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tel +34 963 877 048 | fax +34 963 877 991 | innco@ingenio.upv.es

Does External Knowledge Affect Environmental Innovations? An Empirical Investigation Of Eleven European Countries.

Claudia Ghisetti[a,1]; Alberto Marzucchi[b,c,2]; Sandro Montresor [d,a,3]

[a] Department of Economics, University of Bologna (Italy)
[b] Department of International Economics, Institutions and Development, Catholic University of Milan (Italy)
[c] INGENIO (CSIC-UPV), Valencia (Spain)
[d] JRC-IPTS European Commission, Seville (Spain)

Abstract: This paper investigates the effects that knowledge sources external to the firm have on its environmental innovations (EIs). Using the CIS 2006-2008, we refer to both the probability to introduce an EI and the number of EI-typologies adopted by firms. We estimate the impact of the "depth" and "breadth" of knowledge sourcing. In addition, we test for the moderating role of the firm's absorptive capacity. In general, knowledge sourcing has a positive impact on both types of EI-performance. However, a broad sourcing strategy reveals a threshold, over which the propensity to introduce an EI diminishes. Cognitive constraints in processing knowledge inputs that are too diverse could explain this result. Absorptive capacity generally helps firms in turning broadly sourced external knowledge into EI. Conversely, internal innovation capabilities and knowledge socialization mechanisms seem to diminish the EI impact of knowledge sourced through intense external interactions. The possibility of mismatches between internal and external knowledge and problems in distributing the decision-makers' attention between the two could explain this result.

Keywords: Environmental Innovation, Open Innovation, Absorptive Capacity.
JEL Codes: Q55; O31; O32.

[1] claudia.ghisetti@unibo.it
[2] alberto.marzucchi@unicatt.it
[3] sandro.montresor@unibo.it

1 Introduction

The economic relevance of environmental innovations (EIs) is nowadays undisputed, in both the business and the policy realm (e.g. Wagner, 2006; Ambec et al., 2013; Porter, 2010). An intensive research effort on EIs has recently cumulated and shown important peculiarities for them. EIs are, at the same time, technological, organizational, social, and institutional innovations (Horbach, 2008). Their analysis thus needs to go beyond the focus that environmental studies initially reserved for policies and regulations (Kemp, 2010) and benefit from a multidisciplinary approach. The bridging between ecological economics and innovation studies, for example, has been extremely fruitful to address such issues as the so-called "double-externality problem" and the "regulatory push/pull effect" (Rennings, 1998). More recently, although more hesitantly, EI studies have been spreading also in industrial organization (e.g. Andersen, 2008) and in regional studies (e.g. Mirata and Emtairah, 2005), with an increasing attention to interactive types of EI drivers like: innovation cooperation (e.g. De Marchi 2012), network and agglomeration economies (e.g. Mazzanti and Zoboli, 2005), and international linkages (Cainelli et al., 2012).

With the help of this last group of studies, an important general result has been extended to the field of EI: external knowledge sources are at least as important as those within the firm (e.g. R&D). This result supports a "system" approach to the analysis of EI, in which environmental innovators should be considered in interaction with other players, within specific socio-institutional set-ups and technological systems (Dosi et al., 1988). However, it also creates a new research need. The analysis of the "modes" through which firms can search for external knowledge, then assimilate and exploit it, in order to become environmental innovators, becomes particularly important. Furthermore, the role

that knowledge sourcing has in allowing eco-innovators to further pursue their environmental profile, by broadening their involvement in different kinds of EIs, is also of great interest. Following a neo-Schumpeterian, evolutionary perspective, handling a variety of EI solutions can actually increase the efficiency of the economic selection of their outcomes and improve their impact on a sustainable mode of growth (Faber and Frenken, 2009).

To the best of our knowledge, this research gap is still unfilled. The literature on the so-called "open innovation" mode is proliferating (Chesbrough, 2003, 2006) and offering interesting insights, but mainly with respect to "standard" technological innovations (Laursen and Salter, 2006; Henkel, 2006). Similarly, innovation and organization studies are getting important results about the actual capacity that firms have to absorb external knowledge (Cohen and Levinthal, 1989), but mainly for the sake of product and process innovations (Zahra and George, 2002). Little (or negligible) effort has been made up until now in order to investigate the viability of these results with respect to EIs.

Contributing to fill this research gap is the first element of originality of this paper. A second element is represented by the analysis of a sample of firms in as many as 11 European countries. Research has, up until now, mainly focused on either one selected (usually environmentally "performing") country per time, or on a small set of (usually economically similar) countries (e.g. Ziegler and Rennings, 2004; Kesidou and Demirel, 2012). A third original aspect of this paper is the use of an econometric strategy that permits the investigation of two different kinds of EI processes, which have been found to differ in their drivers: the firm's introduction of an EI, and the enlargement of its EIs-portfolio (i.e. the number of EI-typologies introduced by the firm).

The rest of this paper is structured as follows. In Section 2, we review the literature on the EI-drivers that pertain to the interaction between the firm and its innovation system.

Section 3 illustrates the empirical application through which we test our arguments. Section 4 discusses its main results and Section 5 concludes.

2 Theoretical background

After an intense effort (e.g. Kemp and Pearson, 2007; Kemp, 2010; Rennings, 2000), a consensus has emerged on the definition of EI as: "the production, assimilation or exploitation of a product, production process, service or management or business methods that is novel to the firm [or organization] and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives" (Kemp and Pontoglio, 2007, p. 10). This definition is very articulated and not confined to the technological sphere. On the contrary, it encompasses also organizational and service-based aspects and looks at an array of environmental impacts along the entire environmental "pipe-line".

Given this multi-faceted account, the search for the EI determinants has led to results that pertain to different spheres. A number of driving effects have been identified as the most typical in the field and labeled as: "market-pull", "technology-push" and, above all, "regulation" effects.[4] Furthermore, EI determinants have also been found, generally in the form of controls, by looking at specific firms' characteristics, such as: their size,

[4] As for the market role, EIs have been found to be pulled, among others, by turnover expectations, new demand for eco-products (Rehfeld et al., 2007), past economic performances (Horbach, 2008) and customer benefits (Kammarer, 2009). As far as the "technology-push" is concerned, EIs have been related to the firms' engagement in R&D, knowledge capital endowment (Horbach, 2008), organizational innovations and specific management schemes, like EMS (Rehfeld et al., 2007; Wagner, 2008; Rennings et al., 2006; Ziegler and Nogareda, 2009; Ziegler and Rennings, 2004). As for "regulatory aspects", in spite of the difficulties posed by their characteristics (e.g. strictness, enforcement, predictability, sectoral differences, and credibility of the commitment, on which see Kemp and Pontoglio (2011), extant literature has mainly considered environmental standards and policies (Del Rio Gonzales, 2009; Frondel et al, 2008; Horbach et al., 2012, Rennings and Rammer, 2011; Rennings and Rexhäuser, 2011; Brunnermeier and Cohen 2003; Costantini and Mazzanti, 2012; Jaffe and Palmer, 1997; Johnstone et al., 2010a, 2010b, 2012; Lanjouw and Mody, 1996, Popp, 2010).

location, sector and age (e.g. Mazzanti and Zoboli, 2009; Horbach, 2008; Rehfeld et al., 2007; Wagner, 2008; Rennings et al., 2006; Ziegler and Rennings, 2004).

The extant literature has instead paid little attention to the EI drivers that work through the interaction between the firm and its external environment.[5] Among the few recent contributions, it has been found that innovative oriented industrial linkages and inter-firm networking could trigger EI in a similar way to other innovations (e.g. technological and organizational): for example, by providing firms (SMEs, in particular) with a way to compensate for their lack of economies of scale (Mazzanti and Zoboli, 2009). In contrast, important elements of differentiation have emerged. Information from partners that are external to the supply chain (e.g. KIBS, research institutions, universities and competitors) has appeared more important for EI than for other innovations (De Marchi and Grandinetti, 2012). Furthermore, innovation cooperation (e.g. in R&D) has been shown to work more effectively for EI than for non-environmental innovations (De Marchi, 2012), but also more selectively. For example, business suppliers and universities have turned out to be among the most relevant partners in terms of EI-impact.[6] The need for new environmental solutions that embrace the whole spectrum of elements in the technological system motivates the former of these results (Horbach et al., 2012). The complexity of the knowledge that EIs require, and its degree of scientific codification, have been argued to explain the latter (Cainelli et al., 2012).

The systemic nature of EI requires firms to deal with different techno-economic problems, which entail different kinds of knowledge and knowledge interactions.

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[5] In "standard" innovation studies, the importance of these kinds of determinants has been instead shown since some time, by different research streams on innovation cooperation, knowledge transfer and knowledge sharing (e.g. Arora and Gambardella, 1994; Veugelers, 1997; Tödling and Kaufmann, 2009, Hagedoorn, 1993; Tether, 2002).

[6] As for the geographical location of external relationships, also agglomeration economies impact positively on EI, but only in those industrial districts in which the subsidiaries of multinational corporations inject global environmental pressures at the local level (Cainelli et al., 2012).

Carrillo-Hermosilla et al. (2010), for example, refer to 4 dimensions of change that are entailed by an EI, which they call: “design”, “users’ involvement”, “product-service”, and “governance” dimensions. The first one pertains to technical choices that the firm grounds on its production and engineering knowledge (e.g. Braungart et al., 2007). The second is a market dimension and relates to the users' involvement in the identification, creation, development and application of an EI. The product-service dimension points to the relevance of a supply-chain perspective in EI. Finally, the governance refers to both private (e.g. managerial choices) and public (e.g. policy actions) institutional solutions that the firm needs to use for solving conflicts over environmental resources: in particular, to overcome lock-in conditions (e.g. coming from national security), which act as a barrier to EI (Unruh, 2000). Clearly, the need to cope with all these different dimensions requires of the environmental innovators information and skills that are also distant from the traditional industrial knowledge base in which they operate (De Marchi, 2012). This fact makes knowledge interactions for EIs more overarching than for technological innovations.

Ultimately, evidence begins to emerge that, also with respect to EI, firms could benefit from an “open innovation mode” (Chesbrough, 2003, 2006), in which the knowledge boundaries between the firm and the external environment become permeable. As a further step towards the substantiation of this hypothesis, it is interesting to investigate whether some specific pillars of the open innovation mode are at work with respect to EI too, and eventually with which characterizations.

2.1 Knowledge search patterns and EI

The first of the open innovation pillars is represented by the strategies through which firms search for external knowledge in order to eco-innovate, that is, by their mode of

knowledge sourcing. Following Laursen and Salter (2006), and extending their line of reasoning, we argue that two characteristics of the firms' knowledge search could affect its outcome in terms of EI. The first one is the breadth of the firm's search pattern, which can be accounted by the array of sources firms draw on for accessing external knowledge. The manifold nature of EI, and the different capabilities that it requires (e.g. technological, organization and institutional), could make the potential environmental-innovator at least as reliant as the "standard" one on a number of external knowledge sources.[7] Such a number is thus expected to be a significant predictor of the firm's capacity to deal with the systemic nature of EI and thus to eco-innovate.

Another characteristic of the firm's strategy of knowledge-search that deserves consideration is its depth: the extent to which firms draw intensively on external knowledge providers. A sustained pattern of learning-by-interacting turns out as particularly suitable, given the complexity entailed by EI and the diversity of the knowledge base that it requires. Through a repeated and deep interaction with each of the different possible sources of knowledge, potential environmental innovators are able to share feed-backs with them, mutually adapt their understanding and reach an actual assimilation of external knowledge. For these reasons, we also expect that the depth of external knowledge sourcing positively impacts on the firm's EI.

While both breadth and depth could be relevant for EI, the possibility that their exploitation could become at a certain stage counteracting should be also considered. With respect to technological innovations, this has actually been found (Laursen and Salter, 2006) and motivated by drawing on the attention-based theories of the firm (Simon, 1947; Ocasio, 1997; Koput, 1997). In brief, becoming too widely and/or too

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[7] One may consider the need of obtaining scientific knowledge about the materials to be used (from universities and research institutes), the environmental standards to respect (from specific agencies), and the availability of sustainable production inputs (from the suppliers), to mention a few elements.

deeply reliant on external sources might entail for the firm a subtraction of organizational/managerial energies and cognitive attention from its ultimate innovative effort. In principle, this could equally happen for EI. Accordingly, the presence of non-linear effects in the impact of breadth and depth on EI should be controlled for.

Of course, in investigating all these knowledge-search aspects, the heterogeneity of the firms should be carefully considered. A suitable list of possible controls should be included, in parallel to what has been done in the analysis of technological innovations (see Section 3.2). However, an EI-specific aspect deserves special consideration in this analysis: the different nature of the processes that drive, on the one hand, the firm's propensity to introduce an EI and, on the other hand, the extent of its involvement in the EI realm and its different typologies (e.g. product vs. process ones). For example, the first has appeared mainly driven by a minimum set of customer and societal requirements. On the contrary, the second is likely to be affected by additional factors, like the search for cost-savings, the availability of suitable organizational capabilities and the imposition of a stricter set of environmental regulations (Kesidou and Demirel, 2012; Carrillo-Hermosilla et al., 2010). More in general, the second process, which somehow could represent the extension/intensification of the first process, occurs in a more experienced way and along a certain path of EI-learning, which could be the source of both experience economies and diseconomies.[8] On the basis of these arguments, we expect that the different nature of these processes will lead to differences in the firm's use of external knowledge and in the impact of external knowledge sourcing strategies. In practical terms, we expect that the relative results could differ if, instead of looking at

[8] In the case of "standard" innovations, this is a result that has already emerged by using CIS data, and has led to interesting implications in terms of complementarity of the policy actions (e.g. Mohnen and Röller, 2005).

probability to introduce an EI, we consider the number of EI typologies that an environmental innovator manages.

2.2 Knowledge absorptive capacity and EI

In extending the open innovation paradigm to the EI analysis, a second pillar requires consideration, which has been so far scantly investigated (with the exception of De Marchi, 2012): the firm’s capacity to scan, acquire and implement external knowledge, or its absorptive capacity (AC).

Since the seminal paper by Cohen and Levinthal (1989), much work has been performed in order to understand the factors on which AC depends (in brief, its antecedents) and those responsible for its innovation impact (e.g. Murovec and Prodan, 2009; Lim, 2009; Lewin et al. 2011). This debate has led to some interesting results, whose extension to EI appears noteworthy; firstly, the crucial role of R&D for AC, its so-called “second face”, in reducing the cognitive distance between the firm and the external knowledge sources. In the case of EI, whose technological elements are contaminated by other non-technological ones and whose dimensions involve different knowledge spheres, this “secondary” role of R&D is as important as its “primer” input role.[9] Accordingly, our general expectation is that investing in R&D could positively moderate the impact that firm's external knowledge sourcing (i.e. breadth and depth) has on its EI.

A similar argument can be put forward with respect to what the AC literature has called “social integration mechanisms” (SIM) (Zhara and George, 2002). In brief, these are organizational capabilities, like “connectedness and socialization tactics” (Jansen et al., 2005, p. 999), which substantiate into specific organizational mechanisms like, for

[9] It should be noted that the latter is often found insignificant in several empirical studies (e.g. Horbach, 2008; Horbach et al., 2012; Ziegler and Nogareda, 2009; Cainelli et al., 2012).

instance, cross-functional interfaces and formal communication flows across divisions. These mechanisms can be expected to favor the circulation and diffusion of externally acquired knowledge and thus to augment its "socialization" (Hirunyawipada et al., 2010; Jansen et al., 2009) also for the sake of EI. On this basis, the moderating role of SIM for the impact that knowledge sourcing has for EI deserves consideration.

Possibly more than in the case of sourcing strategies, the analysis of these moderating effects should be carried out by distinguishing the process of becoming eco-innovators from that of increasing the EIs-portfolio. Unlike the former, the latter actually refers to firms that have already proved capable of dealing with the knowledge needs and interactions required to become environmental innovators. Somehow, this step into the EI-realm represents an implicit element of their capacity to assimilate and exploit external knowledge for the sake of EI. Accordingly, we expect that the moderating role of R&D and SIM could turn out to work differently in the two EI-processes.

3 Empirical application

3.1 Econometric strategy

The theoretical arguments presented in Section 2 will be tested through a set of hierarchical econometric models. At first, the impact of the breadth and depth of external sourcing on the firm's EI is estimated through the following model, which includes a proper set of controls for each firm i:

$$EI_i = \alpha + \beta_1\, BREADTH_i + \beta_2\, DEPTH_i + \gamma\, CONTROLS_i + \epsilon_i \qquad (1)$$

In order to account for the potential non-linearity in the relationship between external knowledge sourcing and EI, the benchmark model (1) is augmented by including squared terms for both breadth and depth variables:

$$EI_i = \alpha + \beta_1 \, BREADTH_i + \beta_2 \, DEPTH_i + \beta_3 \, BREADTH_i^{\,2} + \beta_4 \, DEPTH_i^{\,2} + \gamma \, CONTROLS_i + \epsilon_i \qquad (2)$$

Finally, we investigate the moderating effect of factors that affect the absorption of external knowledge and its transformation into actual EI. For this purpose, in Eq. (3) we consider two dummies for the engagement in R&D activities (RD) and the presence of social integration mechanisms (SIM), respectively, and test for their interaction with breadth and depth:

$$EI_i = \alpha + \beta_1 BREADTH_i + \beta_2 \, DEPTH_i + \beta_3 \, BREADTH_i^2 + \beta_4 \, DEPTH_i^2 + \delta_{1\text{-}2} \, [RD, SIM] + \delta_{3\text{-}4} \, [RD, SIM] \, {*}BREADTH_i + \delta_{5\text{-}6} \, [RD, SIM]{*}DEPTH_i + \gamma \, CONTROLS_i + \epsilon_i \qquad (3)$$

In order to analyze the two different processes of adopting an EI by the firm and extending the kind of EIs by the environmental innovator, we define the dependent variable EI as the number of EIs introduced by the firm and then estimate Eqs.(1)-(3) with a hurdle negative binomial model (e.g. Cameron and Trivedi, 1998). As is well-known, its underlying rationale is that a binomial probability model (in our case, a logit one) governs the binary outcome of whether the count dependent variable has a zero or a positive value. If the “hurdle is crossed” (i.e. if the dependent variable has positive values), the conditional distribution of the positive values is instead governed by a zero-truncated count model (in our case, a zero-truncated negative binomial).

Given this latter property, the choice of this model is consistent with our research aim. The different generating processes for the zeros and the positive values of our core variable (EI) actually allow us to integrate the analysis of the EI-propensity with a special focus on the EIs-portfolio of environmentally innovative firms (that is, firms who “crossed the hurdle” of EI). Furthermore, the hurdle model allows us to account for the over-dispersion and the excess of zeros that the dependent variable shows, because of the high number of non-environmental innovators (see Table A1).

3.2 Dataset and variables

The empirical application makes use of the Community Innovation Survey (CIS) for the period 2006-2008 and focuses on the manufacturing firms of 11 countries: Bulgaria, Czech Republic, Germany, Estonia, Hungary, Italy, Lithuania, Latvia, Portugal, Romania and Slovakia.[10]

Drawing on this dataset, we construct the variables for our econometric strategy as follows. First of all, the count dependent variable, EI, is defined by referring to the 9 different types of EI that the CIS encompasses. End-of-pipe, cleaner production technologies and EIs related to the introduction of new products are included among them.[11] In principle, each of the different categories, if not each typology of EI, should deserve a separated investigation (Carrillo-Hermosilla et al., 2010). However, our focus in this paper is different. We are interested in the firm's capacity to enter into the green side of the innovation realm – from whatever "door" – and to adopt a pervasive EI profile - irrespectively from the components of the specific portfolio strategy. Cross-country distribution of EI is depicted in Table A2.

With respect to our independent variables, the knowledge sourcing ones are built up following Laursen and Salter (2006). BREADTH is defined as the number of external information sources the firm relies upon for its innovation activities, out of the list of 9 potential knowledge providers (that is, suppliers; customers; competitors; consultants and

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[10] Data comes from the CIS 2006-2008 anonymized micro-data dataset provided by Eurostat. This CIS wave is the first one that systematically collects harmonized information on EI with a wide European coverage.

[11] The CIS defines EI consistently with the definition we have provided in Section 2. Six types of EI refer to environmental benefits emerging from the production of goods or services: reduced material use per unit of output; reduced energy use per unit of output; reduced CO_2 'footprint' (total CO_2 production); replaced materials with less polluting or hazardous substitutes; reduced soil, water, noise, or air pollution and recycled waste, water, or materials. The other three EIs are related to the benefits emerging from the after-sales use of a good or service: reduced energy use; reduced air, water, soil or noise pollution; improved recycling of product after use. The Cronbach's Alpha of our dependent variable is 0.8832.

private R&D institutes; universities; government or public research institutes; conferences, trade fairs, exhibitions; scientific journals and trade/technical publications; professional and industry associations). DEPTH instead counts the number of these external information sources to which the firm attributes a “high” degree of importance, among the four listed options (i.e. not used, low, medium, high importance). Cross-country distributions or BREADTH and DEPTH are reported in Table A2.

The second set of explanatory variables is represented by the AC antecedents. These are included as individual regressors and, in Eq. (3), as interacting terms. At first, we employ a dummy, RD, to capture the firm’s internal R&D investments.[12] Social integration mechanisms of external knowledge are also captured by a dummy (SIM), by looking at the importance that firms attribute to those internal information channels/flows into which external ones will possibly circulate to be absorbed. In particular, following Fosfuri and Tribò (2008), SIM takes value 1, in case the information coming from within the boundaries of the company (or from the industrial group the firm is part of) has a medium or high importance for the firm’s innovation activities.

As for the controls, we first account for the firm's size, by including the logarithm of its turnover (lnTURNOVER) in the first year of the reference period, i.e. 2006. COUNTRY- and SECTOR-specificities in terms of market and technological opportunities, as well as institutional settings, are controlled for with the inclusion of a series of dummies.[13] We then add two characteristics related to the internationalization of the firm, which extant literature has considered to be important determinants of the EI performance (e.g. Cainelli et al., 2011, 2012): EXPORT, a dummy which reflects whether the company is

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[12] Although available, we do not use the continuous variable for R&D investment. As this refers to the last year of the period (i.e. 2008), some endogeneity problems may emerge with the dependent variable (*EI*), which instead refers to the entire period (i.e. 2006-2008).

[13] In order to control in a more punctual way for these specificities, as a robustness check we also include *COUNTRY*SECTOR* interactions.

engaged in international markets, and MNC, which denotes whether the firm is affiliated to a multi-national corporation. Although a number of technology-push factors are already considered through the inclusion of RD (and SIM) as individual regressors, we add a further control in the same respect: COOP, a dummy which captures the firm's engagement in formal innovation cooperation agreements. Finally, given the relevance that policy and regulation aspects are expected to have on EI (e.g. Del Rio Gonzales, 2009), at first, we tried to account for them in general terms, by looking at whether the firm has received a public support for its innovation activities (INNOPOL). Unfortunately, CIS data do not allow us to directly retain more specific environmental policies at the firm level.[14] We have thus tried to overcome this problem by exploiting EUROSTAT data on "Air emissions accounts by industry and households". In particular, as in some recent contributions (e.g. Costantini and Crespi, 2008), we adopt as a proxy for environmental policy stringency (POLSTR), the logarithm of the CO2 Emission/Value Added ratio in each country-sector combination referred to the year 2006[15].

Tables 1 and 2 provide a synthesis of the variables descriptions and their main statistics, respectively. Table 3 presents the matrix of their correlation coefficients.

[TABLE 1, 2 and 3 ABOUT HERE]

[14] In the Section on "Innovations with Environmental Benefits", the CIS questionnaire includes a question on the role of environmental regulations (either existing or expected). However, its formulation impedes the inclusions of the relative variable in the econometric specification. Given that it addressed only those firms which introduced an EI, endogeneity problems could emerge.

[15] Robustness checks on different years for emissions and value added (2006-2008 emissions and 2006 value added; 2003-2005 emissions and 2003-2005 value added) have been performed.

4 Results

Following the econometric strategy that we have proposed, let us first address the determinants of an EI adoption (Table 4). Our main research hypothesis concerning the importance of external knowledge sources is confirmed. Once the role of the firm's internal and external predictors of EI is controlled for (Model I), knowledge sourcing appears a significant EI driver.[16] The wider the array of knowledge sources the firm draws on (BREADTH), the more probable is the introduction of an EI: BREADTH seems to increase the firm's coverage of the multiple knowledge needs entailed by the multi-dimensionality of EI. The probability to be an environmental innovator also increases with the competences that the firm acquires through a deep interaction with its external knowledge providers (DEPTH): by getting more intensive, such an interaction transforms a spot-like knowledge exchange into learning-by-interacting for the sake of EI.

[TABLE 4 ABOUT HERE]

The effects of the two types of sourcing strategy appear different, when we look at their non-linear impact on the EI-propensity (Model II). On the one hand, the impact of DEPTH does not seem to be bounded (DEPTH2 is not significant). Increasing the intensity of learning-by-interacting always gives to the firm more refined knowledge and enhances the probability to introduce an EI. On the other hand, the benefits of a broad sourcing strategy stop increasing after a certain level (BREADTH2 is significantly negative). In this respect it seems as though, while some knowledge variety is required in order to step into EI, broadening its external search over a certain level could expose the

[16] For the sake of parsimony, we do not comment on the coefficients of the controls. For the same reason, we do not report the results emerging from the robustness checks based on the different specifications for *POLSTR* and country/sector specificities (see Section 3.2). However, these results, available upon request, largely confirm the evidence presented here.

firm to redundant and/or inconsistent information signals. These problems could make the firm less prompt, if not even more reluctant, to introduce an EI.

In this last respect, a closer inspection of the inverted U-shaped effect of BREADTH on the EI-adoption (Figure 1) can help in sharpening our analysis. The marginal return of an increasingly broad sourcing strategy tends to decrease and becomes not significantly different from zero when BREADTH reaches a medium-high number of knowledge sources for the firm (i.e. 7 and 8). When BREADTH reaches its maximum value (of 9 sources), its marginal effect becomes even negative.[17]

[FIGURE 1 ABOUT HERE]

Ultimately, we can conclude that the decision to introduce an EI is such that both the variety and the intensity of the firm's search for external knowledge are beneficial. However, their benefits appear differently constrained.

When we look at the impact of the AC determinants on the logit part of our estimates (Table 4, Models III and IV), interesting results emerge, still pointing to the different role of BREADTH and DEPTH for an EI adoption. As expected, investing in R&D increases the probability to become an environmental innovator. Furthermore, it also positively moderates the EI impact of BREADTH. According to the AC logic, R&D can help the firm to scan and master external knowledge, reducing its cognitive distance from the relative sources. However, this does not occur for DEPTH, which is negatively moderated by R&D, suggesting that their combination could represent an obstacle to EI.

[17] We came to this result by implementing the following test. We calculated algebraically the turning point by equaling to zero the first derivative of the marginal effects function (estimated on the logit part of our hurdle model). The punctual estimation of the *BREADTH* value at which the function has a maximum (i.e. the first derivative equals zero) is 7.63. However, the first derivative is not significantly different from zero (at the 95% level) for values of *BREADTH* between 6.66 and 8.59. Hence, for values of *BREADTH* which are higher than 8.59, the function has a negative slope. Given the way *BREADTH* is created in our application (i.e. an integer number), null marginal effects are in place when *BREADTH* equals 7 or 8, while the presence of negative marginal effect is limited to the cases in which *BREADTH* is at its maximum value (i.e. 9).

Different tentative explanations could be provided for this. On the one hand, the EI implications that the firm obtains through deep and structured interactions with external knowledge sources could conflict with the ones on which it invests internally. In other words, the more the search for external knowledge becomes intense and oriented towards precise aims, the higher is the chance that it creates mismatches with the internal innovation capabilities of the firm (Carlile, 2004). On the other hand, even irrespectively from the occurrence of these mismatches, firm's decision makers could incur problems by allocating their attention between internal and external knowledge sources, thus becoming unable to drive the two towards a final EI outcome (Ocasio, 1997).

Similar results hold true for the role of SIM, but with some qualifications. When its interaction with BREADTH and DEPTH is also retained, SIM loses its significance as an additive regressor. As expected, the investigated integration mechanisms actually seem to work on EI indirectly, through the socialization of external knowledge. However, such socialization only occurs with respect to the organizational diffusion of the diverse knowledge inputs that the firm gets from a broad knowledge sourcing (i.e. with respect to BREADTH). On the contrary, when the firm tries to combine an intense external knowledge interaction with an intense internal knowledge circulation a further source of problems for EI emerges: DEPTH*SIM is significant and negative. Knowledge mismatches and attention problems could be invoked also to explain this result. In addition, the organizational nature of the investigated socialization mechanisms could entail an excessive managerial burden when these are combined with a deep sourcing strategy.

In synthesis, another important differentiation seems to emerge between BREADTH and DEPTH for the probability to EI. The former strategy seems to rely on the firm's absorptive capacity to become exploitable. The latter seems to provide the firm with

more immediately usable knowledge, but can create clashes with the internal innovation capabilities and socialization routines of the firm.

Let us now move to the second part of our econometric analysis, related to the decision of the environmental innovators to enlarge their portfolio of EI typologies (see Table 5). As aforementioned, this second step of the analysis amounts to the investigation of a sub-sample of our firms, which are already environmental innovators.

BREADTH and DEPTH are still relevant in the benchmark model (Model I). This provides us with an important element for generalizing the importance of an open mode of innovation with respect to EI. Knowledge sourcing also helps the environmental innovators to deal with the different realms (e.g. energy, materials, CO2) that different EIs entail. However, as soon as we move to the augmented specifications, some important differences with respect to the logit part of the econometric model emerge. This supports the theoretical and empirical works that have shown how introducing an EI and intensifying the EI-performance could be different processes (Kesidou and Demirel, 2012) and may entail different policy actions (as the work by Mohnen and Röller (2005) implies with respect to technological innovation). More precisely, the fact that environmental innovators have already entered the EI realm, and have thus allegedly already made use of "green" knowledge and knowledge sources, makes of them (more) EI-competent firms. Accordingly, with respect to these firms, the opportunities and the constraints of accessing and managing external knowledge reveal different results.

[TABLE 5 ABOUT HERE]

First of all, the search for non-linear effects (Model II) yields substantially different results from the previous ones. In particular, the constraints to the impact of BREADTH now disappear. The returns from a broad strategy of knowledge sourcing are still non-

linear, but they are now increasingly higher, the higher is BREADTH (BREADTH2 is significant and positive, except from the last model). In the attempt of enlarging the EIs-portfolio with other types of innovations, which are different, but that can still benefit from the firm's EI "knowledge-baseline", the risk of redundant and/or conflicting insights can be more easily accommodated. Furthermore, if the target is an increasing number of EIs typologies, accessing a high number of providers is increasingly more important in terms of knowledge variety.

The impact of a deep knowledge sourcing is still positive (Model I) as in the logit part, but with some important specifications. Models III and IV apparently show that environmental innovators can even benefit from increasing returns from deep external interactions. It should be noted that Model II points to a U-shaped effect of DEPTH: DEPTH and DEPTH2 are both significant, but negative and positive, respectively. A closer analysis of this curvilinearity (Figure 2) reveals that the presence of negative marginal returns is limited to firms with no deep interactions, while marginal effects not significantly different from zero are in place only for firms with few profound interactions (i.e. 1 or 2).[18] Overall, as much as with BREADTH, the presence of an EI "knowledge-baseline" provides the firm with the opportunity of taking (possibly increasing) stock also of an increasing intensity of interactions. This is a quite interesting result, especially if one considers the risks of lock-in that sustained and repeated external interaction could potentially entail.

[FIGURE 2 ABOUT HERE]

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[18] Following the same methodology we described for the curvilinearity of *BREADTH* in the logit part of our model, we analyzed the turning point of the *DEPTH* marginal effects function. The punctual estimation of the *DEPTH* value at which the function has a minimum is 1.54. For *DEPTH* values between 0.74 and 2.33 marginal returns are not different from zero, while for values between 0 and 0.74 the marginal effects are significantly negative. Hence, given the integer nature of *DEPTH*, we can conclude that only when *DEPTH* equals 0 there is a negative return, while when *DEPTH* is 1 or 2 the marginal effects are zero.

The second step of our model estimation shows important elements of differentiation, with respect to the first one, also when the role of AC is considered. First of all, R&D now appears to be of much less help (Model III). While it still has a direct impact on the firm's capacity to extend its EIs-portfolio, investing in R&D does not facilitate the absorption of external knowledge for the same sake at all. As before, sustained patterns of interaction make (some) external knowledge sources more structural and potentially more conflicting with the ones exploited internally, possibly posing to managers problems of choice and attention allocation (RD*DEPTH is significantly negative). This is a general result of our empirical analysis, which suggests an important constraint in the use of R&D for benefiting from the open innovation mode in EI. In addition, R&D also loses the significance in moderating the impact of BREADTH that we found for the decision to adopt an EI. As we already argued, the EI capabilities that the investigated firms (i.e. environmental innovators) implicitly have could work as an AC mechanism itself. Accordingly, they could make the additional moderating role of being engaged in R&D activities vanish.

Interesting variations can be observed in the last specification, where the role of social integration mechanisms (SIM) is considered (Model IV). On the one hand, also with respect to the extension of the EIs-portfolio, SIM switches from an additive to a moderating impact, confirming their indirect role in the open innovation mode for EI. On the other hand, this moderating role becomes even conditional for BREADTH to have any relevance (BREADTH*SIM is the only significant BREADTH related variable). Rather than simply reinforcing the impact of diverse external knowledge inputs, organizational mechanisms for knowledge socialization appear thus necessary for a broad sourcing strategy to make the firm EI more extensively. Furthermore, differently from what emerged from the first part of our analysis, these mechanisms do not clash with the

intensity of external knowledge relationships, although they do not help them either (DEPTH*SIM is not significant). The fact that, in the case of environmental innovators, SIM has probably already been used for transmitting EI-related knowledge, can explain the lack of mismatch with an intense kind of external sourcing.

5 Conclusions

In spite of several common elements, EIs are substantially different from "standard" technological and non-technological innovations. Their peculiar systemic nature has been shown by recent works that have extended the analytical tool-box of innovation studies to environmental and ecological economics (e.g. De Marchi, 2012). The importance of external knowledge for the firm's EI performance is one of the basic insights emerged from this stream of studies. This result represents the starting point of our search for an "open environmental-innovation" mode.

The empirical analysis that we have carried out with respect to 11 European countries has shown that some of the building blocks of open innovation are at work also in the case of EI. However, this holds true under a number of specifications and differences with respect to what has been found by studies focused on technological innovation (e.g. Laursen and Salter, 2006). These peculiarities should inform both business strategies and policy actions aimed to support the adoption and impact of an "open environmental-innovation" mode.

First of all, knowledge sourcing has, per se, a different impact on the firm's propensity to introduce an EI and on the extension of its EIs-portfolio. In the former case, for example, while intensive interactions appears beneficial to whatever extent they are used, broadly acquired external knowledge can become difficult to be managed and, after a certain point, even discourage firms from adopting an EI. In extending the EIs-portfolio, instead,

the search for external knowledge sources benefits from an EI knowledge baseline. This provides the environmental innovators with an important safeguard from potential redundancy problems related to a large resort to external knowledge.

This first set of results seems to suggest that the viability of the open innovation mode is less constrained for those firms that have already acquired some EI capabilities and want to enlarge the number of EI-typologies introduced. In the attempt at increasing the firm's propensity to adopt/introduce an EI, instead, business strategies and policy actions should focus on the support to intense or only moderately broad interactions. Surely, the identification of the specific actors to interact with represents an additional element in the definition of suitable sourcing strategies.

Important conclusions can also be drawn with respect to the firms' leverages that increase the absorption of external knowledge for the sake of EI. While the engagement in R&D is an important EI driver, its AC-leverage role appears as less clear. With this respect, R&D contribution is limited to the understanding of broadly sourced knowledge for the sake of adopting an EI. On the contrary, internal R&D investments generally appear to hamper the exploitation of deep external interactions. In other words, it seems like that, at least in the attempt of obtaining a consolidated kind of knowledge base for EI, internal and external learning processes may not be complementary. This result points to the need of reconsidering the specific circumstances under which a support (either through policy actions or private investment) to R&D is beneficial for EI. Certainly, the role of R&D deserves a deeper investigation. In particular, further research should pay attention to the amount of investment in R&D; an aspect that, for data constraints, we could not address in this paper.

Different arguments hold true for social integration mechanisms (SIM). In spite of the clashes that we have identified in the resort to deep knowledge search strategies for the

potential environmental innovator, their enabling role has also appeared crucial. This is particularly the case of the environmental innovators, for which these SIM are even indispensable to turn a variety of knowledge sources into a variety of EI solutions. Organizational innovations that could increase the socialization of external knowledge, and the support to them, are thus pivotal also in the EI realm.

Overall, the two EI processes that we have tried to analyze – i.e. adopting an EI and extend the EIs-portfolio – seem to differ not only in terms of standard determinants, as the literature has already shown, but also with respect to the benefit of EI drivers related to external interactions.

In spite of the usual caveats posed by the interpretation of the coefficients in econometric models based on cross-sectional data, our evidence has revealed the crucial role played by “open innovation modes” also with respect to environmental innovation. Nevertheless, a complete understanding of the relation between external knowledge and firm’s EI performance is still far from being achieved. In particular, we believe that the next step ahead in this direction should be the investigation of the effects that interactions with different types of knowledge providers have on the introduction of the different types of EIs.

Tables and Figures

Tab. 1 Variables description

Variable	Description
EI	Number of EIs introduced by firms
BREADTH	Number of external information sources the firms rely upon
DEPTH	Number of external information sources to which firms attribute a high degree of importance
COOP	R&D cooperation with cooperation partners (DUMMY)
EXPORT	Engagement into international markets (DUMMY)
INNOPOL	Existence of public support to firm´s innovation activities (DUMMY)
lnTURNOVER	Natural logarithm of firm´s turnover in 2006
MNC	Affiliation to a multi-national corporation (DUMMY)
POLSTR	Logarithm of country/sector CO_2 emission intensity in terms of Value Added in 2006
RD	Engagement in R&D activities (DUMMY)
SIM	Importance of the internal information flows for firm´s innovation activities (DUMMY)

Tab. 2 Variables descriptive statistics

Variable	N	mean	min	sd	max
EI	14366	2.79	0	2.97	9
BREADTH	14366	5.19	0	2.75	9
DEPTH	14366	0.92	0	1.28	9
COOP	14366	0.24	0	0.43	1
EXPORT	14366	0.69	0	0.46	1
INNOPOL	14366	0.21	0	0.41	1
lnTURNOVER	14366	13.44	-6.91	4.01	24.39
MNC	14366	0.15	0	0.36	1
POLSTR	14366	-0.85	-4.99	1.50	2.16
RD	14366	0.42	0	0.49	1
SIM	14366	0.74	0	0.44	1

Tab. 3 Variables correlation matrix

Id	Variables	1	2	3	4	5	6	7	8	9	10	11
1	EI	1										
2	BREADTH	0.28	1									
3	DEPTH	0.16	0.38	1								
4	RD	0.26	0.34	0.17	1							
5	COOP	0.16	0.24	0.17	0.27	1						
6	SIM	0.17	0.38	0.21	0.29	0.16	1					
7	lnTURNOVER	0.19	0.14	0.10	0.12	0.14	0.05	1				
8	MNC	0.11	0.09	0.00	0.10	0.20	0.15	0.22	1			
9	EXPORT	0.15	0.17	0.09	0.29	0.20	0.15	0.22	0.22	1		
10	INNOPOL	0.11	0.20	0.12	0.28	0.21	0.14	-0.04	-0.01	0.14	1	
11	POLSTR	-0.09	-0.04	-0.03	-0.14	-0.03	-0.01	-0.07	-0.02	-0.13	-0.06	1

Tab. 4 Hurdle negative binomial estimation results (Logit part)

Variables	(I)	(II)	(III)	(IV)
BREADTH	0.0984***	0.271***	0.263***	0.255***
	(0.00835)	(0.0288)	(0.0290)	(0.0293)
DEPTH	0.0664***	0.0976***	0.137***	0.182***
	(0.0186)	(0.0358)	(0.0379)	(0.0509)
BREADTH²		-0.0177***	-0.0181***	-0.0196***
		(0.00281)	(0.00290)	(0.00303)
DEPTH²		-0.00744	-0.00551	-0.00443
		(0.00767)	(0.00715)	(0.00774)
BREADTH*RD			0.0337*	
			(0.0181)	
DEPTH*RD			-0.109***	
			(0.0350)	
BREADTH*SIM				0.0486**
				(0.0191)
DEPTH*SIM				-0.119**
				(0.0486)
POLSTR	0.00638	0.00718	0.00700	0.00689
	(0.0236)	(0.0236)	(0.0236)	(0.0237)
COOP	0.439***	0.442***	0.441***	0.441***
	(0.0549)	(0.0551)	(0.0552)	(0.0551)
SIM	0.256***	0.210***	0.207***	0.0730
	(0.0479)	(0.0489)	(0.0491)	(0.0939)
RD	0.345***	0.324***	0.242**	0.323***
	(0.0471)	(0.0475)	(0.105)	(0.0475)
lnTURNOVER	0.0192***	0.0203***	0.0201***	0.0201***
	(0.00689)	(0.00692)	(0.00692)	(0.00693)
MNC	0.171***	0.185***	0.181***	0.184***
	(0.0627)	(0.0628)	(0.0629)	(0.0629)
EXPORT	0.252***	0.250***	0.248***	0.248***
	(0.0471)	(0.0472)	(0.0473)	(0.0473)
INNOPOL	0.126**	0.130**	0.129**	0.129**
	(0.0536)	(0.0537)	(0.0538)	(0.0538)
Country Dummies	YES	YES	YES	YES
Sector Dummies	YES	YES	YES	YES
Constant	-0.631***	-0.922***	-0.902***	-0.865***
	(0.138)	(0.147)	(0.148)	(0.150)
Observations	14.366	14.366	14.366	14.366
Prob > Chi²	0.00	0.00	0.00	0.00
McFadden Adj. R²	0.167	0.169	0.170	0.170
Log PseudoL	-7945.0505	-7922.8386	-7917.458	-7917.7947

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Tab. 5 Hurdle negative binomial estimation results (Zero-truncated negative binomial part)

Variables	**(I)**	**(II)**	**(III)**	**(IV)**
BREADTH	0.0324***	0.0133	0.00946	0.0133
	(0.00308)	(0.0112)	(0.0113)	(0.0114)
DEPTH	0.0125***	-0.0217**	-0.00699	-0.0232
	(0.00481)	(0.00970)	(0.0113)	(0.0172)
BREADTH²		0.00188*	0.00225**	0.000963
		(0.001000)	(0.00105)	(0.00112)
DEPTH²		0.00704***	0.00702***	0.00712***
		(0.00169)	(0.00165)	(0.00169)
BREADTH*RD			-0.000839	
			(0.00612)	
DEPTH*RD			-0.0242***	
			(0.00935)	
BREADTH*SIM				0.0135*
				(0.00791)
DEPTH*SIM				0.000923
				(0.0161)
POLSTR	0.0142*	0.0141*	0.0140*	0.0141*
	(0.00824)	(0.00823)	(0.00823)	(0.00822)
COOP	0.0172	0.0164	0.0185	0.0158
	(0.0152)	(0.0152)	(0.0153)	(0.0152)
SIM	0.0391**	0.0488**	0.0453**	-0.0176
	(0.0189)	(0.0191)	(0.0192)	(0.0424)
RD	0.0943***	0.0989***	0.130***	0.0993***
	(0.0147)	(0.0147)	(0.0387)	(0.0148)
lnTURNOVER	0.0106***	0.0104***	0.0103***	0.0102***
	(0.00306)	(0.00304)	(0.00305)	(0.00304)
MNC	0.0885***	0.0878***	0.0874***	0.0880***
	(0.0173)	(0.0173)	(0.0173)	(0.0173)
EXPORT	-0.0430**	-0.0430**	-0.0431**	-0.0421**
	(0.0171)	(0.0171)	(0.0170)	(0.0170)
INNOPOL	0.0168	0.0148	0.0150	0.0149
	(0.0151)	(0.0151)	(0.0151)	(0.0151)
Country Dummies	YES	YES	YES	YES
Sector Dummies	YES	YES	YES	YES
Constant	1.153***	1.200***	1.195***	1.226***
	(0.0547)	(0.0594)	(0.0601)	(0.0610)
Obs count>0	8841	8841	8841	8841
McFadden Adj. R²	0.3362	0.3365	0.3365	0.3364
Prob > Chi²	0.00	0.00	0.00	0.00
Log PseudoL	-19738.875	-19729.305	-19725.928	-19727.495

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Fig. 1 Curvilinear effect of BREADTH on the predicted EI-probability (Logit part)

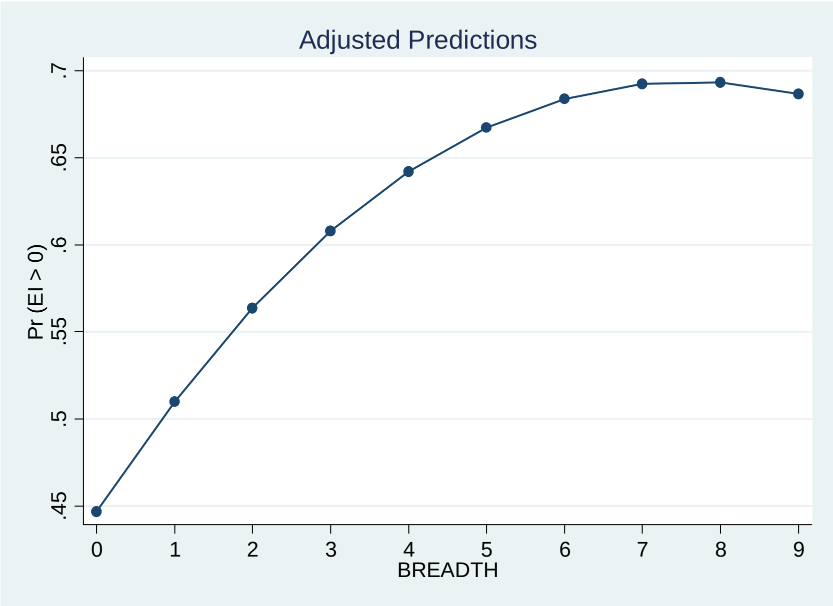
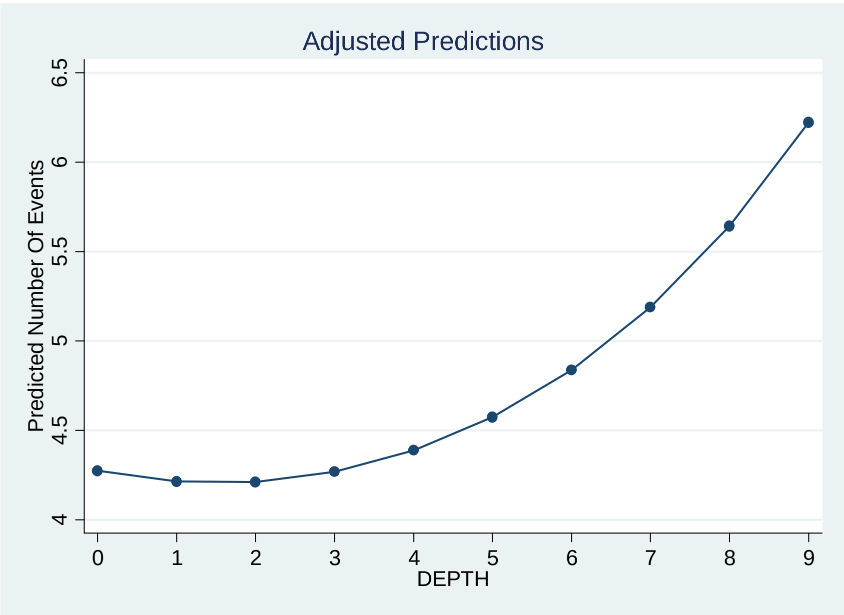


Fig. 2 Curvilinear effect of DEPTH on the predicted number of EI-typologies (Zero-truncated negative binomial part)



Appendix

Tab. A1 Distribution of EI

EI	Freq.	Percent	Cum.
0	5.525	38.46	38.46
1	1.074	7.48	45.93
2	1.314	9.15	55.08
3	1.240	8.63	63.71
4	1.118	7.78	71.50
5	958	6.67	78.16
6	902	6.28	84.44
7	737	5.13	89.57
8	596	4.15	93.72
9	902	6.28	100
Total	14.366	100	

Tab. A2 Distribution of the EI, BREADTH and DEPTH by Country

							EI						
COUNTRY	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total**	**Perc. values >0**	**Mean**
BG	1916	163	158	86	66	48	48	42	31	43	2601	26%	0.94
CZ	266	126	152	174	129	115	111	98	78	84	1333	80%	3.58
DE	632	154	204	199	187	160	145	122	112	238	2153	71%	3.47
EE	496	146	178	140	102	74	54	40	28	22	1280	61%	2.13
HU	144	53	73	74	61	54	52	24	21	25	581	75%	3.11
IT	1184	149	216	207	218	189	193	151	118	107	2732	57%	2.61
LT	94	32	26	21	30	24	21	15	12	17	292	68%	2.97
LV	63	23	10	7	7	9	13	5	1	3	141	55%	2.02
PT	336	146	173	169	192	179	188	150	131	265	1929	83%	4.29
RO	339	73	102	138	108	90	71	81	58	92	1152	71%	3.35
SK	55	9	22	25	18	16	6	9	6	6	172	68%	2.79
							BREADTH						
COUNTRY	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total**	**Perc. values >0**	**Mean**
BG	121	290	301	458	329	219	218	169	71	425	2601	95%	4.44
CZ	34	33	43	69	107	166	203	219	154	305	1333	97%	6.24
DE	604	16	32	62	120	188	226	202	213	490	2153	72%	4.91
EE	20	56	130	144	198	238	210	154	54	76	1280	98%	4.83
HU	25	19	25	44	63	71	75	88	76	95	581	96%	5.74
IT	26	197	231	275	378	350	330	361	187	397	2732	99%	5.24
LT	12	32	24	33	40	36	36	22	21	36	292	96%	4.73
LV	13	3	10	11	16	24	24	18	10	12	141	91%	4.95
PT	26	133	107	136	201	242	280	254	146	404	1929	99%	5.72
RO	38	45	80	81	151	196	170	114	56	221	1152	97%	5.46
SK	2	11	15	22	28	23	23	22	11	15	172	99%	4.94
							DEPTH						
COUNTRY	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total**	**Perc. values >0**	**Mean**
BG	1648	402	309	129	55	27	17	6	3	5	2601	37%	0.76
CZ	566	355	229	108	43	16	9	5	2	0	1333	58%	1.12
DE	1086	552	295	119	62	24	11	3	0	1	2153	50%	0.91
EE	658	412	124	54	20	10	2	0	0	0	1280	49%	0.75
HU	223	149	105	62	24	9	6	2	1	0	581	62%	1.28
IT	1467	772	308	105	49	16	6	5	1	3	2732	46%	0.76
LT	176	63	30	12	6	5	0	0	0	0	292	40%	0.71
LV	70	27	23	13	4	3	1	0	0	0	141	50%	1.06
PT	937	455	270	142	68	27	17	7	1	5	1929	51%	1.06
RO	533	272	159	96	53	21	6	3	1	8	1152	54%	1.15
SK	80	53	23	11	4	1	0	0	0	0	172	53%	0.89

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