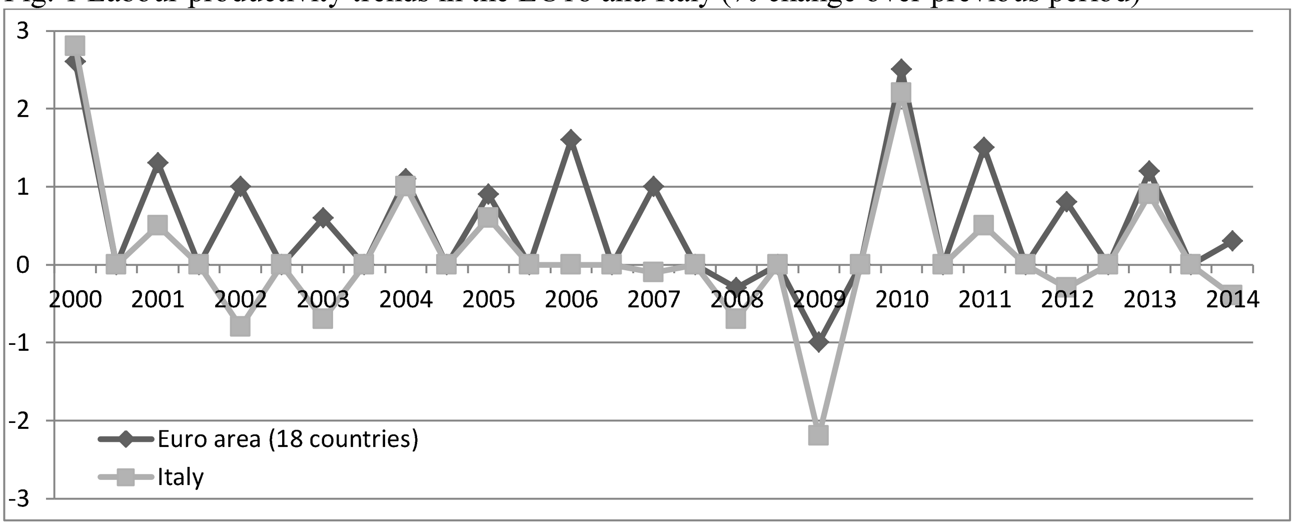
[H2] The *regulatory pressure (EU ETS) increases the firm's incentive to jointly adopt EIs and ICT*.

3. Setting the framework and data description

The context of analysis

In a context of an enduring economic slowdown of the Italian economy, as the graphic on labour productivity shows (Fig. 1)[9], it may be of extreme relevance to single out the micro economic strategies that firms can implement in order to increase the labour force's productivity. Italy is a key example of a relevant economy, with still strong value-added contributions coming from the manufacturing sector, that needs to re-enhance its economic performance through R&D investments and through the adoption and spread of high value-added innovations. A new positive path for the Italian economy would create the conditions for a more stable and sustainable Europe. It is worth noting that this economic trend is not different from the emission trend (e.g., CO2) that highlights the synergy between economic and environmental dynamics (Marin and Mazzanti, 2013).

Fig. 1 Labour productivity trends in the EU18 and Italy (% change over previous period)



Note: Labour productivity per hour worked (source: ESA2010)

[9] Though a slight increase occurred after the downturn, the key Italian problem remains: lower and stagnant labour productivity levels compared to other leading countries, which is largely driven by innovation deficits and the composition of the economy (Cainelli et al. 2013). Italy should exploit EU remanufacturing and environmental strategies to reverse this stagnating trend that started in the '90s.

To test the hypothesis by which the complementary adoption of ICT and EI backs higher labour productivity performance, this article analyses a dataset collected in a leading Italian region, Emilia-Romagna. The Emilia-Romagna region is located in the north of Italy; it has a population of approximately 4.5 million people and a GDP (approximately 143 billion Euros) that accounted for approximately 11% of the national GDP in 2011 (Eurostat – Regional Statistics Database). Though being higher than average when looking at Italian data on GDP per capita and productivity, the region experienced a severe collapse of GDP and exports in 2009 – similar to Germany – from which a new economic phase is possibly emerging through the re-configuration of strategies and innovation adoptions.

For the sake of our reasoning, it is worth noting that Europe is formed by regions with different histories and competitive advantages. Innovations develop specifically at sector and regional levels, as the analysis on regional innovation systems shown in the last decades (see for example Cooke, 1998 and Iammarino, 2005), where most environmental and innovation policies are implemented. Notwithstanding the role of the EU and countries in setting the agenda and frameworks, EU regions play a significant role towards the achievement of a greener, low carbon, resource efficient economy. Its role in this transition has been somewhat overlooked. Even though the EU-wide analysis of EIs -economic performances is a necessity of future research, there is value to analysing regions, in order to address the issue of heterogeneous effects of EIs due to differences in the institutional contexts.

Data

The analysed data come from a survey of manufacturing firms with at least 20 employees carried out in 2009. A structured questionnaire was administered to the management of the sampled firms through Computer Assisted Telephone Interviews (CATI). The method to select the sample was based on the stratification sampling technique with replacement. Three strata were used: sector, size categories and geographical location at the NUTS3 level, which corresponds to the administrative unit called a ‘province’ in Italy. The information collected refers to the period of 2006-2008, and it concerns several innovation spheres: technological, organisational, environmental and related to the ICT. In particular, the survey covered the same questions on EI presented by the community innovation survey (CIS)[10] (see Antonioli et al., 2013) and provided detailed data on the types and scopes of the ICT adopted. The sample includes 555 firms. See Table 1 for a description of the variables used in the analysis and Table 2 for descriptive statistics. The questionnaire includes detailed information related to ICT usage and adoption (see the questionnaire extracts in

[10] http://ec.europa.eu/eurostat/web/microdata/community-innovation-survey

Appendix B) and provides a lot of information that can be usefully correlated to EIs (Appendix B), which includes information on carbon abatement, emission abatement, EMS, and environmental R&D[11]. The sector composition of our sample, compared with that of the population, is described in Table A1 in Appendix A.

The in-depth information stemming from the survey is coupled with the second source of information: the AIDA Bureau Van-Djik dataset on firms' balance sheets. The merger of the two sources of information allows us to test the potential complementarities among EIs and ICT adoption on the firms' economic performance, measured as labour productivity per capita. To our knowledge, this is the first paper that treats and merges ICT and EI information at a relatively detailed level of analysis. This allows in-depth insights into the correlation between ICT/EI (as separate and joint factors) and a firm's productivity gains to be achieved.

[11] See Antonioli et al. (2013) and Cainelli et al. (2012) for further information on the questionnaire data.

Tab. 1 – Construction of the variables used in the analysis

Economic Performance	
LnVAEMP2010-2011	Log of the average value added per capita in the period 2010-2011
Environmental Innovations	
Environmental innovation (**ENVINNO**)	Takes value: 1 if firm introduced an environmental innovation; 0 otherwise
Energy/Material reduction per unit of product (**ENERGY**)	Takes value: 1 if innovations addressed to reduce use of materials and/or energy by output unit (included recycling) have been adopted; 0 otherwise
CO2 reduction (**CO2**)	Takes value: 1 if innovations addressed to reduce CO2 emissions have been adopted; 0 otherwise
Emissions reduction for soil, water and air (**EMISSIONS**)	Takes value: 1 if innovations addressed to reduce emissions for soil, water and air have been adopted; 0 otherwise
Adoption of procedures such as EMAS and ISO14001 (**EMASISO**)	Takes value: 1 if procedures that structurally identify environmental performance have been adopted; 0 otherwise
ICT	
ICTINTRO	Takes value: 1 if the number of ICT management systems implemented is above the sample average; 0 otherwise.
MRP	Takes value: 1 if the ICT management system Material Requirements Planning (MRP) has been introduced; 0 otherwise
ERP	Takes value: 1 if the ICT management system Enterprise Resource Planning (ERP) has been introduced; 0 otherwise
ICT_BS	Takes value: 1 if the ICT systems implemented are addressed to manage buying and selling activities; 0 otherwise
ICT_PROD	Takes value: 1 if the ICT systems implemented are addressed to manage the production process; 0 otherwise.
ICT_COOP	Takes value: 1 if the ICT systems implemented are addressed to manage cooperation with clients and suppliers (e.g., post selling services); 0 otherwise.
ICT_SERV	Takes value: 1 if the ICT systems implemented are addressed to manage the exchange of information and services; 0 otherwise.
INNOVATIONS	
Prod	Takes value 1 if firm introduced product innovation; 0 otherwise
Proc	Takes value 1 if firm introduced process innovation; 0 otherwise
TRAIN_D	Takes value 1 if firm adopted training programmes of any kind; 0 otherwise
Controls	
Size dummies	4 size dummies according to the number of employees: 20-49 employees; 50-99 emp.; 100-249 emp.; more than 249 emp
Sector dummies….	9 sectors dummies according to a two digit Nace Rev2 classification. Sectors are grouped according to the Italian RAMEAdata. The whole set of sector dummies is divided into two subsets of ETS and NonETS sectors:
…ETS	PaperPrinting, CokeChemical, NonMetallicMineralProducts, Metallurgy
…NonETS	Food, Textile, Shoes, WoodRubberPlasticOther, Machinery
CentralReg	Dummy variable: 1 if the firm belongs to one of the provinces constituting the backbone of the Emilia-Romagna industrial system (Bologna, Parma, Modena, Reggio-Emilia); 0 otherwise
Export	Percentage of turnover made on international markets
KStockEmp0608	Average capital stock per capita on the period 2006-2008

Tab. 2 - Descriptive statistics

	Whole sample (555 firms)				ETS firms (183 firms)				Non ETS firms (372 firms)			
	Mean	Standard Deviation	Min	Max	Mean	Standard Deviation	Min	Max	Mean	Standard Deviation	Min	Max
Economic Performance												
LnVAEMP2010-2011	4.01	0.39	2.13	5.40	3.97	0.39	2.13	4.87	4.03	0.38	2.35	5.40
Environmental Innovations												
ENVINNO	0.20	0.40	0	1	0.27	0.45	0	1	0.16	0.37	0	1
ENERGY	0.15	0.36	0	1	0.22	0.42	0	1	0.11	0.31	0	1
CO2	0.12	0.32	0	1	0.16	0.37	0	1	0.09	0.29	0	1
EMISSIONS	0.14	0.35	0	1	0.19	0.39	0	1	0.12	0.32	0	1
EMASISO	0.14	0.35	0	1	0.18	0.39	0	1	0.13	0.33	0	1
ICT												
ICTNTRO	0.44	0.50	0	1	0.30	0.46	0	1	0.51	0.50	0	1
MRP	0.36	0.48	0	1	0.22	0.42	0	1	0.42	0.49	0	1
ERP	0.48	0.50	0	1	0.37	0.48	0	1	0.53	0.50	0	1
ICT_BS	0.42	0.49	0	1	0.42	0.49	0	1	0.43	0.50	0	1
ICT_PROD	0.66	0.47	0	1	0.63	0.48	0	1	0.67	0.47	0	1
ICT_COOP	0.64	0.48	0	1	0.60	0.49	0	1	0.66	0.48	0	1
ICT_SERV	0.93	0.26	0	1	0.87	0.33	0	1	0.95	0.21	0	1
INNOVATIONS												
Prod	0.70	0.46	0	1	0.62	0.49	0	1	0.73	0.44	0	1
Proc	0.68	0.47	0	1	0.69	0.46	0	1	0.68	0.47	0	1
TRAIN_D	0.80	0.40	0	1	0.85	0.36	0	1	0.78	0.41	0	1
Controls												
Size dummies	\	\	0	1	\	\	0	1	\	\	0	1
Sector dummies	\	\	0	1	\	\	0	1	\	\	0	1
CentralReg	0.69	0.46	0	1	0.70	0.46	0	1	0.69	0.46	0	1
Export	0.33	0.31	0	1	0.26	0.27	0	1	0.37	0.32	0	1
KStockEmp0608	3.37	0.94	-0.99	6.11	3.60	0.86	0.04	5.66	3.26	0.95	-0.99	6.11

The information on ICT adoption is, in fact, extremely detailed and offers a wide range of possibilities to test complementarities between ICT and EI (see the ICT variables used, which come from questions Q3 and Q4 reported in Appendix B). At first, we focused on the introduction of management systems and networking integration (ICTINTRO), constructed as the average number of practices introduced, and then we concentrated on two specific systems: Material Requirements Planning (MRP) and Enterprise Resource Planning (ERP), which are more likely related to EI than other types of ICT management systems, because of the intrinsic nature of managerial systems to plan the use of materials and resources. Second, we measure the scope of ICT using the following set of variables: the variable ICT_BS indicates whether the firm uses ICT to manage the buy and sell processes; ICT_PROD measures whether the use of ICT supports product and process activities; ICT_COOP measures if ICT are used to support cooperation activities; and ICT_SERV indicates whether firms use ICT to exchange information and services. This set of ICT variables permits us to measure the enabling impact in the economy as they enable us to dematerialise the economic activities and improve the economic processes.

As for the EIs, first we construct a general measurement of EI adoption: ENVINNO, which indicates whether the firm has adopted any kind of environmental innovation. Then, we elicit four binary detailed variables that inform us about the adoption of specific EIs: the variable ENERGY, which captures innovations designed to reduce the use of materials and/or energy by output unit (included recycling); the variable CO2 measures the adoption of innovations designed to reduce CO2 emissions; the variable EMISSIONS takes a value of one if innovations designed to reduce emissions for soil, water and air have been adopted; and the Eco-Management and Audit Scheme (EMAS), International standard organization (ISO) variable, which is equal to one if procedures such as EMAS and ISO14001 have been adopted.

4. Methodology

To address the research hypothesis of complementarity, we estimate the following multivariate specification:

$$(1)\quad [LABPROD]_{i,10\text{-}11} = a_0[Controls]_{i,06\text{-}08} + a_1[KEmp]_{i,06\text{-}08} + a_2[Export]_{i,06\text{-}08} + a_3[INNO]_{i,06\text{-}08} + a_4[EI]_{i,06\text{-}08} + a_5[ICT]_{i,06\text{-}08} + v_i$$

where $LABPROD_{i,10\text{-}11}$ is a measure of labour productivity given by the ratio between value added and employment between 2010-2011 for firm *i*. In the equation, the subscripts 06-08 and 10-11 represent the time spans in which the variables are measured (2006-2008 and 2010-2011 respectively), while *i* represents each firm. The covariates are standard controls, such as size, sector and geographical dummies, a variable capturing the capital/technological intensity (KEmp), an export variable that is a proxy for the firm's openness towards international markets (Export), a vector of innovation variables (INNO) that includes the adoption of process (Proc) and product (Prod) innovation, the presence of training programmes for employees (Train), and the most important covariates for the present work, which are EIs and ICT variables. To get a first glimpse of the relationship the EIs and ICT variables have with labour productivity, we simply estimate equation (1) through OLS. Our estimation may suffer from endogeneity due to two main factors. The first is related to the cross-sectional nature of our data, which does not allow us to fully check for reverse causality[12]: firms may self-select into EIs and ICT adoption, as better performing firms

[12] With this exercise, we are not able to identify a clear causal relationship between variables, but rather robust correlations in a multivariate framework.

may have higher financial and organizational capabilities for adopting both EIs and ICT. To mitigate this problem, we exploit the diachronic structure of the dataset created thorough the merger of the cross-sectional survey and of the balance sheets data: the dependent variable has a time lag of several years with respect to the covariates[13], being measured over the period 2010-2011, while the explicative variables are measured over the 2006-2008 period, right before the 2009 crisis. The time structure of our data allows us to exclude the data of 2009 from our analysis, which are likely to be influenced by the strong exogenous shock given by the recession. The second main factor causing endogeneity is given by the potential problem of relevant omitted variables. To address this issue, we check for several observable characteristics, some of them capturing the managerial attitudes, a source of high heterogeneity, potentially unobserved, in firm level studies. The complementarity between ICT and EIs is also investigated because, from a methodological perspective, it mitigates the potential unobserved heterogeneity across firms. It is in fact a key strategy that some firms may put in place[14].

Although the estimates from equation (1) can provide some initial evidence on EIs and ICT relationships with productivity, our aim is to test the existence of complementarities between EIs and ICT strategies that increase the gains in labour productivity. Using the terminology of Ballot et al. (2015), we test for complementarities-in-performance, that is to say, we investigate the performance 'effect' of different combinations of innovation couples.

Setting the specification for the analysis

To test for complementarities, we need to set up different specifications with respect to equation (1), (see Mohnen and Roller 2005; Antonioli et al., 2013; Mancinelli and Mazzanti, 2009 and Mazzanti and Zoboli, 2009 for more methodological details regarding testing complementarities).

In particular, we consider the same objective function as specified in equation (1), where the labour productivity of firm j ($LABPROD_j$) is the firm's objective function, but substituting the EIs and ICT variables with quadruplets of states for any given couple of EI and ICT (see Tab.A2 in Appendix A for the distribution of firms jointly adopting EI and ICT). That is, the binary EI and ICT variables interact to create couples of innovation combinations. This methodology defines various strategic scenarios for the firm's innovation adoption choice: the firm may decide to adopt

[13] In innovation and productivity studies, the length of time matters. We attempt to mitigate endogeneity due to simultaneity. Analyses of complementarities and the introduction of many firm's information mitigates endogeneity due to unobserved heterogeneity.

[14] This issue was discussed in the 2014 ISS lecture by Pierre Mohnen. Complementarity is interesting since it seems that firms may react to environmental policies more through the integration of technologies rather than the adoption of isolated EIs (see Borghesi et al. 2015; Antonioli et al., 2013).

both innovations {1,1}, one but not the other {1,0} or {0,1}, or neither one nor the other {0,0}. The specification of equation (1) is then:

(2) $[LABPROD]_{i,10\text{-}11} = a_0[Controls]_{i,06\text{-}08} + a_1[KEmp]_{i,06\text{-}08} + a_2[Export]_{i,06\text{-}08} + a_3[INNO]_{i,06\text{-}08} +$ $+\mathbf{b1}i[EI(1)/ ICT(1)] + \mathbf{b2}i[EI (1)/ ICT (0)] + \mathbf{b3}i[EI (0)/ ICT (1)] + \mathbf{b4}i[EI (0)/ ICT (0)] + v_i$

Innovations are complements, if the following inequality is satisfied:

$$\begin{aligned} &LABPROD_J(11,\Omega_J) - LABPROD_J(00,\Omega_J) \\ &\quad \geq \lfloor LABPROD_J(10,\Omega_J) - LABPROD_J(00,\Omega_J) \rfloor \\ &\quad\quad + \lfloor LABPROD_J(01,\Omega_J) - LABPROD_J(00,\Omega_J) \rfloor \end{aligned}$$

(3)

where Ω_i is a vector of variables, including *Controls*, *KEmp*, *Export* and *INNO,* that are thought to influence the labour productivity. The inequality shows that changes in the labour productivity when the innovations are increased together are higher than the changes resulting from the sum of the separate increases of the two innovations. Increases in *LABPROD* due to an increase of both innovations from (00) to (11) are greater than (or at least equal to) the sum of increases in *LABPROD* due to separate increases of the innovations from (00) to (10) or (01). In other words, we are testing whether doing more of one type of innovation increases the returns of doing more of the other innovation.

Operationalization of the complementarities tests

In what follows, we carefully describe how we test for the presence of complementarity in order to provide the reader with the necessary information to understand the meaning of the tests reported in Tables 5-8.

The operationalization of the procedure to test for the complementarities between innovations passes through the estimation of equation (2) as the first ancillary step, in which all the four states for each couple of innovations are included to get the coefficients associated with each state: b1 for {1,1}; b2 for {1,0}; b3 for {0,1} and b4 for {0,0}. Then, it is necessary to run several *Wald tests*. The Wald test allows us to test the following linear restriction under the null hypothesis on the state-dummies coefficients: b1+b4=b2+b3. The test is distributed as an F statistic with one degree of freedom in the numerator; since we are testing a single linear restriction at a time, we can apply the appropriate procedure for the p-value adjustment, so that we are able to test a non-strict inequality[15]. Indeed, we are interested in the following inequalities, namely, the sign of the scalar linear combination of our parameters of interest: b1+b4-b2-b3≥0 and b1+b4-b2-b3≤0. If we combine the information provided by the standard Wald test with the adjusted p-values for the inequality tests, and with the study of the sign of the linear combination of the coefficients, we can state whether we are in the presence of complementarity (b1+b4-b2-b3>0, here the inequality is strict) between a couple of innovations or, instead, if we are in the presence of substitutability (b1+b4-b2-b3<0, here the inequality is strict).

We apply the above procedure for both the entire sample of interviewed firms and for the sub-samples of the most polluting ones, those subject to the Emission Trading System (ETS) and those not subject to the ETS scheme (Non-ETS). This strategy permits us to disentangle the more polluting and regulated sectors from the others.

5. Results

The first section analyses the results of the regression analysis showing that EIs and ICT seems to be not complementary. The second section delves into the analysis of correlation approach to investigate the complementarities among the different types of both EIs and ICT using the super modularity approach

Non-complementary adoption of Innovations from regression results

The first set of results of the empirical analysis is presented in Table 3. It shows that high levels of productivity are mainly associated with exports and capital stock per capita for the whole sample, as well as for ETS firms and Non-ETS firms. This is a standard result that highlights the robustness of our modelling structure.

When product and process innovations and the usual sector and size variables are properly included in the multivariate analysis, neither EIs nor ICT have a significant direct effect on productivity over the period 2010-2011. Similarly, their interaction (ICTIntro_d*ENVINNO) proves to be not significant in any estimations.

Because the results may depend on the 'general' nature of EIs and ICT variables, simply capturing the introduction of any kind of EI (ENVINNO) and of any kind of ICT based managerial system (ICT_INTRO), we also run a different specification, which includes more specific EIs and ICT terms (Tab. 4). When we detail the applied analysis in such a way, some more interesting results emerge. The first one to be noticed is that the introduction of EI to save energy (ENERGY)

[15] For an appropriate reference, see http://www.stata.com/support/faqs/statistics/one-sided-tests-for-coefficients/.

negatively relates to labour productivity for Non-ETS firms, while the opposite holds true for EIs introduced to reduce CO_2 emissions. Heavier and more regulated ETS firms are economically unaffected by the adoption of specific EI and ICT forms.

Tab 3: Results from OLS regressions: general ICT and EI covariates

	Whole Sample		ETS Sectors LnVaEmp2010-2011		Non ETS Sectors	
Controls						
Sector dummies	Yes	Yes	Yes	Yes	Yes	Yes
Size dummies	Yes	Yes	Yes	Yes	Yes	Yes
KStockEmp0608	0.097***	0.097***	0.135***	0.135***	0.079***	0.080***
	(0.022)	(0.022)	(0.047)	(0.047)	(0.024)	(0.024)
CentralReg	0.044	0.044	-0.000	0.006	0.064*	0.064*
	(0.030)	(0.030)	(0.048)	(0.049)	(0.038)	(0.038)
Export	0.174***	0.175***	0.214*	0.204*	0.164**	0.164**
	(0.061)	(0.061)	(0.121)	(0.119)	(0.070)	(0.071)
Innovation						
Prod	-0.042	-0.042	-0.129**	-0.129**	0.004	0.004
	(0.034)	(0.034)	(0.063)	(0.063)	(0.039)	(0.039)
Proc	0.069*	0.069*	0.171**	0.168**	0.026	0.027
	(0.038)	(0.039)	(0.084)	(0.085)	(0.039)	(0.039)
Training						
Train_d	0.040	0.040	0.060	0.078	0.020	0.022
	(0.035)	(0.036)	(0.067)	(0.071)	(0.042)	(0.042)
EI						
ENVINNO	-0.021	-0.015	0.048	-0.007	-0.060	-0.021
	(0.035)	(0.046)	(0.050)	(0.056)	(0.050)	(0.083)
ICT						
ICTIntro_d	-0.006	-0.003	-0.008	-0.056	-0.000	0.010
	(0.029)	(0.031)	(0.054)	(0.065)	(0.035)	(0.036)
ICT*EI						
ICTIntro_d*ENVINNO		-0.013		0.166		-0.064
		(0.072)		(0.121)		(0.105)
_cons	3.690***	3.688***	3.337***	3.347***	3.743***	3.732***
	(0.100)	(0.101)	(0.209)	(0.210)	(0.108)	(0.109)
N	555	555	183	183	372	372
AdjR2	0.294	0.292	0.301	0.305	0.293	0.292
F(d.f.)	16.219(19)	15.598(20)	9.071(14)	8.644(15)	13.408(15)	12.728(16)
p-value	0.000	0.000	0.000	0.000	0.000	0.000

Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

An additional result worth pointing out from Tables 3 and 4 is that product (Prod) and process (Proc) innovations seem to be relevant only for the ETS firms, showing a negative and a positive sign, respectively. When we turn to the analysis of the ‘effect’ of specific EIs and ICT on productivity (Tab. 4), we see a negative sign (on non-ETS firms) for energy efficiency innovations, which likely depends on the reallocation of investments from brown to green innovations and/or on increases of specific labour force, both of which negatively impact productivity. Finally, CO2 innovations show a positive relation to productivity, especially for non-ETS firms.

Tab 4: Results from OLS regressions: specific ICT and EIs covariates

	Whole Sample	ETS Sectors LnVaEmp2010-2011	Non- ETS Sectors
Controls			
Sector dummies	Yes	Yes	Yes
Size dummies	Yes	Yes	Yes
KStockEmp0608	0.096***	0.137***	0.080***
	(0.022)	(0.048)	(0.022)
CentralReg	0.035	-0.015	0.047
	(0.030)	(0.053)	(0.037)
Export	0.185***	0.220*	0.177**
	(0.061)	(0.120)	(0.073)
Innovation			
Prod	-0.045	-0.128*	0.001
	(0.035)	(0.069)	(0.041)
Proc	0.088**	0.176*	0.044
	(0.039)	(0.098)	(0.039)
Training			
Train_d	0.050	0.059	0.039
	(0.034)	(0.075)	(0.042)
EIs			
ENERGY	-0.175**	-0.048	-0.325***
	(0.076)	(0.112)	(0.102)
CO2	0.169*	0.066	0.296**
	(0.091)	(0.099)	(0.146)
EMISSIONS	-0.060	-0.096	-0.061
	(0.066)	(0.096)	(0.090)
EMASISO	0.063	0.120	0.059
	(0.059)	(0.115)	(0.068)
ICT			
MRP	-0.033	0.001	-0.046
	(0.032)	(0.059)	(0.038)
ERP	0.032	0.030	0.056
	(0.032)	(0.065)	(0.040)
ICT_BS	-0.018	-0.042	-0.010
	(0.030)	(0.055)	(0.038)
ICT_PROD	-0.034	-0.005	-0.041
	(0.034)	(0.067)	(0.040)
ICT_COOP	-0.041	0.022	-0.067*
	(0.033)	(0.065)	(0.039)
ICT_INFOSERV	0.035	0.059	0.021
	(0.073)	(0.070)	(0.150)
_cons	3.705***	3.277***	3.780***
	(0.131)	(0.253)	(0.156)
N	555	183	372
AdjR2	0.302	0.278	0.316
F(d.f.)	12.432(27)	5.929(22)	10.517(23)
p-value	0.000	0.000	0.000

Standard errors in parentheses§; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Complementarity between ICT and EI: all firms in the sample

Synergic adoptions of innovations are possibly needed to reconcile EI with economic performances (the strong version of the Porter hypothesis): more than one innovation has to be adopted to enhance performances by increasing returns to scale and creating value out of complementary innovations

As explained in section 3, we now refine our analysis by testing the complementarity between EIs and ICT sets of variables, showing that interesting results emerge. The set of tests is based on several regressions, where each test refers to a single regression with the four states of innovation couples included as specified in equation (2)[16]. Table 5 details the complementarities tests conducted on couples of variables constituted by a general EI variable (ENVINNO) and ICT specific variables (significant tests are boldfaced). The test suggests that in the whole sample and among ETS sectors, complementarity exists between the introduction of any kind of environmental innovation and the ICT practices related to buy-and-sell activities.

Tab. 5: Complementarity tests for specific ICT and a general environmental innovation. The output variable over which the tests are computed is LnVAEMP2010-2011

ICT_D/ENVINNO		Whole sample		ETS Sectors		NonETS Sectors	
(Mean value used for dichotomization)		Wald test§ (Adj. p-value for: H_0: coeff. 11+00 >= coeff.10+01)^	Sign of the linear combination (b1+b4)+ (-b2-b3)	Wald test§ (Adj. p-value for: H_0: coeff. 11+00 >= coeff.10+01)^	Sign of the linear combination (b1+b4)+ (-b2-b3)	Wald test§ (Adj. p-value for: H_0: coeff. 11+00 >= coeff.10+01)^	Sign of the linear combination (b1+b4)+ (-b2-b3)
ENVINNO	ICT_INTRO	0.02 (0.44)	≤ 0	1.31 (0.87)	≥ 0	0.18 (0.33)	≤ 0
ENVINNO	MRP	2.25 (0.06)	≤ 0	0.39 (0.26)	≤ 0	1.26 (0.13)	≤ 0
ENVINNO	ERP	0.57 (0.22)	≤ 0	0.18 (0.66)	≥ 0	0.58 (0.22)	≤ 0
ENVINNO	ICT_BS	**3.10* (0.96)**	**≥ 0**	**4.07** (0.97)**	**≥ 0**	0.29 (0.7)	≥ 0
ENVINNO	ICT_PROD	0.59 (0.22)	≤ 0	0.03 (0.57)	≥ 0	1.21 (0.13)	≤ 0
ENVINNO	ICT_COOP	0.00 (0.52)	≥ 0	0.56 (0.77)	≥ 0	0.63 (0.21)	≤ 0
ENVINNO	ICT_SERV	0.00 (0.49)	≤ 0	0.00 (0.51)	≥ 0	2.08 (0.92)	≥ 0

§ Since we are testing one linear restriction at a time, the F distribution has 1 degree of freedom in the numerator as the number of the linear restrictions: H0: b1+b4-b2-b3=0; critical values of F distribution with one degree of freedom in the numerator: 6.63, 3.84 and 2.71 (***1%, ** 5% and * 10% level of significance respectively).
^Adjusted p-value for inequality tests when the Wald F statistic has 1 degree of freedom in the numerator.
(b1+b4)+(-b2-b3)≥0 is evidence in favour of supermodularity.
(b1+b4)+(-b2-b3)<0 is evidence in favour of submodularity.

As explained in the section below, when we discuss our results, the existence of this single complementarity may be explained by the idiosyncratic nature of the complementarities among EIs and ICT that make the synergies between them very specific to ICT practices and EIs adoption. To verify the existence of these specificities in complementarity, we run our tests on specific EIs/ICT dimensions as shown in tables 6, 7 and 8.

[16] Because of space constraints, we do not report the regression outputs, but they are available upon request from the authors.

Table 6 presents the results of the EIs/ICT couple-specific complementarity tests for the whole sample of firms for specific EIs. The results suggest that there is a complementarity between ‘energy saving innovations’ and the ‘ICT used to manage buy-and-sell activities’. The same also holds true for the strategy EMASISO/ICT_SERV, which means that jointly adopting certified green processes of production and ICT used to exchange information and services correlates in a stronger way to the productivity than adopting one or the other of the two innovations. The implementation of e-commerce practices seems to work in combination with EIs innovation to increase labour productivity given a better organization of economic activities, which reinforces the enabling effect that ICT can have in the economy.

In the whole sample of firms, energy-oriented and organizational innovation changes prevail as EI adoptions that find synergies with ICT towards the enhancement of productivity. Energy efficiency innovations produce cost savings and are characterized by returns that are relatively more 'appropriable' than CO2 abatement innovations[17].

Although we have evidence of the two complementarities above, we cannot neglect the substitutability relationship that seems to emerge between the following two specific innovations: EIs introduced to reduce emissions and the introduction of the Material Requirement Planning (MRP) management system. This management practice permits the process of production to be improved by using a computer-based management and tracking system, which can be considered an enabling effect of ICT adoption. This allows flexibility and efficiency in the production and distribution process to be increased. The two specific types of innovations seem to increase productivity more when not adopted in combination, rather than when jointly implemented.

[17]Dangelico and Pontrandolfo (2015) find that energy and pollution firm's environmental actions are correlated with enhanced economic performances, for a case study in the Apulia Region in Italy.

Tab 6: Complementarity tests for specific ICT and environmental innovations. The output variable over which the tests are computed is: LnVAEMP2010-2011

ICT_D/ENVINNO		Whole sample					
(Mean value used for dichotomization)		Wald test§	Sign of the linear combination (b1+b4)+(-b2-b3)			Wald test§	Sign of the linear combination (b1+b4)+(-b2-b3)
		(Adj. p-vale for: H_0: coeff. 11+00 >= coeff.10+01)^				(Adj. p-vale for: H_0: coeff. 11+00 >= coeff.10+01)^	
ENERGY	ICT_INTRO	0.28 (0.70)	≥ 0	EMISSIONS	ICT_INTRO	0.45 (0.25)	≤ 0
ENERGY	MRP	1.09 (0.14)	≤ 0	EMISSIONS	MRP	**3.37* (0.03)**	**≤ 0**
ENERGY	ERP	0.51 (0.23)	≤ 0	EMISSIONS	ERP	2.34 (0.06)	≤ 0
ENERGY	ICT_BS	**3.61* (0.97)**	**≥ 0**	EMISSIONS	ICT_BS	0.83 (0.81)	≥ 0
ENERGY	ICT_PROD	0.09 (0.38)	≤ 0	EMISSIONS	ICT_PROD	0.70 (0.20)	≤ 0
ENERGY	ICT_COOP	0.00 (0.49)	≤ 0	EMISSIONS	ICT_COOP	0.09 (0.61)	≥ 0
ENERGY	ICT_SERV	0.06 (0.59)	≥ 0	EMISSIONS	ICT_SERV	0.04 (0.58)	≥ 0
CO2	ICT_INTRO	0.06 (0.59)	≥ 0	EMASISO	ICT_INTRO	0.00 (0.49)	≤ 0
CO2	MRP	0.19 (0.32)	≤ 0	EMASISO	MRP	2.13 (0.07)	≤ 0
CO2	ERP	0.02 (0.44)	≤ 0	EMASISO	ERP	0.28 (0.29)	≤ 0
CO2	ICT_BS	0.17 (0.65)	≥ 0	EMASISO	ICT_BS	2.51 (0.94)	≥ 0
CO2	ICT_PROD	0.23 (0.31)	≤ 0	EMASISO	ICT_PROD	0.10 (0.37)	≤ 0
CO2	ICT_COOP	0.16 (0.34)	≤ 0	EMASISO	ICT_COOP	0.01 (0.53)	≤ 0
CO2	ICT_SERV	2.55 (0.94)	≥ 0	EMASISO	ICT_SERV	**2.85* 0.95**	**≥ 0**

§ Since we are testing one linear restriction at a time, the F distribution has 1 degree of freedom in the numerator as the number of the linear restrictions: H0: b1+b4-b2-b3=0; critical values of F distribution with one degree of freedom in the numerator: 6.63, 3.84 and 2.71 (***1%, ** 5% and * 10% level of significance).
^ Adjusted p-value for inequality tests when the Wald F statistic has 1 degree of freedom in the numerator.
(b1+b4)+(-b2-b3)≥0 is evidence in favour of supermodularity.
(b1+b4)+(-b2-b3)<0 is evidence in favour of submodularity.

Comparing complementarity strategies with and without climate policy (EU-ETS)

Tables 7 and 8 present the complementarity test on the sub-sample of firms belonging, respectively, to ETS sectors and non-ETS sectors.

The complementary tests on the ETS sample presented in Table 7 show that the combination of ICT_BS with different types of environmental innovations, namely, emission reduction, energy saving practices and non-technological standards, such as EMAS, leads to productivity gains. This result is interesting, as it shows that firms that operate in regulated sectors are able to exploit the potential productivity effects of the joint adoption of specific ICT and EIs. In fact, it also emerges that there is a complementarity between the adoption of non-technological standards (EMAS and ISO certifications) and both ICT_INTRO and ICT_SERV.

Tab 7: Complementarity tests for specific ICT and environmental innovations. The output variable for tests is LnVAEMP2010-2011

ICT_D/ENVINNO *(Mean value used for dichotomization)*		Wald test§ (Adj. p-value for: H_0: coeff. 11+00 >= coeff.10+01)^	Sign of the linear combination (b1+b4)+(-b2-b3)	ETS Sectors		Wald test§ (Adj. p-value for: H_0: coeff. 11+00 >= coeff.10+01)^	Sign of the linear combination (b1+b4)+(-b2-b3)
ENERGY	ICT_INTRO	1.41 (0.88)	≥ 0	EMISSIONS	ICT_INTRO	0.03 (0.56)	≥ 0
ENERGY	MRP	0.25 (0.30)	≤ 0	EMISSIONS	MRP	0.62 (0.21)	≥ 0
ENERGY	ERP	0.24 (0.68)	≥ 0	EMISSIONS	ERP	1.00 (0.15)	≤ 0
ENERGY	ICT_BS	**4.01** (0.97)**	**≥ 0**	EMISSIONS	ICT_BS	**2.90* (0.95)**	**≥ 0**
ENERGY	ICT_PROD	0.79 (0.81)	≥ 0	EMISSIONS	ICT_PROD	0.52 (0.76)	≥ 0
ENERGY	ICT_COOP	1.41 (0.88)	≥ 0	EMISSIONS	ICT_COOP	2.39 (0.93)	≥ 0
ENERGY	ICT_SERV	0.19 (0.66)	≥ 0	EMISSIONS	ICT_SERV	0.04 (0.58)	≥ 0
CO2	ICT_INTRO	0.31 (0.70)	≥ 0	EMASISO	ICT_INTRO	**8.85*** (0.99)**	**≥ 0**
CO2	MRP	0.16 (0.65)	≥ 0	EMASISO	MRP	0.63 (0.78)	≥ 0
CO2	ERP	0.01 (0.52)	≥ 0	EMASISO	ERP	1.84 (0.91)	≥ 0
CO2	ICT_BS	1.46 (0.88)	≥ 0	EMASISO	ICT_BS	**3.05* (0.95)**	**≥ 0**
CO2	ICT_PROD	0.25 (0.69)	≥ 0	EMASISO	ICT_PROD	2.23 (0.93)	≥ 0
CO2	ICT_COOP	0.01 (0.54)	≥ 0	EMASISO	ICT_COOP	0.79 (0.81)	≥ 0
CO2	ICT_SERV	0.59 (0.77)	≥ 0	EMASISO	ICT_SERV	**3.69* 0.97**	**≥ 0**

§ Since we are testing one linear restriction at a time, the F distribution has 1 degree of freedom in the numerator as the number of the linear restrictions: H0: b1+b4-b2-b3=0; critical values of F distribution with one degree of freedom in the numerator: 6.63, 3.84 and 2.71 (***1%, ** 5% and * 10% level of significance).

^ Adjusted p-value for inequality tests when the Wald F statistic has 1 degree of freedom in the numerator.

(b1+b4)+(-b2-b3)≥0 is evidence in favour of supermodularity.

(b1+b4)+(-b2-b3)<0 is evidence in favour of submodularity.

The reasoning concerning the results for ETS sectors cannot be translated to the firms belonging to less strictly regulated sectors (NonETS) because, as Table 8 shows, the results are largely in favour of substitutability between EIs and ICT.

Tab. 8: Complementarity tests for specific ICT and environmental innovations. The output variable over which the tests are computed is LnVAEMP2010-2011

ICT_D/ENVINNO				NonETS Sectors			
(Mean value used for dichotomizations)		Wald test§	Sign of the linear combination (b1+b4)+(-b2-b3)			Wald test§	Sign of the linear combination (b1+b4)+(-b2-b3)
		(Adj. p-value for: H_0: coeff. 11+00 >= coeff.10+01)^				(Adj. p-value for: H_0: coeff. 11+00 >= coeff.10+01)^	
ENERGY	ICT_INTRO	0.88 (0.85)	≥ 0	EMISSIONS	ICT_INTRO	0.32 (0.28)	≤ 0
ENERGY	MRP	0.29 (0.29)	≤ 0	EMISSIONS	MRP	2.19 (0.06)	≤ 0
ENERGY	ERP	0.23 (0.31)	≤ 0	EMISSIONS	ERP	0.78 (0.18)	≤ 0
ENERGY	ICT_BS	0.80 (0.81)	≥ 0	EMISSIONS	ICT_BS	0.01 (0.45)	≤ 0
ENERGY	ICT_PROD	1.58 (0.10)	≤ 0	EMISSIONS	ICT_PROD	**5.33** (0.01)**	**≤ 0**
ENERGY	ICT_COOP	1.14 (0.14)	≤ 0	EMISSIONS	ICT_COOP	1.24 (0.13)	≤ 0
ENERGY	ICT_SERV	1.30 (0.87)	≥ 0	EMISSIONS	ICT_SERV	n.f.	
CO2	ICT_INTRO	0.13 (0.63)	≥ 0	EMASISO	ICT_INTRO	0.44 (0.25)	≤ 0
CO2	MRP	0.22 (0.31)	≤ 0	EMASISO	MRP	2.99* (0.04)	≤ 0
CO2	ERP	0.07 (0.60)	≥ 0	EMASISO	ERP	0.66 (0.20)	≤ 0
CO2	ICT_BS	0.15 (0.35)	≤ 0	EMASISO	ICT_BS	0.56 (0.77)	≥ 0
CO2	ICT_PROD	**3.53* (0.03)**	**≤ 0**	EMASISO	ICT_PROD	**4.43** (0.01)**	**≤ 0**
CO2	ICT_COOP	0.93 (0.16)	≤ 0	EMASISO	ICT_COOP	0.47 (0.24)	≤ 0
CO2	ICT_SERV	**2.92* (0.95)**	**≥ 0**	EMASISO	ICT_SERV	n.f.	

§ Since we are testing one linear restriction at a time, the F distribution has 1 degree of freedom in the numerator as the number of the linear restrictions: H0: b1+b4-b2-b3=0; critical values of F distribution with one degree of freedom in the numerator: 6.63, 3.84 and 2.71 (***1%, ** 5% and * 10% level of significance).
^ Adjusted p-value for inequality tests when the Wald F statistic has 1 degree of freedom in the numerator.
(b1+b4)+(-b2-b3)≥0 is evidence in favour of supermodularity.
(b1+b4)+(-b2-b3)<0 is evidence in favour of submodularity.
n.f. means that the test computation is not feasible because one of the states of the world has no firms.

6. Discussion

The first set of results reported in Tables 3 and 4, which shows a substantial lack of linkage between innovations and productivity, is not completely unexpected: innovation 'effects' on productivity, especially for some innovations, are not low-hanging fruits. Various motives might be in place in this case study: the relatively short time span (three years) between innovation and observed economic performances; the effect of the 2009 recession, which is between the innovation introduction/deployment (2006-2008) and the effects we observe (2010-2011); and finally, the inability of single innovations to produce real visible effects.

We observe that in the specific area we examine, the key non-ETS manufacturing sectors for which we observe positive productivity effects are 'machinery' and 'food'. These are the historical specializations of the Italian region we are studying (Emilia-Romagna). These manufacturing sectors might proactively lead to climate change oriented investments due to their high exposure to international markets *and* strong relationships with the territory, two elements that matter even more than regulations in some cases (as commented on by Cainelli et al., 2012).

All in all, the main result of this first step of the analysis is in line with part of the empirical literature on both ICT and EIs productivity effects, as reported in the literature review, confirming that, for the entire sample of firms and the more polluting ETS firms, the single adoption of EIs and ICT does not appear to be a crucial factor behind the enhancement of productivity, while for non-ETS firms, the evidence is mixed, pointing to a positive effect for some EIs and negative effect for some others. This leads the analysis towards the investigation of complementarity and the testing of H1 and H2.

In Tables 5 to 8, we reported tests of complementarities. The results from Tables 5 and 6 suggest that the dematerialization from ICT practices is associated with the introduction of environmental innovations once we consider the whole sample and the ETS sector. As suggested in the literature, the application of ICT can permit the enhancement of the 'impact' of EIs activities on a firm's performance. This evidence supports H1. However, the presence of this single result notes that the existence of EIs/ICT complementarities on productivity is very idiosyncratic in nature and costly, as it derives from reorganizations and new investments in different innovation dimensions. The complementarity between various 'spheres' of innovation activities (e.g., Schmiedeberg 2008; Polder et al. 2010; Hottenrott et al. 2016) cannot be conceived of as a 'low-hanging fruit' that firms can easily reach through simple strategies. In contrast, the exploitation of the potential complementarities probably needs the development of complex innovation strategies that entail techno-organizational changes and human capital empowerment (Antonioli et al. 2013), which are difficult to be reached although they may constitute a source of non-codified competitive advantages.

From tables 7 and 8, when we look at the specific results for Non-ETS and ETS sectors, in order to capture the influence of environmental regulatory pressures, we note that the digitalization of services combined with the adoption of green non-technological standards influence productivity, even in a period of ongoing economic slowdown. Within the ETS sectors, environmental innovation seems to go hand in hand with the enabling effect of ICT adoption and usage. The complementary nature of specific EIs and ICT shown by our results consistently relates with previous literature that underlines the positive effects associated with the dematerialisation of different economic activities in greening the production process. In addition, our evidence for ETS sectors, especially with respect to complementarities between different information technologies and organizational changes adopted to meet green EMAS and ISO requirements, are consistent with other empirical works (Black and Lynch 2001; Aral et al. 2012) that note how synergies among technological and organizational changes lead to productivity gains (Antonioli et al. 2010). The results for ETS firms confirm H2, and they seem to be aligned with the 'strong' version of the Porter hypothesis, as discussed in section 2. Firms in search for productivity gains by EIs, are able to find specific and focused strategies of complementary adoption of EIs and ICT, also because the latter are EIs enabler. The analysis of the 'strong' version of the Porter hypothesis through the lens of complementarity provides new insights on the role of joint adoption of EIs and ICT on productivity, showing that this is a way through which firms can offset the costs generated by environmental regulation.

For the NonETS firms, H2 is not confirmed. It might be the case that the timing of EI and ICT adoption matters in this case. The non-complementary adoption of ICT and EIs is still more fruitful than their combination in the production process. We may argue, in line with the model by Kriechel and Ziesemer (2009), that firms not subject to stringent environmental regulation are late EIs adopters with respect to ETS firms, which are technological leaders. The late adoption by NonETS, closer to the economic recession of 2009 than that by ETS firms, may have displaced these firms more than ETS firms, many of which could have adopted EIs at the beginning of the 2006-2008 period, thus having enough time before the recession to optimally learn how to integrate green processes and technology with other innovations, especially ICT, and gain productivity advantages soon after the 2009 recession. It emerges that the NonETS firms are less able than their ETS counterparts to exploit synergies between information technologies and environmental innovations. In addition, this occurs despite the fact that, among the NonETS sectors, we have the machinery sector – one of the most technologically advanced sectors in the Emilia-Romagna region and the backbone of the regional industrial system.

7. Conclusions

This article investigates the extent to which the joint adoption of environmental innovations and ICTs affects the labour productivity of firms. The evidence highlights that the single adoption of the aforementioned innovations does not impact economic performances. When considering the joint adoption, some combinations of EI and ICT instead appear to be relevant drivers of productivity. Nevertheless, the increase in economic performances due to 'innovation combinations' is not a low-hanging fruit. It appears in some very specific cases, especially those characterised by environmental innovations with a lower public good content, and thus more appropriable returns, such as energy efficiency. The value of complementarity is very specific and case-dependent.

In more detail, once we consider the whole sample of firms, the results show that there is a complementarity between energy saving innovations and the ICT used to manage buy-and-sell activities, which overall supports the hypothesis (H1) that EIs can have an impact on productivity growth once they are jointly introduced with ICT.

Finally, and quite interesting, environmental policies seem to influence the way innovation complementarities are managed by firms (H2). Distinguishing the most polluting and regulated sectors (ETS) from the less polluting and non-regulated ones (NonETS) permits us to enhance our understanding of the complementarities existing between ICT adoption and environmental innovation. On the one hand, the evidence shows that a complementarity between the adoption of certain types of ICT applications, such as e-commerce and digitalization of the economic activities, and specific types of EIs does exist, especially for organizational changes adopted to meet green-certificate requirements (e.g., EMAS, ISO14001). This result corroborates what empirical literature (Black and Lynch, 2001; Aral et al. 2012) has shown in terms of ICT and organizational changes complementarity on productivity, also for green investments and innovation. Such evidence, however, holds only for a certain type of firms – those belonging to the most polluting sectors and subject to ETS regulation. It seems quite clear that we are witnessing the ‘strong’ version of the Porter hypothesis at work: higher (climate/energy) policy stringency pushes the firms to invest in green technologies and organizational changes. It must be noticed that only the most technologically advanced firms, especially in terms of ICT, which also facilitate the adoption of EIs, experience productivity gains. On the other hand, for the less regulated firms, substitutability relationships mainly emerge between EI and ICT couples of innovation; that is to say, larger gains in productivity are reached through the adoption of EIs or ICT, but not by the deployment of their combinations. In the Non-ETS sectors, the EI strategies seem not to be fully embedded with the ICT strategies, lowering the potential ‘impact’ on labour productivity.

The results show that complementarities towards enhanced economic performance are sector specific, policy driven and innovation specific. They do not hold in every manufacturing sector, and they do not hold for any mix of EIs and ICT adoption. The beneficial mix of innovation adoptions for the firms, in terms of increased labour productivity, must be carefully chosen and implemented as a strategic managerial lever to increase productivity.

Our study has some limitations that provide suggestions for future research. We have no detailed information about the reasons that motivated the adoption of ICT and environmental innovation; however, the complementarities tests show that joint adoption affects the labour productivity of firms. The time span after the EIs and ICT adoption could be too short to provide robust evidence on productivity 'effects', especially in a period of enduring economic slowdown. Additionally, a stronger dynamic-oriented study is needed to measure both the short and long-term effects of the joint development of environmental innovation and information communications technologies, in particular with respect to specific technologies, such as smart grids. Larger samples could also allow the testing of the value of complementarity sector by sector, investigating very specific technological and policy features.

Appendix A

Tab. A1 - Distribution by sector and size of population and sample firms

Population								
Sectors	Freq.	Percent	***Size***	Freq.	Percent	*Provincia^*	Freq.	Percent
CokeChemical	130	3.2	20-49	2720	66,86	Out region	91	2.24
Food	382	9.39	50-99	726	17,85	BO	904	22.22
Machinery	1,387	34.1	100-249	414	10,18	FC	346	8.51
Metallurgy	883	21.71	250+	208	5,11	FE	196	4.82
NonMetallic	285	7.01				MO	891	21.9
PaperPrinting	197	4.84				PC	200	4.92
Shoes	236	5.8				PR	381	9.37
Textile	119	2.93				RA	229	5.63
WoodRubberPlasticOther	449	11.04				RE	667	16.4
						RN	163	4.01
Total	4,068	100		4,068	100		4,068	100
Sample								
Sectors	Freq.	Percent	***Size***	Freq.	Percent	*Provincia^*	Freq.	Percent
CokeChemical	28	5.05	20-49	208	37,48	Out region	20	3.6
Food	49	8.83	50-99	193	34,77	BO	115	20.72
Machinery	232	41.8	100-249	96	17,30	FC	40	7.21
Metallurgy	94	16.94	250+	58	10,45	FE	30	5.41
NonMetallic	42	7.57				MO	124	22.34
PaperPrinting	19	3.42				PC	25	4.5
Shoes	12	2.16				PR	49	8.83
Textile	23	4.14				RA	32	5.77
WoodRubberPlasticOther	56	10.09				RE	96	17.3
						RN	24	4.32
Total	555	100		555	100		555	100

^*Provincia* is a statistical geographical unit coded as NUTS3 level by EUROSTAT.

Tab.A2 – Distribution of firms that jointly adopt ICT and EI

			EI	
ICT	ENERGY.	CO2	EMISSIONS	EMASISO
MRP	38 (7%)	28 (5%)	37 (7%)	30 (5%)
ERP	42 (8%)	34 (6%)	39 (7%)	40 (7%)
ICT_BS	40 (7%)	32 (6%)	34 (6%)	38 (7%)
ICT_PROD	67 (12%)	53 (10%)	62 (11%)	65 (12%)
ICT_COOP	58 (10%)	47 (8%)	53 (10%)	56 (10%)
ICT_SERV	76 (14%)	61 (11%)	73 (13%)	77 (14%)

Note: the total number of firms introducing some EI is 111; Percentage calculated with respect to the total sample of 555 firms.

Appendix B

Extracts from selected questions for ICT and EI variables. The answers refer to the period from 2006-2008.

ENVIRONMENTAL INNOVATION (EI)

Q1: Did the firms adopt "environmental" products and/or process technological innovations that induced the following benefits?

	Yes/No
1. Reduction in the use of materials and/or energy by output unit (including recycling)	
2. CO_2 emissions reduction	
3. Emission reductions that improve the quality of soil, water and air	

ENERGY=1 if Reduction in the use of materials and/or energy by output unit (included recycling) marked as Yes; 0 otherwise

CO2=1 if CO_2 emissions reduction marked as Yes; 0 otherwise

EMISSIONS=1 if Emission reductions that improve the quality of soil, water and air; 0 otherwise

Q2: Does the firm have procedures that structurally identify its environmental performance?

Procedure	Yes/No
1. EMAS	
2. ISO 14001	
3. Others such as LCA, ISO14040, ……………………..(specify)	

EMASISO=1 if EMAS or ISO14001 or Others is marked as Yes; 0 otherwise

ICT

Q3. Which types of management systems and network integration did you adopt?

	Yes/No
1. Management information system	
2. Electronic Data Interchange (**EDI)**	
3. Material Requirements Planning (**MRP)**	

4. Supply Chain Management (SCM)	
5. Customer Relationship Management (CRM)	
6. Enterprise Resource Planning (ERP)	

ICT_INTRO=(number of the items in Q3 with a positive answer)/(number of all the items in Q3); dichotomised for complementarity test as 1 if the index is above the average and 0 otherwise

MRP =1 if the firm introduced MRP systems: 0 otherwise

ERP =1 if the firm introduced ERP systems; 0 otherwise

Q4. Which types of activities are supported by ICT?

	Yes/No
1. Acquire information and services	
2. Provide information and services	
3. Manage buy-and-sell orders online	
4. Manage the production process and control quality and time	
5. Cooperate with clients and suppliers (post-selling services)	

ICT_BS=1 if item 3 in Q4 has a positive answer; 0 otherwise

ICT_PROD=1 if item 4 in Q4 has a positive answer; 0 otherwise

ICT_COOP=1 if item 5 in Q4 has a positive answer; 0 otherwise

ICT_SERV=1 if item 1 or 2 in Q4 have a positive answer; 0 otherwise

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