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Technological pervasiveness and variety of innovators in Green ICT: A patent-based analysis

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ABSTRACT

Many eco-innovations have been linked to technical change in the ICT domain. Leveraging the distinctive features of general purpose technologies, ICT have the potential to steer green growth and to help decouple this growth from ecological damage. The paper aims to shed light on innovation dynamics in this emerging sector by investigating the patterns of innovation in the green ICT domains using granted EPO patent data from 1986 to 2006. By means of a network analysis, it identifies existing green ICT domains and examines the characteristics of innovative activity in these domains, focusing in particular on growth and technological pervasiveness, as well as on the variety of innovators. Results indicate that the innovative activity in green ICT domains is characterised by high growth and high levels of technological pervasiveness, considerable entry of new innovators and a variety of actors – with a prevalence of large ICT firms and universities. However, the analysis highlights the existence of three different clusters – emerging fields, established fields and mature fields – that are defined by different structures of innovative activities and by different technological opportunities.

1. Introduction

The quest for sustainability and green growth has become a key policy concern in both developed and developing countries (Tongia and Subrahmanian, 2005; Benhaim and Clarke, 2009). As a consequence, the role of technological and non-technological *eco-innovations* is seen as a crucial factor to ensure a long-run process of sustainable development (Rennings, 2000; OECD, 2011). Within this context, scholars, business practitioners and policy makers have agreed that information and communication technologies (ICT) represent a crucial driver of green growth and sustainable development both in developed and developing countries (GeSI, 2008; UNEP, 2008; Jänicke and Jacob, 2009; Bär et al., 2011). As ICT are general purpose technologies (GPT), they can be applied in different domains with wide-ranging socio-economic and environmental impacts across sectors (Youtie et al., 2008; Ropke, 2012). They go hand in hand with competitive advantage and international competitiveness, both at micro and macro-economic level (Beise and Rennings, 2005; Faucheux and Nicolaï, 2011). As GPT, ICT are pervasive and have an innovation-spawning effect as well as scope for improvement (Helpman and Trajtenberg, 1994; Bresnahan and Trajtenberg, 1995). This means that they have a great potential to directly and indirectly interact with the natural environment, generating both direct and indirect effects at the production and consumption levels (OECD, 2010; Berkhout and Hertin, 2001, 2004; Hilty, 2002, 2008). As far as direct effects are concerned, ICT manufacturers can adopt greener processes of production and improve their environmental performance in the areas of energy use and other material inputs, as well as in waste management. Indirect environmental effects refer to the impacts that ICT applications can have on other sectors, and on society as a whole. ICTs can affect the production and consumption of other products and services through the optimisation of production processes, the dematerialisation and substitution of economic activities, the induction of the use of complementary products, and the improvement of waste management processes. In sum, green ICT have the potential to decouple economic growth from increasing ecological damage (Ropke, 2012).

Given the potential contribution of green ICT to growth and sustainable development, it is paramount to shed light on innovation dynamics in this area, to better understand who the key players are and how to design policies to support them. There is only limited literature that attempts to identify and characterise green ICT (Faucheux and Nicolaï, 2011; Mansell, 2012; Ropke, 2012) and no contribution has yet provided an analysis of the innovative activities associated with this domain in relation to the

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0048-7333/

GPT character of ICT. This article investigates the characteristics of the patterns of innovation in the green ICT domain using patent data. It aims in particular to assess the ability of ICT to spawn eco-innovations and the extent to which two major characteristics of ICT – technological pervasiveness and the variety of actors involved in the innovative activity – are also reflected in green ICT domains.

The empirical analysis is based upon an original dataset derived from the combination of the WIPO Green Inventory and the OECD ICT patent classification based on the IPC. We have selected all patent applications at the European Patent Office (EPO) from 1987 to 2006 on the basis of the co-occurrence of an ICT and a green IPC class (at the 7-digit level) – as primary or secondary classes – within the same patent applications. For each patent we have detailed information on innovators' characteristics. We perform a network analysis on pairwise combinations of technological classes in order to identify the main technological domains in green ICT, which are examined in order to identify patterns of innovative activities in green ICT using cluster analysis, and to evaluate to what extent green ICT spawn different technological areas as well as the variety and dynamics of actors behind the development of these domains.

The article is organised as follows. Section 2 reviews the existing literature on green ICTs, outlines the research questions and the hypotheses to be tested. Section 3 describes the data and the methodology. Section 4 presents the green ICT domains that are detected by the network analysis. Section 5 presents the core of the empirical analysis: it provides descriptive evidence of the emergence and pervasiveness of green ICT technological domains. Section 6 distinguishes between three clusters of green ICT innovations: emerging, established and mature. Section 7 concludes the article.

2. ICT as GPT: technological pervasiveness and variety of actors

ICT are unanimously regarded as one of the most important GPTs. GPTs are characterised by three essential features: pervasiveness, scope for improvement and innovation spawning (Helpman and Trajtenberg, 1994; Bresnahan and Trajtenberg, 1995; Helpman, 1997). First, pervasiveness implies that the technology can be applied in a wide range of uses and has some elements that allow the functioning of a substantial part of existing systems.[1] GPT have upheld a "radical shift of technology" (Laestadius, 1998, p. 393) and have created the conditions for shaping new innovations (Carlsson, 2004). In the presence of GPT applications, there is "easy entry of neighbouring industries" (Fransman, 2001, p. 136). Second, GPT are characterised by a continuous process of improvement, which is related both to knowledge and technology cumulativeness and, to a lesser extent, to the coordination of innovative activity of different actors along a predictable trajectory (Youtie et al., 2008). The scope for improvement allows the operating costs to diminish over time. Finally, GPT are innovation spawning, as they permit the development of new products and processes in multiple areas that are closely linked to the early major invention (David and Greenstein, 1990). Once again, for this to occur, it is argued that a variety of actors – consumers, private companies, public organisations – should share beliefs and expectations regarding the success of that technology (Helpman and Trajtenberg, 1994).

ICT are considered GPT since they can have applications in various sectors and create new areas of technology exploitation and complementary innovations (Rosenberg, 1994, 2000; Consoli, 2005), while also generating important processes of industrial dynamics. Moreover, in the case of ICT there is no unique pattern of diffusion and adoption (Bresnahan and Greenstein, 2001). As underlined by Jovanovich and Rousseau (2005), over time ICT have been widely adopted, have improved consistently, have spawned a considerable number of innovations – as measured by patents and trademarks – and have been characterised by remarkable dynamics in terms of firms' entry and exit.

The potential impact of ICT in different sectors increases the attention given to the direction of their development and specifically their direct and indirect environmental impacts. Empirical evidence (OECD, 2010; Ropke, 2012) suggests that they are responsible for the emergence of an increasing number of applications related to eco-technologies. Clearly these impacts vary substantially depending on the specific characteristics of countries and sectors and on the type of innovation considered (whether it brings genuine novelty or it simply enables incremental changes).

2.1. ICT and the environment: the emergence of green ICT

The European Eco-innovation Action Plan (EcoAp) defines eco-innovation as "...any form of innovation resulting in or aiming at significant and demonstrable progress towards the goal of sustainable development, through reducing impacts on the environment, enhancing resilience to environmental pressures, or achieving a more efficient and responsible use of natural resources".[2]

The dynamics of eco-innovations differs from that of non-environmental innovations (Rennings, 2000; Oltra et al., 2010; Kemp and Oltra, 2011; De Marchi, 2012). First, there is an issue of double externality: eco-innovations produce positive spillovers in both innovation and diffusion stages. In the presence of (positive) externalities, firms have smaller incentives to develop innovations, which might result in underinvestment in eco-technologies given that their benefits are not valued by the market. As a consequence, the role of regulations and policy interventions in the case of eco-innovations is prominent; they ensure that R&D activity is carried out at the firm level by providing a market value to environmental benefits. Second, the development of eco-innovations depends upon the degree of environmental knowledge and sensibility towards green issues on producers' and consumers' sides. Third, firms (and consumers) committed to eco-innovation must face trade-offs between environmental performance and cost/price/quality factors (Oltra and Saint Jean, 2009). These trade-offs apply both to product and process eco-innovations: new products and processes that combine a response to environmental challenges with increased efficiency permit a quicker diffusion of innovations. An interesting example of this is provided by refurbished products/systems distributors, which regenerate ICT products and systems and sell them on the market at lower prices than new products, allowing customers to increase their efficiency by lowering ICT costs.

There is a wide consensus in the literature that many eco-innovations, i.e. innovations that contribute to reducing environmental burdens (Rennings, 2000; Kemp and Pearson, 2008; OECD, 2010; Hilty et al., 2006; Kemp and Oltra, 2011), have been linked to technical change in the ICT domain. Notable examples include the use of regulation, metering and remote management to improve efficiency; the development of thermal and acoustic insulation in sustainable buildings; the application of ICT to renewable energies; and sustainable mobility. Green ICT can be defined as ICT equipment and software that either reduce their own environmental impacts or those of other sectors of the economy and society. These impacts can be any kind of pollution, the depletion of natural resources such as hydrocarbons or rare earth elements, or

[1] For example, in the case of ICT, binary logic would be the pervasive element (Bresnahan and Trajtenberg, 1995).

[2] Source: http://ec.europa.eu/environment/ecoap/index_en.htm, last consulted on 22 July 2012.

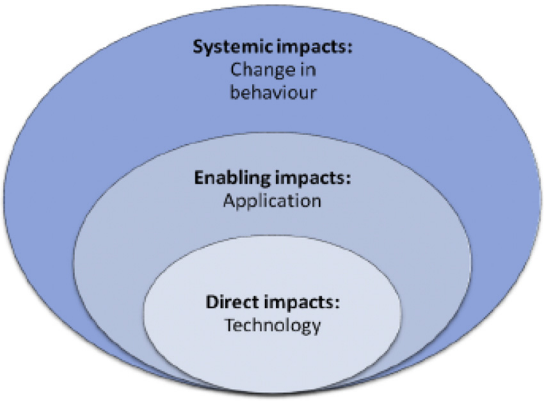

Fig. 1. ICT and the environment.

global changes in natural ecosystems such as global warming and reduction in biodiversity. Situated at the intersection between eco-technologies and ICT, green ICT constitute the combination of two technological paradigms, which have witnessed the emergence of a variety of different technological trajectories.

In discussions of green ICT, it is important to distinguish between two different types of technological domains. On the one hand, there are ICT applications whose production enables a better environmental performance compared to previous generations of such applications. These are usually referred to as "green ICT" per se. On the other hand, there are ICT applications that can be used to improve the environmental performance throughout the economy and society and have an impact on the environmental productivity of other industries, particularly in terms of energy efficiency, waste management and carbon footprints. These are usually referred to as "IT for green" (Faucheux and Nicolaï, 2011). Recent studies from the OECD (2010 and 2011) explicitly distinguish between these two types of green ICT, and argue that the interaction between ICT and the environment can be categorised in a three-level framework comprising direct impacts (first-order effects), enabling impacts (second-order effects) and systemic impacts (third-order effects). The first-order effects include the impacts of ICT themselves. The second-order effects imply that the use of ICT applications can reduce environmental impacts across economic and social activities. Finally, third-order effects cover the systemic impacts of ICT and their applications and involve behavioural change and other non-technological factors, such as rebound effects. Fig. 1 illustrates the interaction among these effects.

In this article we are interested in examining the ability of ICT to spawn eco-innovations. More precisely, we will discuss the emergence and dynamics of green ICT technological domains, and will investigate the characteristics of their innovation patterns, focusing in particular on two features: technological pervasiveness and the variety of innovators. Innovations in ICT involve a very broad set of technological applications, and technological progress in ICT proceeds along many different directions (Corrocher et al., 2007). In addition, the general purpose character of ICT is responsible for the emergence of ICT innovations in different technological domains, often making it difficult to assign a patent to an exogenously defined class. The issue is even more complex when green ICT is considered. Indeed, there is a great diversity in the technological domains that can contribute to reducing the ecological impacts of ICT throughout their whole lifecycle, domains that do not belong to a pre-defined patent field. For example, innovation in metallurgy can help the industry shift away from hazardous lead-based solders (design phase), while a new mechanical shredding technology might help reduce ecological impacts in the end-of-life phase. As far as the variety of actors is concerned, many contributions have underlined the fact that GPT often bring with them a wave of entry and exit, as well as new innovators (Jovanovich and Rousseau, 2005). Helpman and Trajtenberg (1994) argue that the widespread adoption of ICT is related to the variety of actors involved in the innovation process – scientists, entrepreneurs, existing companies and new firms, public organisations, universities and consumers. Youtie et al. (2008) argue that the set of actors needed to coordinate beliefs regarding the applicability of a GPT is very broad, and includes at least private and public organisations (e.g. firms and government). Therefore, we will examine the extent to which the innovative activity in green ICT is distributed across different actors, in particular incumbents vs. new entrants and public vs. private actors.

3. Data and methodology

In order to investigate the extent to which ICT spawn eco-innovations, the first step of our analysis involves selecting the set of patents to be included in the green ICT field.[3] For this purpose, we base our analysis on a dataset of patents granted by the European Patent Office (EPO) in the fields of ICT and green technologies. Each patent document includes the relevant technology codes related to the subject matter of the patent, which is given by the 8-digit International Patent Classification (IPC) code. IPC classes show the technology field the patent belongs to. A patent document is assigned a main code, as well as secondary ones.

As mentioned by Oltra et al. (2010), it is methodologically difficult to investigate "eco-patents", because patent classification systems do not use specific categories for environmental patents. This is particularly true for the case of green ICT, which lie at the intersection of two broad domains – environmental technologies and ICT. To select the green ICT patents, we consider two sources of information: the OECD list of IPC codes in the ICT field, and the WIPO Green Inventory list of IPC codes in the green field. The OECD list of ICT codes consists of four fields: *telecommunications, consumer electronics, computers and office machinery, and other ICT*. This classification includes both IT equipment and communication technologies. The WIPO Green Inventory[4] was created by the IPC Committee of Experts in order to enable searches for patent information relating to so-called Environmentally Sound Technologies as listed by the United Nations Framework Convention on Climate Change (UNFCCC). The WIPO Green inventory includes all the IPC classes that are associated with environment-friendly technologies in a variety of fields. In particular, it includes six technological fields: *alternative energy production, transportation, energy conservation, waste management, agriculture/forestry, administrative/regulatory as well as design aspects and nuclear power generation*.

A straightforward, yet imprecise method to select green ICT patents is to extract those patents in which IPC codes appear both in the OECD and in the WIPO list. For example, IPC class G01R, which refers to "Measurement of electricity consumption", appears both in WIPO and OECD lists (henceforth denoted as *pure green ICT*). However, considering only the patents under these IPC codes might lead one to underestimate the innovative activity related to green ICT, since some technological domains that cut across the two fields – green technologies and ICT – are not represented by these classes. Therefore, when forming the initial dataset, we include both pure green ICT patents and patents which contain at least one IPC code from the ICT list, and one from the green inventory list. Fig. 2 shows the methodology of patent extraction.

[3] As highlighted by Oltra et al. (2010), despite some methodological problems, patents can be a useful means for measuring both environmentally motivated product innovations and technologies with environmental benefits.

[4] See http://www.wipo.int/classifications/ipc/en/est/.

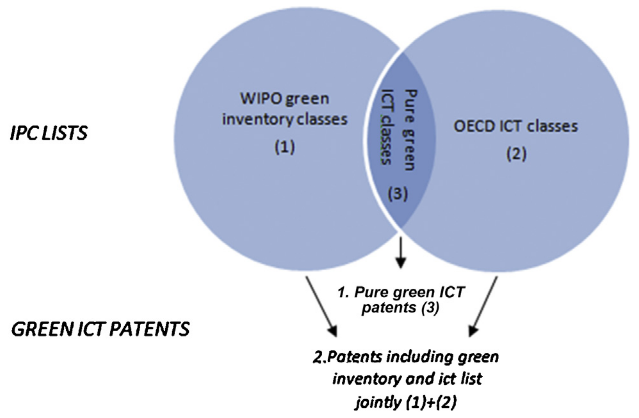

Fig. 2. Methodology of patent extraction.

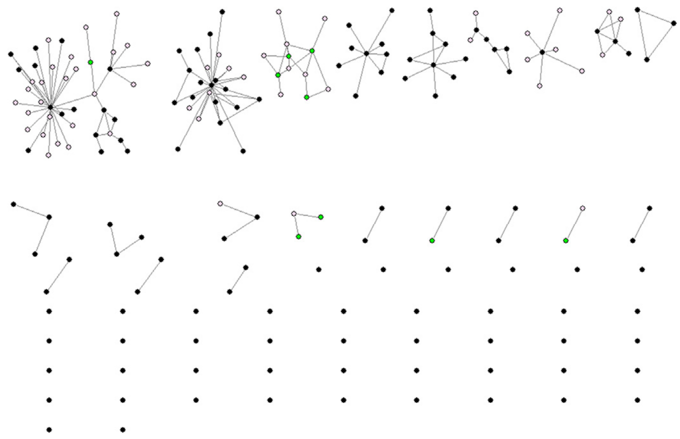

Fig. 3. Network analysis on green ICT technological classes.

First, we extract all the EPO patents which were granted between 1987 and 2006 and which contain at least one IPC code that is included in the OECD ICT list and one IPC code that appears in the WIPO Green Inventory.[5] The dataset includes 16,601 patents. These patents involve a total of 4157 IPC classes at 7 digits (436 pure green ICT, 715 green codes, 3006 ICTcodes).

After the formation of a green ICT patent set, our methodology involves two steps. In the first step we identify the main technological domains within green ICT. The second step consists of analysing the structural properties of these technological domains, so as to reveal patterns of innovative activity in each of them. In what follows, we explain these steps in detail.

A patent network analysis is used to identify the main technological domains in green ICT. This method enables us to identify those couples of IPC codes which co-occur most frequently within our set of patents. In other words, for each possible pair of ICT-Green codes, we count the number of times they appear together on a patent document. We select the top 1% most frequent couples of classes, which results in a set of IPC codes co-occurring in at least 55 patents.[6] The resulting dataset includes 3006 classes at 7 digits (423 pure green ICT, 209 green, 2374 ICT) and 13,210 patents. For the purpose of identifying green ICT technological domains, we form networks in which the nodes are IPC codes, and the links between them are the number of patents in which two codes appear together.

A network analysis is appropriate for our purposes for several reasons. First, our database involves patents which include IPC codes that originate from two distinct IPC domains as green technologies, and ICT. Since we are interested in how these two domains intersect in the development of technologies, we need to have a means of measuring the relationship between ICT on one hand, and green technologies on the other. Building a network of IPC classes permits us to see these relations. In addition, network analysis also permits us to explore the importance of these relations, by constructing weighted links between IPC classes based on the number of their occurrences in patents. Secondly, network analysis permits not only measuring the relations between pairs of IPC classes, but also identifying densely clustered IPC codes which reveal closely related technological fields, something that is not obvious from an analysis of IPC classes directly. Therefore, highlighting such densely clustered technology domains is useful when the purpose of the study is to better understand the nature of a technology. Third, network analysis also reveals the important IPC codes in a particular cluster, especially in newly emerging technological areas where the domains of innovation are only insufficiently established and institutionalised in terms of research activities. Here, important IPC codes are regarded as those which are highly central in terms of their co-occurrence with other IPC codes, or they might refer to classes which act as "brokers", connecting otherwise disconnected domains of technologies and possibly generating radical domains that create discontinuity within the field. Finally, network analysis simplifies complex systems, singling out the important technological domains to be further explored. It also allows us to understand what is the nature of these technologies, and through which mechanisms they have evolved.

While network analysis is a promising avenue for the purposes of this article, it should be interpreted cautiously when studying technological evolution. Indeed, patents reveal only part of innovative activities in a technological domain. In addition, network analysis is a way of describing the system through a relational perspective, but it does not reveal any causal mechanisms explaining the evolution of the system. Rather, networks constructed through patents can be considered a snapshot of a system at certain intervals. Therefore, a patent-based network analysis should not be considered an end by itself, but rather a means which opens the way for further research on why such patterns are observed.

As mentioned above, the second step of our methodology consists of performing a more detailed analysis of each of the components that we obtain through the network analysis. In the process, we explore the capacity of ICT to spawn green innovations, by examining the growth of innovative activity, the degree of technological pervasiveness and the variety of actors for each of the technological domains that we obtain through the network analysis. Through a cluster analysis, we further explore the existence of different patterns of innovative activity within these technological domains.

4. Technological domains in green ICT

The network analysis results in 65 green ICT technological domains (see Fig. 3). Each node corresponds to one of the 3006 technological classes. In particular, as explained earlier, the black nodes are "pure green ICT classes", i.e. IPC classes that are common

[5] Each patent document includes the relevant technology codes related to the subject matter of the patent, which is given by the 8-digit International Patent Classification (IPC) code. A patent document is assigned a main code, as well as secondary ones. IPC classes represent an interesting source of information as they show the technology field which the patent belongs to.

[6] Considering the most frequent couples of codes permits us to identify the most strongly connected codes. If all the patents had been included, obviously one large component would have emerged. This is why it is important to take into account the "weight" of the links between IPC codes, which can be estimated with the number of patents forming this link. In the choice of this parameter, we tried to generate as many disconnected clusters as possible, without damaging the groups of classes which are strongly connected as revealed by the number of patents per link.

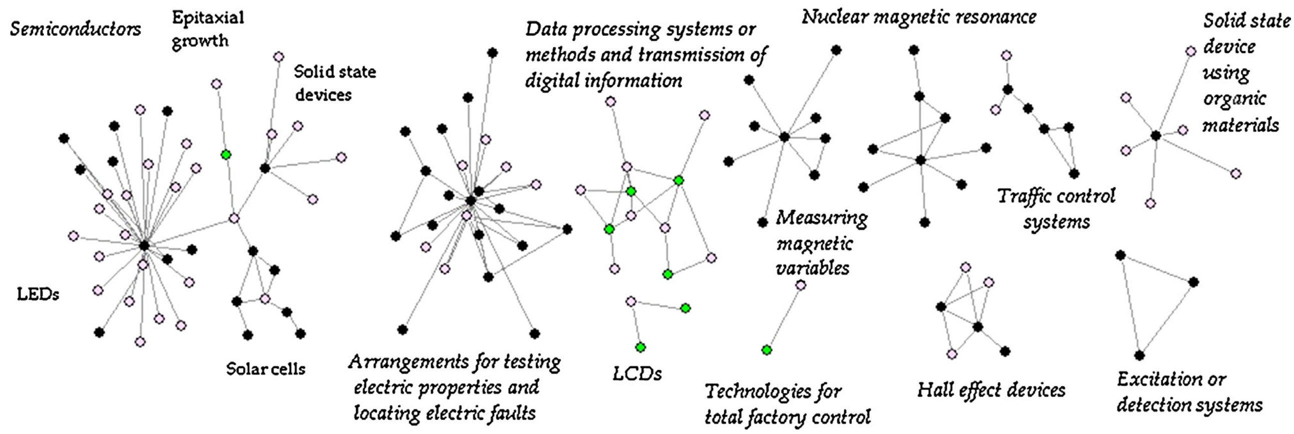

Fig. 4. Most important green ICT domains.

to WIPO green inventory and OECD ICT classifications (group (3) in Fig. 2). The pink nodes are ICT codes which are not included in the Green Inventory (group (2) in Fig. 2); and the green nodes are Green inventory codes which are not included in the OECD ICT classifications (group (1) in Fig. 2). The link between two codes represents the number of patents in which two classes appear simultaneously. In other words, two classes are linked if and only if they simultaneously appear in at least 55 patents. Clearly, not all IPC codes are connected with each other, enabling the identification of non-overlapping technological domains. Furthermore, in the green ICT network we also have some isolated nodes. This happens because our dataset includes pure green ICT patents (i.e. those codes which appear in both lists (shown in Fig. 3 by black nodes)).

The average number of nodes per domain is 2.96, and we observe a highly skewed distribution of nodes, with five domains accounting for 50% of total technological classes, and 44 domains (64% of the total) having just one technological class. The largest domain includes 22% of technological classes, which signals a relatively low level of connectivity within the network. The average degree of centrality is 2.95, with one class having a very high closeness centrality (H01L 21/02 – *Manufacture or treatment of semiconductor devices or of parts*).

Most of the technological domains involve pure green ICT classes, but there are a few components which are made of only green or only ICT classes. This is a very important finding of our descriptive analysis. The way in which we selected the relevant set of green ICT technological classes led us to highlight that innovation in green ICT may not be associated only with the technological classes that appear simultaneously in the WIPO green inventory and in the OECD list of ICT classes, which we have defined as pure green ICT, but may include a broader set of classes. Indeed, the existence of such green ICT domains shows that green ICT technological domains spread across a set of IPC classes, which may be "hidden" when considering only pure green ICT.

It is important to stress that our aim in carrying out the network analysis is not simply to investigate the structure of the network across technological classes. In fact, we use this instrument to identify existing technological domains in the green ICT area, to look at the effective content of the relation (i.e. patents) and analyse the patterns of innovative activity in different green ICT domains. As noted in many studies employing network analysis (Rogers et al., 2001; Cassi and Zirulia, 2008; Cassi et al., 2008), taking the structure of the network independently of the effective content of the relation would be misleading. In the remainder of the Section we discuss the content of these technological domains.

Fig. 4 illustrates the most important technological domains in the green ICT area. We consider here the largest technological domains in terms of the number of IPC classes, and the domains that are formed by green and ICT classes without any pure green ICT (i.e. black nodes). These are particularly relevant in our case, as they show that the green inventory is not enough to capture green ICT fields.

The largest domain in our sample belongs to the broad domain of *Semiconductors*, and includes four well defined subcomponents that are linked to the central node (code H01L21/02 – "Manufacture or treatment of semiconductor devices or of parts"). The first three are related to LED technology[7]: solid state devices, light emitting diodes and epitaxial growth. The fourth one is related to the conversion of energy using solar panels.

Another important domain includes technologies supporting *Data processing systems or methods and transmission of digital information.* This is a particularly relevant domain in the analysis because it does not include any pure green ICT class. The IPC classes which belong to this domain include: inventions in arrangements for secret or secure communication, data switching networks, systems characterised by a protocol, complete banking systems, coded card-free arrangements for money transactions between bank accounts, payment architectures, mechanisms for transactions by coded identity card or credit card as well as card verification systems. It is interesting to note that these technological domains can enable structural changes (third-level systemic impacts) as they introduce behavioural and structural changes by enabling a different organisation of work.

Two other technological domains do not include pure green ICT. The first is *Technologies for total factory control* (i.e. centrally controlling a plurality of machines – direct or distributed numerical control, flexible manufacturing systems, integrated manufacturing systems, computer integrated manufacturing) coupled with *Systems or methods specially adapted for a specific business sector*: in the green inventory this category corresponds to Commuting, High-occupancy vehicle (HOV) and teleworking. This technological domain is an example of a field that can enable a systemic impact in the economy, because it enables environmental changes in mobility and work organisation that impact many socio-economic activities. The second is a component concerning *Liquid crystal displays (LCDs)*.

Other important technological domains in the green ICT area are *Solid state devices using organic materials* and *Traffic control systems*. As far as the first one is concerned, the central technological class (pure green ICT) is H01L51/50, which identifies organic and

[7] Light Emitting Diodes are solid state devices that are based on compound semiconductors. Epitaxial growth is a procedure used in developing compound semiconductor production.

Table 1
Patents and IPC classes in selected green ICT domains.

Technological domain	Number of patents	Number of IPC classes	ICT classes	Green classes	Pure green ICT	Other classes
Semiconductors	2058	1248	33%	2.4%	4.7%	59.9%
Arrangements for testing electric properties and locating electric faults	2849	1085	34.8%	2.3%	4.7%	58.2%
Data processing systems or methods and transmission of digital information	669	406	48.1%	1.7%	0.2%	50%
Arrangements or instruments for measuring magnetic variables	705	370	7.3%	2.4%	4.6%	85.7%
Nuclear magnetic resonance technologies	658	160	12.5%	2.5%	10%	75%
Solid state devices using organic materials	470	489	9.6%	1%	0	89.3%
Traffic control systems	899	335	38.8%	1.2%	2.4%	57.6%
Hall effect devices	284	126	55.5%	0.8%	5.5%	38.2%
Liquid crystal displays	209	643	1.7%	0.2%	0	98.1%
Technologies for total factory control	75	77	23.4%	3.9%	0	72.7%
Excitation or detection systems	360	68	20.6%	0	13.2%	66.2%

polymer light emitting diodes (OLED and PLED), in which the active ingredient is organic. The second one concerns sustainable mobility systems, and includes technologies designed to assist drivers and to monitor various environmental parameters.

Within the green ICT area, a very large set of components refers to the broad technological domain of the *Measurement of electricity consumption*, whereby the central technological class – G01R – identifies the measurement of electric and magnetic variables. This technological domain includes the technologies used in smart grids to measure electricity consumption. In particular, four domains are worth mentioning: *Arrangements or instruments for measuring magnetic variables*, *Arrangements for testing electric properties and locating electric faults, Nuclear Magnetic Resonance Technologies*, and *Hall effect devices.*

5. The ability of ICT to spawn eco-innovation: descriptive evidence

Our empirical analysis intends to investigate the patterns of innovative activity in green ICT technological domains. To this end, we compute a set of indices in order to characterise each technological domain identified above in terms of degree of innovativeness (growth and geographical pervasiveness of innovative activity), variety of actors (pervasiveness of innovative activity across organisations and degree of entry of new innovators), and technological pervasiveness in terms of pervasiveness of innovative activity across technological classes as well as of variety of knowledge sources (internal vs. external; academic vs. non-academic).

Table 1 provides information on the number of patents and the distribution of ICT/green classes by (most innovative) domains. The evidence shows that the domains with the highest number of patents are *Arrangements for testing electric properties and locating electric faults*, *Semiconductors*, and *Traffic control systems*. The domains spreading across most technological classes are *Semiconductors, Arrangements for testing electric properties and locating electric faults, Liquid crystal displays*, and *Solid state devices using organic materials.* Besides the sheer number of IPC classes, it is important to understand the distribution of these classes across ICT and green technologies. *Technologies for total factory control, Nuclear magnetic resonance technologies, Semiconductors*, and *Arrangements or instruments for measuring magnetic variables* display the highest share of green IPC classes. ICT classes are particularly present in the following domains: *Hall effect devices, Data processing systems or methods and transmission of digital information*, and *Traffic control systems.* Finally, *Excitation or detection systems, Hall effect devices, Semiconductors*, and *Arrangements for testing electric properties and locating electric faults* show a relatively high percentage of pure green ICT classes. The results of the network analysis confirm that green ICT are applied in a wide range of technological domains such as semiconductors, traffic measurement, and telecommuting technologies which generate both indirect and enabling impacts.

5.1. Growth and geographical distribution of green ICT innovative activity

In order to assess the evolution of green ICT patents, we define P_{it} as the number of patents in the domain i in time t, and we calculate the growth rate GROWTH_i of the innovative activity from 1987 to 2006. The average growth rate is about 34% per year, with a peak of net growth of 275 patents in 2005. Fig. 5 shows the average annual growth rate of patents for the different technological domains. The three technological domains with the highest average annual growth rate are (in descending order) *Solid state devices using organic materials, Arrangements or instruments for measuring magnetic variables*, and *Manufacture or treatment of semiconductor devices.*

Given the potential worldwide impact of green ICT, it is also relevant to look at the geographical distribution of its innovative activity. To this end, we look at the most active countries in terms of patenting in different domains, at the (potentially) emerging countries, and at the concentration of innovative activity across countries.

Tables 2 and 3, respectively, show the top three most innovative countries by main technological domain and the emerging countries. The evidence of innovative activities by country not surprisingly shows that US, Japan and Germany are the most innovative countries in the green ICT technological domains, especially in *Semiconductors, Arrangements for testing electric properties and locating electric faults*, *Solid state devices using organic materials* and *Traffic control systems*. It should be noted that Switzerland is similarly largely active in the domains of *Nuclear magnetic resonance technologies* and *Excitation or detection systems*, e.g. *using radiofrequency signals*. As for the emergence of new innovative countries, the evidence shows that the latest emerging countries in the most important technological domains are Ireland and India, which started patenting in the green ICT field in 2001 and 2003, respectively.

As far as the geographical concentration is concerned, let C_i be the total number of countries, P_i the total number of patents applied for in the technological domain *i*, and P_{ic} the total number of patents in technological domain *i* applied for by country *c* ($P_i = \sum_o P_{ic}\ o = 1, \ldots, C_i$). Therefore, $s_{ic} = P_{ic}/P_i$ is the country *c*'s share of patents in the technological domain *i*. In order to investigate the concentration of innovative activity at the level of countries, we build the Herfindahl index: $H_{\text{COUNTRY}i} = \sum_o s_{ic}^2$. Here we use the corrected version that controls for the small sample bias (Hall, 2000).[8] The overall level of concentration of innovative activity by country is fairly low (0.20), which indicates that there is a certain degree of geographical pervasiveness of innovative activity in the green ICT domains. The technological domains with the highest

[8] $\text{Corr}H_{\text{COUNTRY}i} = (P_i H_{\text{COUNTRY}i} - 1)/(P_i - 1)$.

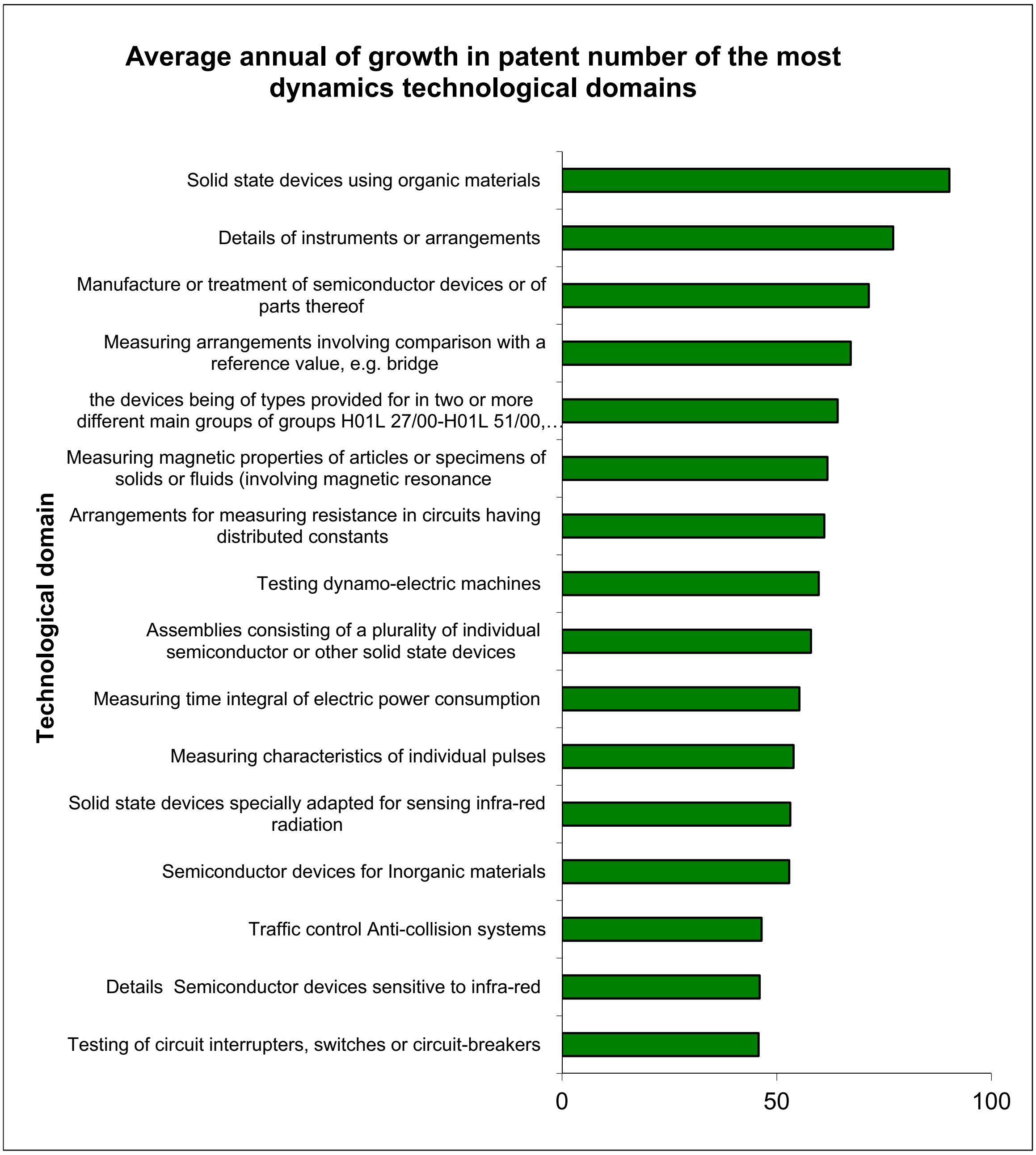

Fig. 5. Average annual growth in most dynamic domains.

concentration of innovative activity at the level of countries are *Excitation or detection system*, *Energy conversation design*, *Instruments for arrangement of terminals*. Examples of firms patenting in these domains are Tektronix, NTT and Hewlett-Packard. On the other hand, the technological domains recording the lowest levels of concentration of innovative activity by country are *Traffic control systems for road vehicles – Identifying vehicles*, *Indicating the presence of current or voltage* and *Locating faults in cables, transmission or networks*. Examples of firms belonging to these domains are, respectively, Denso, Electrowatt Technology innovation and ABB.

5.2. Variety of actors in green ICT innovative activity

In order to investigate the characteristics and the variety of innovators, we look at the types of organisations patenting in the domains, at the concentration of innovative activity across organisations, and at the entry of new patenting organisations. Our sample contains 3153 organisations, which include 763 individuals and 330 research institutes and universities. Tables 4 and 5, respectively, show the top 20 most innovative organisations, and the three most innovative organisations for each of the largest domains. These largest innovators are mostly ICT firms.[9] This seems to suggest that ICT companies tend to diversify their innovation activity in the green area rather than green companies acquiring ICT competencies.

[9] The largest number of patents are granted to the Siemens building technology divisions, which shows the widespread use of Green ICT in the building sector. An exception is Buderus Heiztechnik, which has been recently acquired by Bosch and which is active in the heating systems business.

Table 2
Top 3 innovative countries by most important domain.

Technological domain	Number of patents	Country
Semiconductors	716	US
	704	JAPAN
	177	GERMANY
Arrangements for testing electric properties and locating electric faults	1151	US
	472	JAPAN
	329	GERMANY
Data processing systems or methods and transmission of digital information	329	US
	220	JAPAN
	130	FRANCE
Arrangements or instruments for measuring magnetic variables	345	US
	89	UNITED KINGDOM
	66	JAPAN
Nuclear magnetic resonance technologies	329	US
	81	UNITED KINGDOM
	62	SWITZERLAND
Solid state devices using organic materials	170	US
	109	JAPAN
	74	GERMANY
Traffic control systems	295	JAPAN
	252	GERMANY
	115	US
Hall effect devices	92	US
	50	JAPAN
	44	GERMANY
Liquid crystal displays	89	GERMANY
	36	HUNGARY
	24	UNITED KINGDOM
Technologies for total factory control	25	JAPAN
	17	GERMANY
	13	US
Excitation or detection systems, e.g. using radiofrequency signals	173	US
	53	UNITED KINGDOM
	48	SWITZERLAND

The breakdown statistics of innovative activities by organisation show that IBM and SIEMENS AS are the most important innovators, and they are particularly active in the domains of *Arrangements for testing electric properties and locating electric faults* and in the *Technologies for total factory control.* In addition, telecom operators (e.g. AT&T and France Telecom) are ranked among the top innovators in green ICT domains and innovate in particular in the *Semiconductors* and in the *Data processing systems or methods and transmission of digital information* technological domains. Also of interest is the observation that some telecom operators also appear among the latest innovators (i.e. among firms that have patented for the first time in a specific technological domain in 2006): SK Telekom (*Traffic control systems*) and Deutsche Telekom (*Arrangements for testing electric properties and locating electric faults*). Among the research centres, new innovators include Katholieke Universiteit Leuven (*Arrangements for testing electric properties and locating electric faults*) and the University of Surrey (*Semiconductor devices for Inorganic materials*).

Table 3
Emerging countries by main domain.

Technological domain	Latest innovator	Year of first patent
Semiconductors	CHINA	1998
Arrangements for testing electric properties and locating electric faults	IRELAND	2001
Data processing systems or methods and transmission of digital information	IRELAND	2001
Arrangements or instruments for measuring magnetic variables	UNITED KINGDOM	1995
Nuclear magnetic resonance technologies	UNITED KINGDOM	1995
Solid state devices using organic materials	SINGAPORE	1991
Traffic control systems	IRELAND	2001
Liquid crystal displays	POLAND	1990
Technologies for total factory control	FINLAND	1988
Excitation or detection systems, e.g. using radiofrequency signals	INDIA	2003

Table 4
Top 40 most innovative companies.

Firm	Number of patents
SIEMENS[a]	681
KONINKLIJKE PHILIPS ELECTRONICS	483
IBM	336
ROBERT BOSCH	270
TOSHIBA	262
HEWLETT-PACKARD	215
GENERAL ELECTRIC	210
CANON	181
HITACHI	177
MATSUSHITA ELECTRIC INDUSTRIAL	177
NEC	170
FUJITSU	167
SHARP	156
AT & T	154
TEKTRONIX	135
MITSUBISHI DENKI	128
PHILIPS CORPORATE INTELLECTUAL PROPERTY	114
SONY	99
TEXAS INSTRUMENTS	96
STMICROELECTRONICS	94
PICKER INTERNATIONAL	87
EASTMAN KODAK	85
THALES	85
INFINEON TECHNOLOGIES	83
AGILENT TECHNOLOGIES	80
MOTOROLA	77
SUMITOMO ELECTRIC INDUSTRIES	75
STMICROELECTRONICS	69
SHIN-ETSU HANDOTAI	66
MERCK PATENT	65
HUGHES AIRCRAFT	62
TOYOTA JIDOSHA	62
COMMISSARIAT A L'ENERGIE ATOMIQUE (CEA)	61
MINNESOTA MINING AND MANUFACTURING	61
DAIMLERCHRYSLER	59
TERADYNE	59
ASEA BROWN BOVERI	57
HONEYWELL	57
FRANCE TELECOM	56
PIONEER ELECTRONIC	52

[a] Siemens Building Technology has acquired ELECTROWATT TECHNOLOGY INNOVATION in 1999 but this firm continues to patent using Electrowatt Technology Innovation name until 2009.

To measure the concentration of innovative activity, let O_i be the total number of organisations, P_i the total number of patents applied for in the technological domain i and P_{io} the total number of patents in domain i applied for by organisation o ($P_i = \sum_o P_{io}$ $o = 1, \ldots, O_i$). Therefore $s_{io} = P_{io}/P_i$ is the organisation's share of patents in the technological domain i. In order to investigate the concentration of innovative activity at the level of organisations, we build the Herfindahl index: $H_{\mathrm{ORG}i} = \sum_o s_{io}^2$. Here we use the corrected version (Hall, 2000) that controls for the small sample bias.[10] On average, the innovative activity in green ICT domains is extremely pervasive across actors. The technological domains that show the highest (and still limited) level of concentration of innovative activity are *Liquid crystal display*, *Excitation or detection system*, and *Traffic*

[10] The corrected version is: $\mathrm{Corr}H_{\mathrm{ORG}i} = (P_i H_{\mathrm{ORG}i} - 1)/(P_i - 1)$.

Table 5
Top 3 innovators by most important domain.

Technological domain	Number of organisations	Top 3 firm	Number of patents
Semiconductors	555	CANON	120
		SHARP	101
		KONINKLIJKE PHILIPS ELECTRONICS	70
Arrangements for testing electric properties and locating electric faults	814	IBM	156
		SIEMENS	172
		HEWLETT-PACKARD	107
Data processing systems or methods and transmission of digital information	326	IBM	26
		FUJITSU	28
		FRANCE TELECOM	22
Arrangements or instruments for measuring magnetic variables	197	GENERAL ELETRONIC	106
		KONINKLIJKE PHILIPS ELECTRONICS	56
		PICKER	37
Nuclear magnetic resonance technologies	168	GENERAL ELETRONIC	69
		PICKER	49
		KONINKLIJKE PHILIPS ELECTRONICS	103
Solid state devices using organic materials	146	EASTMAN KODAK	52
		CAMBRIDGE DISPLAY TECHNOLOGY	35
		SEIKO EPSON	26
Traffic Control Systems	268	BOSCH	109
		SIEMENS	47
		AISIN AW	51
Hall effect devices	105	IBM	34
		BOSCH	14
		KONINKLIJKE PHILIPS ELECTRONICS	12
Liquid crystal displays	39	MERCK PATENT	63
		CHISSO	36
		F. HOFFMANN-LA ROCHE	14
Technologies for total factory control	59	IBM	5
		SIEMENS BUILDING TECHNOLOGY AS	4
		TOYOTA JDOSHA	4
Excitation or detection systems, e.g. using radiofrequency signals	102	PICKER	29
		KONINKLIJKE PHILIPS ELECTRONICS	64
		GENERAL ELETRIC	28

control systems for road vehicles: Controlling traffic signals, while the domains with the lowest concentration indexes are *Data processing systems or methods and transmission of digital information, Apparatus for testing electrical condition of accumulators or electric batteries*, e.g. *capacity or charge condition.*

For the entry of new firms, which measures the new patenting organisations and thus the relevance of the technological domain as an emerging field of research, we compute the share of firms patenting for the first time in domain i ($\text{New}O_i$) over the total number of patenting firms:

$$\text{ENTRY}_i = \frac{\text{New}O_i}{O_i}$$

Overall, the evidence shows that the degree of entry of new innovators is quite low. However, some domains stand out as recording relatively high rates of entry such as *Measurement of electricity consumption* (the most recent new innovators are ELECTROLUX ZANUSSI and TRANSGRID), *Semiconductors* (the most recent new innovators are UNIVERSITY OF SOUTHERN CALIFORNIA and Northern Telecom), *Data processing systems or methods and transmission of digital information* (the most recent new innovators are: CREDIT LYONNAIS and Yahoo). The technological domains with a low rate of new entry are *Energy conservation devices* (examples of the most recent new innovators are Siemens and Sharp), *Arrangements or instruments for measuring magnetic variables superconductive devices* (examples of recent new innovators are IBM, Siemens, Hitachi), and *Controlling traffic signals* (here Siemens is the most recent new innovator).

5.3. Technological pervasiveness and sources of knowledge

Since green ICT lie at the intersection of two broad technological domains, one of the most relevant variables for our analysis is the technological pervasiveness of green ICT domains, i.e. the extent to which the domains spread across different technological classes. This is an indication of the diversification of the knowledge output of green ICT domains and also provides information on the potential fields of applications. To investigate this, we analyse the distribution of each technological domain across technological classes. Let K_i and P_i be the total number of technological classes and the total number of patents for each domain. In particular, P_{ik} is the total number of patents in technological domain i belonging to the technological class k. Therefore $s_{ik} = P_{ik}/P_i$ is the share of patents in the technological domain i falling into class k. We can compute the Herfindahl index measuring the concentration of patents across specific technological classes for each domain i. $H_{\text{TECH}i} = \sum_k s_{ik}^2$ is the Herfindahl index which illustrates the concentration of patents across specific IPC classes for each technological domain i. A low level of concentration indicates a high degree of technological pervasiveness of each technological domain i. Here we use the corrected version that controls for the small sample bias (Hall, 2000).[11] Overall, the degree of technological pervasiveness is high, highlighting the capability of ICT to spawn green innovation in a very pervasive set of technological fields. In particular, the descriptive evidence shows that the domains with a larger share of pervasiveness are *Solid state devices using organic materials as the active part specially adapted for sensing infrared radiation*, *light*, *Liquid crystal display, Arrangements for measuring time integral of electric power.* These technologies are essential to measuring electric power and are thus closely connected to energy-saving devices; while the domains which perform at a low level of pervasiveness are *Measurement of electricity consumption*, *Semiconductors*, *Traffic control device*.

[11] $\text{Corr}H_{\text{TECH}i} = (P_i H_{\text{TECH}i} - 1)/(P_i - 1)$.

Table 6
Descriptive statistics.

Variable	Obs.	Mean	Std. Dev.	Min	Max
Number of patents	65	269.6615	462.0234	57	2999
Number of technological classes	65	818.4	1850.121	110	11,687
Share of ICT classes	65	0.5082421	0.0411233	0.4182306	0.7400442
Share of green classes	65	0.4917579	0.0411233	0.2599558	0.5817695
GROWTH$_i$	65	0.3475701	0.1669447	0.0971514	0.8044047
ENTRY$_i$	65	0.0344032	0.037749	0.0101458	0.258085
$H_{\mathrm{ORG}i}$	65	0.0279814	0.029906	0.0048756	0.2110953
$H_{\mathrm{COUNTRY}i}$	65	0.2016453	0.0537544	0.1264003	0.4248914
$H_{\mathrm{CITTECH}i}$	65	0.0192141	0.0151048	0.0041719	0.0966121
ACADEMIC_KNOW$_i$	65	0.0337818	0.0314276	0	0.1595745
SELF_CITATION$_i$	65	0.2015612	0.0705702	0.0627306	0.4
$H_{\mathrm{TECH}i}$	65	0.0396431	0.0277021	0.0014406	0.1556497

We also look at the sources of knowledge of green ICT domains and investigate the variety of sources of knowledge across technological classes and innovative actors. This index gives important insights into the dynamics (and pervasiveness) of knowledge within each technological domain. The relative variety of knowledge sources across technological classes is calculated by using Herfindahl indexes (see also Trajtenberg et al., 1997; Hall, 2000 for originality indexes). Let c_{ik} be the total number of cited patents by technological domain i belonging to the IPC class j ($c_i = \sum_k c_{ik}$; $k = 1, \ldots, K_i$; K_i is the number of cited IPC classes, at the 7-digit level). Accordingly, $b_{ik} = c_{ik}/c_i$ is the share of backward citations by technological domain i belonging to class k. We define the corrected Herfindahl index as: $H_{\mathrm{CITTECH}} = (c_i \sum_k b_{ik}^2 - 1)/(c_i - 1)$. The green ICT technological domains show a very high dispersion of sources of knowledge (very low Herfindahl index), although with some variance. The technological domains that present the highest pervasiveness of sources of knowledge are *Control traffic signals*, *Energy conservation devices*, and *Arrangements or instruments for measuring magnetic variables superconductive devices*. The technological domains with a low degree of pervasiveness of sources of knowledge are *Arrangements for measuring currents or voltages or for indicating presence or sign thereof*, *Measuring arrangements involving comparison with a reference value*, e.g. *bridge, Semiconductors*.

With regard to the variety of sources of knowledge in terms of actors, we first compute for each domain the share of self-citations at the level of the individual organisation, i.e. the number of self-citations over the total number of backward citations: SELF_CITATION$_i$ = SELFCIT$_i$/c_i. Self-citations are an important indicator in the context of the present analysis. They are citations coming from patents assigned to the same organisation as the one holding the cited patent. As carefully explained by Jaffe et al. (1993) and Jaffe and Trajtenberg (2002), self-citations are different from other citations, particularly because they provide different signals on the value to the organisation of the related innovations. As pointed out by Hall et al. (2005), on the one hand, self-citations may signal the cumulativeness of innovation and the "increasing returns" of knowledge accumulation, thus reflecting the organisation's competitive advantage within a specific technological area. On the other hand, a high share of self-citations might also signal a "self-bias", making their knowledge content weak in terms of market value. Patents in the green ICT domains record a very low share of self-citations. In particular, the technological domains with the highest share of self-citations are *Measuring nuclear magnetic resonance*, *Measurement of electricity devices*, *Excitation or detection systems*, e.g. *using radiofrequency signals*, while the technological domains which do not rely much on internal knowledge sources are *Solid state devices using organic materials as the active part specially adapted for sensing infrared radiation*, *Measuring arrangements involving comparisons with a reference value*, e.g. *bridge, Liquid crystal displays*.

Second, given the science-based nature of the knowledge involved in the green ICT domains, we look at the role of "academic" knowledge (i.e. knowledge coming from universities and public research centres). To this end, we compute the share of citations belonging to these organisations for each domain, i.e. the number of citations of universities and public research centres divided by the total number of citations: ACADEMIC_KNOW$_i$ = ACADEMIC_CIT$_i$/c_i. Universities do not play a very important role as sources of knowledge in green ICT domains; the average share is 0.003. The technological domains that rely the most on academic knowledge are *Semiconductor devices used for Inorganic materials*,[12] *Component parts of indicators for measuring arrangements not specially adapted for a specific variable*, *Measuring characteristics of individual pulses*, e.g. *deviation from pulse flatness, rise time, duration*. The technological domains that are based less on academic knowledge are *Arrangements for measuring currents or voltages indicating that current or voltage is either above or below a predetermined value or within or outside a predetermined range of values*, *Assemblies consisting of a plurality of individual semiconductors or other solid state devices*, *Measuring arrangements involving comparisons with a reference value*, e.g. *bridge*.

Table 6 illustrates the descriptive statistics for all the variables.

6. Clusters of green ICT domains

Despite the evidence discussed above that, on average, green ICT domains are characterised by a growing potential for innovation, technological pervasiveness and a great variety of actors, there may be important differences across domains in terms of patterns of innovation. Therefore, the aim of this section is to present the results of a cluster analysis of green ICT technological domains based upon the following dimensions (see Corrocher et al., 2007; Youtie et al., 2008): growth of patents and geographical distribution of innovative activity by country, variety of actors (entry of new innovators and concentration of innovative activity by organisation), technological pervasiveness, and knowledge sources. We carry out a cluster analysis in order to identify the characteristics of the innovative process within this complex technological area. In particular, we perform a k-mean cluster on the variables described above, which results in three clusters of technological domains. Table 7 illustrates the mean values of the variables under investigation for the three clusters.

Cluster 1 – EMERGING DOMAINS – includes technological fields with a very high rate of growth of innovative activity and which have a high share of ICT classes as opposed to green ones. These

[12] Semiconductor device sensitive to infrared radiation, light, electromagnetic radiation of shorter wavelength, or corpuscular radiation and adapted either for the conversion of the energy of such radiation into electrical energy or for the control of electrical energy by such radiation.

Table 7
Patterns of innovation in green ICT.

Variable	Cluster 1 (14 domains) EMERGING	Cluster 2 (12 domains) ESTABLISHED	Cluster 3 (39 domains) MATURE
Average number of patents	122.21	234.588	333.385
Average number of tech classes	291.86	538.42	1093.564
Share of ICT classes	0.517	0.497	0.508
Share of green classes	0.483	0.503	0.492
GROWTH_i	0.611	0.387	0.241
ENTRY_i	0.020	0.034	0.039
$H_{\mathrm{ORG}i}$	0.022	0.020	0.033
$H_{\mathrm{COUNTRY}i}$	0.194	0.196	0.206
$H_{\mathrm{TECH}i}$	0.062	0.033	0.034
$\mathrm{SELF\_CITATION}_i$	0.210	0.131	0.220
$\mathrm{ACADEMIC\_KNOW}_i$	0.042	0.036	0.030
$H_{\mathrm{CITTECH}i}$	0.013	0.019	0.034

domains are characterised by a low concentration of innovative activity across firms and by a low rate of entry of totally new innovators. Concentration across technological classes is high, but these domains rely upon a variety of knowledge sources in terms of technologies. Furthermore, knowledge coming from universities and public research centres constitutes one of the most important sources of innovation for these domains, showing that the innovative activities rely on science-based knowledge. Examples of technological domains belonging to this cluster are *Solid state devices using organic materials* and *Technologies for electricity and magnetic measurement*. The most innovative companies in this cluster are Cambridge Display Technology, Eastman Kodak and Siemens Building Technology AS.

Clearly, these technological domains represent a very important group in terms of innovative activities in green ICT. Innovation is concentrated in a few technological classes, most of which belong to the ICT domain, and it is dispersed over many actors. In addition, although this is the domain in which the highest growth occurs, the extent of innovative activity attributable to new entrants is small. This could suggest that innovative activity has been carried out through the acquisition of new competences outside the core domain by established firms. Both of these features underline the high level of opportunity associated with this area.

Cluster 2 – ESTABLISHED DOMAINS – identifies technological domains which are characterised by a medium rate of growth. Moreover, they record a relatively higher share of green technological classes and a lower share of ICT classes. Innovative patterns in this area are defined by a low concentration across countries and by a low share of knowledge coming from universities and public research centres. Examples of technological domains belonging to this cluster are *Hall effect devices, Traffic control systems*, *Storage of electrical energy*. The most innovative companies in this cluster are Tektronix, Hamamatsu Photonics and Siemens Building Technology AS.

Innovation activity in these technological areas is still fairly dispersed across actors, countries and technological classes, and more oriented towards the green areas. Furthermore, knowledge coming from private actors seems to play an important role for the definition of the innovation path, but there is a very low degree of self-citations that might signal a low degree of knowledge cumulativeness as well as a lack of specific firms' competitive advantage. Alternatively, it can suggest that these firms are implementing radical changes in their technological activities.

Cluster 3 – MATURE DOMAINS – is defined by a relatively lower rate of growth of innovative activity, and by the coexistence of a high number of new innovators (entry is high) with a high level of concentration of innovative activities across countries and organisations. As expected for mature green ICT domains, there is no prevalence of green or ICT classes, and the concentration across technological classes appears to be quite low. These domains are characterised by a low variety of knowledge sources across technological classes. Examples of technological domains belonging to this cluster are *Semiconductors, Data processing systems or methods and transmission of digital information, Arrangements or instruments for measuring magnetic variables, Nuclear Magnetic Resonance technologies*. The most innovative companies in this cluster are Siemens Building Technology AS, Minnesota Mining and Manufacturing and ABB.

This cluster includes technological areas in which the innovative activity has been well established for a long time and is concentrated in a few actors and countries. However, given the combination of different types of knowledge characterising these domains, technological pervasiveness is high – although knowledge tends to be concentrated in terms of sources – and there are continuous opportunities for the entry of new actors.

7. Conclusions

This article has studied the patterns of innovative activity in green ICT, a growing area of eco-innovations that includes both ICT that have improved their own environmental performance and ICT used to improve the environmental performance of other sectors. In particular, it has intended to examine the extent to which ICT are able to spawn eco-innovations.

We have provided an original methodology to detect the technological domains in this area, and have then clustered these domains on the basis of a series of variables identifying the structure of innovative activity in terms of actors and countries involved, characteristics of the knowledge base and potential technological applications.

The analysis has highlighted the existence of 65 technological domains, corresponding to different combinations of green and ICT classes. Through this methodology, we have improved our understanding of innovation dynamics in green technologies and have shed light on the fact that the current set of technological classes in the green inventory neglects some important green ICT domains that stem from the combination of existing green and ICT classes. Despite their central role in environment-friendly growth, green ICT have surprisingly not received the attention they deserve within the area of innovation studies, or in the official classifications of technological activities.

As expected, the innovative activity located at the intersection between ICT and green technologies is characterised overall by very high degrees of technological pervasiveness and a variety of knowledge sources, as well as by a high variety of actors, with a prevalence of large firms related to the ICT sector. This is in line with other studies that have investigated the potential of GPT to spawn innovations and the extent to which these technologies are pervasive. However, the results of the cluster analysis performed on the domains show that there are significant differences across green ICT domains in terms of patterns of innovative activity. These clusters differ substantially in the structure of innovative activity, particularly with reference to the concentration of innovation across organisations and countries, entry of innovators and sources of knowledge. Particularly interesting within the scope of the article is the identification of *emerging* domains in green ICT. These domains are characterised by the prevalence of ICT-related technological classes and companies, and by the variety of sources of knowledge, with an important role for universities and public research centres. The innovative activity in this domain is carried out by established firms through the acquisition of new competences outside their core area of technological expertise. These domains represent areas with a high level of opportunity for future development. The identification of the three clusters is also relevant for a discussion of the relation between "innovation overall" and "eco-innovation", not necessarily confined to the case of green ICT. Furthermore, since patents are only a (limited) part of a wider discussion on eco-innovation, they represent only a small component at the level of systemic innovation or innovation clusters. Future research should therefore expand the understanding of the innovation dynamics of eco-innovations by considering the co-evolution of green technologies and other established technologies at the level of systems of innovation.

The findings of the paper have important implications both in relation to the literature on GPT and eco-innovations, and in relation to policy. We have shown how ICT have over time been able to spawn eco-innovations in a large set of technological areas, and have demonstrated that the GPT character of ICT is clearly reflected in the innovative patterns in green ICT domains. Indeed, both technological pervasiveness – in terms of innovation and sources of knowledge – and variety of actors – in terms of innovators – are distinctive features of innovation in these fields. However, there are important differences across domains. In particular, the cluster analysis highlighted that, while technological pervasiveness is particularly high in mature domains, emerging domains are characterised by a higher variety of actors as opposed to other domains. In particular, ICT firms stand out as important innovators in green ICT fields, suggesting that innovation is led to a great extent by leading ICT companies diversifying into green areas, while universities and research centres do not play as important a role.

Based on the findings of this research, a number of policy recommendations can be formulated. First, we have shown that innovations in green ICT are based on a broad set of knowledge sources, and rely on a wide range of technological domains. In particular, our analysis has enabled us to identify key technological domains and actors that could be the focus of policy support. The environmental improvements associated with the use of ICT can be considered an important policy instrument to reduce the footprint of related sectors, and our findings show that ICT play an important role in generating behavioural and organisational changes which are normally difficult to implement. The key technological domains that could receive policy support concern the sectors of lighting (e.g. LEDs), sustainable mobility (e.g. traffic control systems), and environmental monitoring (e.g. electrical testing). Indeed, these domains are related to technologies that can substantially contribute to reducing ecological impacts and have a high economic potential in terms of market outlets. For example, the future of lighting and displaying lies in LED and OLED technologies, which will permit substantial energy savings. They pertain to the domain with the most dynamic innovative activity, i.e. *Solid state devices using organic materials*. As for sustainable mobility technologies, they contribute to reducing the environmental impacts of transport, a major emitter of greenhouse gases. They are thus important drivers of the sustainable transition of "smart cities", notably in the EU where 75% of the population lives in urban communities. Finally, concerning environmental monitoring technologies, many of them aim at improving energy efficiency (e.g. smart metres and smart grids). Policies supporting those technologies would also benefit other types of innovations, since, as discussed above, energy efficiency technologies tend to enable a faster diffusion of innovation. These policies could also support the use of green ICT for environmental monitoring, in order to raise awareness about the ecological impacts of our societies, for example by supporting the use of smart metres that display in real time the evolution of households' electricity consumption both in terms of kWh and in monetary terms.

Concerning green ICT players, we have highlighted that the main ones are ICT firms investing in greener technologies, such as companies from the telecom industry, rather than firms from green sectors investing in green ICT. Specific policy support could target the ICT sector, enabling it to further address environmental issues, for example by supporting ecodesign and the systematic and transparent use of life cycle assessments. In this context, a specific policy push could be given to the emerging domains. Since this cluster of technological activities very much relies on academic knowledge, the collaboration between public and private research could be prioritised to stimulate eco-innovation in areas where new entrants do not seem to innovate much.

In term of environmental policy, the results suggest that dematerialisation of the certain activities allows a reduction of their footprints and encourages structural and behaviour transformation.

Finally, the great knowledge variety involved in the development of green ICT innovations, notably evidenced by a low concentration of innovative activity across technological classes and actors, calls for policies supporting interdisciplinary research and technological niches, in order to harness the discoveries of a variety of knowledge fields necessary to develop green ICT that can have systemic impacts. In this context, particular attention could be placed on technological classes that act as "brokers" by connecting otherwise disconnected domains and that therefore might be responsible for the development of radical innovations.

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References

Bär, H., Jacob, K., Werland, S., 2011. Green Economy Discourses in the Run-up to Rio 2012. FFU-Report 07-2011. Environmental Policy Research Center, Freie Universität Berlin.
Beise, M., Rennings, K., 2005. Lead markets and regulation: a framework for analyzing the international diffusion of environmental innovations. Ecological Economics 52 (1), 5–17.
Benhaim, F., Clarke, R., 2009. The Green Growth Race. OECD Observer 273.
Berkhout, F., Hertin, J., 2001. Impacts of Information and Communication Technologies on Environmental Sustainability: Speculations and evidence. Report to the OECD. University of Sussex, Brighton, pp. 21.
Berkhout, F., Hertin, J., 2004. De-materialising and re-materialising: digital technologies and the environment. Futures 36 (8), 903–920.
Bresnahan, T.F., Trajtenberg, M., 1995. General purpose technologies 'engines of growth'? Journal of Econometrics 65 (1), 83–108.
Bresnahan, T.F., Greenstein, S., 2001. The economic contribution of information technology: towards comparative and user studies. Journal of Evolutionary Economics 11 (1), 95–118.
Carlsson, B., 2004. The digital economy: what is new and what is not? Structural Change and Economic Dynamics 15 (3), 245–264.
Cassi, L., Zirulia, L., 2008. The opportunity cost of social relations: on the effectiveness of small worlds. Journal of Evolutionary Economics 18 (1), 77–101.
Cassi, L., Corrocher, N., Malerba, F., Vonortas, N., 2008. The impact of EU-funded research networks on knowledge diffusion at the regional level. Research Evaluation 17 (4), 283–293.
Consoli, D., 2005. The dynamics of technological change in UK retail banking services: an evolutionary perspective. Research Policy 34 (4), 461–480.
Corrocher, N., Malerba, F., Montobbio, F., 2007. Schumpeterian patterns of innovative activity in the ICT field. Research Policy 36, 418–432.
David, P.A., Greenstein, S., 1990. The economics of compatibility standards: an introduction to recent research. Economics of Innovation and New Technology 1, 3–41.
De Marchi, V., 2012. Environmental innovation and R&D cooperation: empirical evidence from Spanish manufacturing firms. Research Policy 41 (3), 614–623.
Faucheux, S., Nicolaï, I., 2011. IT for green and green IT: a proposed typology of eco-innovation. Ecological Economics 70, 2020–2027.
Fransman, M., 2001. Analysing the evolution of industry: the relevance of the telecommunication industry. Economics of Innovation and New Technologies 10 (2–3), 109–140.

GeSI, 2008. Smart 2020: Enabling the Low Carbon Economy in the Information Age, Available from: http://www.gesi.org/ReportsPublications/Smart2020/tabid/192/Default.aspx
Hall, B.H., 2000. A Note on the Bias in the Herfindahl Based on Count Data. Mimeo. UC Berkeley and Nuffield College, Oxford, Available from: http://emlab.berkeley.edu/users/bhhall/hhibias.pdf
Hall, B.H., Jaffe, A.B., Trajtenberg, M., 2005. Market value and patent citations. RAND Journal of Economics 36, 16–38.
Helpman, E., Trajtenberg, M., 1994. A Time to Sow and a Time to Reap: Growth Based on General Purpose Technologies. NBER Working Papers 4854. National Bureau of Economic Research Inc.
Helpman, E., 1997. General Purpose Technologies and Economic Growth. MIT Press, Cambridge, MA.
Hilty, L.M., 2002. Sustainable development and information technology. Environmental Impact Assessment Review 22 (5), 445–447.
Hilty, L.M., Arnfalk, P., Erdmann, L., Goodman, J., Lehmann, M., Wäger, P., 2006. The relevance of information and communication technologies for environmental sustainability – a prospective simulation study. Environmental Modelling & Software 21 (11), 1618–1629.
Hilty, L., 2008. Information Technology and Sustainability: Essays on the Relationships Between Information Technology and Sustainable Development. Books on Demand, Norderstedt.
Jaffe, A., Trajtenberg, M., Henderson, R., 1993. Geographic localization of knowledge spillovers as evidenced by patent citations. Quarterly Journal of Economics 108, 577–598.
Jaffe, A., Trajtenberg, M., 2002. Patents, Citations and Innovations: A Window on the Knowledge Economy. MIT Press, Cambridge.
Jänicke, M., Jacob, K., 2009. A Third Industrial Revolution? Solutions to the Crisis of Resource-intensive Growth. FFU Report 2/2009, Available from: http://www.polsoz.fu-berlin.de/polwiss/forschung/systeme/ffu/09_publikationen/2009/jaenicke_martin_jacob_klaus_2009/index.html
Jovanovich, B., Rousseau, P.L., 2005. General purpose technologies. In: Aghion, P., Durlauf, S.N. (Eds.), Handbook of Economic Growth. Elsevier, Amsterdam, The Netherlands.
Kemp, R., Oltra, V., 2011. Research insights and challenges on eco-innovation dynamics. Industry and Innovation 18 (3), 249–253.
Kemp, R., Pearson, P., 2008. Final Report MEI Project About Measuring Eco-innovation: Deliverable 15 of MEI Project (D15). Project Report. http://www.merit.unu.edu/MEI/
Laestadius, S., 1998. The relevance of science and technology indicators: the case of pulp and paper. Research Policy 27 (4), 385–395.
Mansell, R., 2012. ICT innovation and sustainable development. In: Souter, D., MacLean, D. (Eds.), Changing our Understanding of Sustainability: The Impact of ICTs and the Internet. International Institute for Sustainable Development.
Oltra, V., Saint Jean, M., 2009. Sectoral systems of environmental innovation: an application to the French automotive industry. Technological Forecasting & Social Change 76, 567–583.
Oltra, V., Kemp, R., De Vrief, F.P., 2010. Patents as a measure of eco-innovation. International Journal of Environmental Technology and Management 13, 130–148.
OECD, 2010. Greener and Smarter – ICT, the Environment and Climate Change. OECD, Paris.
OECD, 2011. SMEs and Entrepreneurship: Green Growth, Innovation and Employment Centre for Entrepreneurship, SMEs and Local Development. OECD, Paris.
Rennings, K., 2000. Redefining innovation – eco-innovation research and the contribution from ecological economics. Ecological Economics 32, 319–332.
Rogers, J.D., Bozeman, B., Chompalov, I., 2001. Obstacles and opportunities in the application of network analysis to the evaluation of R&D. Research Evaluation 10 (3), 161–172.
Ropke, I., 2012. The unsustainable directionality of innovation – the example of the broadband transition. Research Policy 41 (9), 1631–1642.
Rosenberg, N., 2000. Schumpeter and the Endogeneity of Technology: Some American Perspectives. The Graz Schumpeter Lectures, Routledge, London.
Rosenberg, N., 1994. Exploring the Black Box. Cambridge University Press, Cambridge, UK.
Tongia, R., Subrahmanian, E., 2005. Information and Communications Technology for Sustainable Development: Defining a Global Research Agenda. Allied Publishers, Bangalore.
Trajtenberg, M., Jaffe, A.B., Henderson, R., 1997. University versus corporate patents: a window on the basicness of invention. Economics of Innovation and New Technology 5, 19–50.
UNEP, 2008. Green Jobs Towards Decent Work in a Sustainable, Low-Carbon World, Available from: http://www.unep.org/labour_environment/features/greenjobs.asp
Youtie, J., Iacopetta, M., Stuart, G., 2008. Assessing the nature of nanotechnology: can we uncover an emerging general purpose technology? Journal of Technology Transfer 33, 315–329.